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Naval Facilities Engineering Command
ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4370

CONTRACT REPORT
CR 11.003-OCN

NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

OTEC Technology Development Report

Contract N62583-09-C-0083, CDRL A002

Prepared for:
Naval Facilities Engineering Service Center (NAVFAC ESC)

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The Navy views OTEC technology as a potentially viable means to reduce dependence on fossil fuel for electricity generation at bases located in tropical areas, including Naval Support Facility Diego Garcia (NSFDG), as well as naval facilities in Hawaii and Guam. The Navy's long term objective is the commercialization of OTEC technology to permit purchase of power and water from a privately developed OTEC facility at cost effective rates. Advancing OTEC technology to a commercially viable level is the subject of this design work.

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Executive Summary

Lockheed Martin supported by Makai Ocean Engineering, John Halkyard & Associates, and Sound & Sea Technology, conducted several critical component development tasks associated with the interface between an Ocean Thermal Energy Conversion (OTEC) system Cold Water Pipe (CWP) and platform. This work was part of the effort performed for the Naval Facilities Engineering Service Center, Port Hueneme under Contract N62583-09-C-0083, initiated 21 August 2009. This OTEC Technology Development Report provides the results of the selected critical component work.

The Navy views OTEC technology as a potentially viable means to reduce dependence on fossil fuel for electricity generation at bases located in tropical areas, including Naval Support Facility Diego Garcia (NSFDG), as well as naval facilities in Hawaii and Guam. The Navy's long term objective is the commercialization of OTEC technology to permit purchase of power and water from a privately developed OTEC facility at cost effective rates. Advancing OTEC technology to a commercially viable level is the subject of this design work. A key step to OTEC commercialization is deployment of a Pilot Plant of sufficient size to validate environmental assessment models, system performance, and system cost estimates such that commercial financers will be encouraged to invest in commercial scale projects. Therefore, Pilot Plant requirements included 5 MW net capacity a two year test phase, and eventual scale up to 10 MW.

This report provides the critical component development results. The Lockheed Martin’s OTEC team developed a composite CWP that is fabricated on the platform to eliminate the need to deploy the pipe from shore to the platform site. The critical components addressed under this contract included the CWP termination (the transition from a composite CWP to the steel of the platform), the gripper (the mechanism to hold and lower the CWP during fabrication, the guides (positions the CWP during fabrication), and the environmental enclosure for the CWP fabrication apparatus.

Contract efforts included design development and prototype testing.

1. INTRODUCTION

1.1 Background

The Naval Facilities Command (NAVFAC) Ocean Thermal Energy Conversion (OTEC) Project is structured to advance commercialization and promote future development of OTEC technology for Navy applications. The Navy views OTEC technology as a potentially viable means to reduce dependence on fossil fuel at bases located in tropical areas, including Naval Support Facility Diego Garcia (NSFDG), as well as naval facilities in Hawaii and Guam.

Navy's *long term objective* is the commercialization of OTEC technology to permit purchase of power and water from a privately developed OTEC facility at cost effective rates. Advancing OTEC technology to a commercially viable level is expected to involve several significant interim steps. At present, both industry and the Government are working on development of various subsystems and testing to validate component designs. As an example, the Department of Energy (DOE) is currently funding cold water pipe development/testing; and NAVFAC is supporting Congressional funded heat exchanger development/testing and conducting additional efforts to assess OTEC feasibility and perform seafloor surveys at potential Navy OTEC locations.

The Navy’s *near term objective* is to support technical efforts that reduce overall system developmental risks with respect to critical components and subsystems. The Navy awarded a contract in 2009 to a Lockheed Martin (LM) Industry Team to accomplish elements of the near term objective. One major task developed the interface between the Cold Water Pipe (CWP) and the platform. The LM Industry Team separately developed a composite CWP design fabricated on-site, at-sea to eliminate the risk of deploying the long CWP from shore. For perspective, a 10 Megawatt (MW) capacity CWP has a diameter of four meters and a length of 1,000 meters, whereas a 100 MW CWP has a diameter of 10 meters. The CWP design is based on the ability to mold sections of pipe, lowering the assembly as each section cures. The NAVFAC task developed the hardware to hold the pipe during fabrication and to lower the assembly in preparation for the next molding step.

1.2 Document Scope

This report provides the results of the development and test activities associated with the interface design. The CWP interface to the platform comprises three areas. First, the pipe must be handled during the fabrication phase. The concept for the LM Industry Team approach includes a gripper mechanism to hang onto the pipe and to lower the pipe as the fabrication process increases the pipe length. Second, the approach includes guides attached to the platform through which the CWP is lowered. The guides limit pipe excursion during the fabrication phase. Finally, the pipe must be terminated and attached to the platform. Summaries of activities, test data, and analysis results for each area are provided to document the interface design.

1.3 Organization of the Technology Development Report

Major sections of the report are organized to make it easy for the reader to understand how the critical components were identified and to follow the analysis and design thread in the document. The following is a list of the top level sections in the report.

2. REFERENCE DOCUMENTS

2.1 Program Documents

Document Title/Author	Date/Rev Status
Contract CDRL A001 Technology Development Plan	
Contract CDRL A002 Technology Development Report	
Contract CDRL A007 First Quarterly Status Briefing Materials Quarterly	
Contract CDRL A007 Second Quarterly Status Briefing Materials Quarterly	17 February 2010
Contract CDRL A007 Third Quarterly Status Briefing Materials Quarterly	28 May 2010 (?)
Contract CDRL A008 Environmental Compliance Plan	
Contract CDRL A009 Project Health and Safety Plan	
Contract CDRL A010 Technology Development Briefing	
Contract CDRL A011 OTEC System Design Briefing	
To be completed for final submission	

3. CRITICAL COMPONENTS

The critical components selected for development and testing for the NAVFAC project are all associated with the safe, reliable and survivable mechanical and hydraulic connection of the recommended Fiberglass Reinforced Plastic (FRP) CWP to the Steel Platform. There are two distinct operational "phases" of concern as well as several specific components associated with the successful handling of the CWP and attachment of the CWP to the platform. The first phase is the CWP fabrication phase and the second is the Operational phase or power production phase. These phases and components are described briefly in this section.

3.1 Integrated System Overview Context for Critical Components

The successful development, deployment, installation, operations and de-installation of an OTEC system is dependent upon several other major systems. Figure 1 illustrates the relationship between the Operational OTEC System and the supporting Installation System. A significant component of the Installation System for a commercial OTEC system is expected to be the CWP Fabrication System, consisting of the Gripping and Handling Segment, CWP Fabrication Apparatus (CWP-FA) Segment and the CWP Fabrication Environmental Enclosure (CWP-FEE) Segment. The CWP-FA Segment is being developed outside of the scope of this contract, but it very much drives the design of the Environmental Enclosure and the Gripping and Handling Segment, not to mention the OTEC Platform itself. Together, these three segments allow for fabrication and safe handling of the pipe during its on-site manufacturing process.

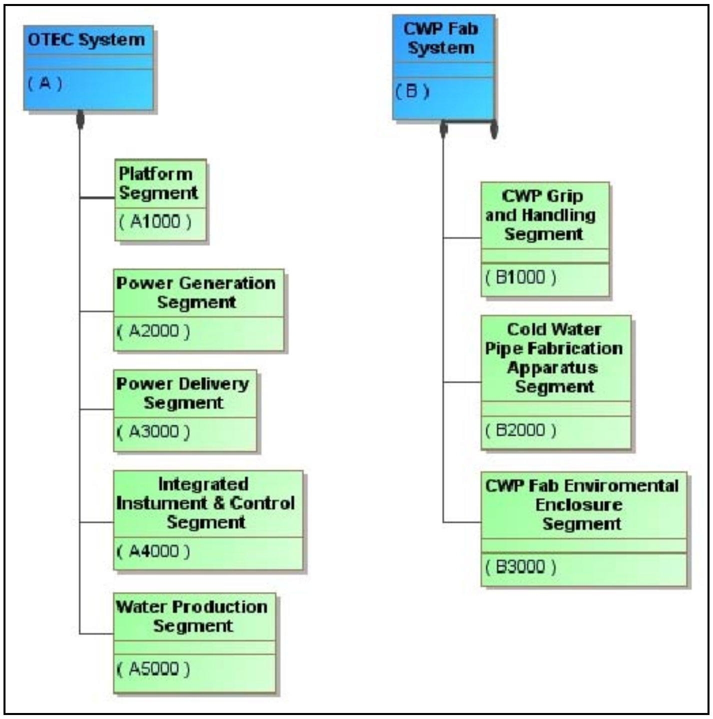


Figure 1. OTEC System and CWP Fabrication System Relationship

3.2 System Architecture

As a reminder, the operational OTEC System is made up of Segments, Elements, Subsystems and Components as shown in Figure 2. The CWP is a component of this system, and is connected to the Platform Hull structure via two additional critical components, the CWP-Termination which transitions from composite material to steel and the CWP and Platform Connection which may be either a fixed flange coupling or a gimbaled coupling.

3.3 Critical Components and Top Level Requirements

Requirements for the critical components were derived during the course of this contract and are reflected in the applicable sections of this document. The Top Level Requirements (TLR) are included in the appendix. These include requirements for:

- Gripping & Handling Segment and all of its major components
- CWP-FEE Segment
- Pipe Termination
- Pipe and Platform Attachment and Gimbal

3.4 Critical Component Design

Preliminary design of the critical components was completed to varying levels of detail based, in large part, on the need to prototype and tests certain components while others needed to be understood in terms of their ultimate size and weight as well as cost. This report will detail the rigorous analysis employed in this design along with design trades conducted and ultimate designs captured in detailed drawings and specifications.

3.5 Testing Program

Some of the components were selected for scaled testing, based upon technical needs and budgetary limitations of the project. Testing plans evolved over time as the designs matured and detailed analysis revealed greatest risk areas on which to focus. Details on the tests performed for each critical component are provided in relevant sections herein.

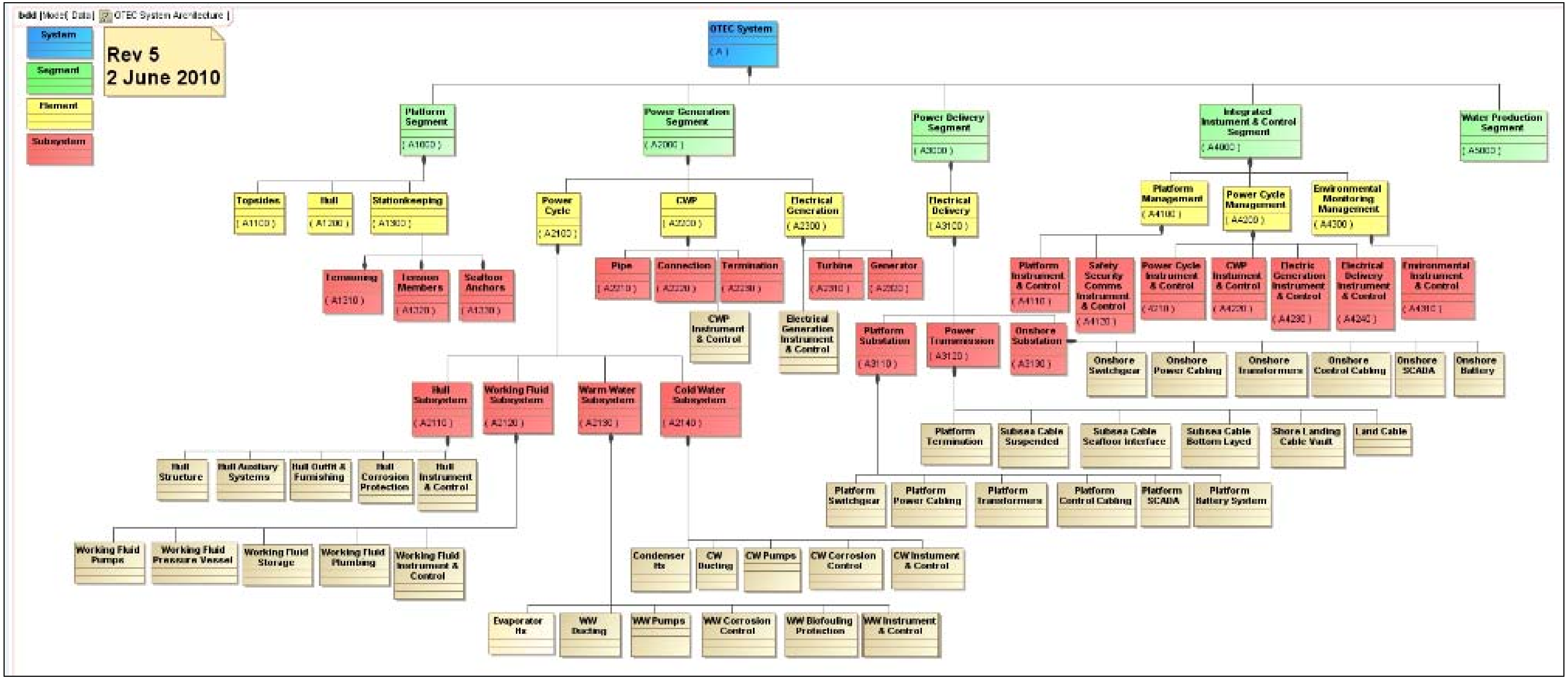


Figure 2. OTEC Systems Architecture

4. PIPE AND PLATFORM BACKGROUND

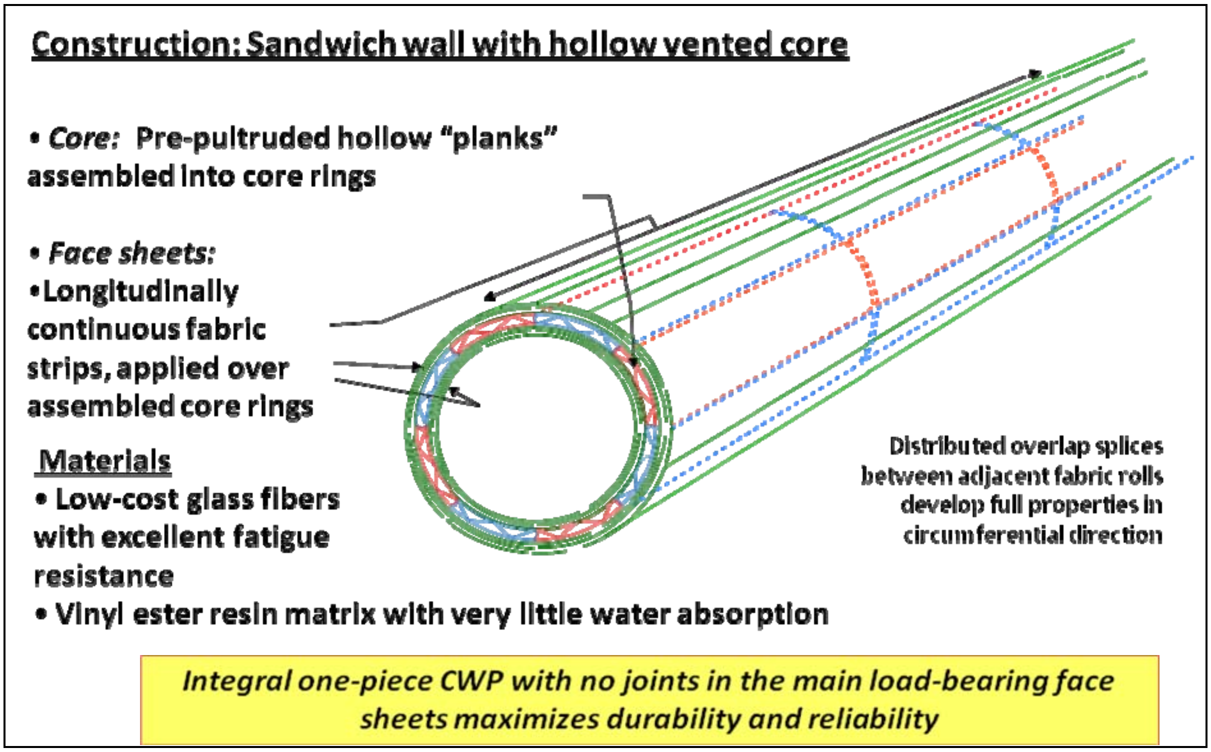
This section describes the CWP and Platform components. The next section describes the interfacing of these two main components and how the CWP attaches to the Platform.

The OTEC program design employs metric dimensioning however as the detailed design of the gripper and guides, and the CWP progress units are being switched to English dimensioning since US fabricators will be building the components.

4.1 Cold Water Pipe

4.1.1 General Arrangement

The architecture of the composite Cold Water Pipe (CWP) is shown in Figure 3. The use of fiberglass as the structural material confers a relatively high strain tolerance, to handle the dynamic transverse bending motions created by platform motions (with or without a gimbal). The sandwich wall construction resists global buckling from net suction external pressure, and local buckling from constrained gripper and guide bushing pressures. The hollow pultruded sandwich core is fully vented to seawater which eliminates trapped air inside the core. It also makes the CWP only slightly negatively buoyant, and ensures that only the laminate itself has to resist high water pressures at depth and eliminates the usual problem of crushing of the core of a sandwich laminate used at depth. The integral one-piece construction enhances structural reliability and eliminates the major stress concentrations that would be present in a pipe assembled from separate sections.



Construction: Sandwich wall with hollow vented core

- ***Core:*** **Pre-pultruded hollow "planks" assembled into core rings**
- ***Face sheets:***
- **Longitudinally continuous fabric strips, applied over assembled core rings**

Materials

- **Low-cost glass fibers with excellent fatigue resistance**
- **Vinyl ester resin matrix with very little water absorption**

Integral one-piece CWP with no joints in the main load-bearing face sheets maximizes durability and reliability

Figure 3. Composite CWP Architecture

4.1.2 Fabrication Process Summary

The integral CWP is fabricated directly on the OTEC platform, as illustrated in Figure 4. The fabrication process is termed "stepwise infusion molding and is illustrated schematically in Figure 5. This figure shows how dry fabric (and pultruded core) can be introduced into the molding region and one step of the fabric infused by resin and molded by VARTM, without having to cut the fabric from the supply rolls. This in turn is what enables the one-piece CWP manufactured off of the platform. A 4m CWP version of the apparatus is illustrated in Figure 6, illustrating the complete concept design that implements the process. The actual molding region of this apparatus is shown in Figure 7 illustrating the size and maturity level of the hardware-based validations being conducted under the DoE AWPP program.

A gripper and guide bushings are needed to support the CWP vertically and horizontally, and hold it stationary during the actual molding operation as shown in Figure 4. The gripper must also serve as a "translator" to control the movement of the CWP downward in between molding steps. The fiberglass fabric, resin, and curing agents must all be kept free from excessive moisture during fabrication, which leads to the need for an environmental enclosure. The environmental enclosure also performs the material handling function of elevating the rolls of fabric and pultruded core "planks" to the upper portions of the apparatus where they are utilized.

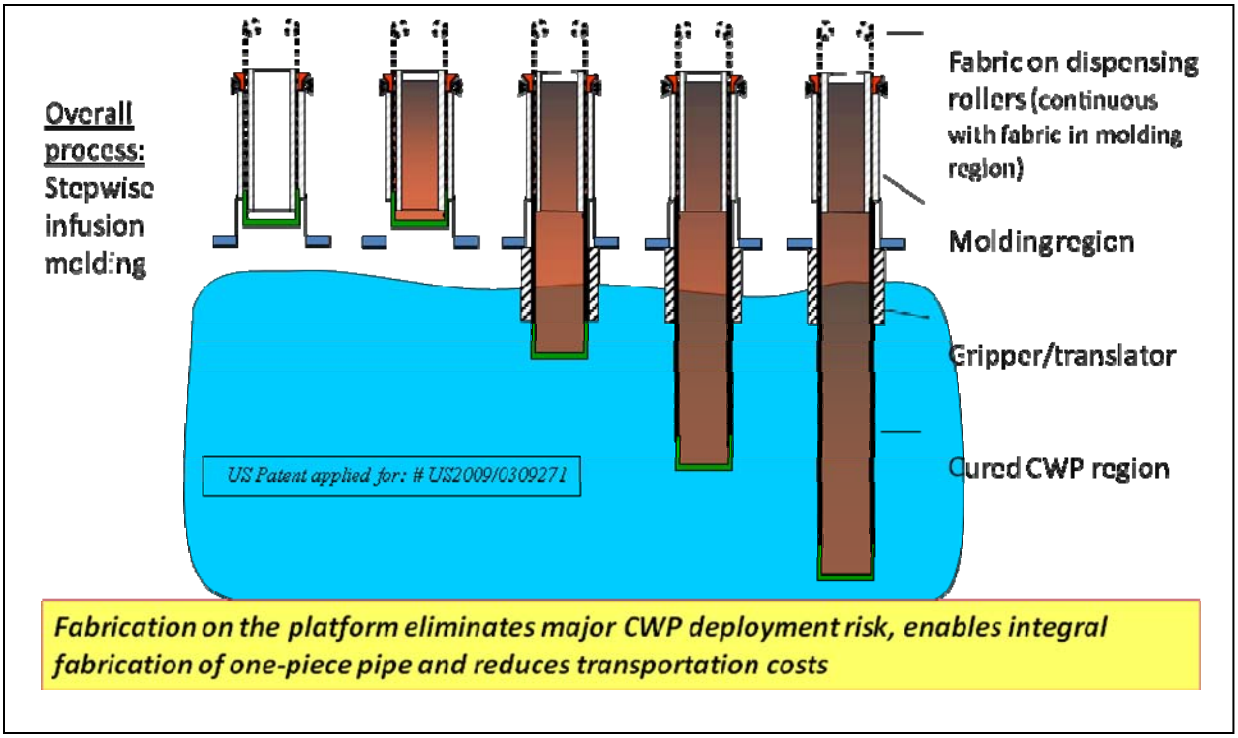
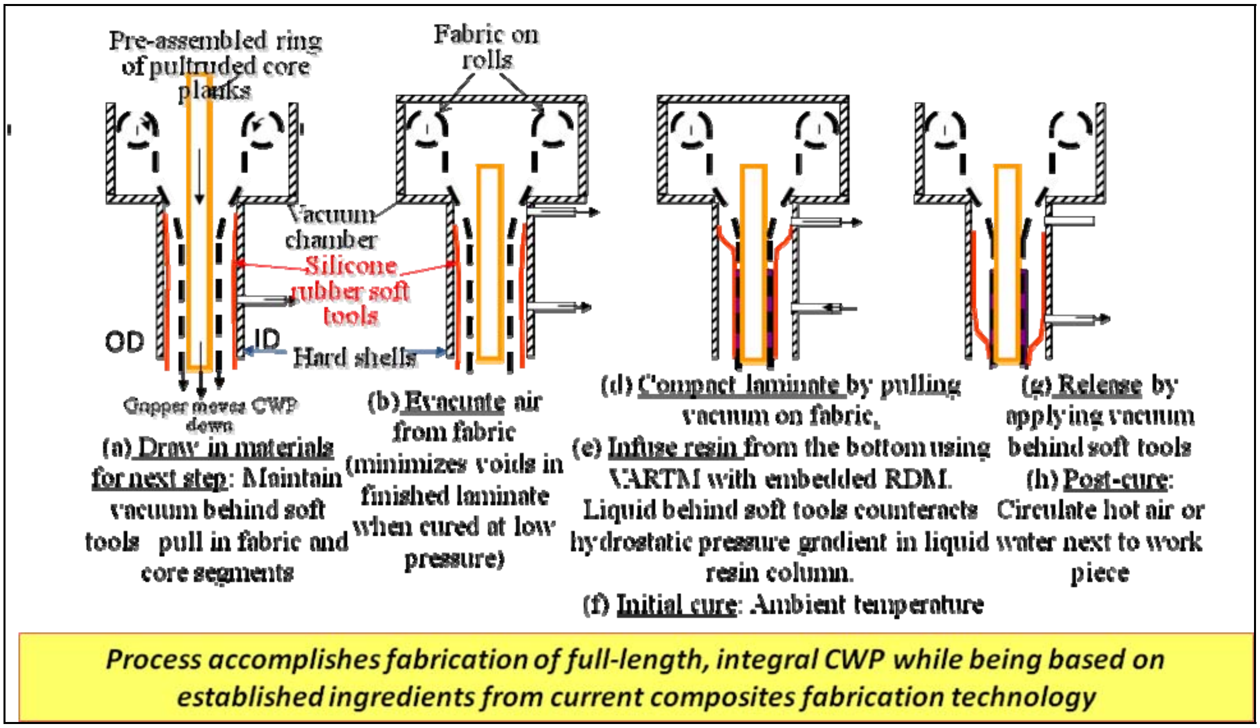


Figure 4. Fabrication Strategy: Manufacture CWP on OTEC Platform



(a) Draw in materials for next step: Maintain vacuum behind soft tools pull in fabric and core segments

(b) Evacuate air from fabric (minimizes voids in finished laminate when cured at low pressure)

(d) Compact laminate by pulling vacuum on fabric,

(e) Infuse resin from the bottom using VARTM with embedded RDM. Liquid behind soft tools counteracts hydrostatic pressure gradient in liquid resin column.

(f) Initial cure: Ambient temperature

(g) Release by applying vacuum behind soft tools

(h) Post-cure: Circulate hot air or water next to work piece

Process accomplishes fabrication of full-length, integral CWP while being based on established ingredients from current composites fabrication technology

Figure 5. Stepwise Infusion Molding Process Using VARTM

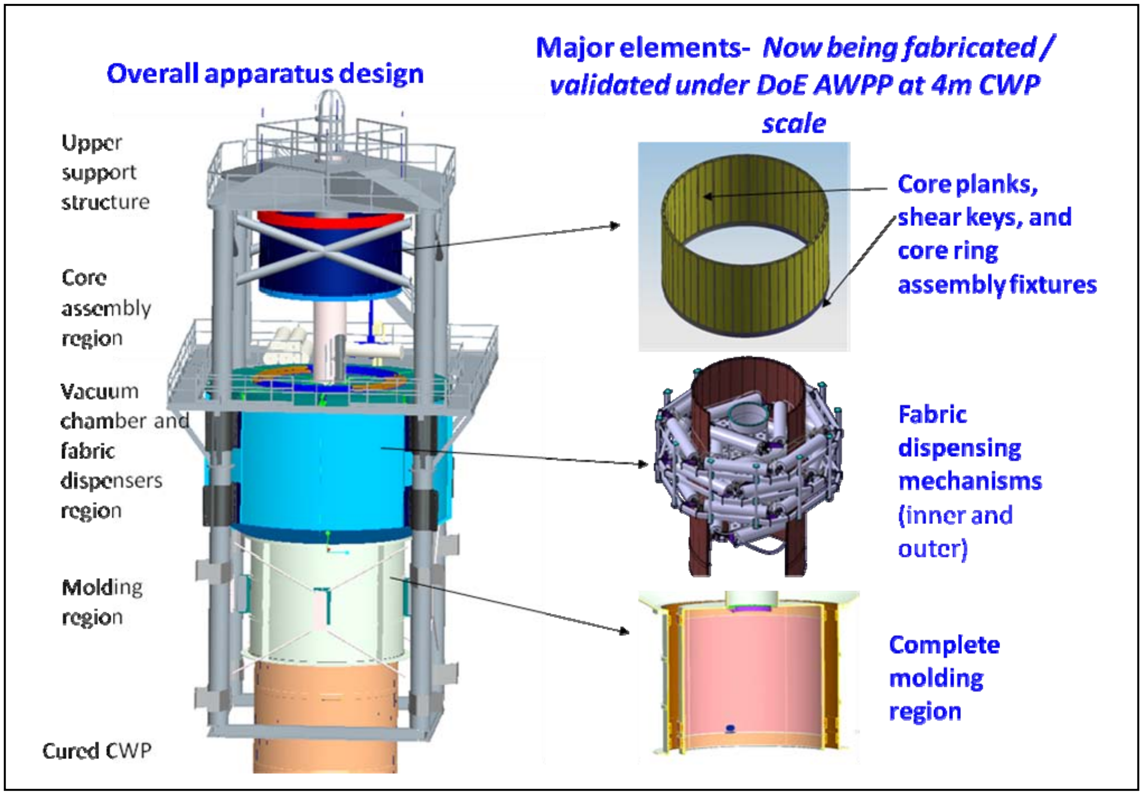


Figure 6. Solid Model of 4m CWP Fabrication Apparatus

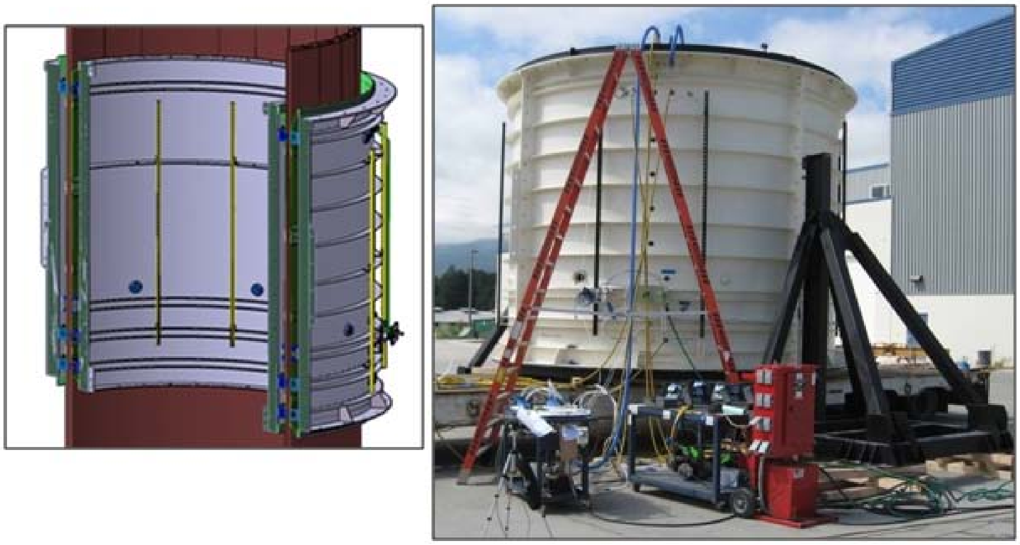


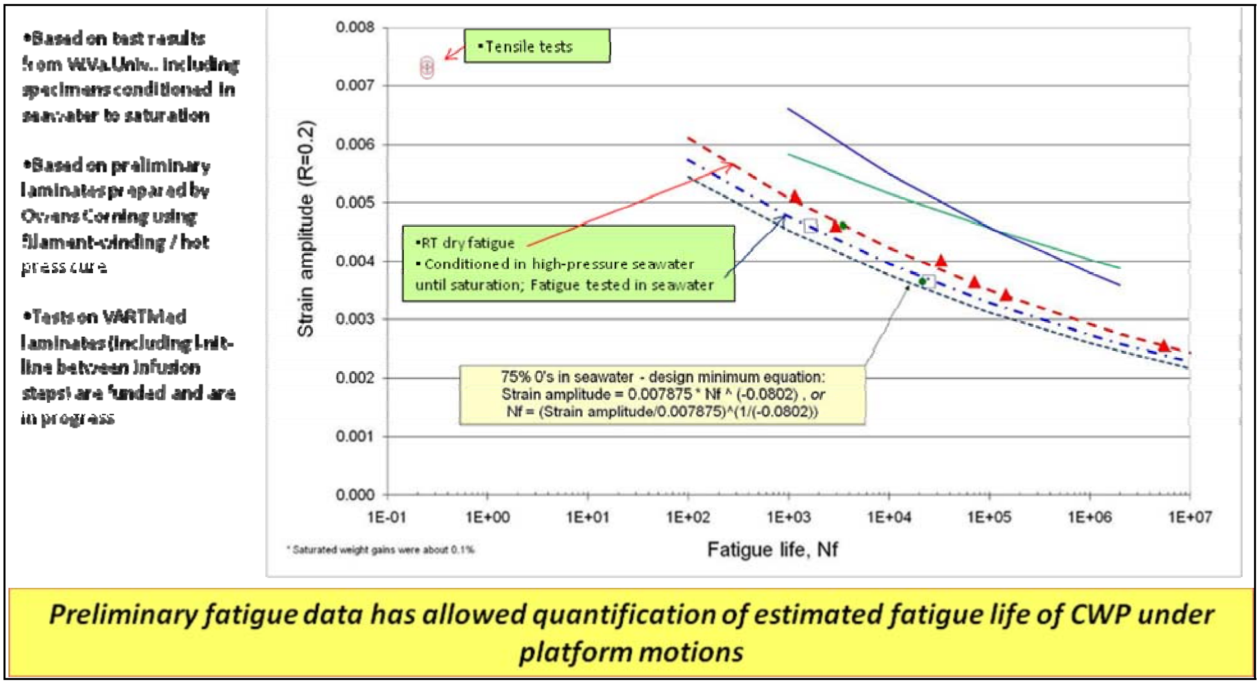
Figure 7. Molding Region of 4m CWP Fabrication Apparatus

4.1.3 Fatigue Characteristics of the CWP Material

A partial characterization of the fatigue characteristics of the selected CWP material (X-Strand/vinyl ester) is complete at this point and is shown in Figure 8. It is based on preliminary laminates prepared from available X-Strand “tow” by Owens Corning using a filament-winding / hot press cure. This test data will soon be supplanted by repeating the tests using the actual 4m CWP X-Strand fabric with the actual VARTM process. The data for fatigue in air on unconditioned specimens indicate an S-N behavior typical of fiberglass; over the range of data a 20% change in strain level produces a roughly 100X change in cycles to failure. The data for specimens conditioned in high-pressure, ambient-temperature to saturation and tested in seawater show only about a 6% decrease in strain capability for equal Nf, which is a primary reason for use of a vinyl ester resin.

4.1.4 Pressure Capability

Resistances to both global and local buckling are important requirements for the CWP. Global buckling strength is required for this large pipe to resist the roughly ½ atm (7.5 psi) net external pressure at the top of the pipe). Figure 9 shows that the triangular core design works well, conferring a global buckling pressure roughly 5X the requirement.



- Based on test results from W.Va.Univ., including specimens conditioned in seawater to saturation
- Based on preliminary laminates prepared by Owens Corning using filament-winding / hot press cure
- Tests on VARTM'ed laminates (including knit-line between infusion steps) are funded and are in progress

- Tensile tests

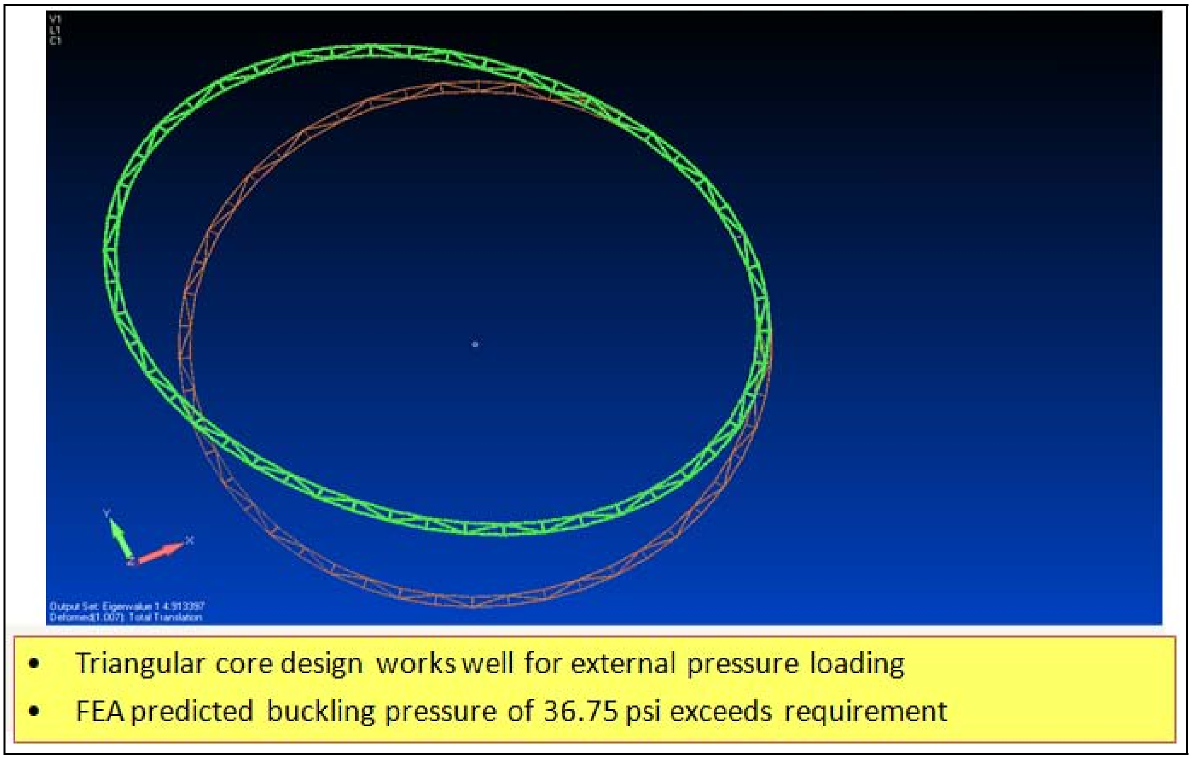
- RT dry fatigue
- Conditioned in high-pressure seawater until saturation; Fatigue tested in seawater

75% 0's in seawater - design minimum equation:
Strain amplitude = 0.007875 * Nf ^ (-0.0802) , *or*
Nf = (Strain amplitude/0.007875)^(1/(-0.0802))

* Saturated weight gains were about 0.1%

Preliminary fatigue data has allowed quantification of estimated fatigue life of CWP under platform motions

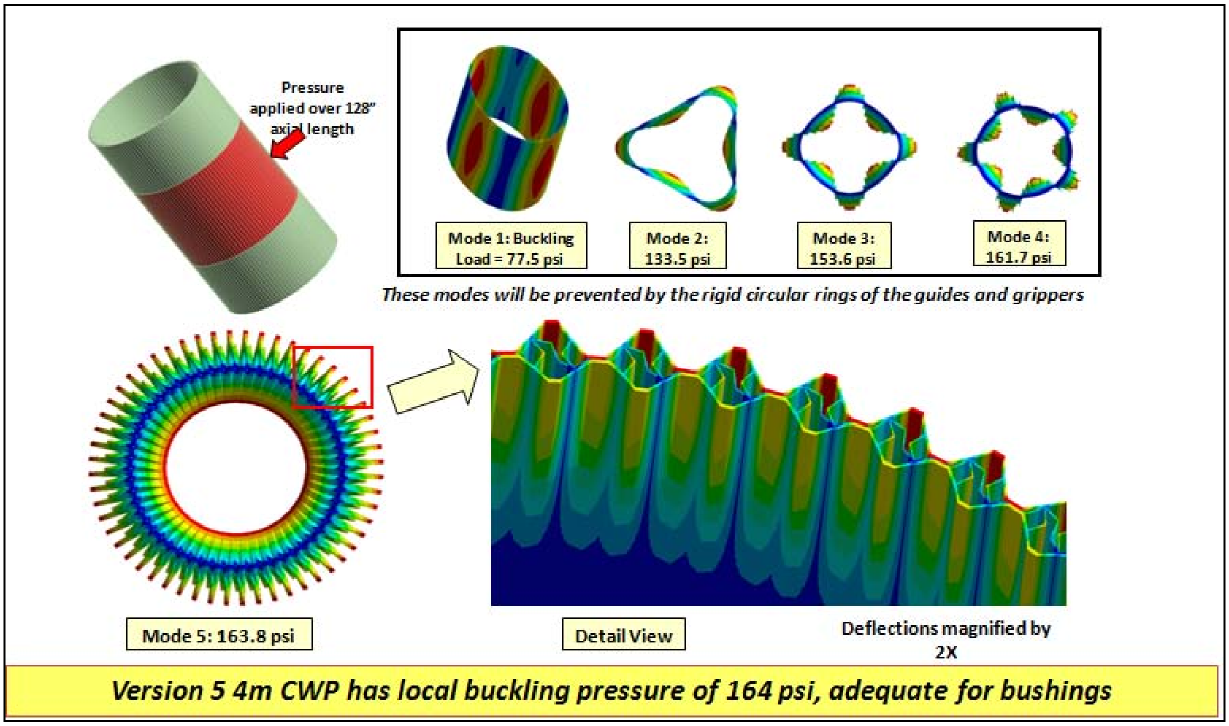
Figure 8. Fatigue From Platform Motions



- Triangular core design works well for external pressure loading
- FEA predicted buckling pressure of 36.75 psi exceeds requirement

Figure 9. Global Buckling: 10m CWP Capability

In the gripper and guide bushing regions, the pipe is held circular by the mechanisms and cannot undergo global buckling to a non-circular shape. However, higher pressures are induced where the gripping and guiding elements contact the pipe, and these local pressures can induce local buckling. The current bushing design is calculated to impose 50 psi, and 70 psi is envisioned in future designs. Figure 10 shows by FEA that the current Version 5 CWP undergoes local buckling at 164, and would have a Safety Factor of 2.4 which is considered sufficient.



These modes will be prevented by the rigid circular rings of the guides and grippers

Version 5 4m CWP has local buckling pressure of 164 psi, adequate for bushings

Figure 10. Local Buckling: 4m CWP Capability

4.2 Platform

The design basis for this project is focused on a pilot plant rated at 10 MW net average power delivery. However, in order to evaluate the scale up of the pilot plant and its adequacy for proving a commercial scale system, some analysis was carried out for the pipe-platform interface for a commercial 100 MW platform. This section describes the platform adopted for this purpose. It is based on a conceptual study conducted in 2008. This configuration is used for the analysis of termination strength and fatigue for the 10m pipe.

4.2.1 100 Megawatt Platform

The full production configuration consists of a semi-submersible and eight Remoras as shown in Figure 11 and Figure 12. Figure 11 shows the elevation profile and Figure 12 shows the deck plan. Each Remora includes either a condenser (cold water) or evaporator (warm water) system rated at 25 MW. Cold water is fed from the cold water pipe, suspended at the center of the pontoon deck, to the condenser remoras through large ducts. Figure 13 shows the pontoon plan including the cold water ducts. Table 1 gives the principle particulars for the platform without and with the full complement of remoras. The remoras will be absent for the pipe fabrication stage.

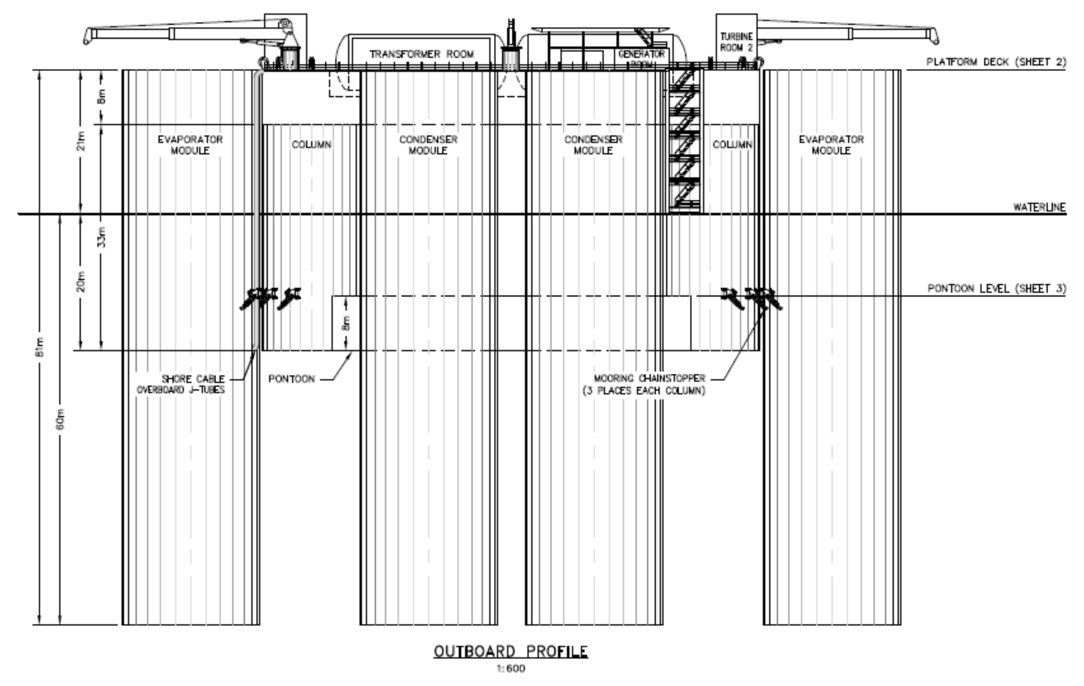


Figure 11. Outboard Profile, 100 MW OTEC Platform

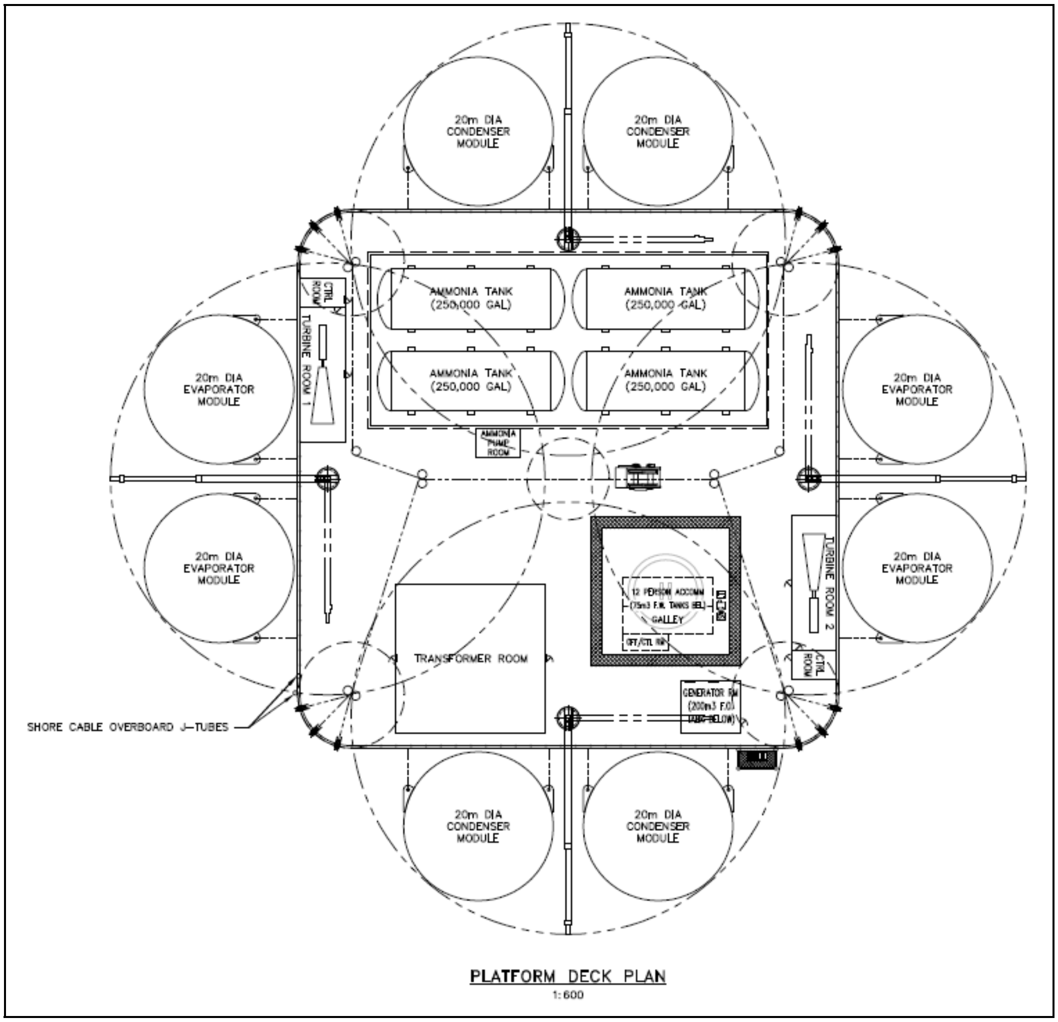


Figure 12. Deck Plan, 100 MW OTEC Platform

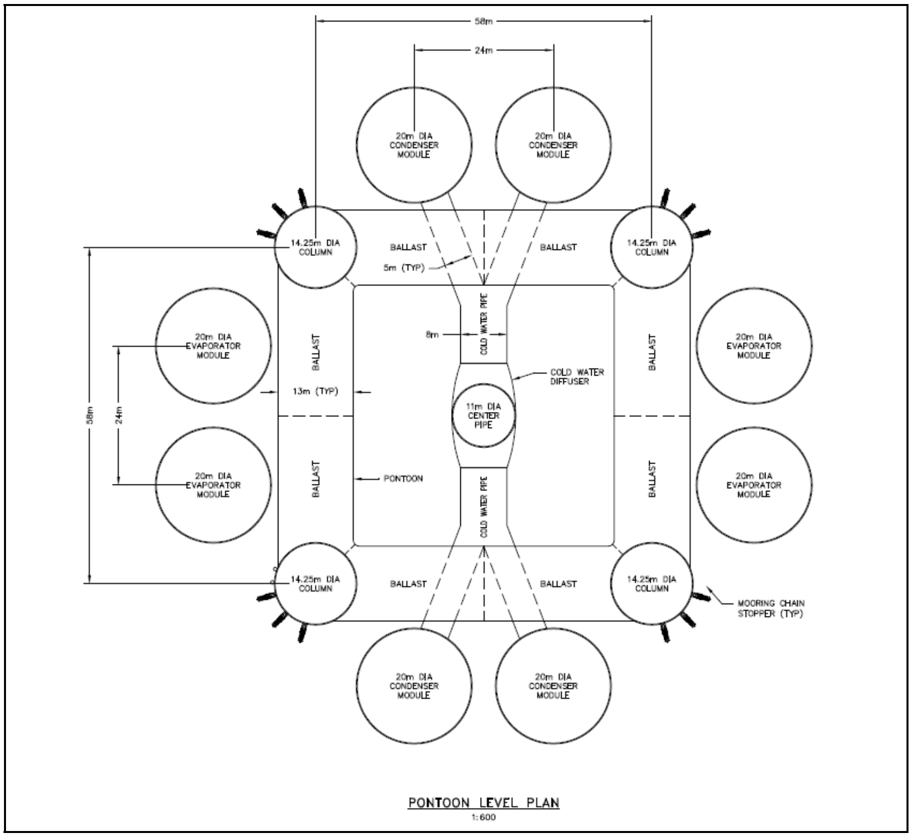


Figure 13. Pontoon Level Plan, 100 MW Platform

Table 1. Particulars for the 100 MW OTEC Platform

	Production	**Pipe Fab No Remoras**
Topsides Equipment Weight, t	4600.0	4600.0
Total Topsides Weight, t	9091.1	9091.1
Draft (hull), m	20.0	20.0
Draft (Remora), m	60.0	60.0
Freeboard, m	21.0	21.0
Air Gap, m	13.0	13.0
Column Spacing, m	58.0	58.0
Column Diameter, m	14.3	14.3
Hull Weight, t	5864.1	5864.1
Ballast Weight, t	15253.0	15637.8
Entrained Water Weight, t	3419.7	3419.7
OTEC Module Weight, t	155253.6	1.0
Total Weight, t	188881.5	34013.7
CG, m (from waterline)	-29.2	-4.3
External Vertical Loads, m	3500.0	3500.0

	Production	Pipe Fab No Remoras
Total Displacement, t	192381.5	37513.7
GM, m	20.4	5.6
Number of Mooring Lines	12	12

4.2.2 10 Megawatt Platform

The proposed pilot plant platform is illustrated in Figure 14 and the dimensions are shown in Figure 15. It is a smaller version of the 100MW platform described above, with two remoras instead of eight. In the case of the pilot plant, each remora contains both condensers and evaporators. During pilot plant operations with only 5MW produced, there will be only a single remora present.

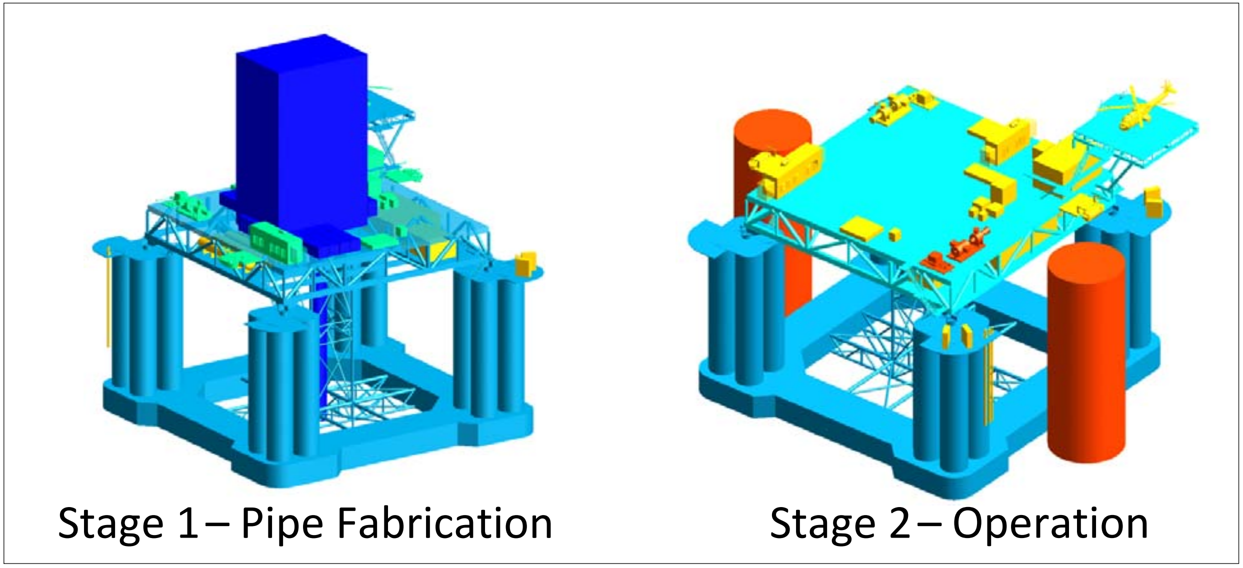


Figure 14. 10MW Pilot Plant

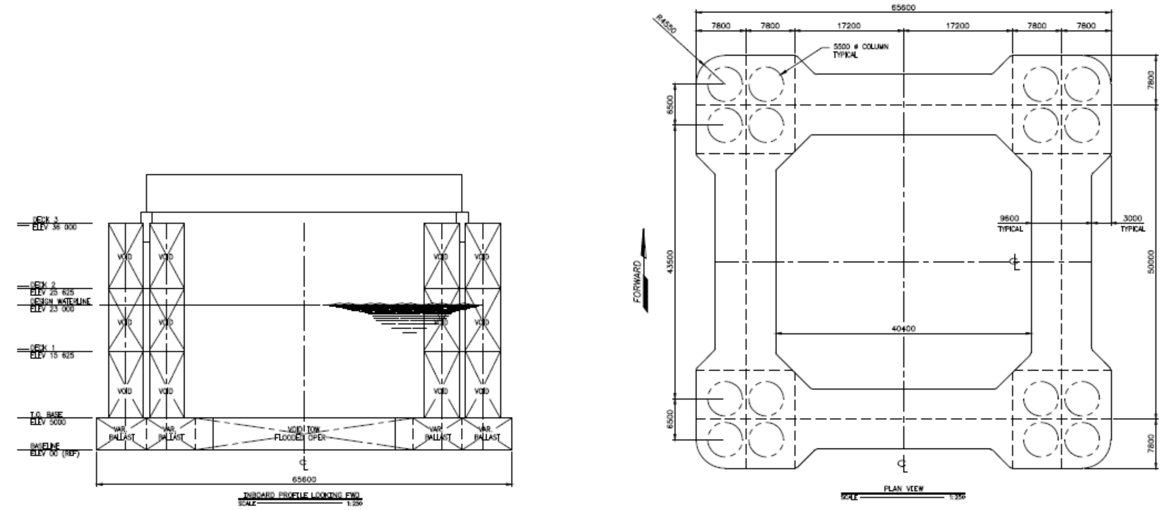


Figure 15. Pilot Hull Plant Dimensions

Table 2 gives the principle particulars for the pilot plant platform for Stage 1 during pipe fabrication when Remoras are not present and for Stage 2 during operations when Remoras are present.

Table 2. Particulars for 10MW Pilot Plant

Particulars	Stage 2 Pipe Manufacturing	Stage 1 Production
Topsides Equipment Weight, t	1989	1500
Draft (hull), m	23.0	23.0
Draft (Remora), m	71.0	71.0
Freeboard, m	21.0	21.0
Air Gap, m	13.0	13.0
Column Spacing, m	50.0	50.0
Column Diameter, m	11.0	11.0
Topsides Weight, t	4153.0	3668.0
Hull Weight, t	6481.0	6481.0
Ballast Weight, t	8067.	8067.
Entrained Water Weight, t	261.0	261.0
OTEC Module Weight, t	16122.0	16122.0
Total Weight, t	18879.0	34598.0
CG, m (from waterline)	-8.0	-20.6
External Vertical Loads, m	1158.0	1159.0
Total Displacement, t	19635	35757.0
GMx, m		8.0
GMy, m		30.2

5. PIPE TO PLATFORM ATTACHMENT

5.1 Introduction

This chapter focuses on the final connection between the CWP and the platform. The connection between these two systems during CWP fabrication are the subject of the following chapter.

Throughout this chapter and the next, two different OTEC systems are discussed and analyzed. The first is a commercially sized100MW OTEC system with its corresponding 10m diameter CWP that is the long term goal of the program. The second is a 10MW prototype OTEC plant with a 4m diameter CWP that is the immediate goal and the detailed design focus of this program. The purpose of the pilot plant is to gain experience in order to be able to design and build the much larger commercial plant. Thus, a preliminary understanding of the 10m CWP and connection is necessary in order to design the smaller prototype. Preliminary work has been performed on the 10m CWP and platform,. A more detailed analysis has been completed on the 10MW prototype system.

The CWP toPlatform connection design has been highly iterative. This relationship is shown in Figure 16. The CWP geometry, size and material characteristics dictate the limits and the response of this large structure. The Platform's shape and dynamic behavior coupled with the sea states and currents were the driving forces of the design. Throughout the design, alterations in all these factors were actively considered.

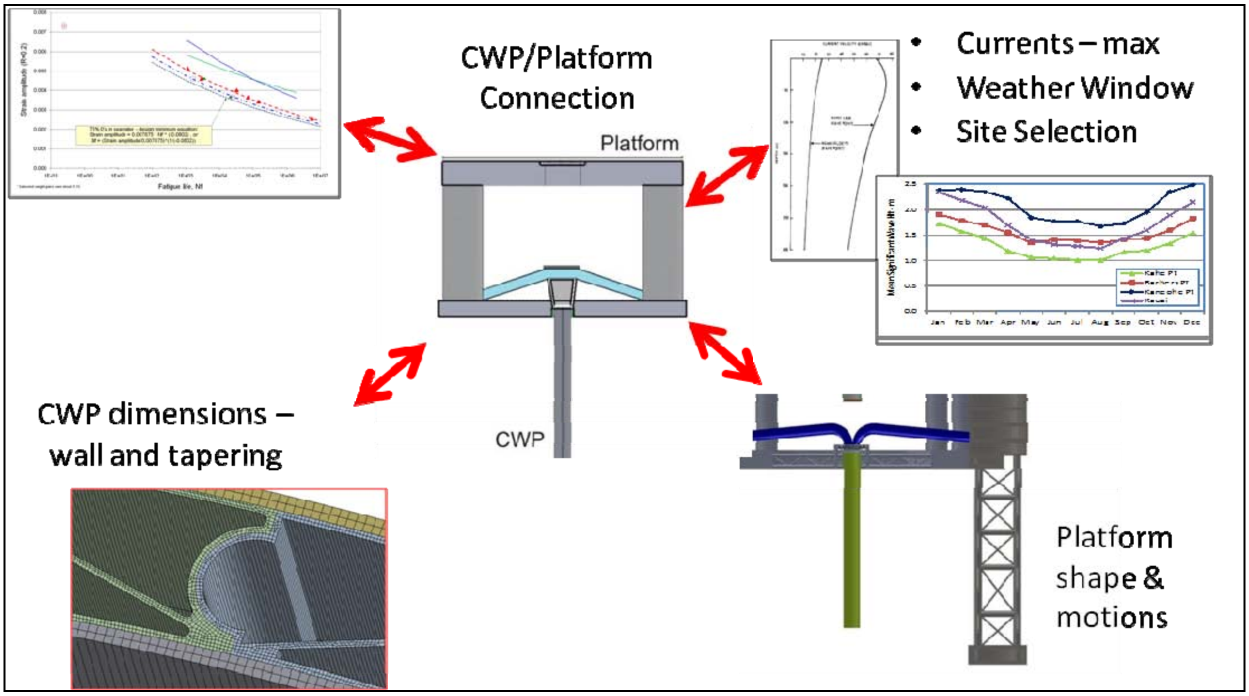


Figure 16. CWP/Platform Connection

As an example, early in the program the dynamic analysis indicated that the fatigue life of the CWP directly coupled with the platform was not satisfactory. As a result the following were considered:

a. Is the analysis correct; are the programs being used valid? The offshore oil programs being used were being challenged by analyzing two large coupled structures, each of which are sufficiently large to dramatically affect the motions of the other.

b. Is physical model testing needed?

c. Should we consider wave directionality? Conventional fatigue analysis considers all waves from one direction and thus fatigue is concentrated on one side of the CWP; by taking into account actual wave directionality, strains are distributed around the CWP.

d. Is the stiffness between the structures being adequately represented? The programs indicated that the results were significantly affected by this stiffness.

e. Why is there a difference between the 10m and the 4m CWPs?

f. Can a Gimbal be used to decouple the two structures?

g. Can a tapered sleeve be added to the platform to relieve the strains in the CWP?

h. Would an alternate platform shape perform better?

i. Could a tapered sleeve be built into the CWP near the platform to relive strains?

j. Can the materials of the CWP near the connection be changed to increase fatigue life – such as S-Glass and carbon fiber?

The logic tree that was established for this analysis is presented in Figure 17. If the fatigue analysis was unsatisfactory, we would consider tapers, alternate fibers and wave directionality. If these were not viable solutions, then a gimbal would be analyzed. If unsatisfactory, large changes to the CWP and platform would have to be considered. If satisfactory, then the details of the gimbal had to be considered for installation ease.

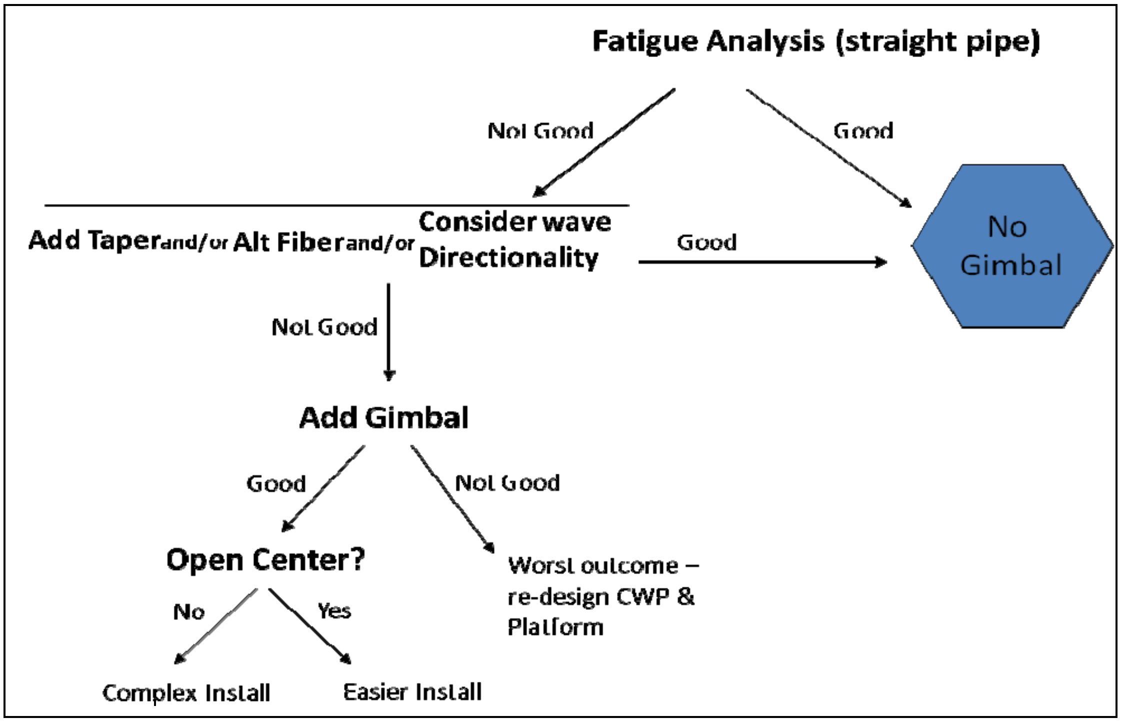


Figure 17. Logic Diagram for Gimbal or No Gimbal

5.2 CWP/Platform Dynamics during Operation

5.2.1 Reference Reports by Halkyard and Shi

Table 3 lists various reports and other references produced in conjunction with the CWP analysis effort, and summarizes the contents. Specific citations are included in the text where appropriate.

Table 3. Cold Water Pipe and Platform Analysis Reports

1. Makai Ocean Engineering, “Preliminary Gripper Analysis - Sizing, Arrangement & Performance”, Nov. 2, 2009	Initial design of 10m Gripper and Guides: forms basis for subsequent analysis [6]
2. Houston Offshore Engineering, “OTEC FRP Pipe Design - Results for Various CWP Bottom Clump Weights and CWP Top Connections”, 4th December, 2009	Analyze sensitivity to clump weight: none required for 10m pipe.
3. John Halkyard & Associates, “Metocean Design Conditions for a Moored OTEC Pilot Power Plant (Barbers Point)”, Technical Note 2009-124, December 9, 2009	Design Environments for Barbers Point
4. John Halkyard & Associates, “Cold Water Pipe / Gripper Analysis Plan”, Technical Note TN09-125, December 16, 2009	Defines metocean conditions and load cases for Gripper Analysis.
5. John Halkyard & Associates, “Metocean Design Conditions for a Moored OTEC Pilot Power Plant (Kahe, Pt)”, Technical Note 2009-123, December 17, 2009	Design Environments for Kahe Point
6. Houston Offshore Engineering, “OTEC Cold Water Pipe Analysis - CWP Gripper Load Dynamic Analysis”, 17th December, 2009	Explicit analysis of loads on grippers and guides, and deflection of pipe at top.
7. John Halkyard & Associates, “Metocean Data for Potential OTEC Power Plant Sites”, Report 2009-1-2, December 21, 2009	Tabulation of Hindcast Data results used to derive design criteria for Kahe Point, Barbers Point and other potential OTEC sites.
8. Houston Offshore Engineering, “OTEC Cold Water Pipe Analysis - CWP Termination Fatigue Analysis, 4th January, 2009	Initial fatigue analysis of 10m pipe termination. Error in method resulted in incorrect, higher strains, but information on modal responses is useful.
9. Houston Offshore Engineering, “OTEC Cold Water Pipe Analysis - Comparison Study of 4 m OD CWP and 10 m OD CWP for 100 Year Cyclone Environment”, 25th January, 2010	Compares the upper bending strain in a 10m CWP and a 4m CWP for the same top platform motions. The dynamic bending strains for a 4m pipe were about 20% less than a 10m pipe.
10. Shan Shi, OTEC_HOE_mar3_Meeting.ppt, Meeting PowerPoint Presentation, March 3, 2010	Describes validation of HARP Analysis
11. Halkyard, John, “MEMO - Subject: March 3 OTEC Cold Water Pipe / Platform Analysis Meeting Notes”, March 5, 2010	Documents March 3 meeting to discuss software issues
12. Horton Wilson Deepwater, “Global Performance Report Ocean Thermal Energy Conversion (OTEC) MCF”, April 10, 2010	Describes the 10MW Pilot Plant configuration.
13. Houston Offshore Engineering, “OTEC Coupled Analysis Benchmark - HARP vs. FLEXCOM”, April 15, 2010	Benchmarking of two programs: HARP and FLEXCOM to validate approach. Results indicate about 10% accuracy of strains.
14. Horton Wison Deepwater, “Cold Water Pipe Strain Comparisons – ABAQUS vs. CHARM3D”, Technical Note TN-HWD09-008-01, April 15, 2010	Benchmarking of CHARM3D (HARP) vs. ABAQUS. Similar accuracy to that from [13].
15. Houston Offshore Engineering, “100MW OTEC Hydrodynamic Panel Model Sensitivity Study Report”, May 26, 2010	Sensitivity of results to platform hydrodynamic mesh density used. The selected mesh is adequate.
16. John Halkyard & Associates, “OTEC Platform Data for Benchmarking of Pipe – Platform Analysis, TN-10-102, March 30, 2010	Defines platform and pipe properties to be used in software benchmarking activities.
17. Houston Offshore Engineering, “OTEC Termination Study”, 24th June 2010	4m Pipe Termination Study, gimbal & fixed fatigue life, angles, moments and shears in 25-yr and 100-yr conditions at 1E7 and 1E9 N-m/rad top stiffness (to simulate a real gimbal response)
18. Houston Offshore Engineering, “OTEC CWP ANALYSIS - Top Termination Study for 4 m and 10 m Cold Water Pipe – Strength and Fatigue Report”, 25th June 2010	Expanded version of [17] including 10m pipe results for different gimbal stiffness and with tapering.

5.2.2 Physics of Pipe and Platform Responses

The pipe and platform response is essentially a vibration problem, and because ocean waves are irregular, it is a random vibration problem[i].

The response of the cold water pipe to platform motions is driven by two phenomena:

- Resonant excitation of natural modes ("standing waves") due to periodic excitation from platform motions and wave kinematics (wave particle motion in the water column acting on the pipe)
- Transient, traveling waves, from impulsive or non-periodic excitation

The natural mode shapes of an Euler beam are illustrated in Figure 18. Each natural frequency has a natural mode shape. The shape is characterized by points of zero-deflection (nodes) and points of maximum deflection (anti-nodes). From a structural standpoint, nodes are locations of low bending strain because the curvature is low. Anti-nodes are points of relatively large bending strain because the curvature is highest there. Also, for given amplitude, the curvature and bending strain is higher for the higher mode numbers.

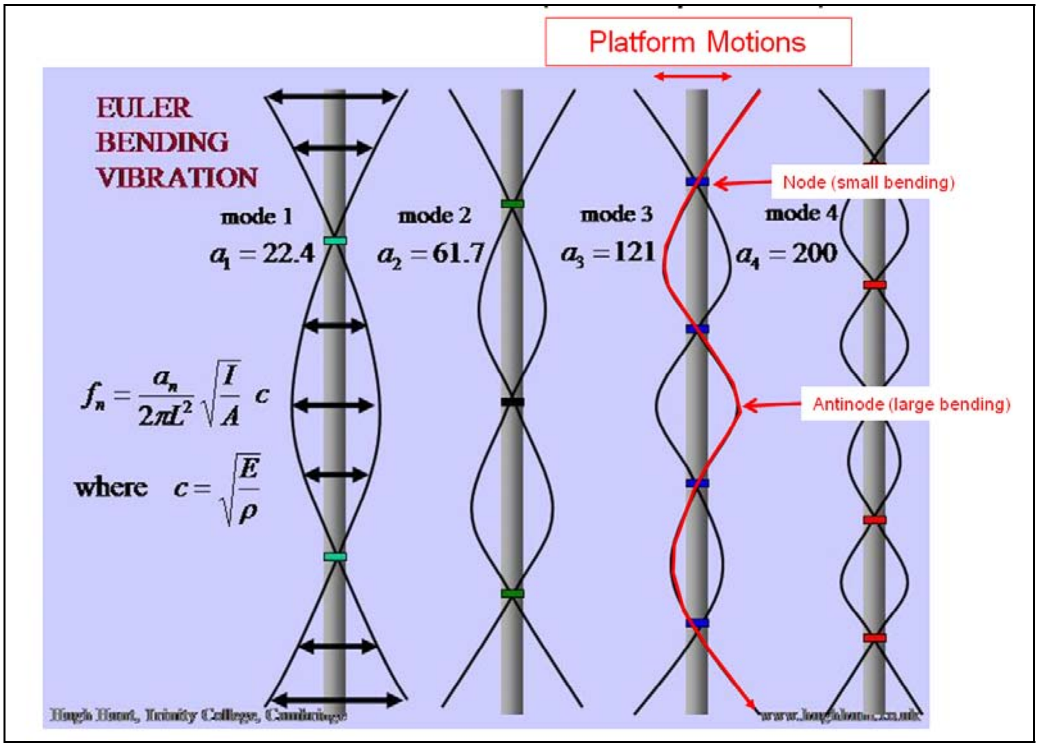
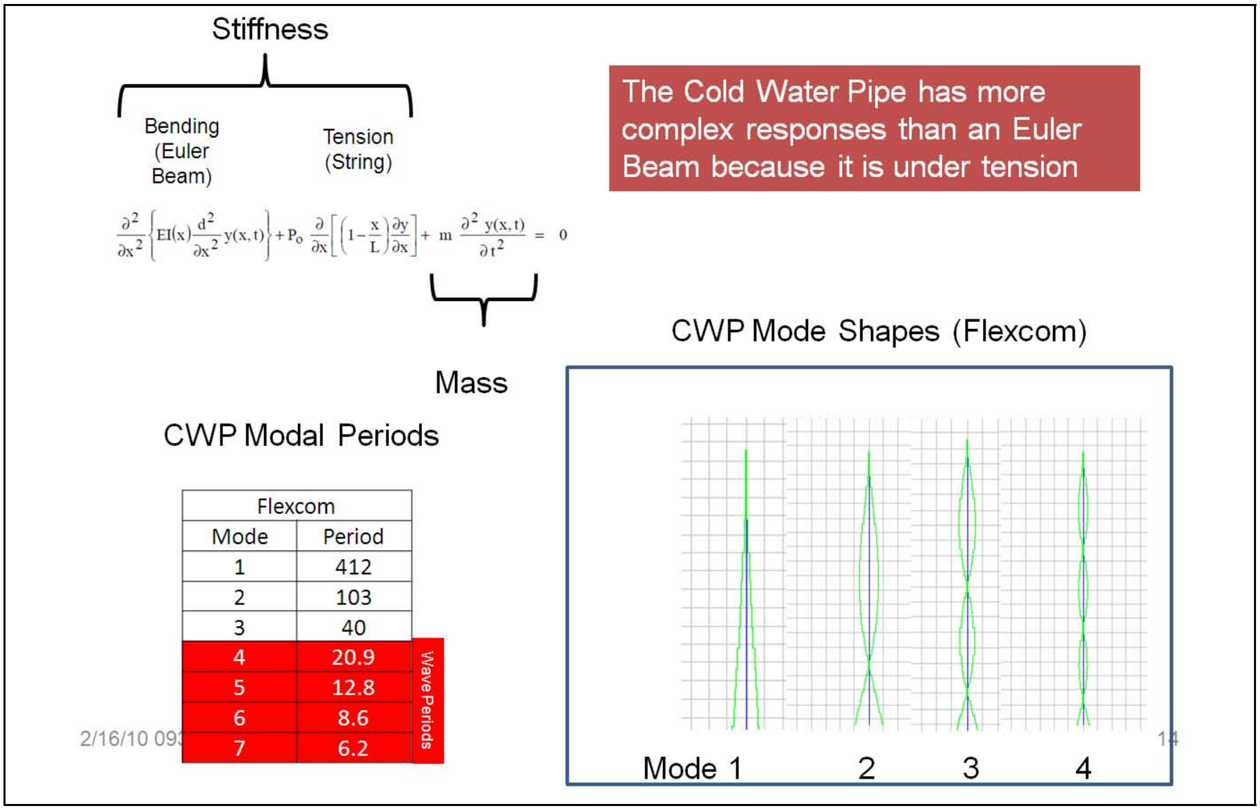


Figure 18. Euler Beam Vibration Modes

Euler beam formulas include only the beam stiffness ("EI") as a restoring force. In risers and the cold water pipe, the tension in the pipe acts as a restoring force, like a violin string. This affect is important near the top of the pipe where the tension is highest, while the pipe stiffness dominates near the bottom of the pipe where tension is low. This tension effect is sometimes referred to as "strain stiffening". It is common in membrane structures as well. The differential equation for a tensioned bean is shown in Figure 19 along with the first four mode shapes for the 10 m CWP (Version 1). The table in Figure 19 shows periods corresponding to the modes. Modes 5 & 6 are in the range of wave energy (5 – 20 seconds) and are the modes most likely to be excited. In practice all the modes are excited to a greater or lesser extend because the excitation (ocean waves) is broad banded and has a range of periods.



Stiffness

Bending (Euler Beam)

Tension (String)

$$\frac{\partial^2}{\partial x^2}\left\{EI(x)\frac{d^2}{\partial x^2}y(x,t)\right\}+P_o\frac{\partial}{\partial x}\left[\left(1-\frac{x}{L}\right)\frac{\partial y}{\partial x}\right]+m\frac{\partial^2 y(x,t)}{\partial t^2}=0$$

Mass

The Cold Water Pipe has more complex responses than an Euler Beam because it is under tension

CWP Modal Periods

Flexcom	
Mode	Period
1	412
2	103
3	40
4	20.9
5	12.8
6	8.6
7	6.2

Wave Periods

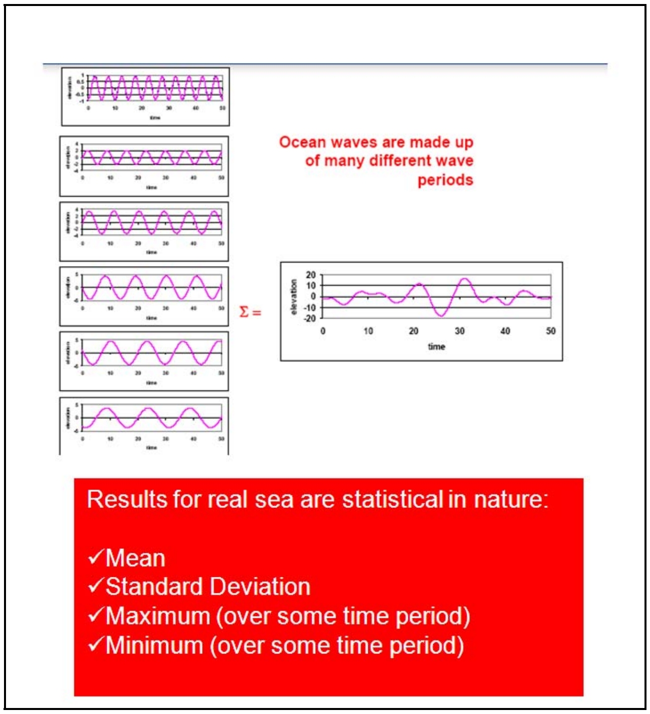
2/16/10 09

CWP Mode Shapes (Flexcom)

Figure 19. CWP Vibration Modes Including Tension

The pipe vibrations are a result of irregular waves, which may be considered as the summation of a large number of small sinusoidal regular waves of varying amplitude and phase as illustrated in Figure 20. The amplitude of the individual wave components follows the distribution of a wave spectrum. Figure 21 illustrates an example of responses in irregular seas. The results can only be interpreted statistically, typically in the form of the parameters:

- Mean
- Standard Deviation
- Maximum
- Minimum
- The mean value may be derived from a static analysis; however a dynamic analysis is required to derive the other parameters. Standard deviation (sometimes equated to the Root Mean Square, or RMS for a zero-mean dynamic analysis), may be derived from a frequency domain analysis. In this report we only use time domain simulations and the standard deviation, maximum and minimum values presented are samples from a single simulation of finite length.



Ocean waves are made up of many different wave periods

Results for real sea are statistical in nature:

✓Mean
✓Standard Deviation
✓Maximum (over some time period)
✓Minimum (over some time period)

Figure 20. Irregular Seas

Figure 21 includes a typical graph of pipe strains along its length. The curves represent a maximum, minimum and standard deviation value for each point. This is a typical way of presenting stress or strain (or bending moment) values along a riser.

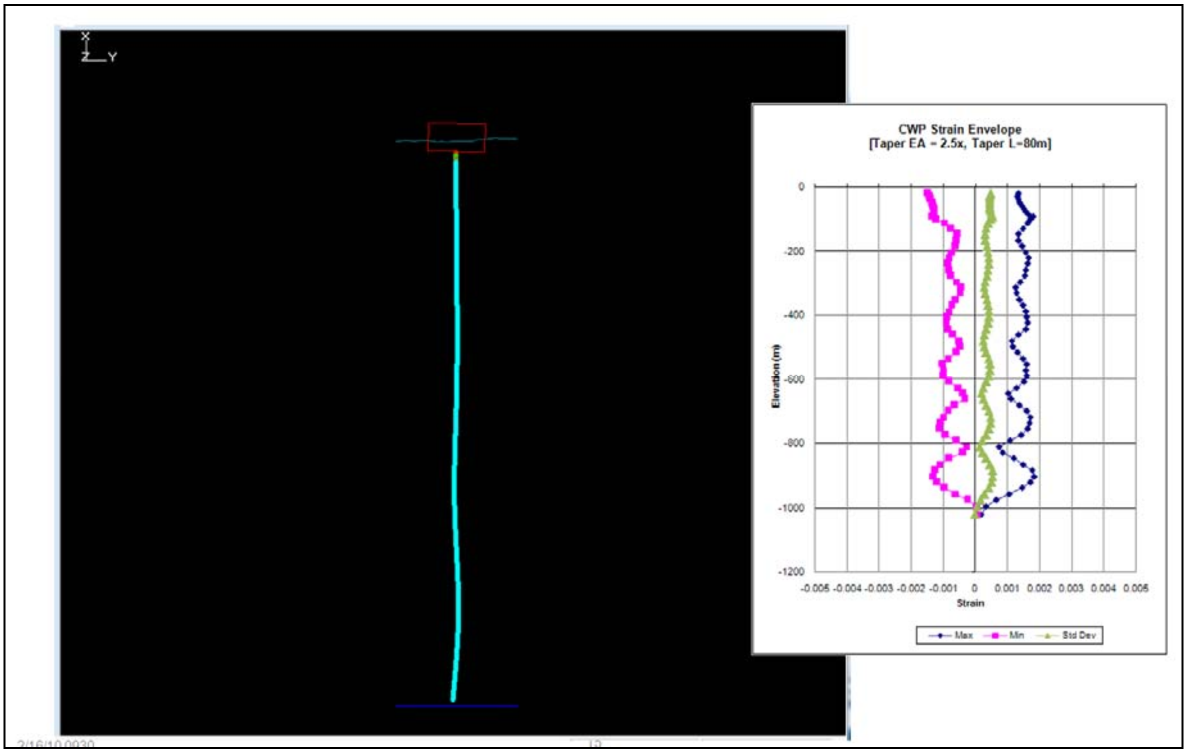


Figure 21. Responses in Waves

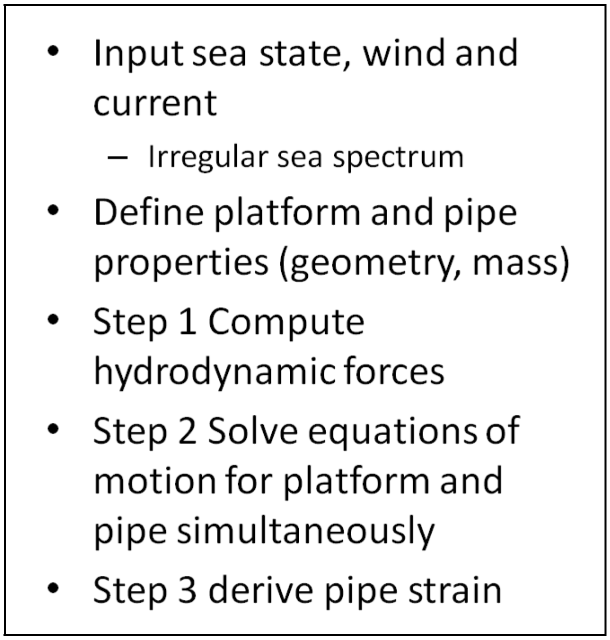
The curve in Figure 21 shows the characteristic locations of minimum (nodal) strains and maximum (anti-nodal) strains. Also note that the bending and tension is zero at the bottom of the pipe (because it is not attached to anything), and maximum at the fixed connection at the top. We will see later that when a gimbal is used, the bending is zero at the top as well and the total strains along the pipe are greatly reduced because the exciting moment input at the interface is eliminated. Only the surge motions of the platform excite the pipe.

5.2.3 Coupled Analysis

The above discusses the pipe response to excitation introduced by vessel motions and waves. The actual situation is more complicated than this because the pipe motions also excite the platform. In fact, for the 100MW design, the mass of the pipe and its entrained water is about the same as the platform (without remoras). Special software is required to solve the equations of motion for the platform, pipe and moorings simultaneously for a given sea state.

Table 4 shows the process for performing this analysis. The input is the sea states in the form of wave spectral parameters, wind and current. By defining the geometry and certain hydrodynamic coefficients, the environmental forces are defined as a time series. These are random forces conforming to the statistical description of wave and wind gust spectra. Current turbulence is ignored, and only a steady current velocity is applied (the current force is variable because the relative current velocity depends on wave motions and body motions.)

Table 4. Process for Coupled Analysis



- Input sea state, wind and current
  - Irregular sea spectrum
- Define platform and pipe properties (geometry, mass)
- Step 1 Compute hydrodynamic forces
- Step 2 Solve equations of motion for platform and pipe simultaneously
- Step 3 derive pipe strain

Figure 22 shows the geometry for a fully coupled analysis that includes the platform, pipe, mooring lines and power cable, all in one model.

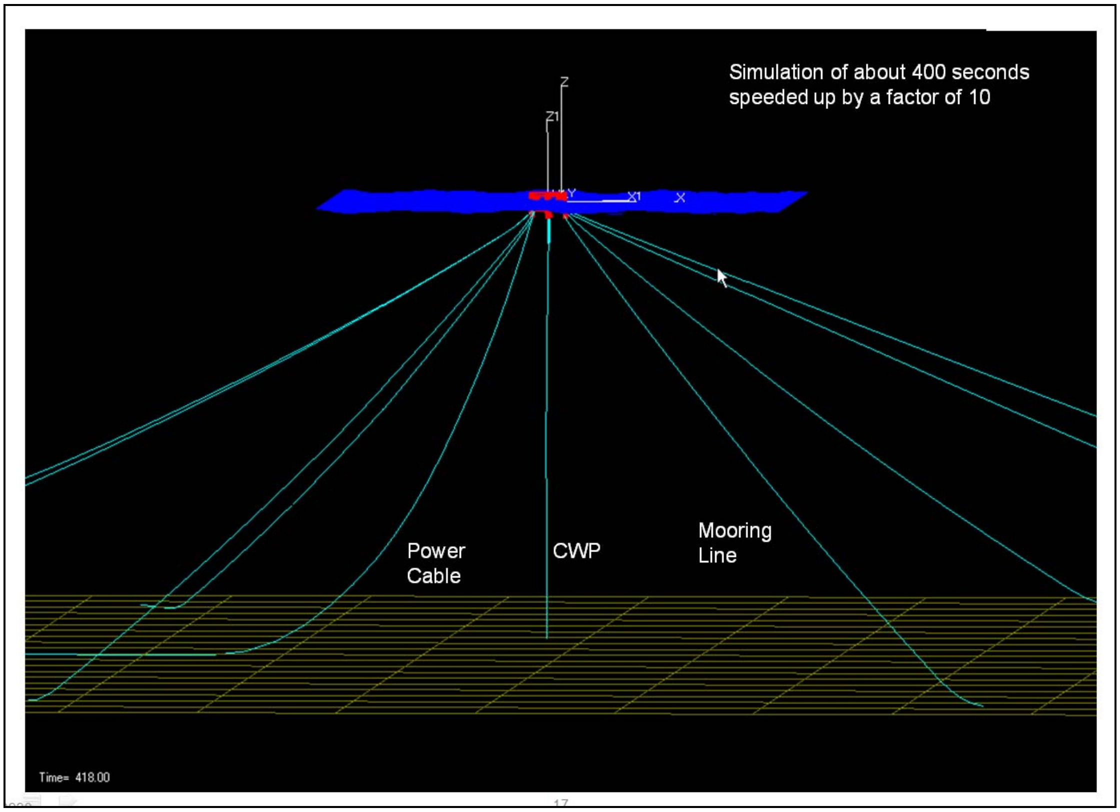


Figure 22. Fully Coupled Analysis Model

Analysis for this project was primarily performed using the program HARP (www.HARPONline.com). This is one of the leading programs for this sort of analysis in the offshore industry.

HARP is actually a pre- and post-processing program which integrates three separate programs:

- WAMIT (www.wamit.com)
- PROFLEX
- CHARM3D

WAMIT computes the hydrodynamic coefficients of the platform (including remoras) in the form of frequency dependent values for added mass, damping and wave excitation forces. These coefficients are used in CHARM3D when performing the motions calculations. PROFLEX is a static riser and mooring program. It computes the mooring and cold water pipe configuration in calm water conditions which establishes the initial finite element description of the mooring and pipe, which is used in CHARM3D.

CHARM3D is the main solver. It computes wave, wind and current forces on the platform and wave and current forces on the pipe and mooring lines, and solves the equations of motion for the combined system of finite elements representing the pipe and moorings, and a rigid body representing the platform. In our case the mooring lines are each represented by 19 elements and the cold water pipe by 46 elements. Altogether there are about 1200 degrees of freedom for an eight-leg mooring system. A time domain simulation representing 1-hour of full scale response takes about 1-hour of processing on a desktop PC. Although HARP may also do frequency domain analysis, time domain allows most non-linear affects to be captured and allows statistical analysis of the extreme and cyclic values (for fatigue).

CHARM3D includes viscous drag in the form of a quadratic function of the relative velocity between the platform elements (columns, pontoons) and the fluid. Viscous drag is not included in the WAMIT calculations. CHARM3D also includes fluid inertial and drag forces on the mooring lines and pipe using a modified Morison's Equation whereby forces are computed based on the relative velocities and accelerations.

The Cold Water Pipe entrained water represents a huge amount of mass and affects the dynamics of the pipe significantly. To properly account for this, the entrained water needs to be included in the mass relative to motions perpendicular to the axis of the pipe, but not in-line with the axis of the pipe. This phenomenon is also true for marine risers, but the affect is not as important because the water mass is usually much less than the riser mass. CHARM3D did not originally include this anisotropy in its finite element model. Other computer programs, notably FLEXCOM, do include this effect, and benchmarking of HARP against FLEXCOM showed that the results for bending moment along the pipe were not affected much by the assumption of isotropic mass; however the axial forces were of course affected. Some of the early analysis reported herein, e.g. the clump mass affect, were performed with the mass considered isotropic. CHARM3D was modified in March to include the anisotropic affect, and later results correctly reflect this.

Extensive benchmarking of HARP against other programs including FLEXCOM and ABAQUS is reported in the Appendix. Our conclusion at this point is that the results have an accuracy compared to other programs (using different mathematical models) of +/- 10 – 15%. Since this could have a large impact on fatigue life, we recommend that model test be performed to further calibrate and verify the results.

5.2.4 Cold Water Pipe Configurations Analyzed

We have performed analysis on both the commercial (100MW) and pilot plant (5/10MW) configurations to support the associated design efforts. The 100MW configuration was considered primarily to validate the approach to the gripper and termination design which would be tested at a smaller scale in the pilot plant. In effect, we wanted to make sure the approach was valid at the larger scale before devoting a lot of effort designing the smaller scale version. The platform configurations were described above.

As the gripper and pipe design progressed, the pipe properties evolved. As a result, the analysis results reported here are based on various pipe properties as identified in Table 5 and Table 6. Version 4 is considered the base case as of this writing.

Table 5. Various 10m Pipe Properties used in Analysis

	Vers. 1 (1)	**Vers. 2A (3)**	**Vers. 2B (1)**	**Vers. 3 (1)**	**Vers. 4 (1)**
ID, m	10.01	10.01	10.01	10.01	10.00
OD, m	10.55	10.51	10.51	10.39	10.57
Mass Pipe, kg/m	3529.9	4036.9	4764.5	2898.6	4626
Mass Pipe & Water in Walls, kg/m	10469	10099	10429	7505	11313
Mass Pipe & Water, kg/m	91095	90725	91055	88130	91827.6
Wet Weight, mt/m	1.582	1.811	2.142	1.298	1.996
Clump Weight, mt	0	0	0	0	0
Total Wet Weight, mt	1583.0	1812.4	2143.6	1299.0	1997.6
EA, kN	57826881	65242320	76909182	26709705	72017396
EI, kN-m^2	757631070	846963409	996043693	343811050	937445000
Used in Reference (see Table 3)	[3,5]	[5,12, 14]			

Table 6. Various 4m Pipe Properties used in Analysis

	Vers. 1 (1)	**Vers. 2 4/20/10 (1)**	**Vers. 4, Rev. 7 (1)**	**Vers. 4 Current (1) and (2)**
ID, m	4.00	3.99	4.00	4.00
OD, m	4.21	4.21	4.21	4.21
Mass Pipe, kg/m	570.1	795.8	789.5	744
Mass Pipe & Water in Walls, kg/m	1618	1763.5	1660	1713.2
Mass Pipe & Water, kg/m	14501	14598.2	14552	14560.7
Wet Weight, mt/m	0.255	0.324	0.322	0.301
Clump Weight, mt	40.9	40.9	196.1	40.9
Total Wet Weight, mt	297.0	366.0	520.0	342.7
EA, kN	8527557	11183139	10664534	10481042
EI, kN-m^2	17694990	23148262	22130310	21755558
Used in Reference (see Table 3)			[11,12]	

5.2.5 Sea States

This analysis used environments based on site-specific hindcasts developed by Oceanweather, Inc. for numerous possible OTEC sites in the Hawaiian Islands, Figure 23[ii]. Of particular interest here are the conditions at Kahe Point (for a commercial plant) and Barbers Point (for a pilot plant). While the two sites are very close (22 km) and the conditions similar, there is a significant difference in the operational environments due to the shielding effect of the island. Hence we have used different fatigue criteria for Kahe Point (for the commercial plant) and Barbers Point (for the pilot plant).

Figure 23. Hawaii Sites

Both sites are in the lee of Oahu, and are thus shielded from the prevailing easterly trade winds. Nevertheless the operational conditions are characterized by two distinct events: swells from higher latitude storms (from north in the winter and south in the summer), and local seas from squalls. Operational analysis must thus consider both cases, although swell has been found to be more critical at these sites.

Figure 24 shows the seasonal variability in the operational environment statistics. The mean period of the waves remains in the swell domain throughout the year for Kahe and Barbers Point, showing the dominance of this condition (note that Kaneohe Point, on the windward side of Oahu, is sea dominated in the summer. The significant wave height (Hs) for Kahe and Barbers Point is about 1 m less in the summer than it is in the winter. This indicates, for example, that pipe installation has a much greater chance of success in the summer!

Extreme events also may be divided into sea and swell conditions, corresponding to local extreme storms (cyclones) and distant high latitude extreme storms which generate extreme swell. The OTEC sites are too deep to be affected by Tsunami waves.

Hawaii rarely has severe hurricanes (about one hurricane passes through the islands every 10 years, compared to 3 per year for the Gulf of Mexico) and no recorded hurricane strength storm has ever come closer than about 75 miles to the Kahe Point or Barbers Point sites. Figure 25 shows the 15 strongest tropical cyclones to affect Hawaii since 1950. The wind and waves caused by these storms at the OTEC sites have been hindcast by Oceanweather, and the results have been used to extrapolate extreme events. A hindcast of continuous non-cyclonic weather events over 25-years was used to derive non-cyclonic extreme events and fatigue environments.

“Permanent” offshore facilities with 20 – 30 year operating lives are typically designed for a 100-yr event, i.e. a storm with a probability of 0.01 of being exceeded in any given year. The hindcast 100-yr cyclone at Kahe Point has these conditions: 30 minute wind speed of 34.9 m/sec (68 kts), Hs of 10.2 m and peak spectral period of 12.8. This is barely reaching hurricane strength.

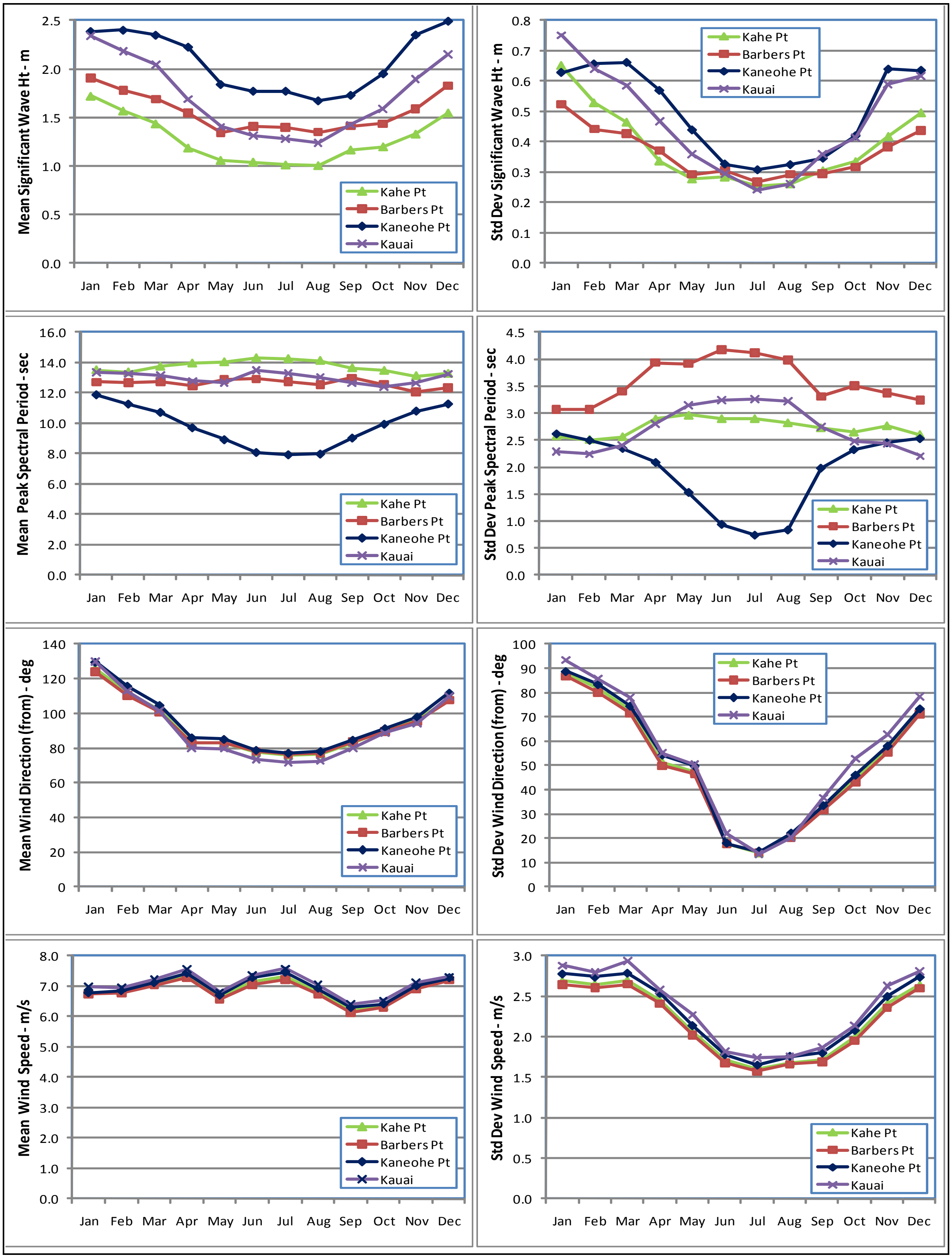


Figure 24. Monthly Statistics of Wave and Wind for Hawaiian OTEC Sites

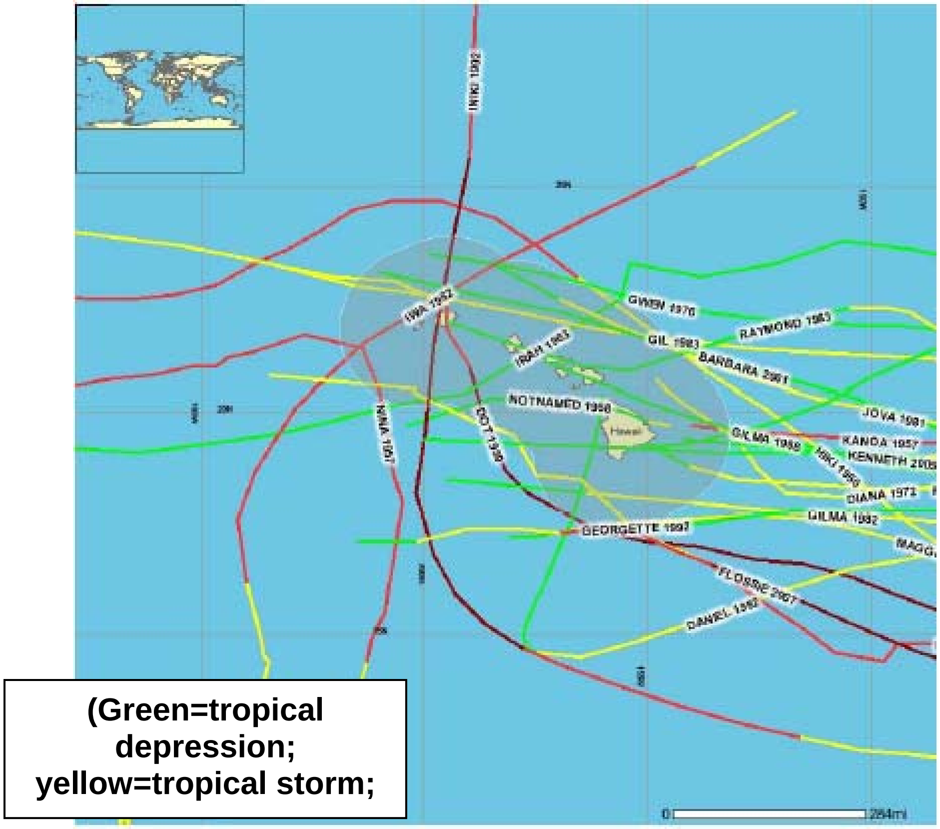


Figure 25. 15 Largest Tropical Cyclones to Affect the Hawaiian Islands since 1950

A 25-yr return period event is more suitable as an extreme design event for a 2-year pilot plant operation. The rationale for this is as follows. It is customary to use a 100-yr event to design a "permanent" platform with a life of 20-30 years. This criterion, coupled with normal safety factors used in offshore design, has proven to result in safe structures. The probability of exceeding the 100-yr criterion in 30 years may be calculated as $1-(1-0.01)^{30} = 0.26$ (the 100-yr storm is, by definition, a condition which has a probability of .01 of occurring in any one year, so the probability of it NOT happening is 1-0.01, or 0.99. The probability of NOT exceeding this in 30-years is thus 0.99^{30}, or .74). Assuming we can accept the same risk of exceeding our design criterion for a 2-yr operation, we could actually accept a 10-yr storm, which would have a probability of being exceeded in any two year period of $1-(1-0.1)^2 = 0.19$. The probability of exceeding a 25-yr event in two years is $1-(1-0.04)^2 = 0.08$. Thus a 25-yr criterion for a 2-yr period is more conservative than a 100-yr criterion for a 30 year operation.

The above argument has been used to specify a 25-yr environment for the mooring lines and anchors of the pilot plant, which can be relatively easily upgraded if an "afterlife" is desired. However the pipe and platform need to be designed for the 100-yr event since it would be impractical to upgrade these after two years. Thus for the purposes of specifying the strength of the CWP, the 100-yr criterion still has to be applied.

Pipe manufacturing has an even shorter exposure than the pilot plant, measured in months. We propose the 10-yr environment as controlling for the survival of the pipe in a state of manufacturing (this would be a standby condition). We have assumed a criterion for the manufacturing of the pipe (makeup, molding, and running) to the environment which would not be exceeded 90% of the time on a year-round basis. Once the true sea state limits for this operation are better understood, an operational analysis using the actually time series hindcast data is recommended to determine the availability of this operation.

These various criteria are summarized in Table 7. Associated current effects are based on interpolating one year's worth of measurements taken at Kahe Point[iii].

Table 7. Design Environments

Criteria Used for:	100 Year Cyclone	25 Year Cyclone	25 Year Non-Cyclone (sea)	25 Year Non-Cyclone (swell)	Max Current	10-yr Sea (Barbers Hindcast) 2 sigma current	10 -yr Swell (Barbers Hindcast) 2 sigma current	90% Sea (Kahe) 4 sigma current	90% Swell (Kahe) 4 sigma current
Pipe Installation								X	X
CWP Fab Standby Survival					X	X	X		
Production Extreme	X				X				
Pilot Extreme		X	X	X	X				
Hs, m	10.2	4.3	4.5	4.5	1.5	4.2	3.8	2.0	1.5
Tp, sec	12.8	10.6	8.8	14.1	14	8.3	15.7	5.3	14
Spectrum, Jonswap gamma	2	2	1	6	6	1	6	1	6
U_{wind}, m/sec (10-min ave)	33.8	13.7	16.2	16.2	8	15.7	14.6	7.5	8
Uc, m/sec @ surface	1.4	.5	.6	.6	.9	.5	.5	.7	.7
Uc, m/sec @ 50m	.5	.5	.5	.5	.8	.5	.5	.7	.7
Uc, m/sec @ 100 m	.3	.3	.3	.3	.7	.3	.3	.5	.5
Uc, m/sec @ 150 m	.3	.3	.3	.3	.7	.3	.3	.5	.5
Uc, m/sec @ 350 m	.2	.2	.2	.2	.3	.2	.2	.3	.3
Uc, m/sec @ 800 m	.2	.2	.2	.2	.3	.2	.2	.3	.3
Uc, m/sec @ 1000 m	.2	.2	.2	.2	.3	.2	.2	.2	.2

In order to perform fatigue analysis, a reasonable number of sea states has been defined which parses the complete range of Hs and wave period (Tp) values in discrete "bins" for analysis. These bins are defined for Barbers Point and Kahe Point in Table 8 and Table 9, respectively.

Table 8. Fatigue Bins for Barbers Point, 4m Pipe

Bin	Freq of Occurrence	Hs m	Tp sec
1	0.00005	0.875	4.500
2	0.00545	1.125	5.340
3	0.07827	1.607	6.048
4	0.01173	2.179	6.490
5	0.00366	0.875	9.399
6	0.04110	1.125	9.988
7	0.16883	1.495	10.670
8	0.03050	2.478	8.853
9	0.00285	0.875	13.595
10	0.02866	1.125	13.571
11	0.25834	1.631	13.603
12	0.08433	2.297	14.010
13	0.00496	0.874	17.405
14	0.03106	1.125	17.554
15	0.18350	1.598	17.331
16	0.06664	2.397	16.943
Total	0.99993	1.677	13.160

Table 9. Fatigue Bins for Kahe Point, 10m Pipe

Bin	Freq of Occurrence	Hs m	Tp sec
1	0.0063	0.85	5.90
2	0.0051	1.13	6.35
3	0.0039	1.54	6.14
4	0.0015	2.29	6.47
5	0.0375	0.86	10.78
6	0.0692	1.13	11.04
7	0.0560	1.45	10.95
8	0.0093	2.67	9.38
9	0.0594	0.86	13.57
10	0.1136	1.13	13.51
11	0.2479	1.56	13.60
12	0.0495	2.37	14.05
13	0.0643	0.86	17.40
14	0.1006	1.13	17.33
15	0.1343	1.53	17.17
16	0.0419	2.47	16.62
Total	1.0001	1.40	14.24

5.2.6 Quality Control Checking of Dynamic Analysis Software

The 10m termination fatigue analysis performed at the end of 2009[iv] resulted in much higher dynamic strains than previous results. As a result, the analytical approach was brought into question. Upon investigation, it was found that the procedure used in this analysis, while ok for offshore riser analysis, was flawed for the OTEC Cold Water Pipe analysis.

The procedure used employed two programs, one for prediction of platform motions and another for the cold water pipe analysis. The first program, HARP, was a coupled analysis program which included the response of the pipe, but it required a finite stiffness between the pipe and the platform, a torsion spring, to represent the interaction between the pipe and the platform. The second program, FLEXCOM, constrained the top of the cold water pipe to the translations and rotations of a point on the platform at the attachment point. In effect, this represented an infinite stiffness between the pipe and the platform.

The problem with this approach is that the stiffness of the pipe connection actually can affect the pitch motions of the platform, and the pitch motions of the platform are a primary determinant of the bending moments and strains at the connection. Hence, if one program is used to predict platform motions and another is used to compute pipe responses, the stiffness between the pipe and the platform needs to be the same in both cases to be consistent. In references 5 and 8 in Table 3 the motions from HARP which were imported to FLEXCOM were too large because of the finite stiffness assumed in HARP.

It was concluded that the best practice for this analysis was to use a single, coupled program which would solve motions and pipe strains simultaneously in a fully coupled manner. To validate this approach, the following benchmarking was performed:

- Sensitivity of pipe responses to size of the FEA mesh.
- Sensitivity of the hydrodynamic forces to the hydrodynamic mesh size
- 10m Pipe strains independently computed by HARP and FLEXCOM for the same platform motions and connection stiffness.
- Independent computation of coupled motions and strains using CHARM3D and ABAQUS[v]
- Independent computation of coupled motions and pipe strains using HARP and FLEXCOM[vi]

The following is concluded from the work described below.

a. For a given platform motion the pipe strains compare to within 1-2%.
b. Differences in hydrodynamic modeling can produce large differences in platform motions especially near the resonant period.
c. Using radiation/diffraction theory, the difference of motions and strains appears to be on the order of +/- 10 – 15%. This corresponds to a factor of four on fatigue life.

5.2.6.1 Pipe Mesh Size

FLEXCOM runs were performed with 50 and 650 elements for the CWP [10]. Results as illustrated in Figure 26 were identical.

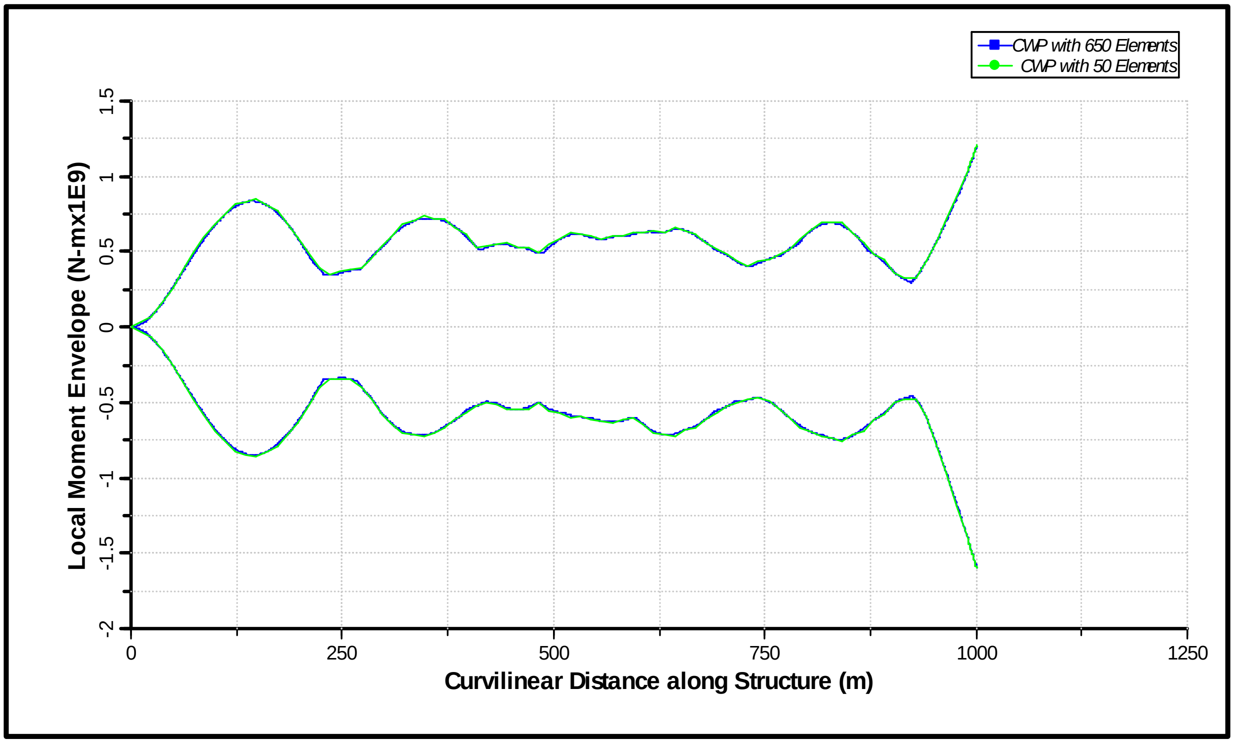


Figure 26. Top Node Moment Envelope Comparison for 50 and 650 CWP Elements

5.2.6.2 Sensitivity to Hydrodynamic Mesh Size

A comparison of hydrodynamic coefficients for two mesh sizes was developed[vii]. The results, shown in Figure 27, are essentially identical, indicating that convergence has been achieved.

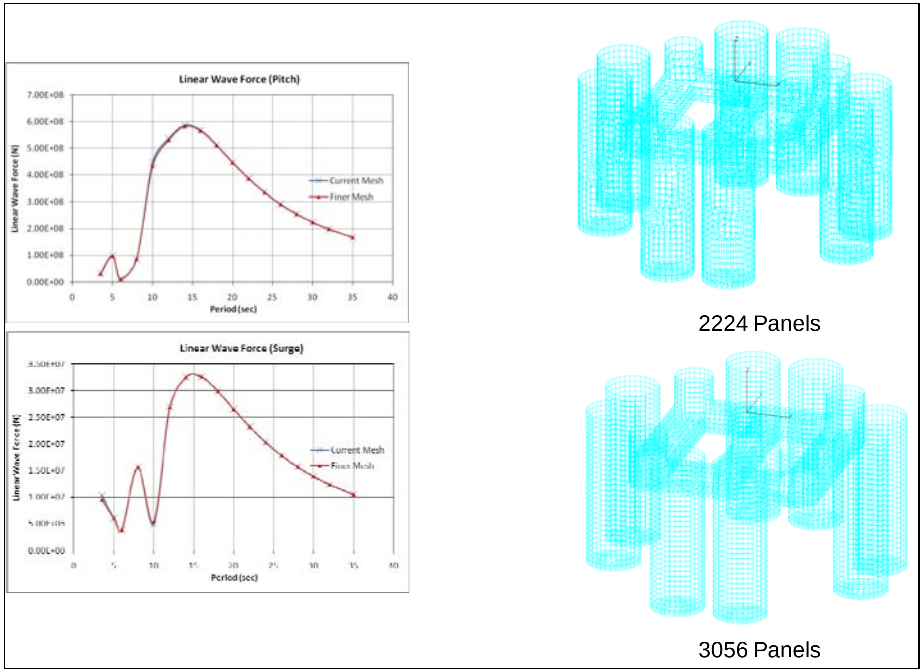


Figure 27. Sensitivity of Hydrodynamic Forces to Mesh Size

5.2.6.3 FLEXCOM and HARP Comparison, Pipe Response

Pipe responses and loads from the FLEXCOM and HARP programs were compared when the same motions were imposed on the upper node of the pipe. The computations were performed for the 10-year swell environment. Statistics and time traces of the responses were compared. See Figure 28 through Figure 32 below. The two programs gave essentially the same results, except for the mean shear load. The dynamic loads are identical, except for the tension. Since the tension is dominated by the mean value, the error in dynamic tension (20%) is inconsequential. Note that both of these programs treat the mass of the water inside the pipe as a lateral mass, but they do not include the internal water as axial mass. This feature is not available in all programs and larger errors in dynamic tension would occur if this anisotropic effect were not modeled correctly.

These results essentially suggest that the pipe strains are consistently predicted to within 1-2% for a given platform motion and attachment stiffness. The primary uncertainty is therefore in the prediction of vessel motions and pipe attachment stiffness. See below for additional benchmarking of these effects.

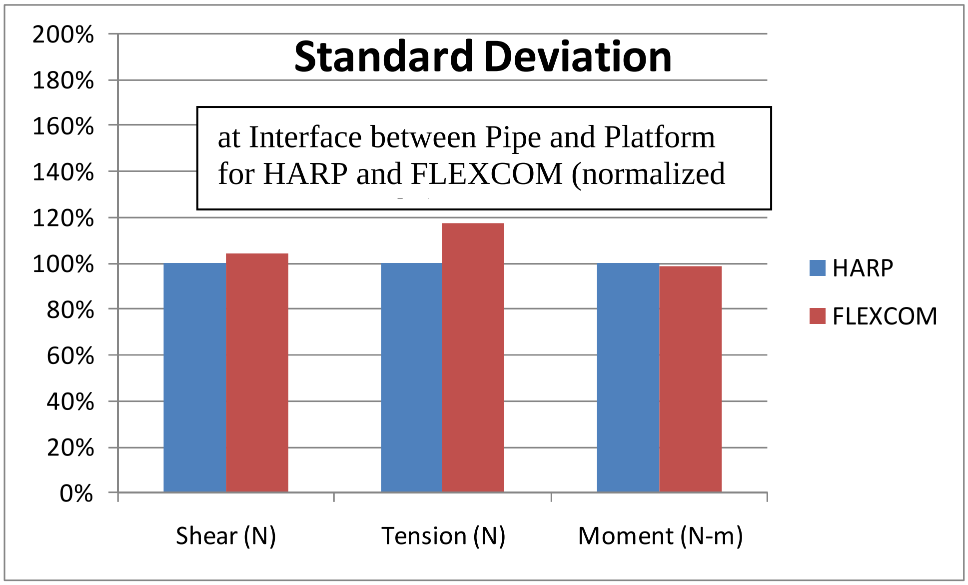


Figure 28. Standard Deviation Comparison of Pipe Loads

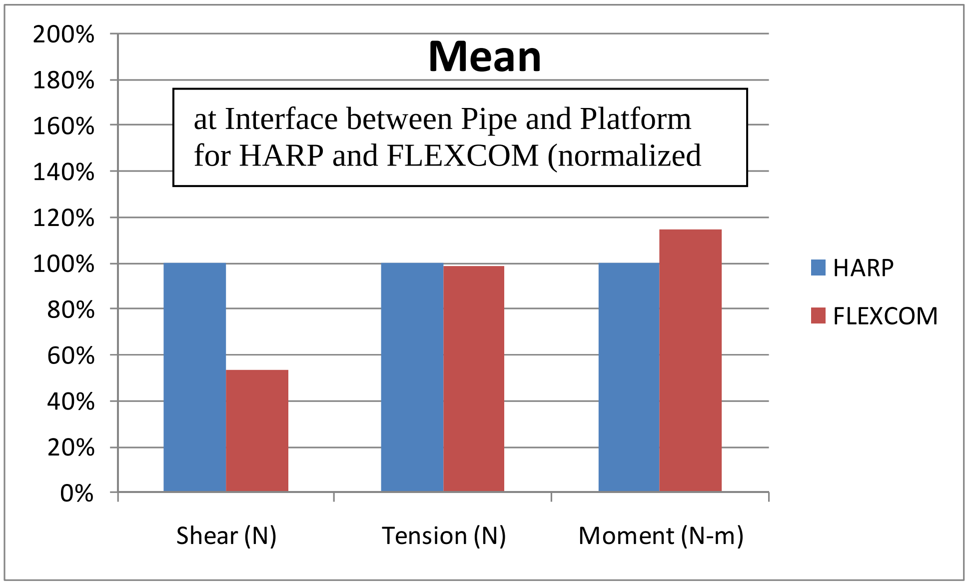


Figure 29. Mean Comparison of Pipe Loads

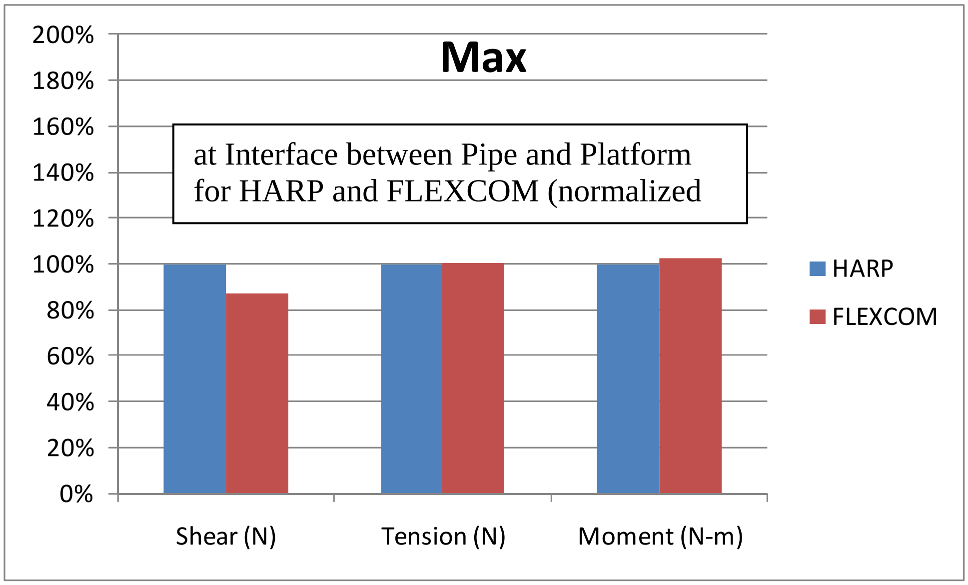


Figure 30. Maximum Comparison of Pipe Loads

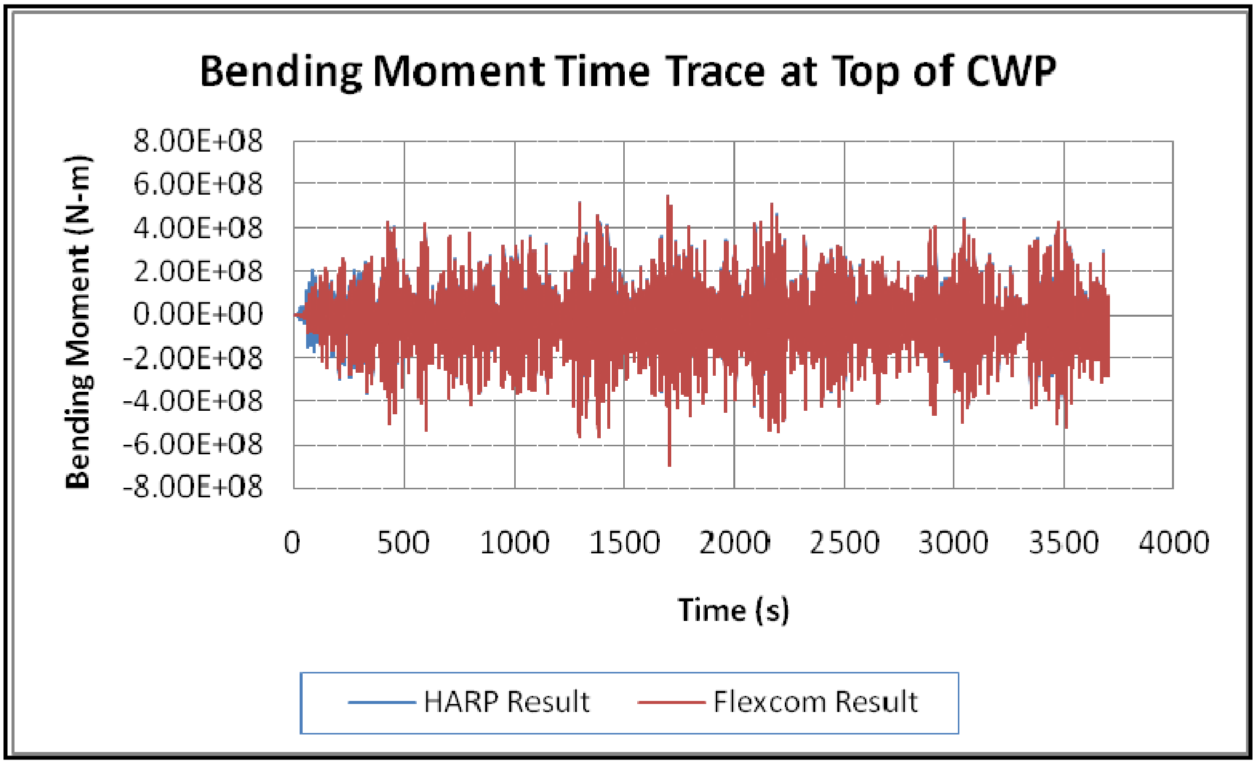


Figure 31. Comparison of the Time Trace of Bending Moments

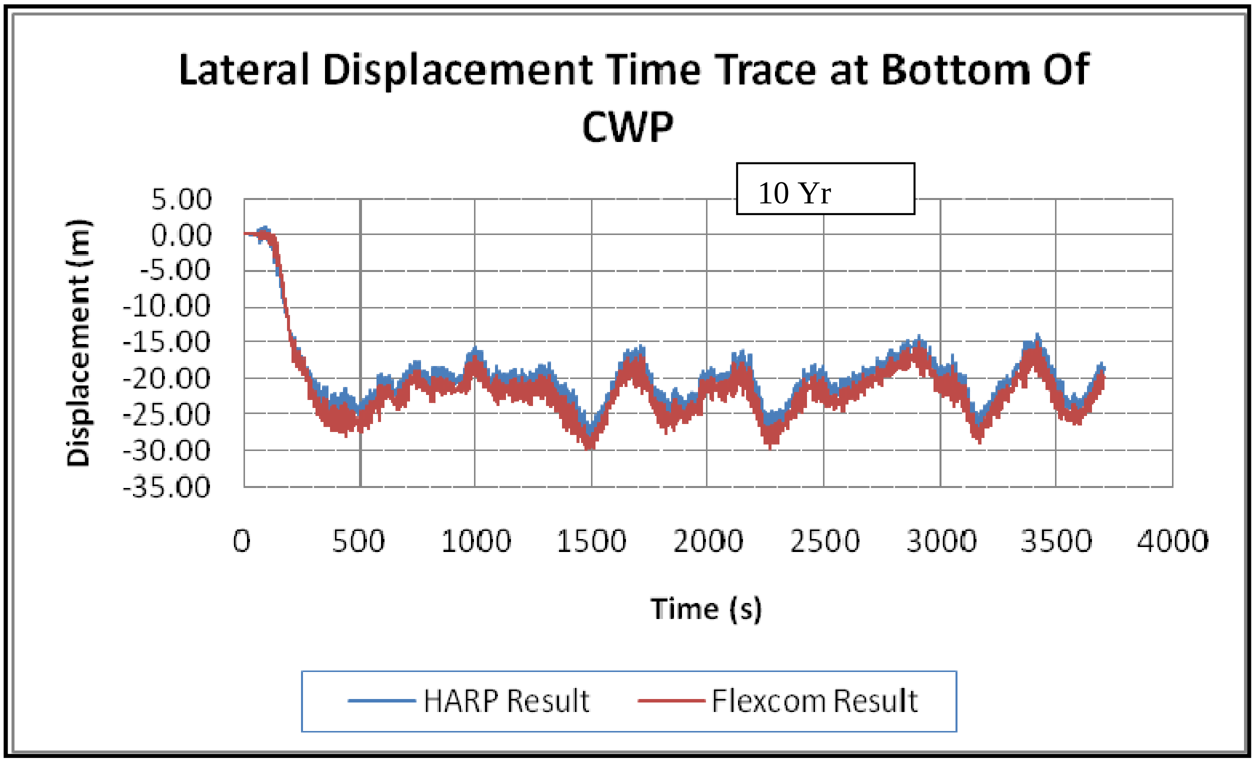


Figure 32. Comparison of Time Trace of Bottom CWP Motions

5.2.6.4 FLEXCOM and HARP Comparison, Fully Coupled Hydrodynamic Model

The previous section presented the results for FLEXCOM and HARP when the platform motions were identical. A separate comparison was run using both programs to independently compute the hydrodynamic responses [Table 3-7]. The analysis in both models is based on the 100MW platform, 10m pipe, version 1 pipe and Kahe Point bin 16 environment (Table 9) and connection stiffness between the pipe and the platform of 10^{13} N-m/rad. Results for current only were also included.

The FLEXCOM coupled analysis module is called Floating Body Module. It is a very new feature in FLEXCOM. The version used in this study is new release of version 7.9.4. FLEXCOM coupled analysis module is able to directly obtain the vessel force RAOs from the WAMIT output file.

The 100MW OTEC FLEXCOM coupled analysis model shown in Figure 33 was generated in the same way as the HARP model. The same WAMIT hydrodynamic analysis results are also used for the FLEXCOM model. Morrison members with the same drag coefficients and integration points used in HARP were also modeled in FLEXCOM for constancy. Mooring lines and CWP are modeled using the same number of elements, locations, and pretensions.

The results are illustrated in the tables and figures below. Time history plots should not be compared point by point because the wave input is random and while the statistics are the same (same power spectrum for the waves) the exact time history of the waves is different. The statistical comparisons are more meaningful.

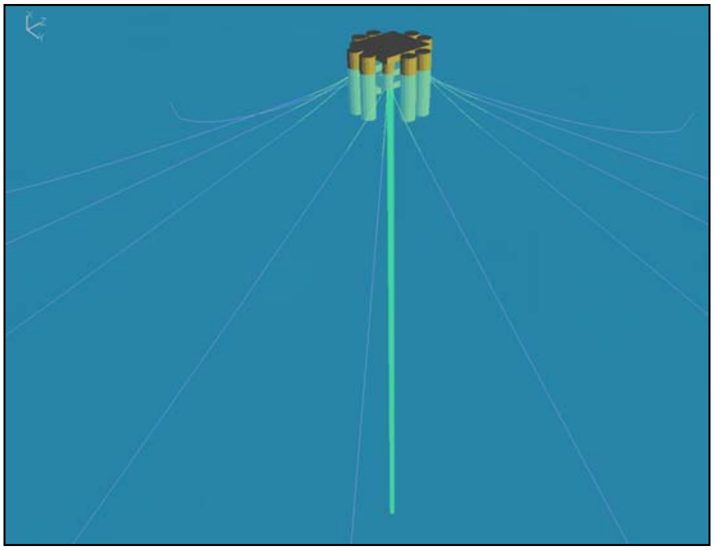


Figure 33. FLEXCOM Model

Motions are compared in Table 10 and Figure 34 (normalized to the HARP results). The difference in mean surge and pitch is due to the different way drift forces were computed in each program, and is not a significant factor in bending strains. In either event the mean values are insignificant. The important comparison is the dynamic response as reflected in the standard deviations which greatly affects the fatigue life. Here we see that the important pitch parameter is about 8% less for FLEXCOM than HARP.

Table 10. Statistical Comparison of Motions

Random Wave						
	HARP			FLEXCOM		
	Surge m	Heave m	Pitch deg	Surge m	Heave m	Pitch deg
MAX	0.88	2.47	3.00	0.88	2.44	2.89
MIN	-3.39	-2.50	-2.88	-5.53	-2.40	-2.66
MEAN	-0.85	-0.01	0.06	-1.95	0.03	0.10
STDDEV	0.81	0.92	1.20	0.91	0.73	1.04

These results are reflected in the corresponding comparisons for bending strain shown in Figure 36. The standard deviation predicted by FLEXCOM is 11% less than that predicted by HARP. Based on the current fatigue SN curve for the CWP, this difference would result in a factor of four difference in predicted life. A comparison of the bending strain envelope in Figure 37, shows that both programs compute similar envelopes. It is noted that the pipe motion is maximum at 175m from the bottom. Both HAARP and FLEXCOM show the same trend.. Some possibilities for this behavior are:

- Dynamics of the pipe are less damped at the deeper depths due to lower current velocities
- Tensions are lower at the bottom which result in less strain stiffening

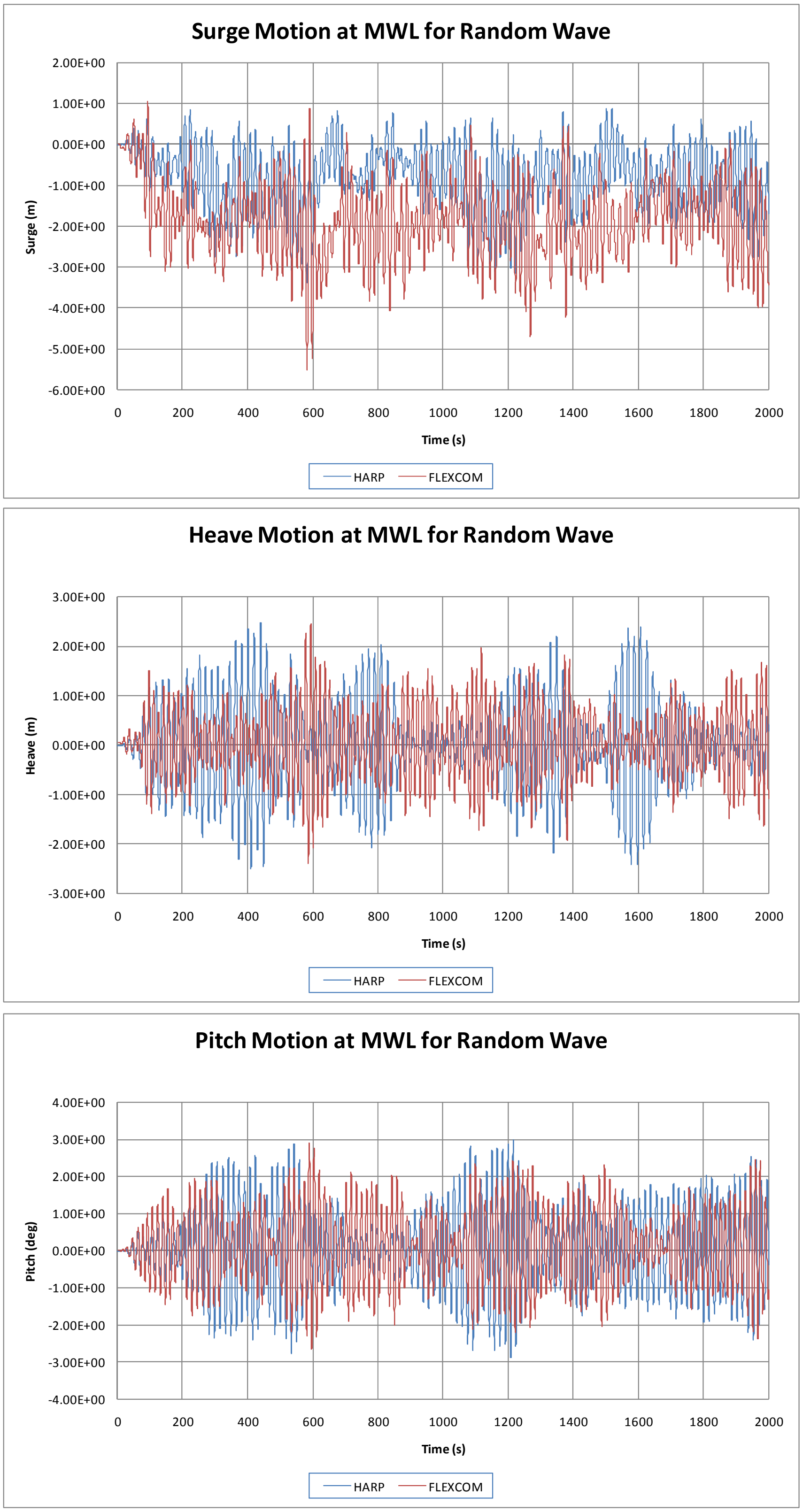


Figure 34. Time History Comparisons

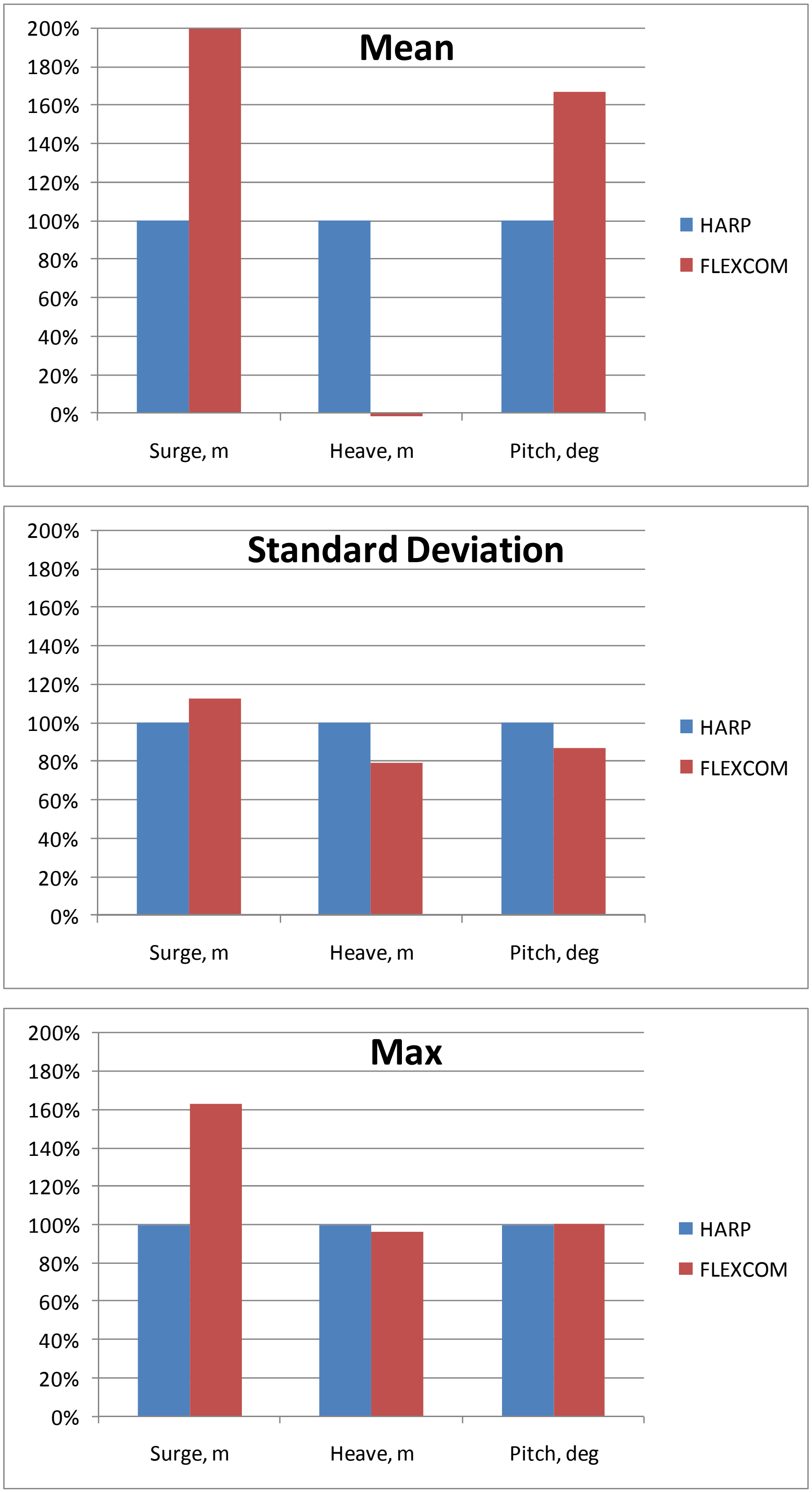


Figure 35. Motion Comparisons

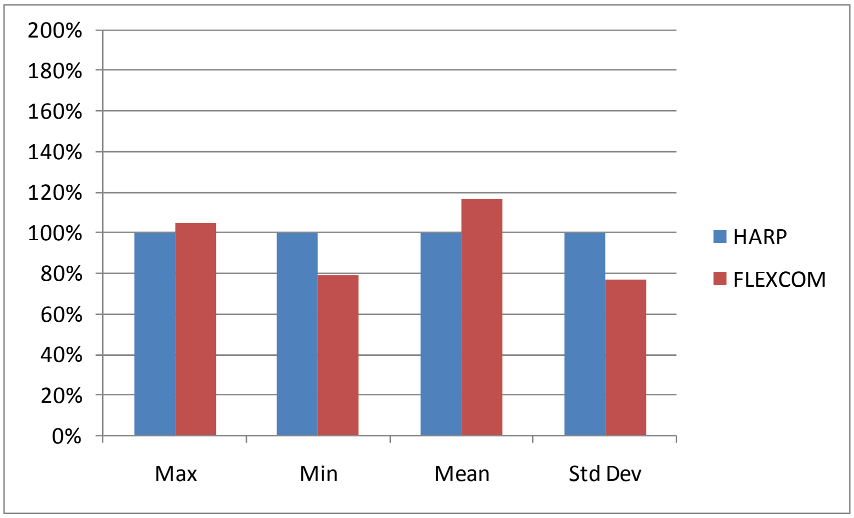


Figure 36. Bending Strain Comparison

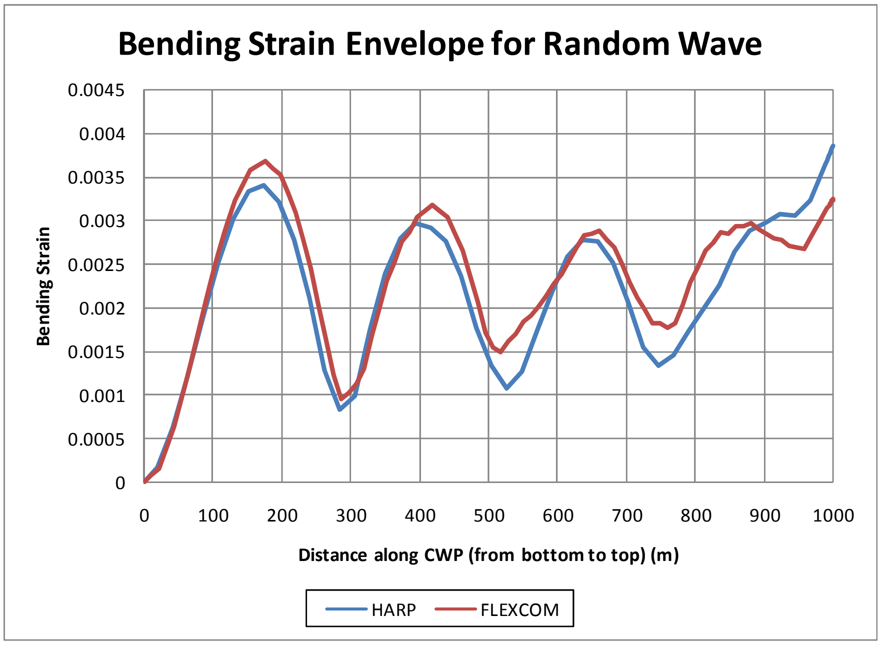


Figure 37. Bending Strain Envelope Comparison

These comparisons were made with a common connection stiffness of 10^{13} N-m/rad between the pipe and the platform. Additional FLEXCOM analysis was performed to show the effect of connection stiffness. Three cases were run for different rotational stiffness values: rigid (infinite stiffness), 10^{13} and 10^{8} N-m/rad. The rigid case can be modeled in FLEXCOM, but not in HARP because of the way the coupled analysis FEA is formulated. The results for motions are summarized in Table 11 and Figure 38. The results indicate that 10^{13} N-m/rad is a good proxy for a rigid connection for the 10m pipe version analyzed. We have separately determined that 10^{8} N-m/rad is a good proxy for the stiffness of an elastomeric gimbal.

Table 11. Motion Sensitivity to Pipe Connection Stiffness

	HEAVE (m)			SURGE (m)			PITCH (deg)		
	Case 1 (Rigid)	Case 2 (k=1E13 N-m/rad)	Case 3 (k=1E8 N-m/rad)	Case 1 (Rigid)	Case 2 (k=1E13 N-m/rad)	Case 3 (k=1E8 N-m/rad)	Case 1 (Rigid)	Case 2 (k=1E13 N-m/rad)	Case 3 (k=1E8 N-m/rad)
MAX	2.42	2.43	2.42	-0.07	-0.04	-0.25	2.79	2.70	4.41
MIN	-2.38	-2.39	-2.37	-4.03	-4.00	-4.33	-2.51	-2.42	-4.16
MEAN	0.04	0.04	0.04	-2.19	-2.17	-2.21	0.12	0.12	0.04
STD DEV	0.73	0.73	0.73	0.64	0.64	0.70	1.00	0.98	1.63

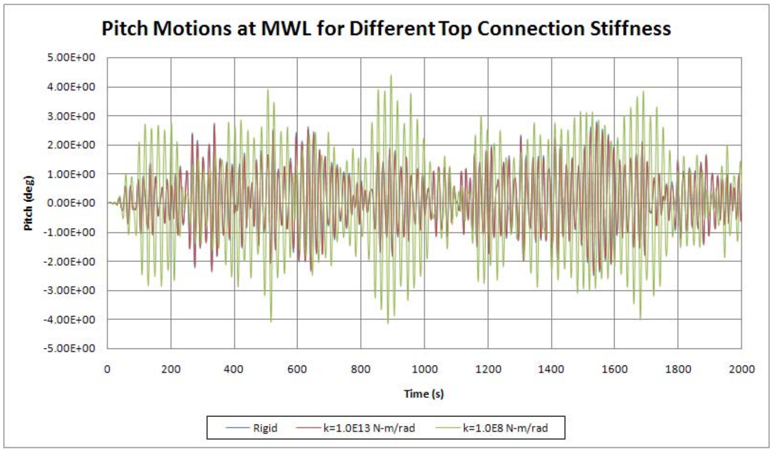


Figure 38. Pitch Motions for Different Pipe/Platform Connection Stiffnesses

It is useful to consider this stiffness in terms of the stiffness of a certain length of the CWP. Linear beam theory gives the following formulas for the rotational stiffness of a beam of length L subjected to a moment, M_0 and the equivalent length of beam to result in a given stiffness.

$$K_\theta = \frac{EI}{L}$$

$$L_{eq} = \frac{EI}{K_\theta}$$

For this example, $K_\theta = 10^{13}$ N-m/rad and EI = $8.47E^{11}$ N-m2, L_{eq} = .0847m (=.00847 x diameter). In using HARP to represent a “rigid” connection, therefore, it appears that the stiffness equivalent to a length of about 1% of the pipe diameter may be appropriate.

5.2.6.5 HARP vs. ABAQUS Comparison

A separate benchmarking exercise was conducted by Horton Wison Deepwater for the pilot plant, 4m pipe configuration [Table 3-]. They used the HARP solver CHARM3D and ABAQUS (http://www.simulia.com/products/abaqus_fea.html) to model the platform and pipe. Both are fully coupled models, however ABAQUS uses the modified Morison equation to model wave forces but HARP uses WAMIT, a frequency dependent radiation/diffraction program. The ABAQUS “stick” model is illustrated in Figure 39 and Figure 40.

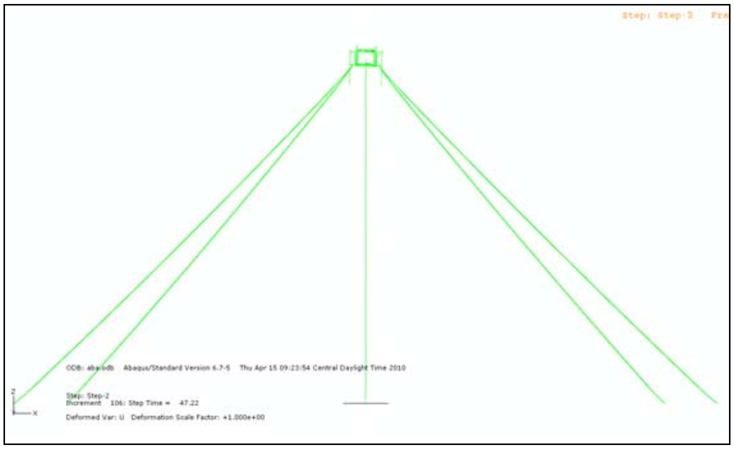


Figure 39. Fully-coupled Analysis Model using ABAQUS

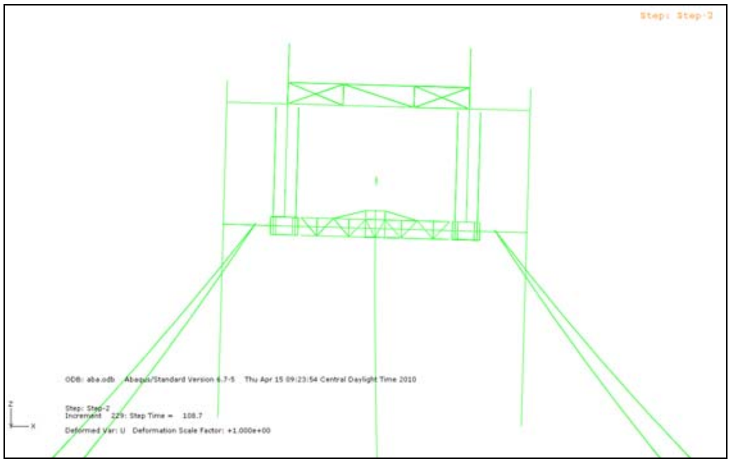


Figure 40. Detailed Fully-coupled Analysis Model using ABAQUS

The connection stiffness and pipe properties are shown in **Error! Not a valid bookmark self-reference.** and Table 13.

Table 12. Stiffness Coefficients

Stiffness CWP to Truss				
Kx	6.85E+06	lb/ft	1.00E+08	N/m
Ky	6.85E+06	lb/ft	1.00E+08	N/m
Kz	6.85E+06	lb/ft	1.00E+08	N/m
Kxx	1.92E+10	lb.ft/rad	2.60E+10	N.m/rad
Kyy	1.92E+10	lb.ft/rad	2.60E+10	N.m/rad
Kzz	1.92E+10	lb.ft/rad	2.60E+10	N.m/rad

Table 13. Cold Water Pipe Properties (Version 2, January 2010)

Property					
Inside Diameter	157.5	in		4.00	m
Outside Diameter	165.1	in		4.19	m
Wall Thickness	3.80	in		0.10	m
Outside Circumference	518.7	in		13.17	m
Length below transition	39400	in		1,000.8	m
Cross sectional area, solid:	512.85	in ^2		0.33087	m^2
Void inside core, cross sectional area	1413.80	in^2		0.91	m^2
% wall that is void	73%			73%	
Density of composite, average	0.06713	lbm/in^3		1,858.3	kg/m^3
Mass (excludes internal water)	34.4	lbm/in		614.8	kg/m
CWP (no bottom weight) Total Mass (excludes internal water)	1,356,542	lbm		615,317	kg
Mass including internal water in walls only	86.8	lbm/in		1,550	kg/m
Mass including internal water, FRP walls and interior wall water	808.2	lbm/in		14,434	kg/m
Dry Weight CWP (no bottom weight)	34.4	lb/in		6,030	N/m
Total Dry Weight (no bottom weight)	1,356,542	lbs		6,034	kN
Total Dry Weight (no bottom weight)	1,356,542	lbs		615	tonnes
Wet weight (no bottom weight)	15.44	lb/in		0.276	tonnes/m
Total wet Weight (no bottom weight)	608,293	lbs		276	tonnes
Total wet Weight inc bottom weight	699,293	lbs		317	tonnes
EI of wall - bending (ignore internal ribs)	3.65E+06	lb-in^2/in		4.12E+02	kN-m^2/m
EA	2.15E+09	lbs		9,542,554	kN
EI	6.90E+12	lb-in^2		19,807,317	kN-m^2
Cm	2			2	
Cd	1			1	

The comparisons were made for a regular wave: H = 3.54 seconds, T = 15.7 seconds. Runs were made with and without current (.48 m/sec at the surface and decaying with depth). Neither of the programs could model the pipe entrapped water effect, so two different methods of treating the mass of entrapped water were used. First, the entire mass was included. Secondly, the internal mass was not included, but an equivalent lateral mass was added. Since the focus was on lateral motions and bending this distinction was not too important. Figure 41 shows a comparison of the free decay simulation for the two programs indicating almost identical periods and damping.

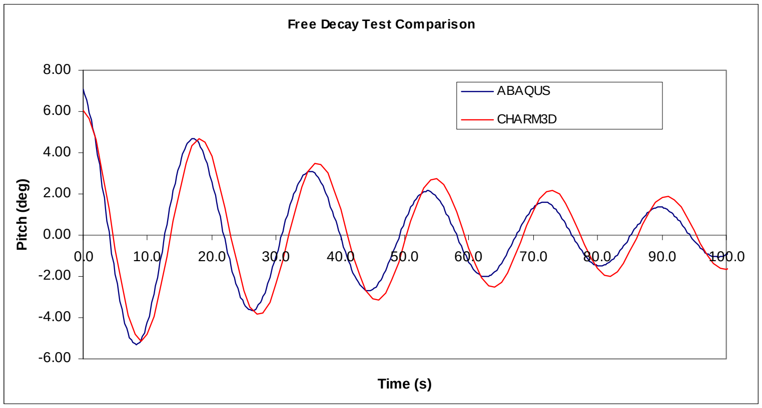


Figure 41. Free Decay Comparison for Platform Pitch Motions

Figure 42 shows a comparison of pitch motions computed for the regular wave. Pitch amplitude is remarkably different.

CHARM3D: 3.2 deg

ABAQUS: 5.2 deg

This comparison may be slightly unrepresentative because the wave period is close to the pitch natural period; nevertheless it indicates a large difference in responses.

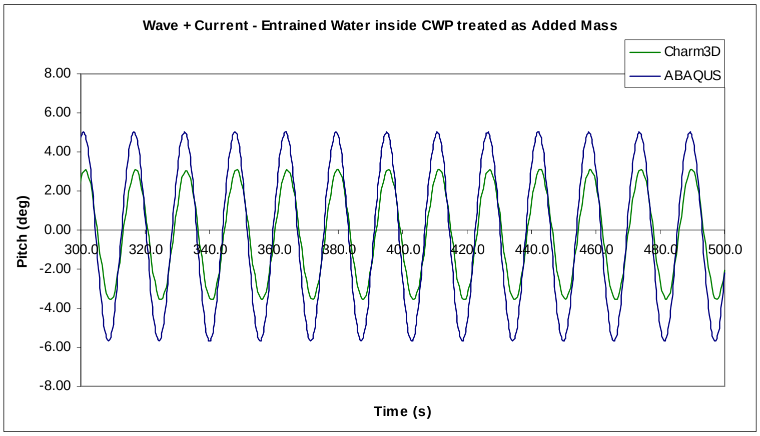


Figure 42. Pitch Motion Comparison

The corresponding pipe strain amplitudes along the length of pipe are plotted in Figure 42 the top strain amplitudes are compared in Figure 44. In spite of the pitch motions being almost 40% less for Charm3D than ABAQUS, the strain amplitudes are only 15-20% less.

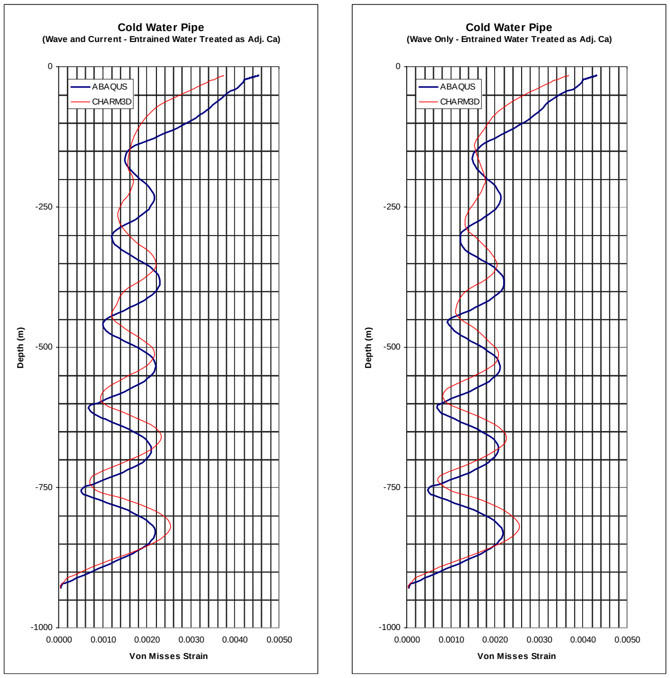


Figure 43. Strain Comparison

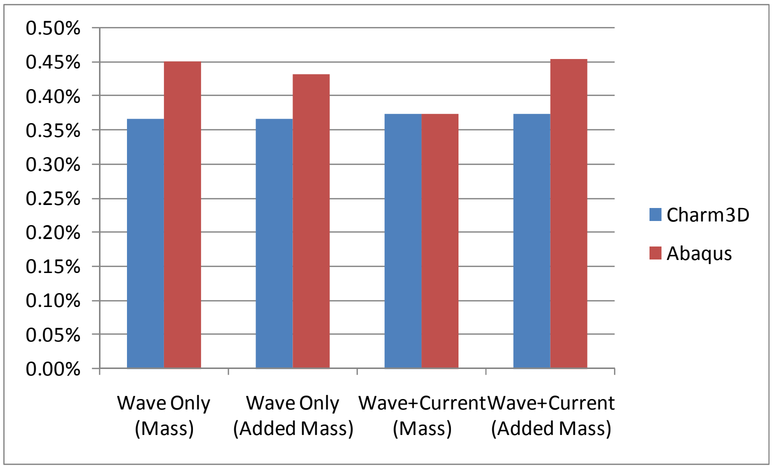


Figure 44. Strain Amplitude Comparison (top node)

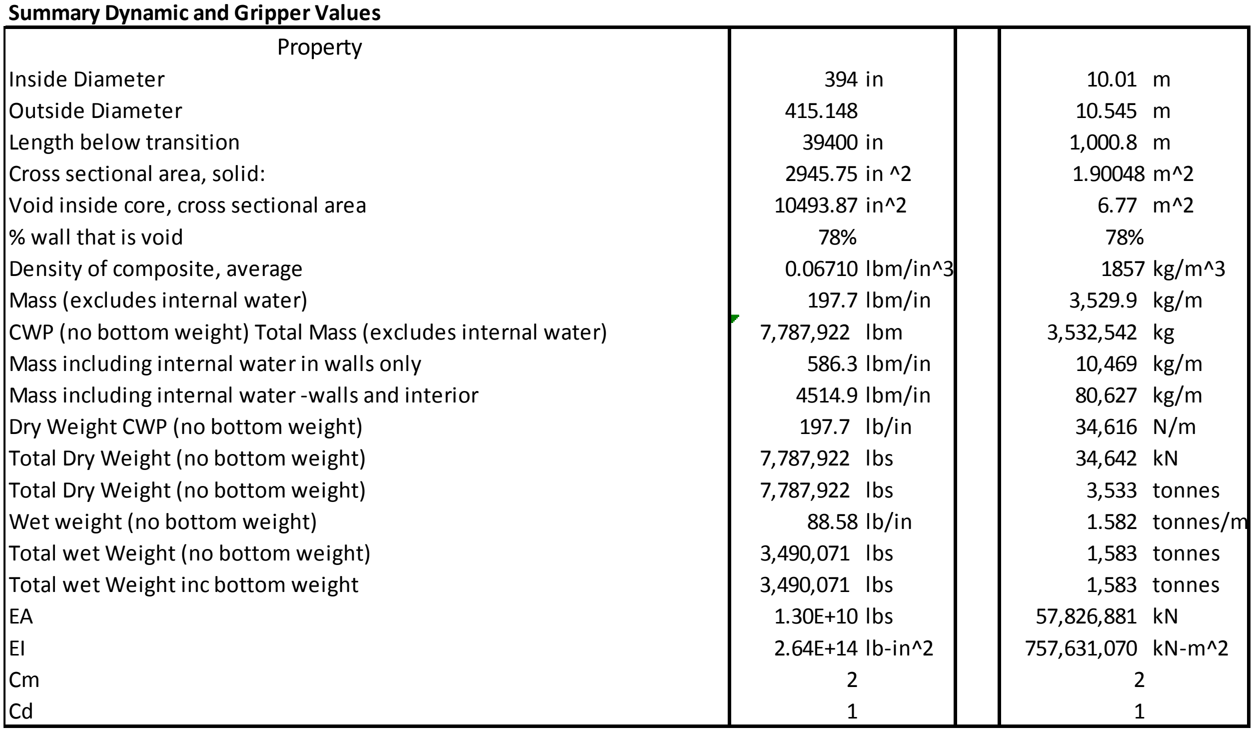
5.2.7 Clump Weight Sensitivity

A trade study in 2008 lead to the conclusion that a 45 ton clump weight was optimal for the 4 m pipe. This was based in part on a desire to keep offsets limited in a maximum current condition. All fatigue analysis done in 2010 used this 45 ton clump weight. Since the 2008 study, it was concluded that the offset criterion used may have been too stringent and a clump weight may not be needed for the 4 m pipe.

The sensitivity of pipe responses was conducted using Version 1 of the 10m pipe (Table 5) and the Full Production 100MW Platform. Detailed pipe properties are shown in Table 14. Clump weights of 0, 200 and 400 tons were examined. The results are summarized in Table 15 and Table 16 for the 100-yr cyclone and maximum current events, respectively and are graphically displayed in Figure 45 and Figure 46. Figure 47 shows the maximum bending strain envelope for the 100-yr cyclone for the three clump weight values.

From this data our conclusions are that a clump weight is not necessary for the 10m pipe. A previous analysis[viii] considered the sensitivity of the 4m pipe to clump weights and concluded that a 45 ton clump weight was adequate for that diameter. However, this analysis only considered weights from 45 – 1200 tons, hence zero clump weight was not considered. A re-analysis might indicate that a clump weight is not necessary on the 4m pipe either.

Table 14. Version 1 Pipe Properties (no clump weight)



Summary Dynamic and Gripper Values

Property					
Inside Diameter	394	in		10.01	m
Outside Diameter	415.148			10.545	m
Length below transition	39400	in		1,000.8	m
Cross sectional area, solid:	2945.75	in ^2		1.90048	m^2
Void inside core, cross sectional area	10493.87	in^2		6.77	m^2
% wall that is void	78%			78%	
Density of composite, average	0.06710	lbm/in^3		1857	kg/m^3
Mass (excludes internal water)	197.7	lbm/in		3,529.9	kg/m
CWP (no bottom weight) Total Mass (excludes internal water)	7,787,922	lbm		3,532,542	kg
Mass including internal water in walls only	586.3	lbm/in		10,469	kg/m
Mass including internal water -walls and interior	4514.9	lbm/in		80,627	kg/m
Dry Weight CWP (no bottom weight)	197.7	lb/in		34,616	N/m
Total Dry Weight (no bottom weight)	7,787,922	lbs		34,642	kN
Total Dry Weight (no bottom weight)	7,787,922	lbs		3,533	tonnes
Wet weight (no bottom weight)	88.58	lb/in		1.582	tonnes/m
Total wet Weight (no bottom weight)	3,490,071	lbs		1,583	tonnes
Total wet Weight inc bottom weight	3,490,071	lbs		1,583	tonnes
EA	1.30E+10	lbs		57,826,881	kN
EI	2.64E+14	lb-in^2		757,631,070	kN-m^2
Cm	2			2	
Cd	1			1	

Table 15. Results for Clump Weight Analysis 10m Pipe – 100 Yr Cyclone

		100 year cyclone					
		CWP **rigid connected** to Semi			CWP **pin connected** to Semi		
	Units	No clumped weight	200 t clumped weight attached	400 t clumped weight attached	No clumped weight	200 t clumped weight attached	400 t clumped weight attached
CWP Max Bottom Offset	m	86.95	73.48	65.22	92.88	76.84	67.15
Max Bending Moment	N-m	1.37E+09	1.31E+09	1.27E+09	3.77E+08	3.82E+08	3.92E+08
Location of Maximum Bending (Location from keel)	m	0	0	0	797.1	798	796
Max Bending Strain		0.0095	0.009	0.0088	0.00273	0.00266	0.00262
Max Effective Tension at CWP Top	t	2.77E+03	2.57E+03	2.24E+03	2.75E+03	2.43E+03	2.12E+03
CWP Top Connection angle of rotation	deg	-	-	-	8.16	7.32	6.93

Table 16. Results for Clump Weight Analysis 10m Pipe - Maximum Current

		Max Current for CWP Design					
		CWP **rigid connected** to Semi			CWP **pin connected** to Semi		
	Units	No clumped weight	200 t clumped weight attached	400 t clumped weight attached	No clumped weight	200 t clumped weight attached	400 t clumped weight attached
CWP Max Bottom Offset	m	34.65	26.22	22.2	42.8	34.2	28.82
Max Bending Moment	N-m	6.22E+08	5.60E+08	5.60E+08	1.22E+08	1.15E+08	1.08E+08
Location of Maximum Bending (Location from keel)	m	0	0	0	137.6	135.9	124.7
Max Bending Strain		0.0043	0.0039	0.0039	0.00085	0.0008	0.00075
Max Effective Tension at CWP Top	t	2.03E+03	1.82E+03	1.61E+03	2.02E+03	1.81E+03	1.61E+03
CWP Top Connection angle of rotation	deg	-	-	-	4.25	3.87	3.64

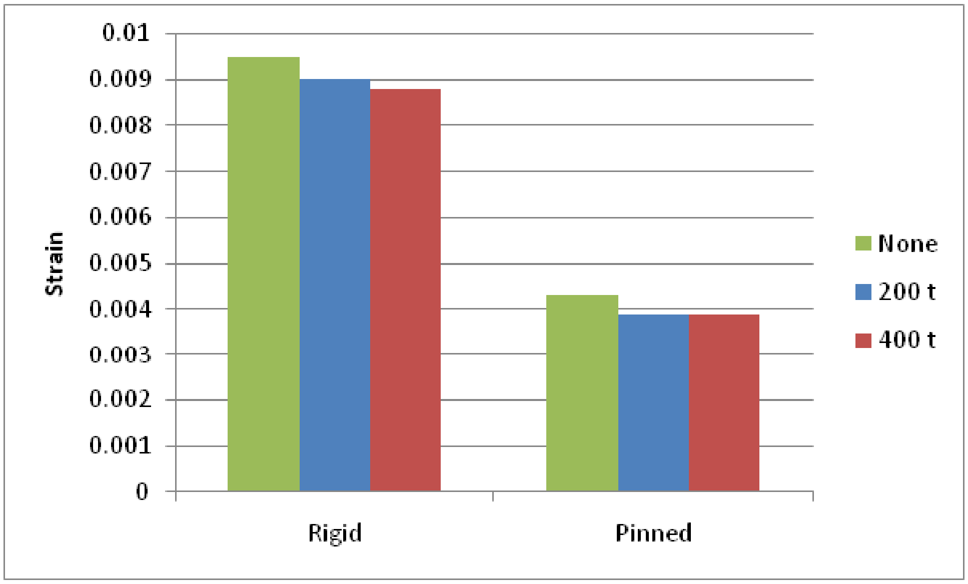


Figure 45. Effect of Clump Weight on Strain, 100 Yr-Cyclone

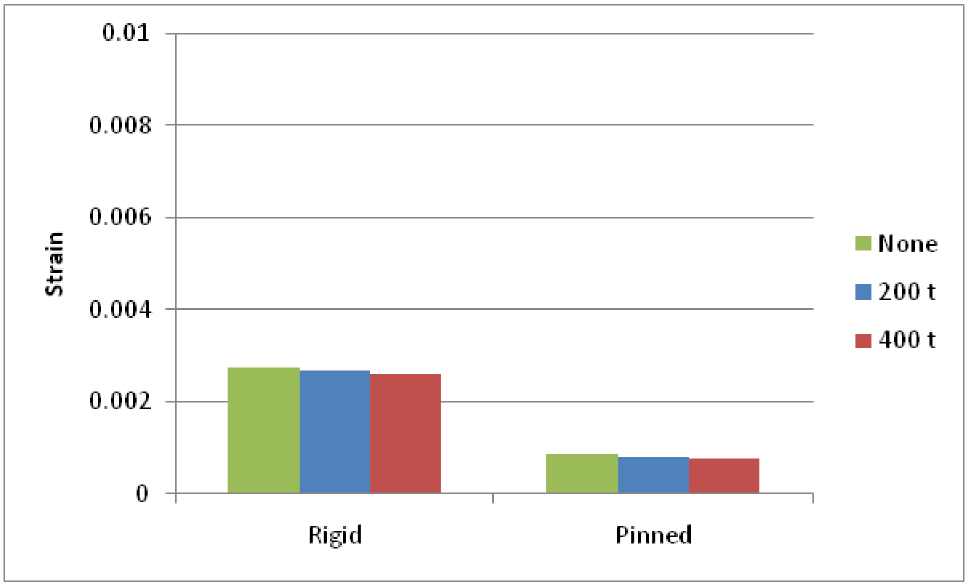


Figure 46. Effect of Clump Weight on Maximum Strain, Max Current

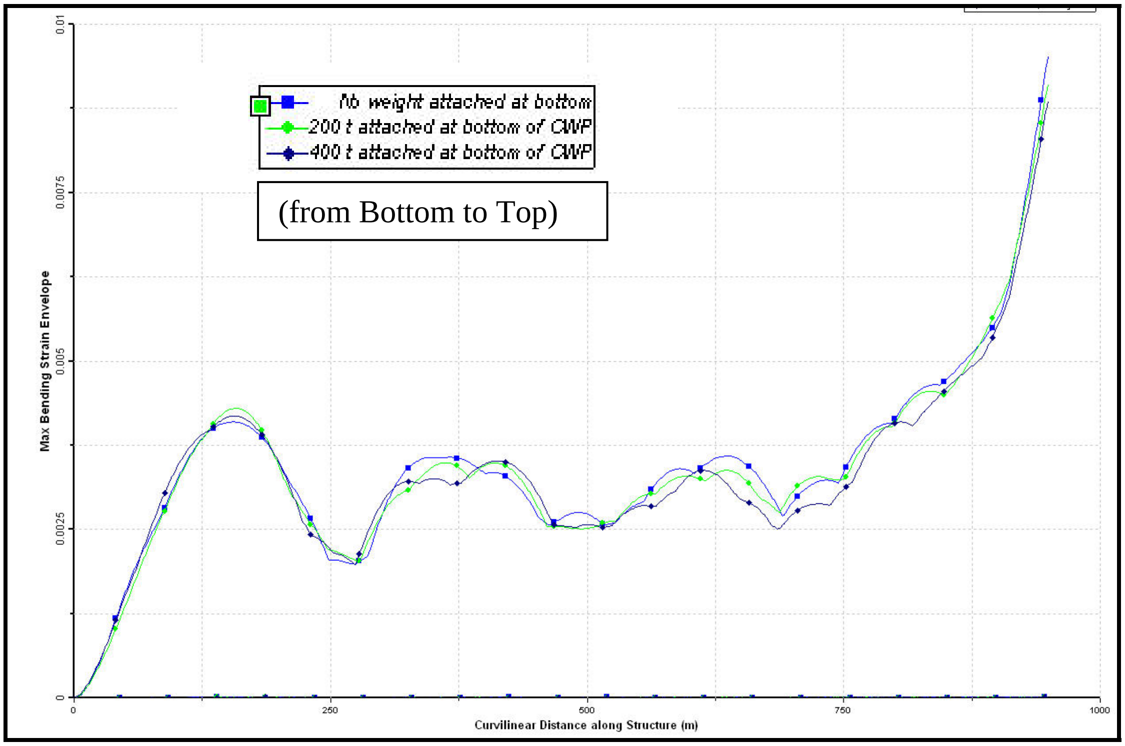


Figure 47. 100 Yr Cyclone Bending Strain Envelope for CWP Rigid Connected to Semi

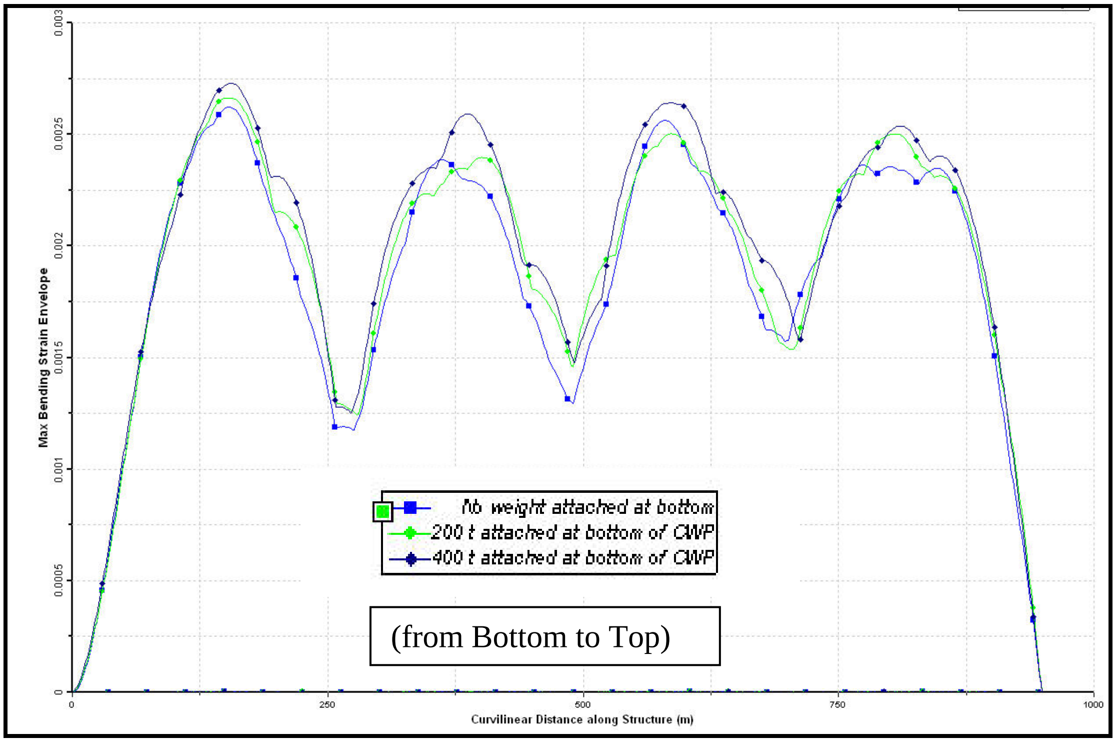
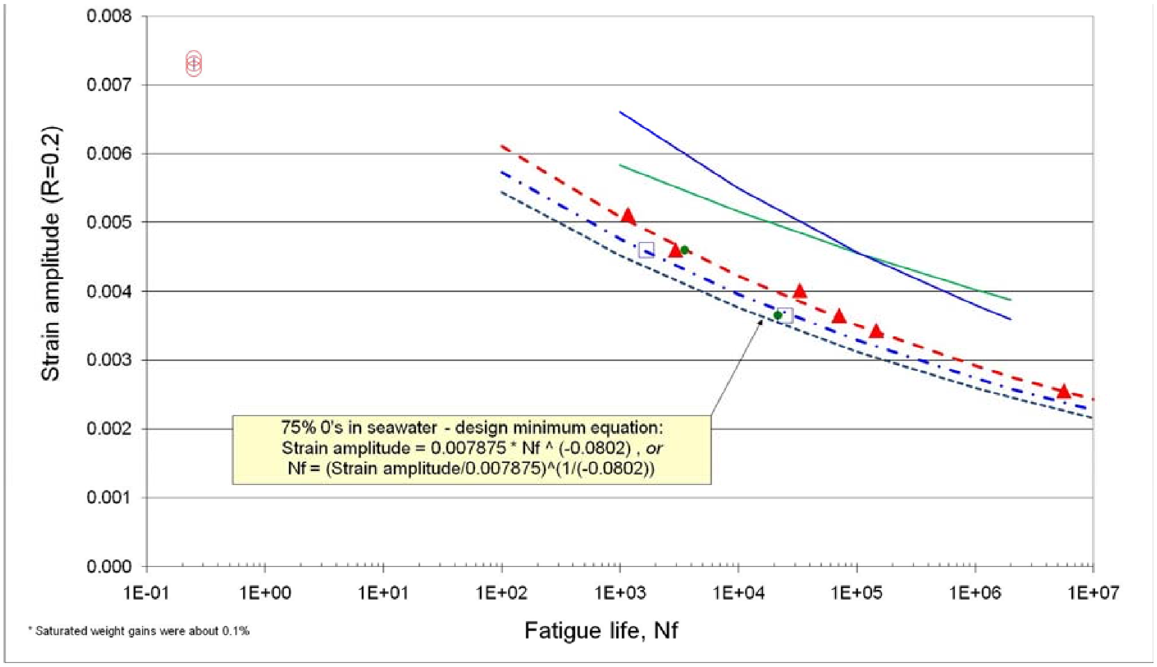


Figure 48. 100 Yr Cyclone Bending Strain Envelope for CWP Pin Connected to Semi

5.2.8 Fatigue – 10 meter Pipe

5.2.8.1 Assumed Fatigue Properties

A fatigue analysis was performed for Version 1 of the 10m diameter pipe. The analysis consisted of running a thirty minute coupled simulation for each of the 16 fatigue bins (Table 9) using HARP. The strain time histories were processed using the rainflow counting of the strain cycles[ix] together with the fatigue SN Curve (Figure 49)[x].



75% 0's in seawater - design minimum equation:
Strain amplitude = 0.007875 * Nf ^ (-0.0802) , *or*
Nf = (Strain amplitude/0.007875)^(1/(-0.0802))

* Saturated weight gains were about 0.1%

Figure 49. Fatigue Design Curve

The design curve is plotted as strain amplitude vs. the log of the number of cycles to failure and represented by the equation:

$$N_F = \left[\frac{\varepsilon_{amp}}{.007875} \right]^{-12.5}$$

where

ε_{amp} = strain amplitude.

The fatigue life is estimated based on cumulative damage theory whereby a cycle of strain amplitude A_i causes damage equal to A_i/N_F. The failure is assumed to occur when the sum of damage from all strain cycles is equal to one. The fatigue life (in years) is thus the inverse of the cumulative damage in one year. For example, if the cumulative damage in one year is 0.010, then the fatigue life is 1/.01 = 100 years.

Based on the formula above, the damage is proportional to strain amplitude raised to the power 12.5. Thus the life estimate is very sensitive to strain amplitude: a 20% increase in strain amplitude reduces the fatigue life by an order of magnitude.

5.2.8.1.1 Results

The statistics of the motions of the platform for each fatigue environment are summarized in Table 17. The assumed heading is 180 deg (waves approaching along the x-axis), hence the motions in sway and roll are negligible. In actuality wave directions will vary. This means the fatigue strains on the pipe will not occur at the same circumferential position which will result in greater fatigue life than is calculated here. This affect is normally ignored in design at this level, but could be employed to qualify a design if the fatigue results are marginal. Typically, taking directionality into account may increase expected fatigue life by a factor of two.

Pitch is the most important motion for a fixed connection and surge (at the hangoff point) is most important for a pinned or gimbaled connection. Figure 50 and Figure 51 show the dynamic pitch and surge (standard deviation) as a function of significant wave height, Hs. The results are highly dependent upon wave period and have been plotted for different period bands to show this effect. Figure 52 shows the results for pipe strain for a fixed connection[1].

The pitch responses not only show a period affect, but a fairly strong non-linearity in the responses in the period range of 9-14 seconds. This is suggestive of a resonant response which is limited by damping. In our case damping is dependent upon viscous drag which is non-linear.

Interestingly strain results are much more linear.

Figure 53 and Figure 54 show the dynamic strain (standard deviation) and fatigue damage vs. the bin numbers. The computation of fatigue damage is based on the dynamic strain results, *plus the frequency of occurrence of the particular environment*. From Figure 54 it is clear that virtually all of the fatigue damage is arising from two bins: 12 and 16, these being the most severe swell events. From Table 9, we see that these conditions exist about 9% of the time, i.e. virtually all of the fatigue damage is coming from events occurring 9% of the time. This conclusion applies to this platform configuration and may not apply to other platforms.

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[1] We have found that the motions are actually sensitive to the connection stiffness. All these results are for a “fixed” connection to illustrate the effect.

Table 17. Platform Motions

		DISPLACEMENT					
		Surge(m)	**Sway(m)**	**Heave(m)**	**Roll(rad)**	**Pitch(rad)**	**Yaw(rad)**
Bin 1	**Maximum**	3.09E-06	7.22E-12	2.02E-04	1.49E-11	9.77E-04	1.74E-09
	Minimum	-1.32E+00	-9.50E-07	-3.35E-02	-8.23E-10	-2.63E-04	-1.05E-09
	Mean	-9.43E-01	-7.12E-07	-9.32E-03	-5.39E-10	4.19E-04	2.83E-10
	Std Dev	1.47E-01	1.04E-07	3.02E-03	9.99E-11	1.64E-04	4.90E-10
Bin 2	**Maximum**	7.38E-05	7.22E-12	1.21E-02	2.00E-11	1.36E-03	3.02E-09
	Minimum	-1.40E+00	-9.96E-07	-3.35E-02	-8.51E-10	-4.42E-04	-1.89E-09
	Mean	-9.85E-01	-7.40E-07	-9.00E-03	-5.36E-10	4.20E-04	4.75E-10
	Std Dev	1.60E-01	1.11E-07	6.73E-03	1.10E-10	2.52E-04	9.25E-10
Bin 3	**Maximum**	8.59E-05	7.22E-12	2.23E-02	3.18E-11	1.49E-03	5.73E-09
	Minimum	-1.49E+00	-1.05E-06	-4.01E-02	-8.69E-10	-5.55E-04	-3.68E-09
	Mean	-1.04E+00	-7.74E-07	-8.68E-03	-5.34E-10	4.18E-04	8.61E-10
	Std Dev	1.80E-01	1.20E-07	1.00E-02	1.17E-10	2.95E-04	1.69E-09
Bin 4	**Maximum**	2.24E-04	7.22E-12	6.99E-02	9.20E-11	2.36E-03	1.17E-08
	Minimum	-1.93E+00	-1.19E-06	-8.20E-02	-9.80E-10	-1.67E-03	-7.38E-09
	Mean	-1.22E+00	-8.61E-07	-7.16E-03	-5.16E-10	4.26E-04	1.82E-09
	Std Dev	2.61E-01	1.44E-07	2.42E-02	1.78E-10	5.36E-04	3.60E-09
Bin 5	**Maximum**	4.94E-03	7.22E-12	1.41E-01	2.87E-10	3.68E-03	1.40E-09
	Minimum	-1.37E+00	-9.51E-07	-1.39E-01	-1.33E-09	-3.37E-03	-1.66E-09
	Mean	-9.85E-01	-7.21E-07	-8.88E-03	-5.29E-10	4.61E-04	-2.40E-11
	Std Dev	1.71E-01	1.06E-07	4.08E-02	2.44E-10	9.48E-04	4.56E-10
Bin 6	**Maximum**	7.50E-03	7.22E-12	2.04E-01	7.24E-10	5.41E-03	2.54E-09
	Minimum	-1.58E+00	-9.76E-07	-1.98E-01	-1.73E-09	-5.24E-03	-3.15E-09
	Mean	-1.04E+00	-7.42E-07	-8.42E-03	-5.26E-10	4.90E-04	-9.55E-11
	Std Dev	2.04E-01	1.14E-07	5.79E-02	3.44E-10	1.45E-03	8.66E-10
Bin 7	**Maximum**	9.75E-03	7.22E-12	2.64E-01	1.05E-09	6.56E-03	3.94E-09
	Minimum	-1.88E+00	-1.01E-06	-2.42E-01	-2.00E-09	-6.56E-03	-4.91E-09
	Mean	-1.13E+00	-7.72E-07	-7.68E-03	-5.27E-10	5.27E-04	-1.27E-10
	Std Dev	2.50E-01	1.27E-07	7.26E-02	4.08E-10	1.78E-03	1.34E-09
Bin 8	**Maximum**	1.16E-02	7.22E-12	3.30E-01	1.00E-09	7.31E-03	8.08E-09
	Minimum	-2.97E+00	-1.32E-06	-3.15E-01	-2.04E-09	-5.38E-03	-6.33E-09
	Mean	-1.56E+00	-9.11E-07	-2.96E-03	-5.33E-10	6.36E-04	1.22E-09
	Std Dev	4.48E-01	1.83E-07	8.29E-02	4.33E-10	1.65E-03	2.60E-09
Bin 9	**Maximum**	6.61E-03	7.22E-12	3.65E-01	2.65E-09	1.36E-02	2.42E-09
	Minimum	-1.72E+00	-1.01E-06	-3.73E-01	-3.67E-09	-1.20E-02	-2.77E-09
	Mean	-1.01E+00	-7.38E-07	-8.83E-03	-5.37E-10	5.17E-04	-1.90E-10
	Std Dev	2.32E-01	1.20E-07	1.25E-01	1.18E-09	4.62E-03	8.77E-10
Bin 10	**Maximum**	9.21E-03	7.22E-12	4.61E-01	3.31E-09	1.77E-02	3.97E-09
	Minimum	-2.01E+00	-1.05E-06	-4.79E-01	-4.44E-09	-1.71E-02	-4.87E-09
	Mean	-1.08E+00	-7.74E-07	-8.37E-03	-5.51E-10	5.55E-04	-3.55E-10
	Std Dev	2.84E-01	1.37E-07	1.57E-01	1.29E-09	5.64E-03	1.50E-09
Bin 11	**Maximum**	3.01E-02	7.22E-12	6.30E-01	3.75E-09	2.60E-02	7.26E-09
	Minimum	-2.76E+00	-1.28E-06	-6.75E-01	-4.67E-09	-2.44E-02	-9.61E-09
	Mean	-1.26E+00	-8.61E-07	-7.40E-03	-6.08E-10	6.25E-04	-7.13E-10
	Std Dev	3.95E-01	1.83E-07	2.16E-01	1.52E-09	8.47E-03	2.80E-09
Bin 12	**Maximum**	1.43E-01	7.22E-12	1.13E+00	4.70E-09	2.96E-02	1.67E-08
	Minimum	-3.75E+00	-1.98E-06	-1.17E+00	-6.56E-09	-2.89E-02	-2.17E-08
	Mean	-1.61E+00	-1.07E-06	-4.85E-03	-7.10E-10	7.30E-04	-1.68E-09
	Std Dev	5.64E-01	3.38E-07	3.69E-01	1.86E-09	1.06E-02	6.42E-09
Bin 13	**Maximum**	1.21E-01	7.22E-12	8.21E-01	3.66E-09	2.13E-02	4.08E-09
	Minimum	-1.98E+00	-1.14E-06	-8.46E-01	-4.76E-09	-1.94E-02	-2.79E-09
	Mean	-1.07E+00	-7.95E-07	-8.82E-03	-5.97E-10	5.70E-04	1.36E-11
	Std Dev	2.97E-01	1.33E-07	2.99E-01	1.57E-09	7.45E-03	1.08E-09
Bin 14	**Maximum**	1.72E-01	7.22E-12	1.06E+00	4.21E-09	2.45E-02	6.03E-09
	Minimum	-2.25E+00	-1.25E-06	-1.09E+00	-5.46E-09	-2.21E-02	-5.75E-09
	Mean	-1.16E+00	-8.59E-07	-8.47E-03	-6.39E-10	6.12E-04	-5.14E-11
	Std Dev	3.47E-01	1.67E-07	3.80E-01	1.59E-09	8.72E-03	1.90E-09
Bin 15	**Maximum**	2.41E-01	7.22E-12	1.39E+00	5.53E-09	2.52E-02	1.12E-08
	Minimum	-2.72E+00	-1.49E-06	-1.41E+00	-7.14E-09	-2.45E-02	-1.15E-08
	Mean	-1.27E+00	-9.56E-07	-7.89E-03	-6.93E-10	6.56E-04	-1.74E-10
	Std Dev	4.08E-01	2.31E-07	4.88E-01	1.77E-09	9.56E-03	3.49E-09
Bin 16	**Maximum**	4.66E-01	1.06E-07	2.00E+00	9.24E-09	3.04E-02	2.65E-08
	Minimum	-3.65E+00	-2.46E-06	-2.01E+00	-1.24E-08	-2.88E-02	-2.69E-08
	Mean	-1.68E+00	-1.26E-06	-5.56E-03	-8.65E-10	7.89E-04	-8.08E-10
	Std Dev	6.09E-01	4.73E-07	6.82E-01	2.89E-09	1.23E-02	8.57E-09

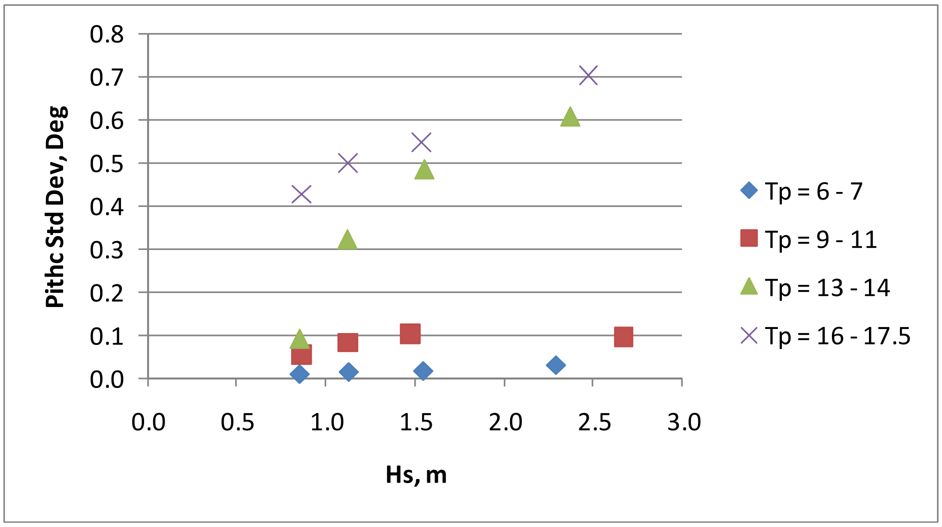


Figure 50. Pitch Standard Deviation vs. Significant Wave Height

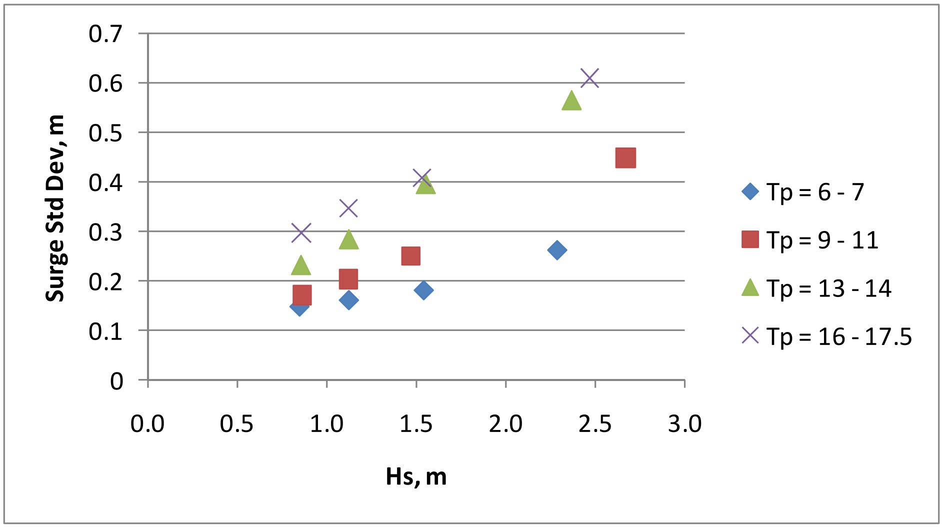


Figure 51. Surge Standard Deviation vs. Significant Wave Height

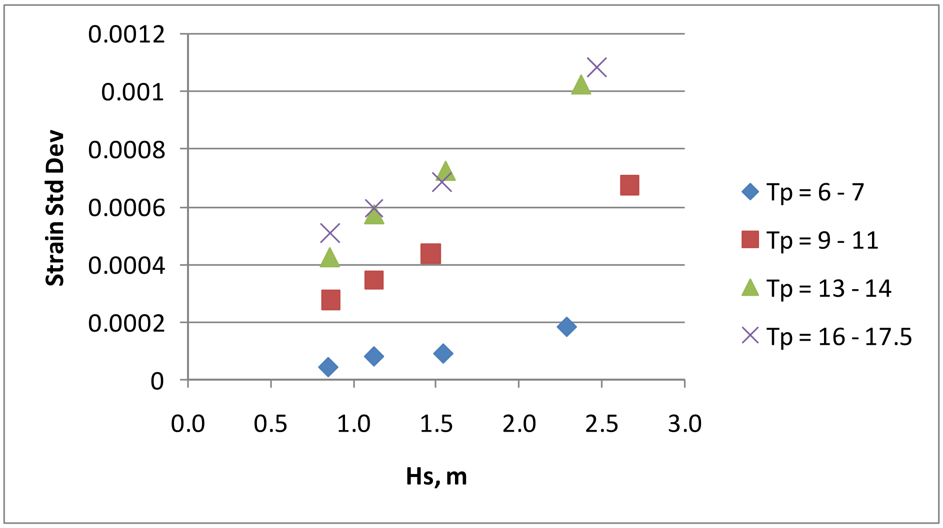


Figure 52. Strain Standard Deviation vs. Significant Wave Height

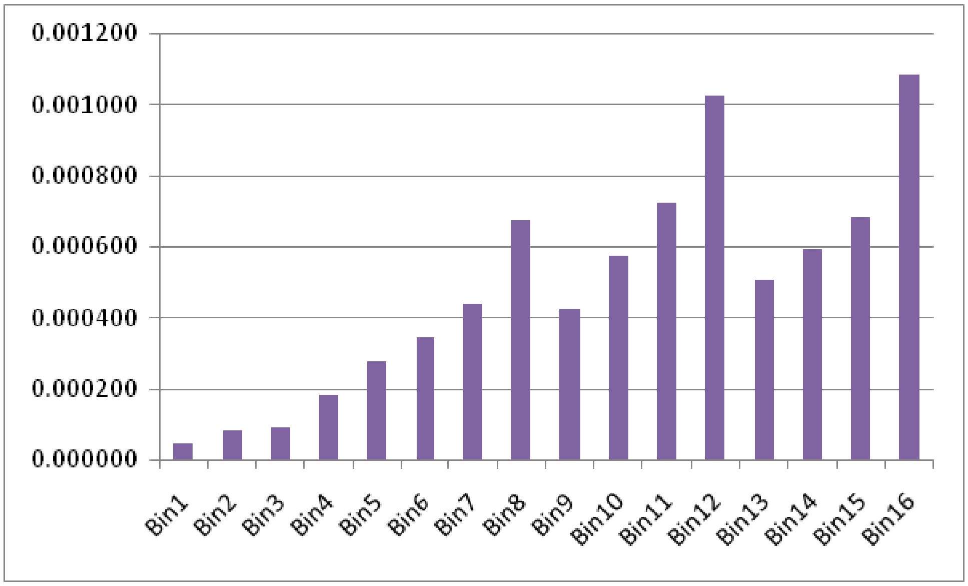


Figure 53. Standard Deviation of Strain at Top

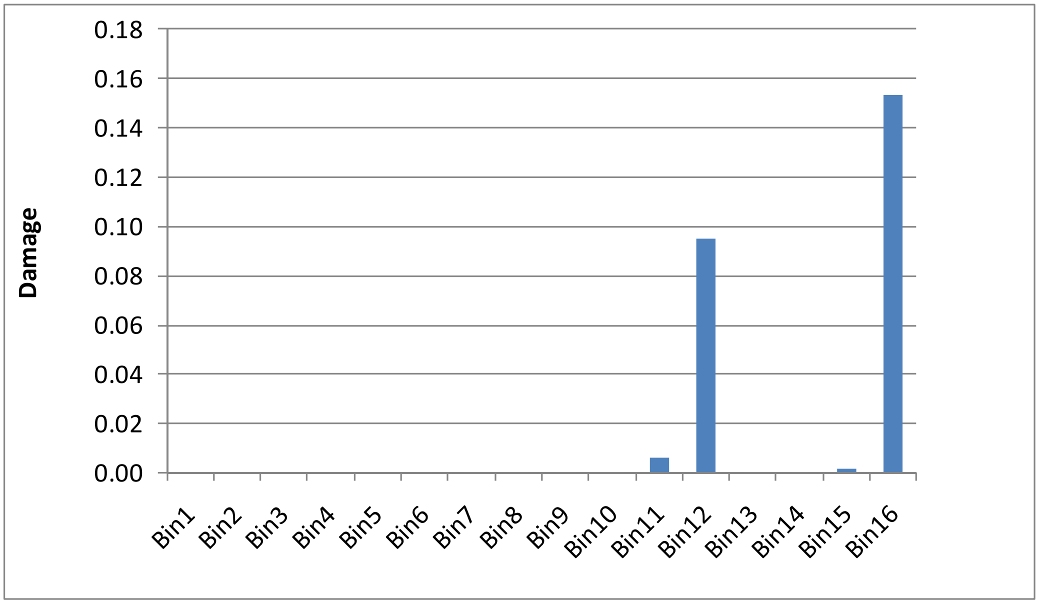


Figure 54. Spectral Fatigue Damage by Bin No. at Top Node, Fixed

The above strain results are for the top node of the pipe. The strain dynamics at the top 21 nodes of the pipe model were computed and used to derive fatigue life. The results for fixed and pinned top connections are shown in Figure 55. The fixed connection fails to meet the required fatigue life at the top to a depth of 160 m, as well at (presumably anti-nodal) points further along the pipe. The pipe greatly exceeds the required fatigue life for the pinned connection.

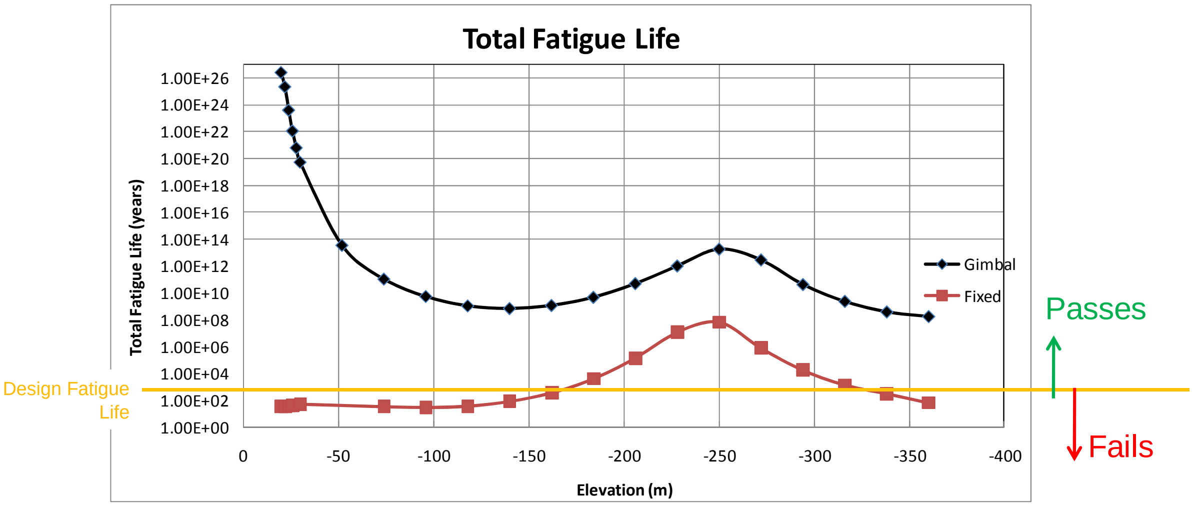


Figure 55. Fatigue Life Estimate along Length of Pipe

An alternative to the pinned connection is a tapered pipe section near the termination. The tapered section consists of a thicker pipe section at the end with the thickness diminishing to the nominal pipe value at some length away from the end. The theory of tapering is that the angle between the platform and the pipe which results in large strain (curvature) at the termination can be spread out over a finite length so the maximum curvature at any point can be minimized.

The taper is usually specified by the thickness at the termination and the length of the taper. Since our pipe diameter is so large, EA or EI is a proxy for the thickness, and we specify the properties at the termination as “n x EI” or “n x EA” meaning “n” times the nominal pipe properties. Figure 56 illustrates the tapered section we analyzed for the 10 m pipe which has three times the wall thickness at the termination and a length of 100 m.

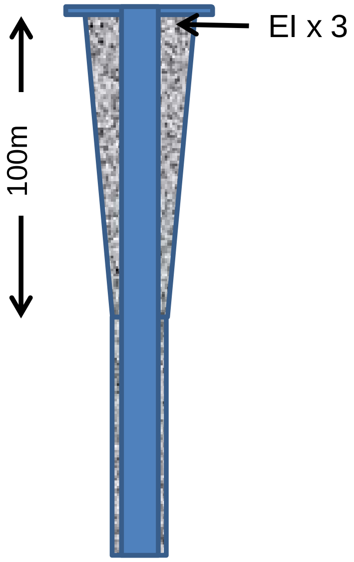


Figure 56. Tapered Pipe Section

The results for this analysis are shown in Figure 57 and Figure 58. This example shows a large reduction in strain at the termination; however the dynamic strain 10 m below the termination is almost as high as the strain in the original pipe at the termination. This would nominally not represent a large improvement in the fatigue life based on the present analysis. However, we have not taken into account a stress concentration at the termination which will result in a lower fatigue life there, for a given nominal strain, than elsewhere in the pipe. Thus, even if we have only succeeded in moving the point of maximum nominal strain away from the termination, we might expect much longer fatigue life of the pipe when the fatigue factor of the termination is included.

The taper may be optimized by selecting different termination properties and lengths. We have only considered one value for the 10 m pipe shown here, but a more comprehensive sensitivity analysis has been performed for the 4 m pipe and reported below.

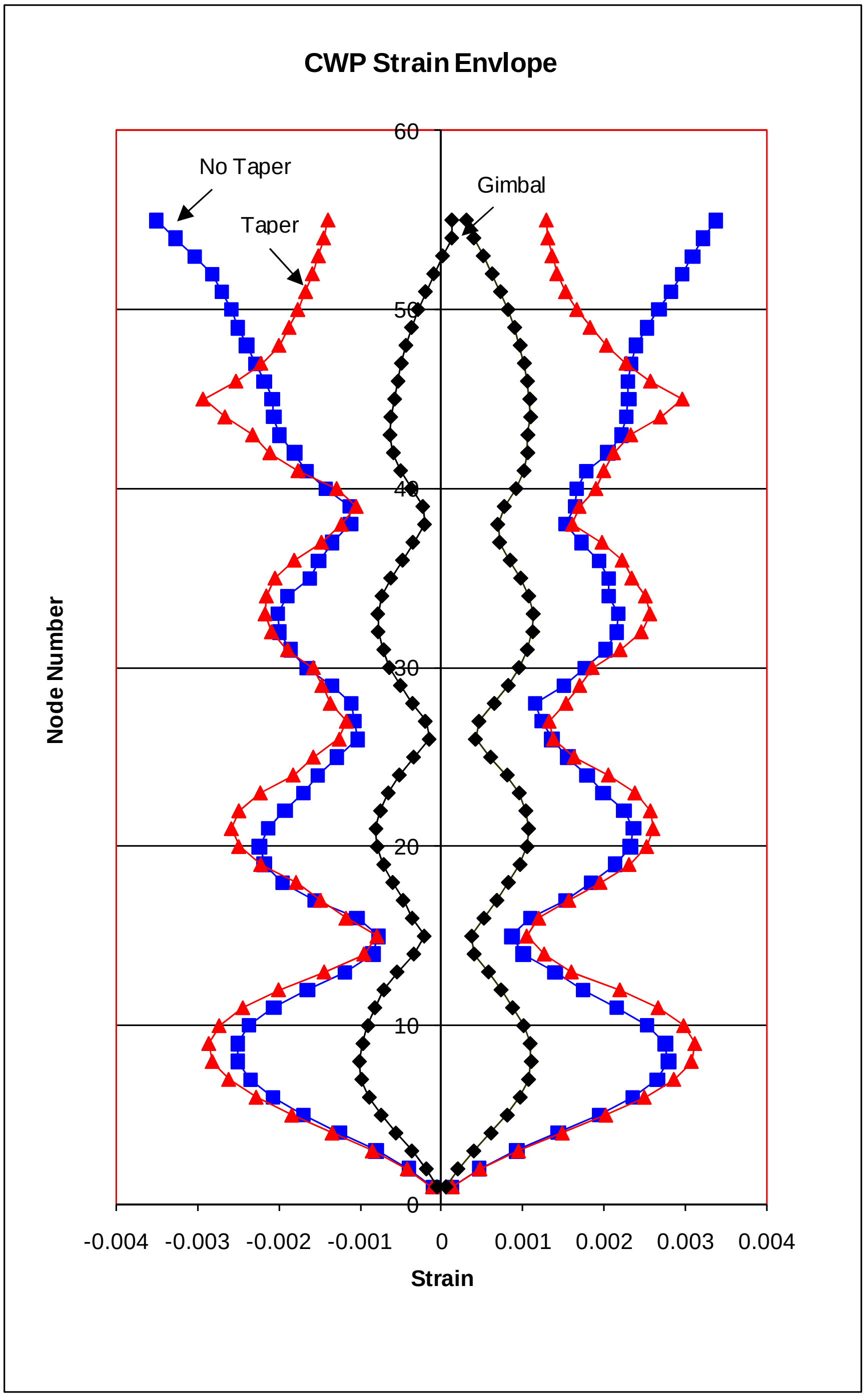


Figure 57. Strain Envelope for 10 m Tapered Pipe

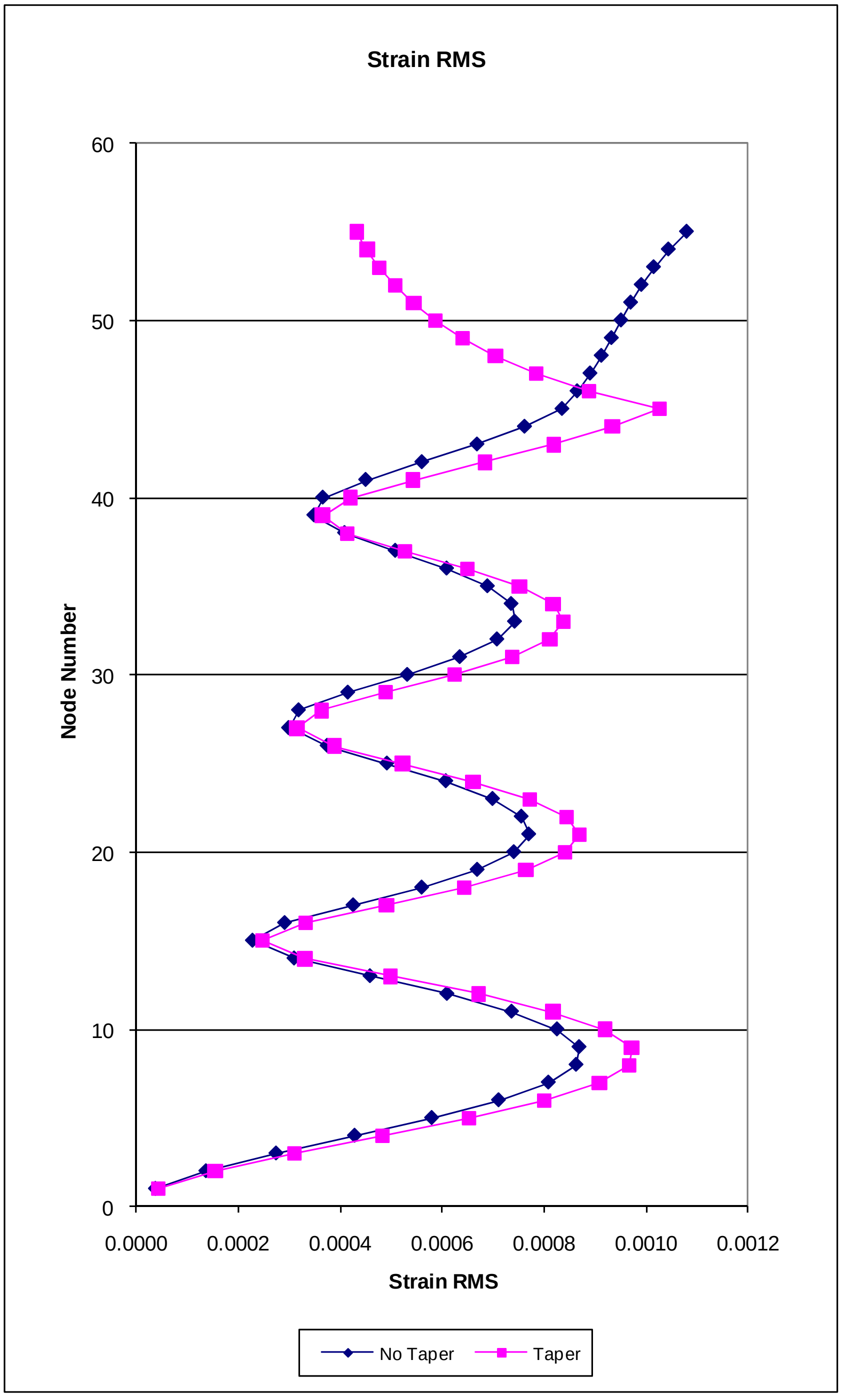


Figure 58. Envelope of Strain Standard Deviation for 10 m Tapered Pipe

5.2.9 Fatigue – 4 meter Pipe

Fatigue analysis of the 4 m pipe was carried out in an identical manner as the 10 m pipe[xi]. The results for a fixed and pinned connection are shown in Figure 59. In this case the fixed connection meets the design requirements, but just barely. If the stress risers are considered it is likely that this would also fail to meet the fatigue requirements.

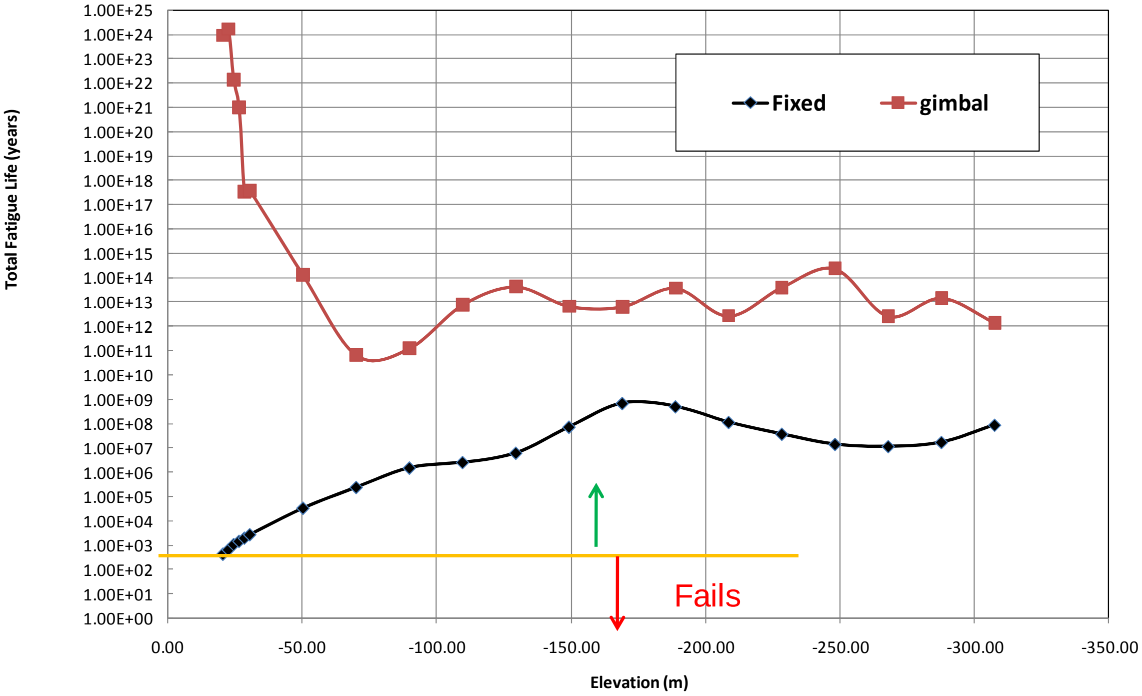


Figure 59. 4m Pipe Fatigue, Fixed and Pinned at Top

Figure 60 and Figure 61 show the extreme strain profile for bin 16 for a gimbaled and fixed connection, respectively. Note that the plots include both axial and bending strain, so the strain values at the top are not zero for the pinned connection.

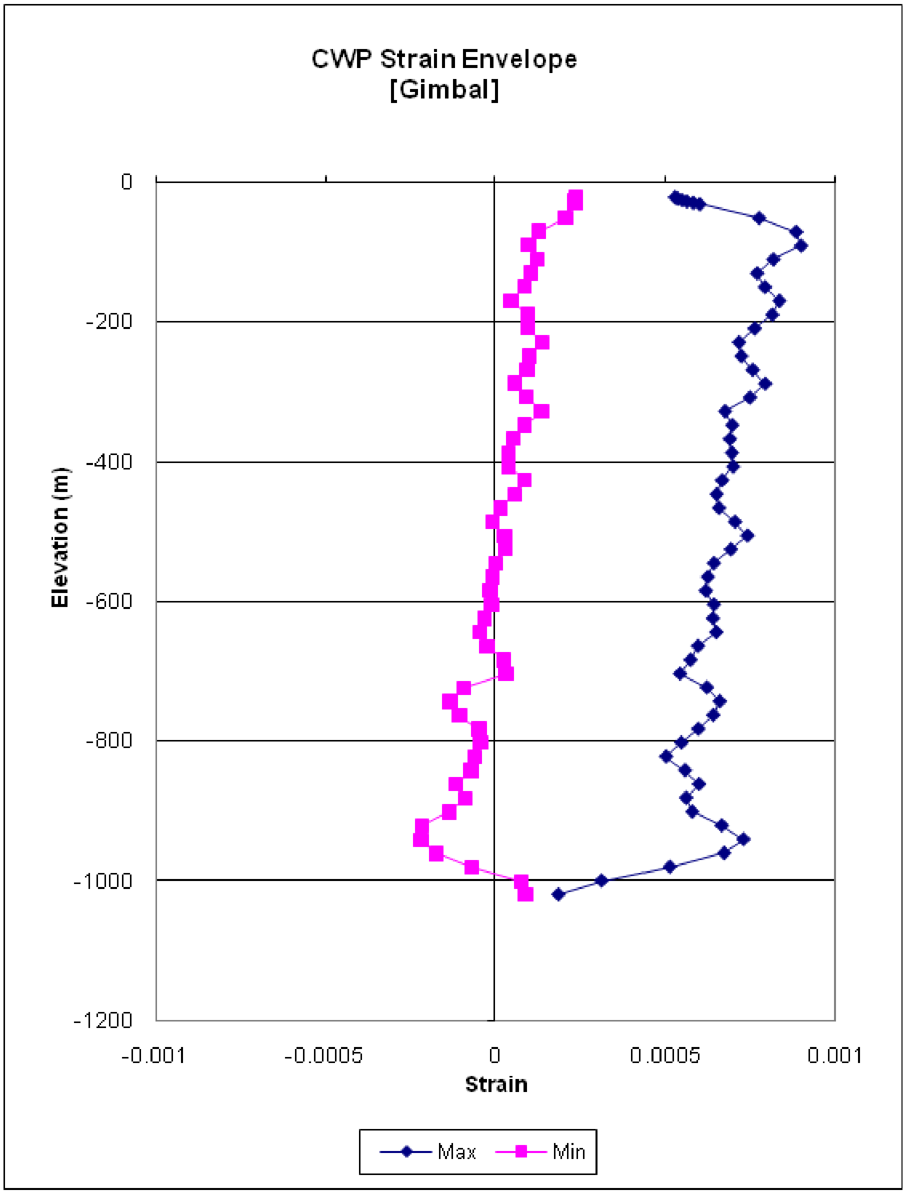


Figure 60. 4m CWP Bin 16 Strain Envelope for Gimbal

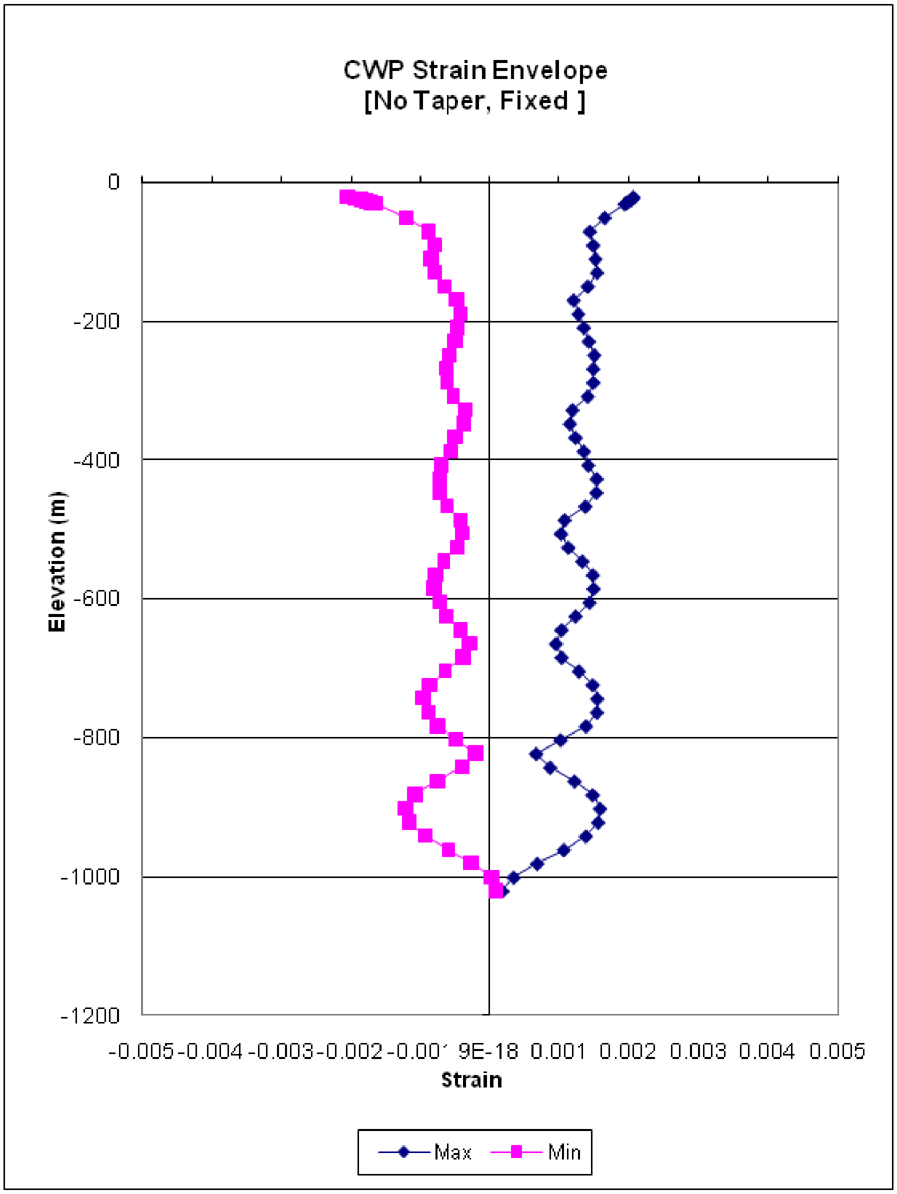


Figure 61. 4m CWP Bin 16 Strain Envelope for Fixed

5.2.10 Taper Optimization – 4 meter Pipe

As mentioned above a taper is an alternative to a gimbal for relieving the strain at the termination of the pipe. Calculations were performed for a number of different tapers as shown in Table 18. As above, the taper is defined by the thickness at the termination as a multiplier of the nominal thickness (2X, 3X etc.) and the length of the taper. All of the calculations were performed for fatigue bin 16, Table 8, which has been shown to be the most damaging case.

Table 18. 4m Pipe Taper Cases

Case #	EA	Taper Length (m)	Max Strain	Min. Strain	Max Std Dev
Gimbal	1 X	0	0.000898	-0.000217	0.000130
Fixed No Taper	1 X	0	0.002073	-0.002054	0.000742
Taper 11	2 X	20	0.002032	-0.001749	0.000654
Taper 12	2 X	30	0.002100	-0.001851	0.000622
Taper 13	2 X	40	0.001927	-0.001568	0.000595
Taper 14	2 X	60	0.001802	-0.001500	0.000545
Taper 15	2 X	80	0.001754	-0.001608	0.000536
Taper 21	2.5 X	20	0.001966	-0.001665	0.000674
Taper 22	2.5 X	30	0.002051	-0.001802	0.000651
Taper 23	2.5 X	40	0.002031	-0.001727	0.000630
Taper 24	2.5 X	60	0.001935	-0.001513	0.000585
Taper 25	2.5 X	80	0.001854	-0.001463	0.000547
Taper 31	3 X	20	0.002147	-0.001928	0.000691
Taper 32	3 X	30	0.002113	-0.001903	0.000674
Taper 33	3 X	40	0.002100	-0.001841	0.000658
Taper 34	3 X	60	0.002022	0.002022	0.000616
Taper 35	3 X	80	0.001912	-0.001454	0.000559
Taper 36	3 X	100	0.001880	-0.001409	0.000551

An example strain envelope (including the standard deviation) for bin 16 is shown in Figure 62.

The results for the maximum, minimum and maximum standard deviation of strain for all cases are shown in Figure 63 and in Figure 64.

The “optimum” taper reduces the dynamic stresses by about 26% compared to the fixed case. A complete fatigue analysis (all bins) was performed on Case 25. The results for the top 20 pipe nodes are shown in Figure 65. The taper increases the predicted fatigue life by 2-3 orders of magnitude and meets the design requirements, although the results are not as favorable by a large margin as those with the pinned connection.

Fatigue damage calculations reported here are based on operational seas. Rare, episodic events are not usually included in the fatigue damage calculation as they are normally

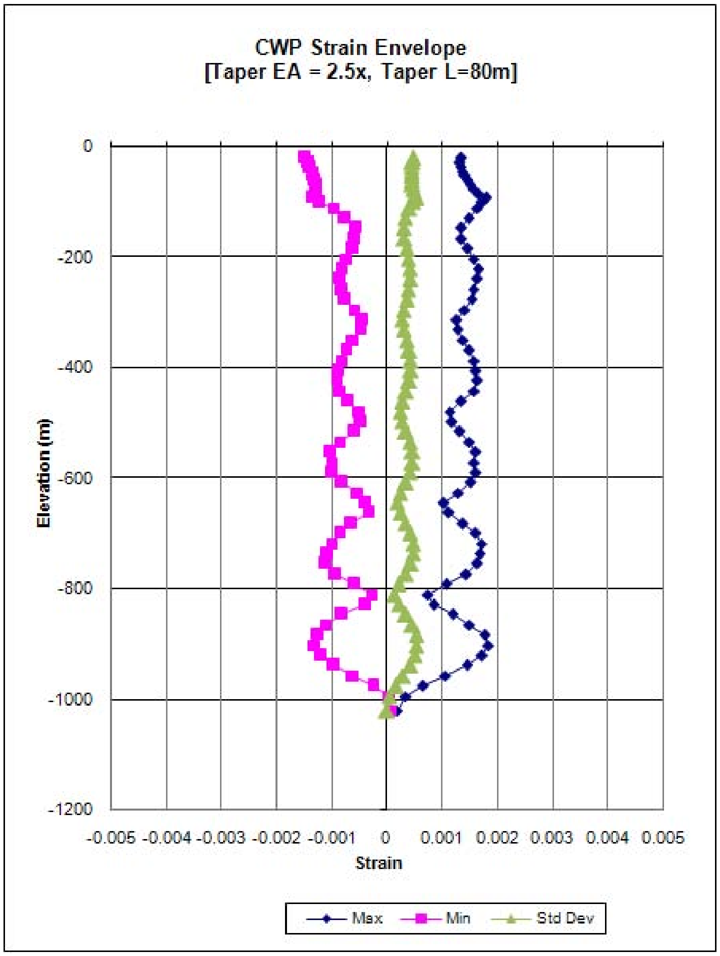


Figure 62. Example of Strain Envelope with Taper - 4 m Pipe

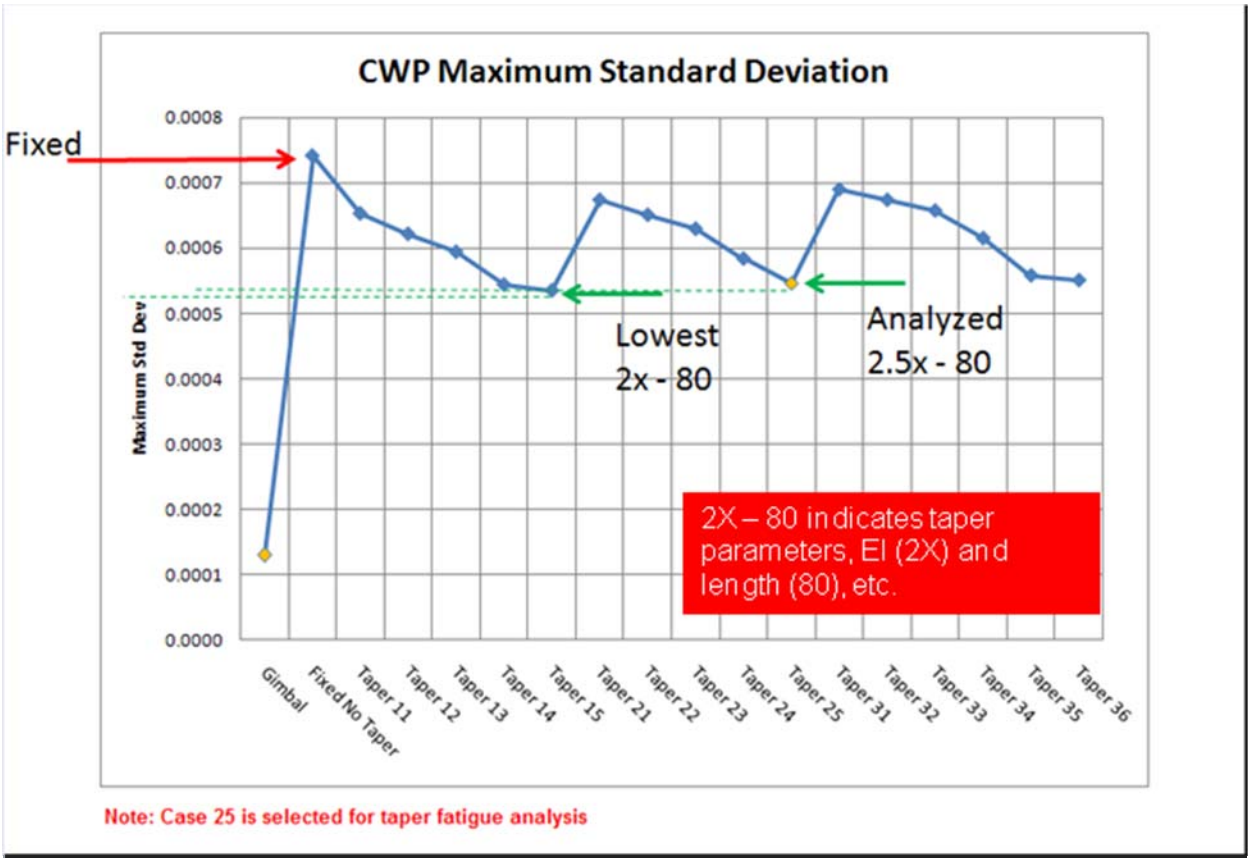


Figure 63. Maximum Strain Standard Deviation for 4m Pipe Taper Cases, Bin 16

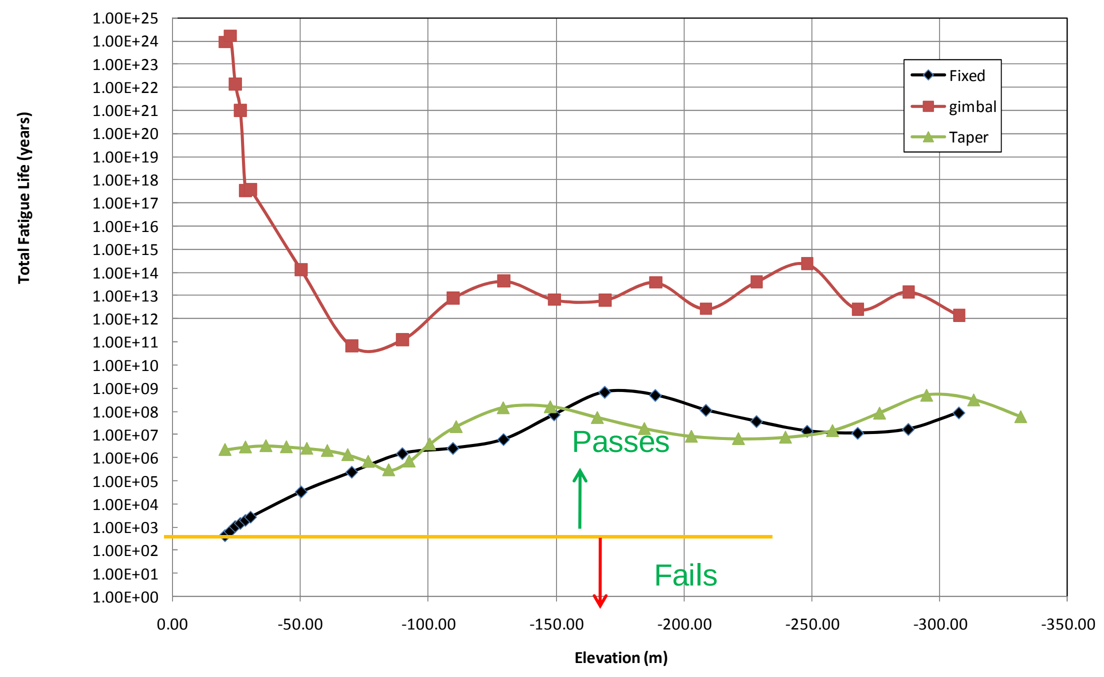


Figure 64. Fatigue Life Prediction for Top 20 Elements with Taper - 4 m Pipe

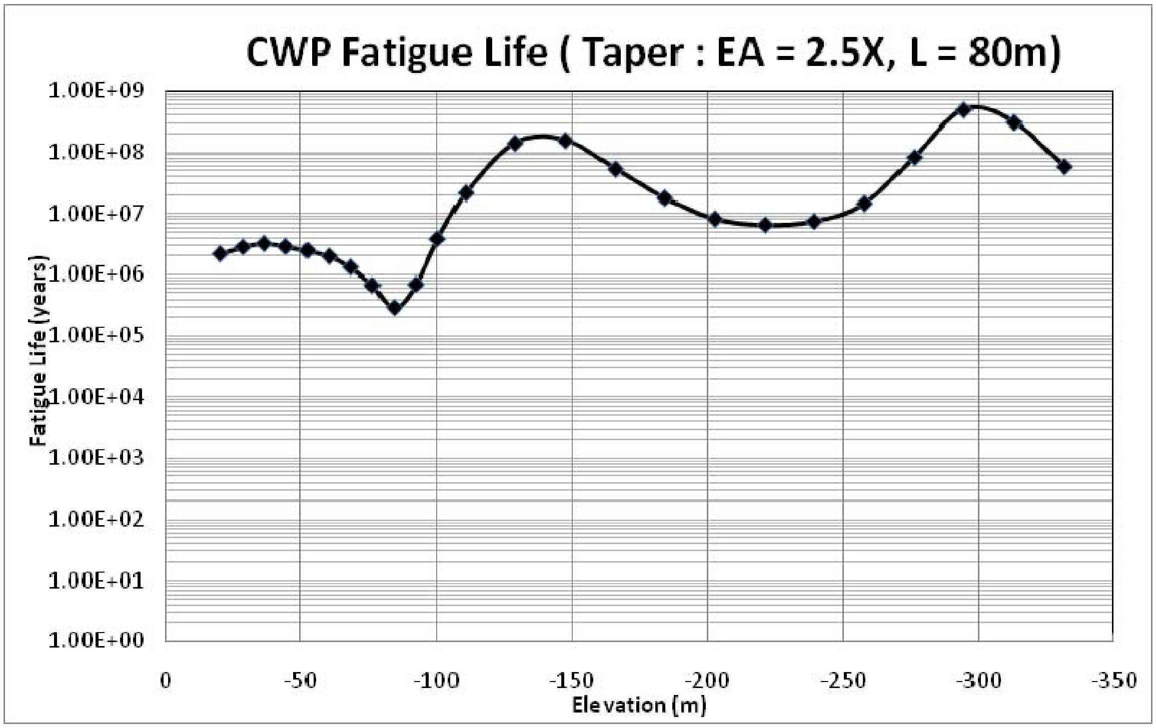


Figure 65. 4m Pipe Taper Fatigue for Top 20 Elements, Case 25

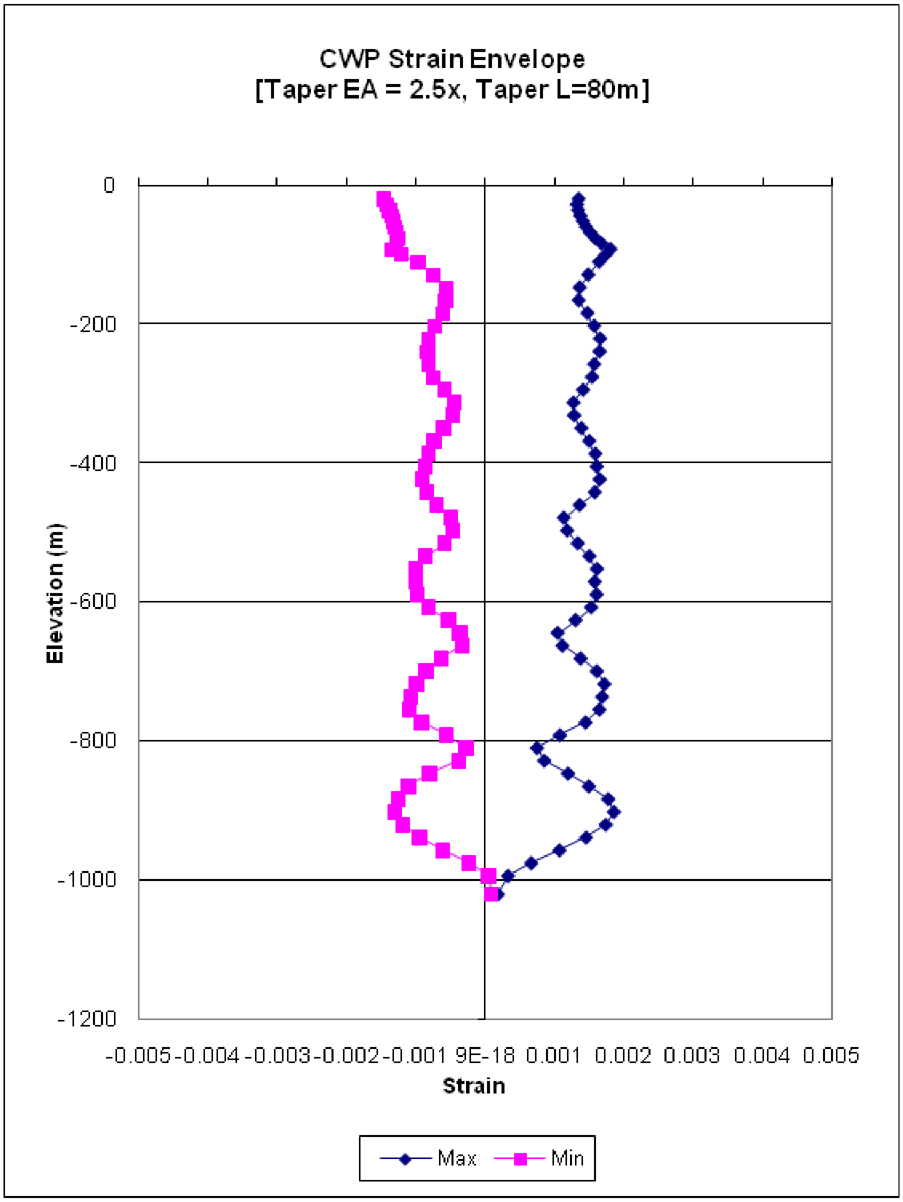


Figure 66. Taper Case 25 Strain Envelope for Bin 16

5.2.11 Responses in Extreme Events

The results presented above are for operational seas and, in particular, focus on fatigue behavior. It was shown that the fatigue life was controlled by swell events that occur about 9% of the time. If the platform is designed for "permanent" service, e.g. 20-years or more, there is a chance that it will encounter a hurricane of tropical storm with wave heights exceeding those considered in the case above. The design environments identify the "100-year storm" as appropriate for a 20-year installation, and a "25-yr storm" as appropriate for a two year pilot operation. See Table 19 which lists the pipe properties and Table 20 which lists the load cases that were analyzed[xii]. Note that for this analysis a finite stiffness at the upper termination for the gimbaled cases was used to reflect the approximate stiffness of the current gimbal design. The fatigue analysis results above assumed an ideal gimbal, or pinned connection. All of these cases were run using HARP and a rotational connection stiffness of 10^{13} N-m/rad to represent a "fixed" connection.

Table 19. Pipe Properties for Extreme Event Analysis

10 m CWP for 100 MW Plant		
Parameter	Unit	Value
Length	m	1000.8
OD	m	10.509
EA	N	6.52E+10
EI	N-m	8.47E+11
4 m CWP for 10 MW Plant		
Parameter	Unit	Value
Length	m	1000.8
OD	m	4.21
EA	N	1.07E+10
EI	N-m	2.21E+10

Table 20. Load Case Table for Extreme Event Analysis

Load Case Table						
Case	**OD (m)**	**Length (m)**	**Top Connection**	**Top Stiffness (N-m/rad)**	**Taper**	**Environment**
1	4.21	1000.8	Fixed	-	No	25 Year Swell
2	4.21	1000.8	Fixed	-	No	100 Year Cyclone
3	4.21	1000.8	Gimbal	1.00E+07	No	25 Year Swell
4	4.21	1000.8	Gimbal	1.00E+07	No	100 Year Cyclone
5	4.21	1000.8	Fixed	-	Yes	25 Year Swell
6	4.21	1000.8	Fixed	-	Yes	100 Year Cyclone
7	10.509	1000.8	Gimbal	1.00E+07	No	100Year Cyclone
8	10.509	1000.8	Gimbal	1.00E+09	No	100 Year Cyclone
9	10.509	1000.8	Fixed	-	No	Fatigue Bins (16 nos)
10	10.509	1000.8	Gimbal	1.00E+07	No	Fatigue Bins (16 nos)

5.2.11.1 Results

The results for the top loads and angles for the 4 m and 10 m pipe runs are summarized in Table 21 and Table 22, respectively. The angle is the *relative* angle between the pipe and the platform. This corresponds to the angle of rotation for the gimbal.

The corresponding strain values for the 10 m pipe are shown in Table 23. All results for the 10 m pipe are without a clump weight. As noted in Section 5.2.7, Table 16, a 200 ton clump weight decreased the maximum bending moment on the pipe with a fixed connection by 7%, but increased it by 3% for a pinned connection.

Table 21. Summary of Results for Extreme Events - 4 m Pipe

SUMMARY OF RESULTS - 4 m Pipe			
	Shear Force at Top	Bending Moment at Top	Rotation at Top
	N	N-m	deg
4 m CWP Fixed at Top (25 Yr Swell)			
Maximum	5.25E+05	1.36E+07	-
Minimum	-2.72E+05	-2.93E+07	-
Mean	1.48E+05	-7.58E+06	-
Std Dev	1.16E+05	6.68E+06	-
4 m CWP Fixed at Top (100 Yr Hurricane)			
Maximum	1.22E+06	4.26E+07	-
Minimum	-1.21E+06	-4.41E+07	-
Mean	1.19E+05	-5.07E+06	-
Std Dev	3.10E+05	1.34E+07	-
4 m CWP Gimbaled at Top (25 Yr Swell)			
Maximum	3.90E+05	1.49E+05	0.85
Minimum	-1.53E+05	-5.70E+05	-3.26
Mean	1.33E+05	-1.99E+05	-1.14
Std Dev	8.02E+04	1.34E+05	0.77
4 m CWP Gimbaled at Top (100 Yr Hurricane)			
Maximum	9.45E+05	4.12E+05	2.36
Minimum	-7.93E+05	-9.72E+05	-5.57
Mean	2.04E+05	-2.67E+05	-1.53
Std Dev	2.25E+05	2.34E+05	1.34
4 m Tapered CWP (25 Yr Swell)			
Maximum	1.26E+06	4.15E+07	-
Minimum	-6.31E+05	-7.83E+07	-
Mean	2.19E+05	-1.33E+07	-
Std Dev	2.28E+05	1.34E+07	-
4 m Tapered CWP (100 Yr Hurricane)			
Maximum	2.13E+06	7.89E+07	-
Minimum	-1.45E+06	-1.25E+08	-
Mean	3.99E+05	-2.23E+07	-
Std Dev	5.63E+05	3.11E+07	-

Table 22. Summary of Results for Extreme Events - 10 m Pipe

SUMMARY OF RESULTS - 10 m Pipe			
	Shear Force at Top	Bending Moment at Top	Rotation at Top
	N	N-m	deg
10 m CWP Gimbaled at Top (k = 1.0E07 N-m/rad)			
Maximum	6.37E+06	6.87E+05	3.94
Minimum	-5.25E+06	-8.57E+05	-4.91
Mean	5.41E+05	-2.11E+05	-1.21
Std Dev	1.75E+06	2.38E+05	1.37
10 m CWP Gimbaled at Top (k = 1.0E09 N-m/rad)			
Maximum	6.32E+06	6.29E+07	3.60
Minimum	-4.77E+06	-7.40E+07	-4.24
Mean	5.24E+05	-1.55E+07	-0.89
Std Dev	1.71E+06	2.17E+07	1.24

Table 23. Top Strains in Extreme Event – 10 m Pipe

Stiffness	10^7 N-m/rad	10^9 N-m/rad
Max	.00004	.0039
Min	-.00001	-.0046
Mean	.000013	.00096
Std Dev	.000015	.0013

Figure 67 shows the envelopes of maximum and minimum strain for a 4 m pipe in a 100-yr cyclone event. This would represent the design condition for a "permanent" installation, 20+ year life. The criterion for an extreme event, as opposed to a fatigue requirement, is a maximum strain of 1%. This is approximately ½ of the ultimate strain of 2% usually used for fiberglass[xiii]

The maximum strains of .3% (fixed) and .2% pinned are well within the design allowance for an extreme event. This suggests that fatigue is the governing criterion for this application.

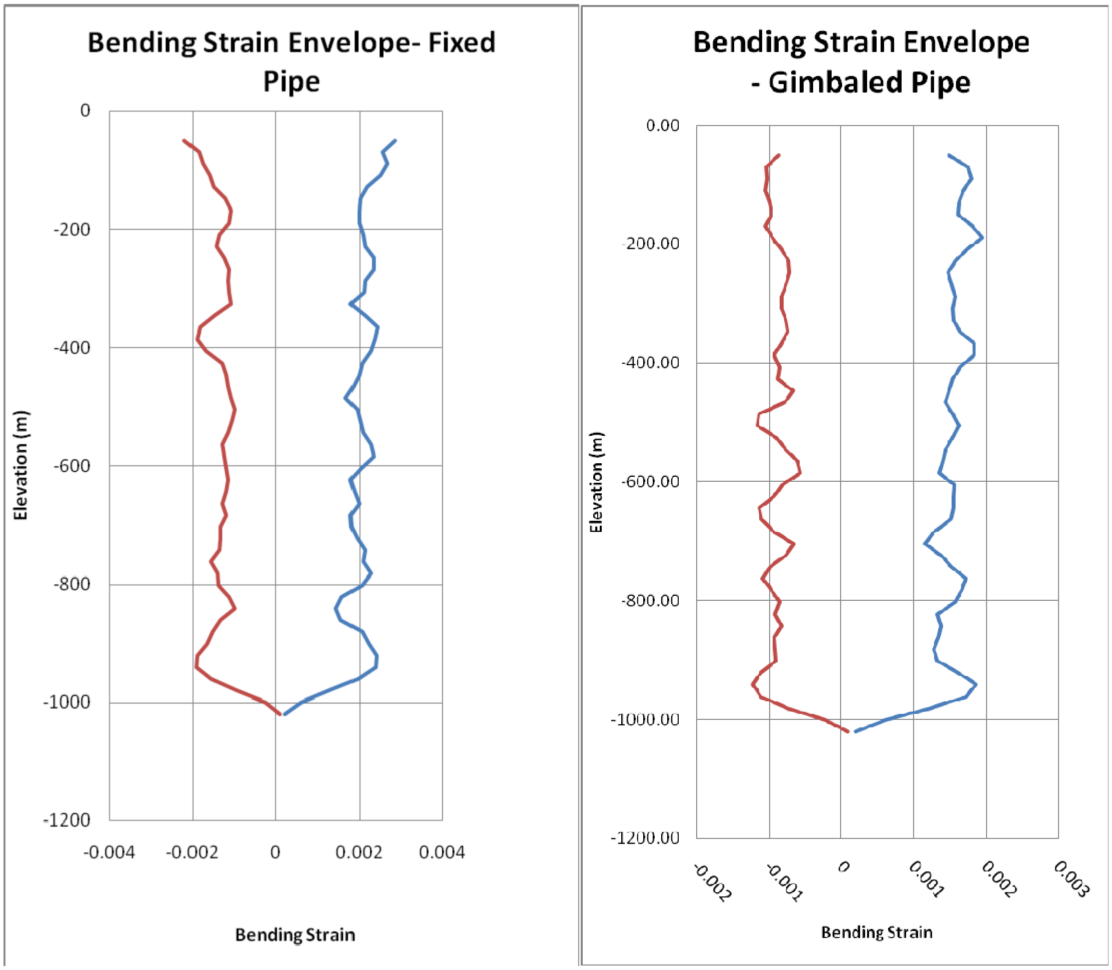


Figure 67. Responses in 100-yr Cyclone 4 m Pipe

5.2.11.2 Fatigue in 100-Year Cyclone

While the extreme strain in the 100-yr event is within the allowance for ultimate strength it is prudent to consider the fatigue damage that would occur if the platform experiences a 100-yr storm. This is not usually considered in offshore designs. The fatigue bins used in the fatigue analysis above are based on long term hindcasts of operational seas. This excludes episodic events like tropical cyclones which account for the extreme design conditions. The theory is that there is a small chance of the platform encountering a 100-yr storm, and if it did the duration would be too short to cause significant fatigue damage. Statistically, there is a 20% chance of encountering a 100-yr storm in 20 years, so some pro-rated number of fatigue cycles from the storm could be incorporated into the fatigue bins. However, this is not a realistic way to account for the storm. Instead, we consider here the cumulative fatigue damage resulting from a storm encounter resulting in a particular strain standard deviation, and compute the number of hours the cold water pipe would survive before the design fatigue life is exceeded.

Figure 68 shows the results of this analysis. The following conditions are assumed:

- Use the fatigue SN Curve in Figure 68
- Assume the strain cycles
- A zero crossing period of 10 seconds
- A Fatigue Factor of 1.2 on strain.

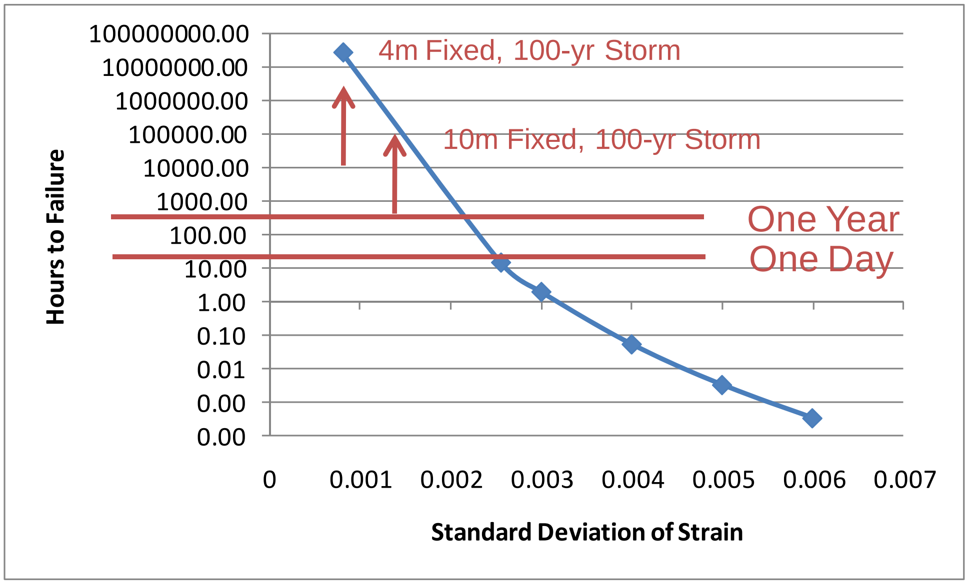


Figure 68. Hours of Fatigue Life vs. Strain Standard Deviation

This plot can be used to predict the fatigue life under particular storm conditions. For example, as shown in the figure, the storm duration to use up the entire design fatigue life would be about 200 years for the 10-m fixed pipe, and close to 10000 years for the 4 m fixed pipe. It is interesting that these values are higher than the fatigue life predicted for the operational seas. This suggests that the swells which occur operationally are more severe from a fatigue standpoint than the cyclonic storms which have a lower spectral period.

5.3 CWP Termination Design

5.3.1 Requirements

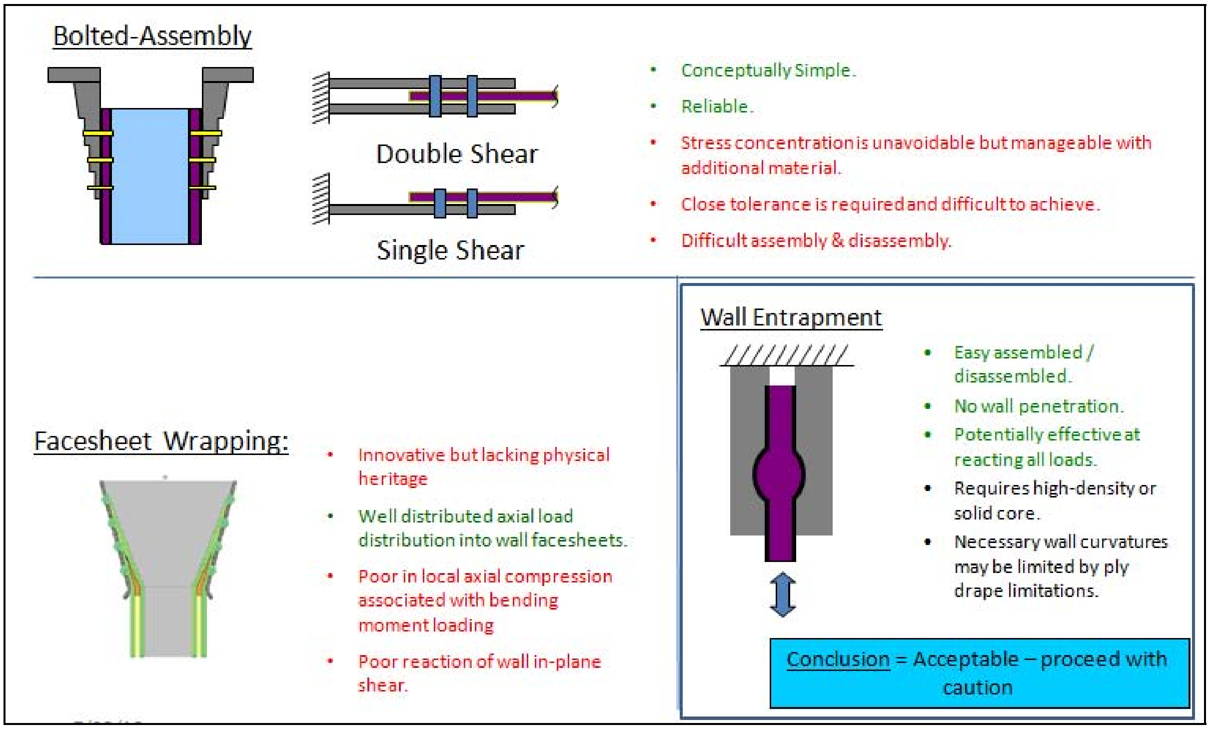
The Top Level Requirements for the CWP termination are to:

- Attach the CWP to the platform or to the gimbal, if used
- Survive loadings as calculated by CWP-Platform interaction analysis
- Withstand shear loads
- Withstand bending moment (if no gimbal)
- Withstand fatigue life of 30 years immersed in ambient-temperature seawater including any stress concentrations
- Be fabricated on the OTEC platform
- Contain the flowing Cold Water

5.3.2 Trade Studies

5.3.2.1 Selection of Termination Concept

The first step in the CWP termination design was a broad consideration of the many types of terminations that might be used for this fiber composite structure. This comparison is illustrated in Figure 69 with the principal advantages in green and the principal disadvantages in red.



Bolted-Assembly

- Conceptually Simple.
- Reliable.
- Stress concentration is unavoidable but manageable with additional material.
- Close tolerance is required and difficult to achieve.
- Difficult assembly & disassembly.

Facesheet Wrapping:

- Innovative but lacking physical heritage
- Well distributed axial load distribution into wall facesheets.
- Poor in local axial compression associated with bending moment loading
- Poor reaction of wall in-plane shear.

Wall Entrapment

- Easy assembled / disassembled.
- No wall penetration.
- Potentially effective at reacting all loads.
- Requires high-density or solid core.
- Necessary wall curvatures may be limited by ply drape limitations.

Conclusion = Acceptable – proceed with caution

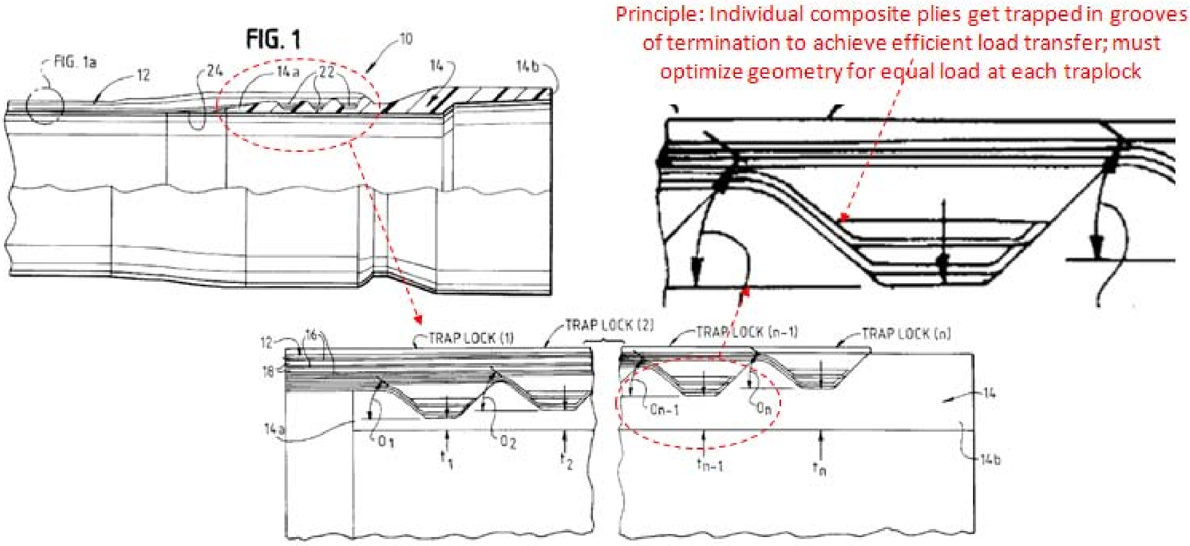
Figure 69. Trade Studies - Selection of Termination Concept

The most obvious initial candidate was bolted assembly. However for fiber composites, the load transfer is by bearing stresses on the sides and ends of the fibers within the holes that would be cut in the laminate. Close tolerances are required for a bolted joint to work reliably, and these tolerances would be difficult to achieve in a structure of this size. Also, the cut laminate surfaces at the drilled holes would absorb seawater over the long term, introducing structural risk.

A second candidate, eliminating drilled holes in the laminate, consisted of wrapping the individual thick face sheet fabric plies around steel pins that are secured to the termination structure. This candidate was derived from some concepts considered for aircraft composite structures. It would most likely work well in tension, but was considered a poor choice under the compressive forces inherent in supporting the large bending moment.

The third candidate considered, and ultimately adopted as the primary path, is wall entrapment. This concept contains features within each wall of the composite side of the termination that are mechanically trapped by the surrounding metallic structure. Its primary advantages are cited in the figure.

Another reason for proceeding with the wall entrapment concept is the substantial heritage on this general concept in a “trap-lock” design used for developmental composite risers for offshore oil applications. This trap lock design is illustrated in Figure 70.



Principle: Individual composite plies get trapped in grooves of termination to achieve efficient load transfer; must optimize geometry for equal load at each traplock

DD Baldwin, JA Reigle, MD Drey, “Interface System Between Composite Tubing and End Fittings,” US Patent 6,042,152, March 28, 2000

Figure 70. Multiple Entrapment Regions Termination – Trap Lock Concept

For the sandwich wall of our CWP, the trap-lock concept has been extended in order to transfer load directly to each face sheet (inner and outer), as illustrated in Figure 71. Traps are placed on both the outside and the inside of the CWP. Advantage is taken of the likelihood that the face sheet thickness will be increased in a tapered region near the top of the CWP (to better spread the otherwise concentrated rotations and displacements imparted to the pipe by the platform motions) and the core is totally eliminated within the termination. This allows the high radial forces required for good entrapment to be supported by laminate and not core. Bolts tie together the inner and outer entrapment backing structures, which are made thick enough to properly support the entrapment region in between. Note that these tie bolts do not transfer any shear load and therefore do not have to be precisely fit to the laminate, as is the case in a normal bolted joint. In fact, the tows of the composite fabric can be spread at the bolt locations, avoiding the need to cut fibers. The space between the bolts and the fabric gets totally filled by resin during fabrication by infusion, isolating the holes from seawater.

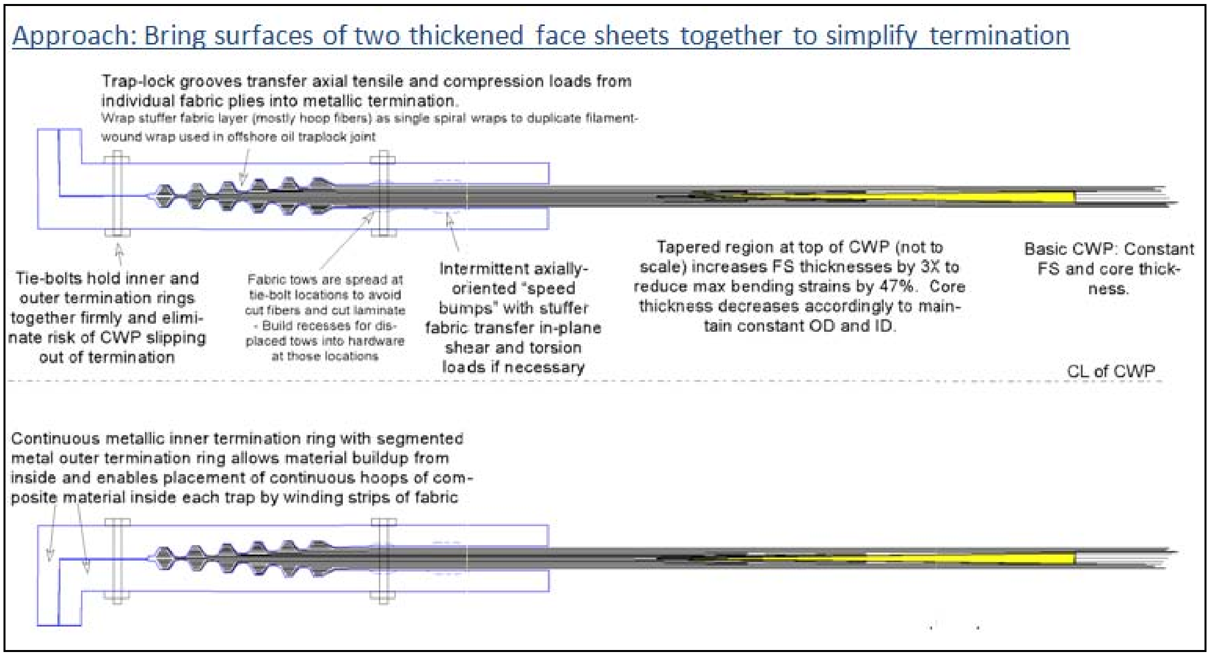


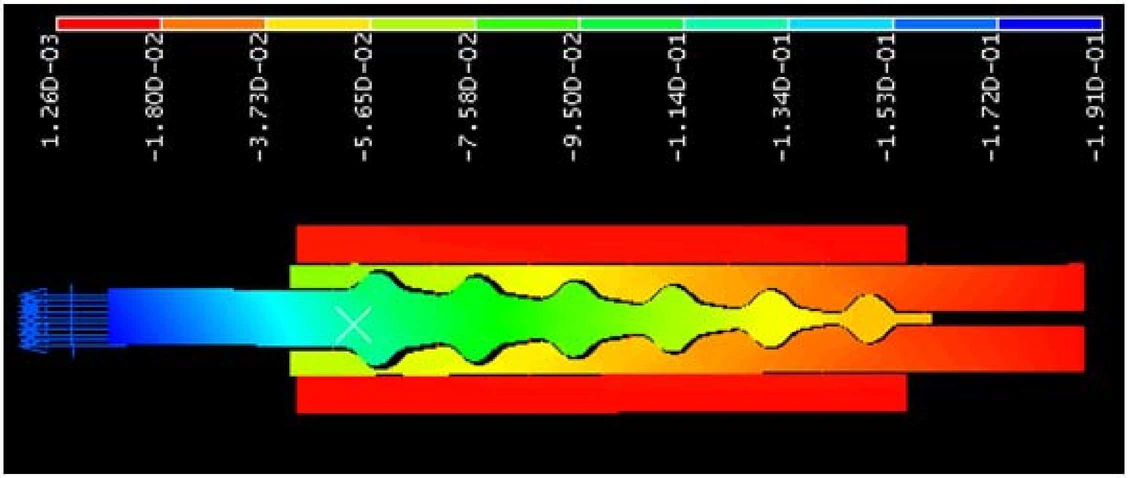
Figure 71. Multiple Entrapment Regions Concept for FRP CWP

5.3.3 Detailed Trap Lock Design

5.3.3.1 Initial Finite-Element Analysis

To get started on designing an entrapment-type termination suitable for our CWP, an initial guessed configuration was analyzed, shown in Figure 72. Entrapments are present on both sides of a laminate which is held between metallic entrapment plates backed up by metallic backing plates. Note that the entrapment plates are free to slide relative to the backing plates. It can be seen that some gaps are opening up between the composite and the metal, especially towards the left side. These indicate some slippage between composite and metal. This figure also provides a visual indication that the load transfer from composite to metal may not be uniform, with higher loads transferred at the left. Both of these behaviors are explored in Figure 73 and Figure 74.

1. Axial Displacement Plot illustrating slippage (displacements magnified x10)

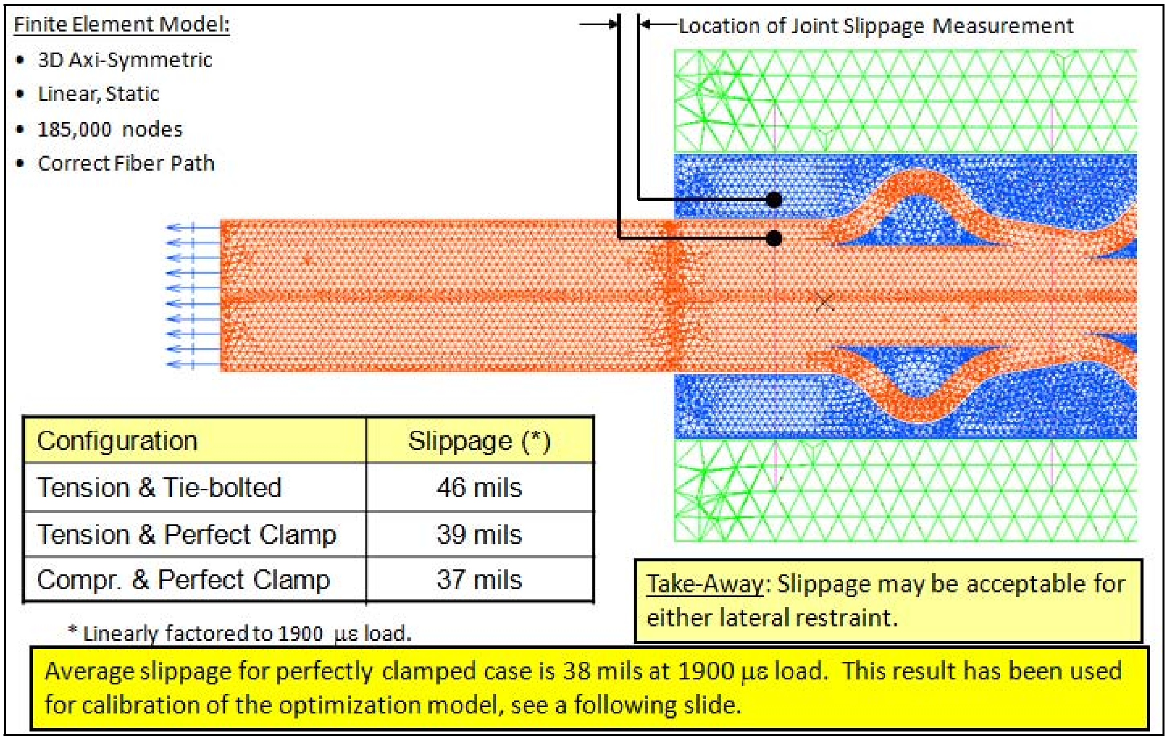


- 2500 $\mu\varepsilon$ tension (vs. 1900 $\mu\varepsilon$ true)
- Aluminum trap plates
- Tie-bolted constraint plates (steel plates, ½" steel tie-bolts)

Figure 72. FEA of Initial Entrapment Configuration

5.3.3.2 Quantification of Slippage

Figure 73 quantifies the slippage seen in Figure 72. Slippage of 38 mils is an ideal case of perfect clamping by the backing plates, and somewhat higher for the more realistic tie-bolted case.



Finite Element Model:

- 3D Axi-Symmetric
- Linear, Static
- 185,000 nodes
- Correct Fiber Path

Configuration	Slippage (*)
Tension & Tie-bolted	46 mils
Tension & Perfect Clamp	39 mils
Compr. & Perfect Clamp	37 mils

* Linearly factored to 1900 µε load.

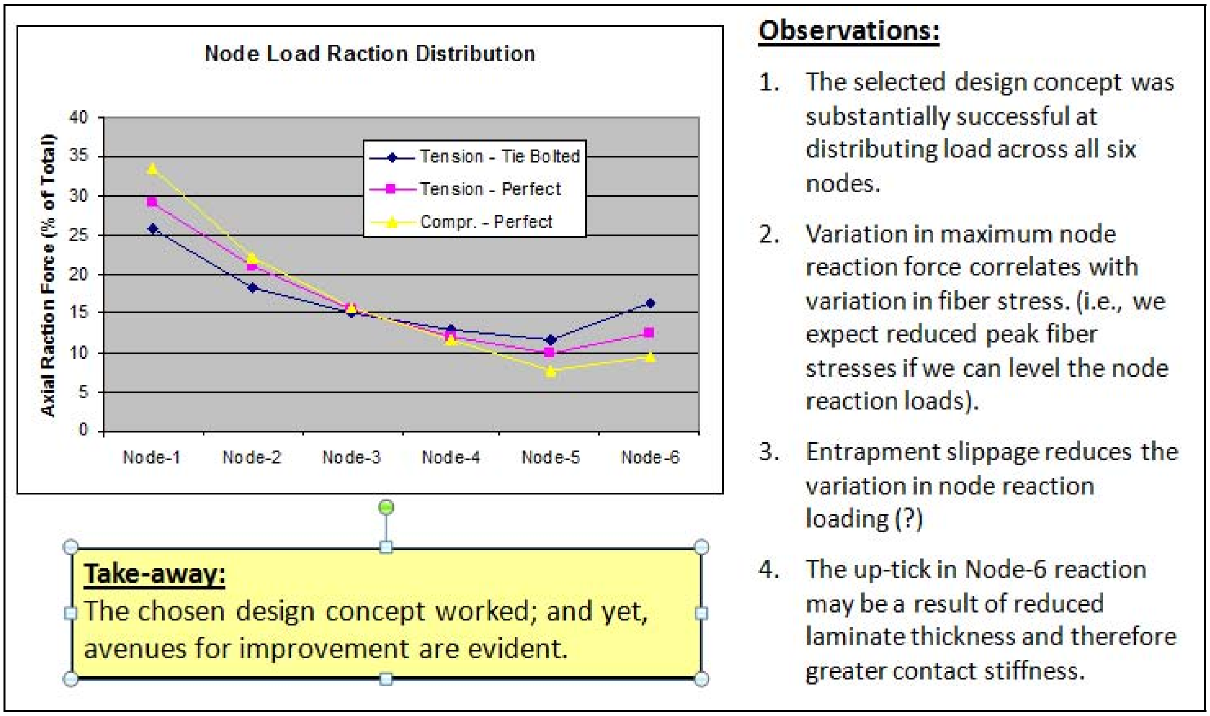
Take-Away: Slippage may be acceptable for either lateral restraint.

Average slippage for perfectly clamped case is 38 mils at 1900 µε load. This result has been used for calibration of the optimization model, see a following slide.

Figure 73. Slippage Between Laminate and Metal Fitting

5.3.3.3 Quantification of Load Sharing

Figure 74 plots the finite-element results in terms of the load transferred at each trap. As was anticipated from the deformed configuration shown in Figure 72, the load transfer is not uniform but concentrates towards the leftmost traps. This behavior provided the motivation for developing a fast-running design optimization procedure intended to spread the load more equally among the traps.



Take-away:
The chosen design concept worked; and yet, avenues for improvement are evident.

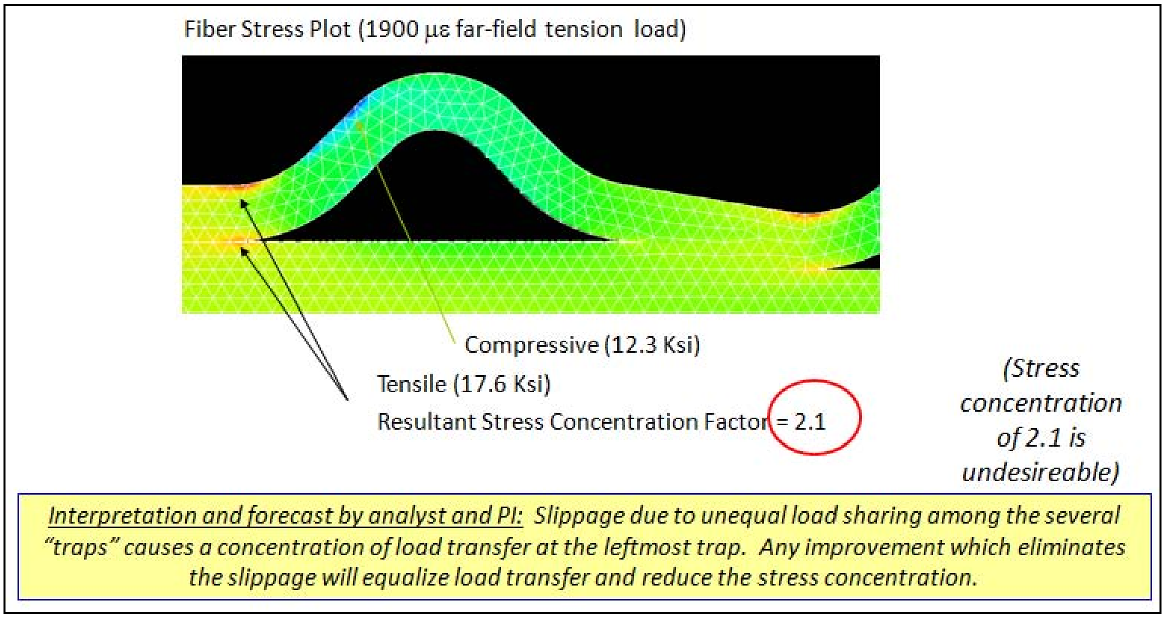
Observations:

1. The selected design concept was substantially successful at distributing load across all six nodes.
2. Variation in maximum node reaction force correlates with variation in fiber stress. (i.e., we expect reduced peak fiber stresses if we can level the node reaction loads).
3. Entrapment slippage reduces the variation in node reaction loading (?)
4. The up-tick in Node-6 reaction may be a result of reduced laminate thickness and therefore greater contact stiffness.

Figure 74. Unequal Load Sharing Among Layers

5.3.3.4 Stresses in Fiberglass Laminate

Fatigue failure is the result of local stresses and strains, therefore it is desirable to have a stress concentration as low as possible within the termination. Figure 75 shows that for this particular design, the maximum stress concentration is 2.1. It appears that the stresses at this location may be the result of local bending of the angled portion of the laminate, under the bearing reaction forces from the metallic structure.



Interpretation and forecast by analyst and PI: *Slippage due to unequal load sharing among the several "traps" causes a concentration of load transfer at the leftmost trap. Any improvement which eliminates the slippage will equalize load transfer and reduce the stress concentration.*

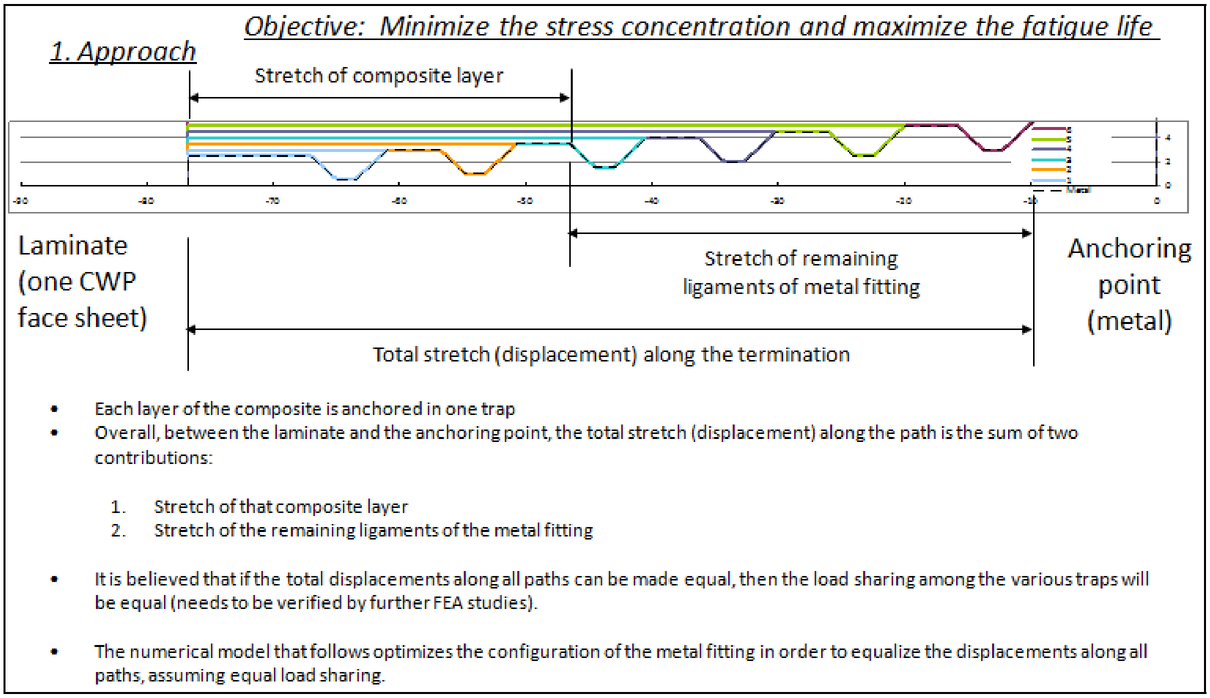
Figure 75. Stresses in Fiberglass Laminate

5.3.3.5 Spreadsheet-Based Optimizer for Multiple-Node Terminations

It was noted in the FEA just described that load sharing among the traps was unequal. Equal load sharing arises when the stiffnesses of the composite and metallic portions are well-matched to each other, so that both have the same axial displacement distribution. The principal variable affecting stiffness within the metallic portion is the distribution of metal thicknesses at the base of the traps. The FEA showed that these thicknesses were set rather arbitrarily at ½", 1", 1-1/2", etc.

It is believed that there is some distribution of metal thicknesses that will lead to equal sharing of the load among all of the traps. It is believed that when that situation is reached, the displacements along all of the parallel load paths (one load path consists of one layer of the composite plus the remaining ligament of metal that supports that load) will be equal. This belief forms the basis for the fast-running model that was created for automated preliminary design of an optimized distribution of metal thicknesses.

To simplify the modeling, the above belief was turned around: The model finds the distribution of metal ligament thicknesses that produces equal calculated end-to-end displacements among all of the layers, and finite-element analysis is then used to check whether or not the load distribution among the traps is uniform. As illustrated in Figure 76, under the applied external far-field load, the model calculates the stretch in each composite layer, and for any given distribution of metal thicknesses it also calculates the stretch in the corresponding remaining ligament of the metal fitting. The addition of these two is the total stretch along that load path. If there are substantial differences among the various total stretches, there will be offsets between the composites and the metal. The objective is to make the total stretches associated with all layers the same, thereby eliminating this offset.



- Each layer of the composite is anchored in one trap
- Overall, between the laminate and the anchoring point, the total stretch (displacement) along the path is the sum of two contributions:
  1. Stretch of that composite layer
  2. Stretch of the remaining ligaments of the metal fitting
- It is believed that if the total displacements along all paths can be made equal, then the load sharing among the various traps will be equal (needs to be verified by further FEA studies).
- The numerical model that follows optimizes the configuration of the metal fitting in order to equalize the displacements along all paths, assuming equal load sharing.

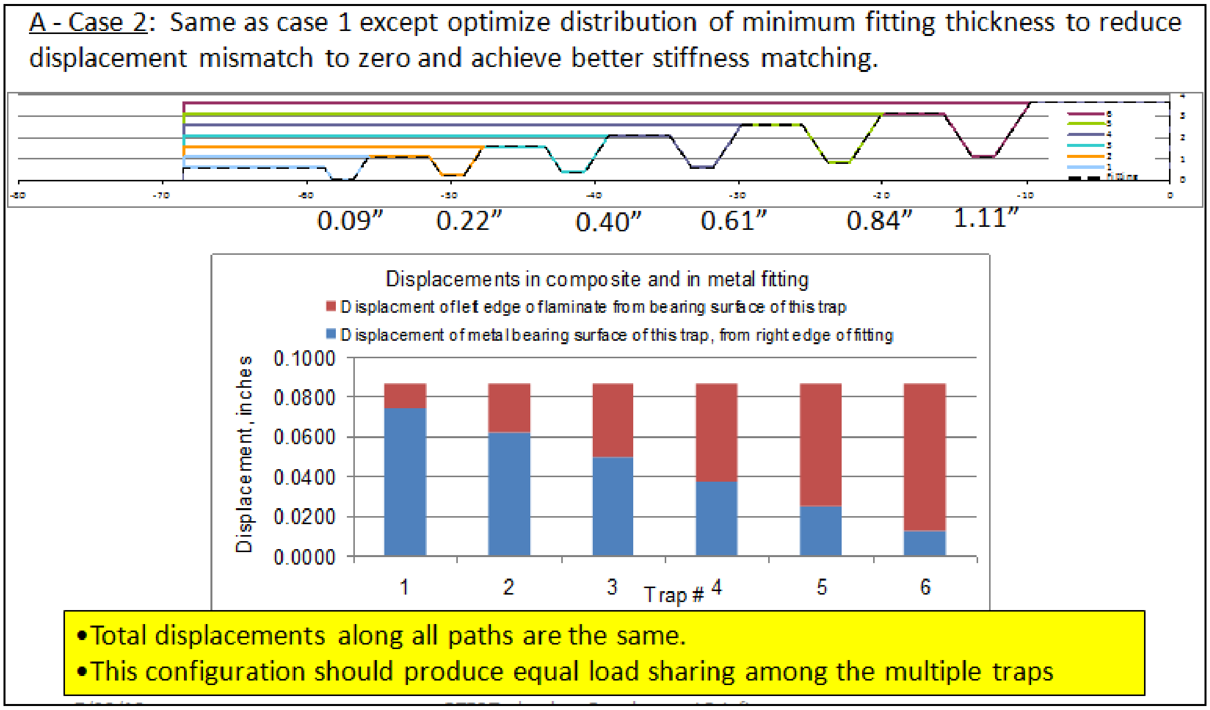
Figure 76. Spreadsheet-Based Optimizer for Multiple-Node Terminations

5.3.3.6 Benchmark Model to Finite-Element Analysis Results

Once the model was created, the next task was to compare its predictions against some known case. The case previously analyzed is suitable. As shown in Figure 76, when the model is set up with the same distribution of metal ligament thicknesses as was used in the FEA, a range in total stretch of 0.038” is predicted. It is emphasized that this was a totally independent prediction, not an adjustment to fit known results. It agrees almost perfectly with the prediction of the offset (0.038” average with perfect clamping) shown in Figure 73. This agreement may be better than the assumptions would justify, but it does lend some confidence to the analysis.

5.3.3.7 Optimized Configuration for Metallic Fitting

Having benchmarked the model in Figure 76, the model was then used to generate a distribution of metal thicknesses producing equal total stretch among all of the load paths. This was conveniently and rapidly done by using the “Solver” add-on that is present in Excel. Figure 77 shows the solution.



A - Case 2: Same as case 1 except optimize distribution of minimum fitting thickness to reduce displacement mismatch to zero and achieve better stiffness matching.

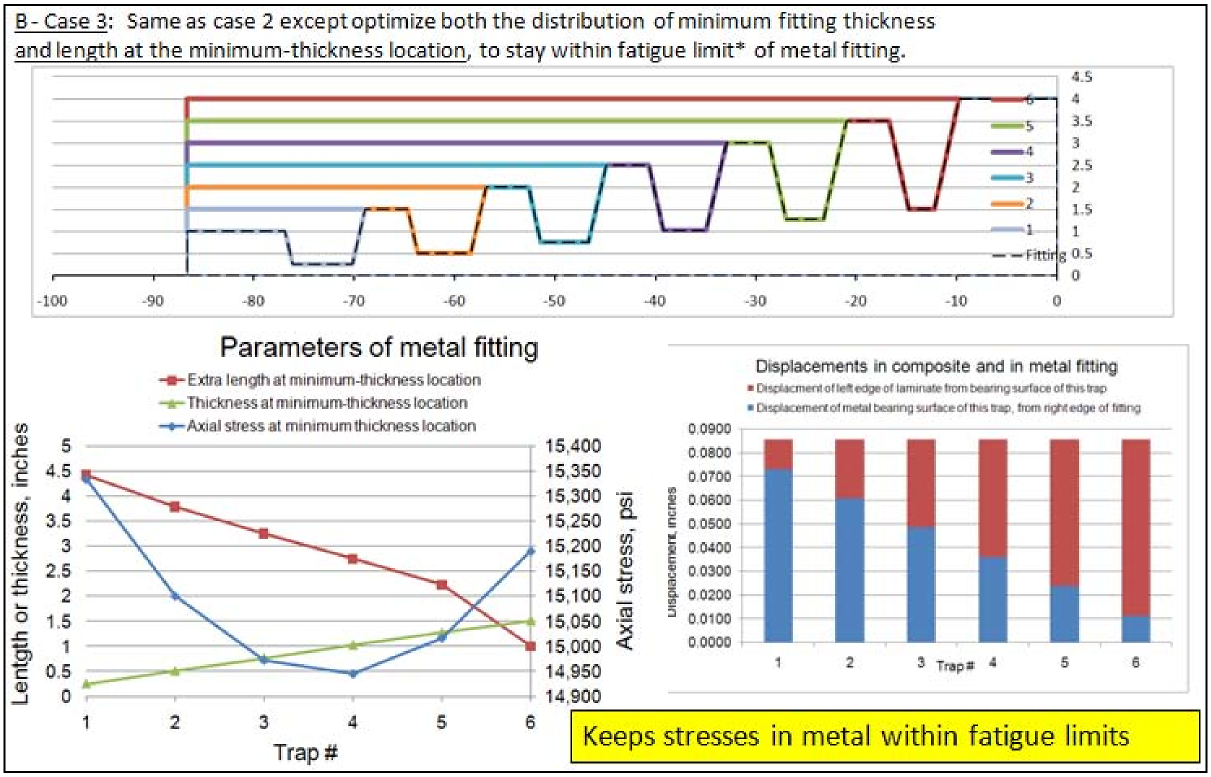
- Total displacements along all paths are the same.
- This configuration should produce equal load sharing among the multiple traps

Figure 77. Optimized Configuration for Metallic Fitting

5.3.3.8 Fatigue Limit of Metal Fitting

In Figure 77, the bases of all traps have the same width, and some of the ligaments end up being rather thin in order to provide the correct stiffness. These would be subject to metal fatigue. Accordingly, the widths of the bases of the traps were allowed to vary, and a new constraint was added keeping the stresses in the metal within the fatigue limit of the alloy chosen. The resulting solution is shown in Figure 78.

This model formed the basis for the final tool with which the current generation of test hardware was designed.


B - Case 3: Same as case 2 except optimize both the distribution of minimum fitting thickness and length at the minimum-thickness location, to stay within fatigue limit* of metal fitting.

Keeps stresses in metal within fatigue limits

Figure 78. Fatigue Limit of Metal Fitting

5.4 Coupon Tests

5.4.1 Design of Tests

5.4.1.1 7 inch Single-sided Axial Tension-compression Termination Fatigue Specimen

Figure 78 shows the design of the initial test specimen. Two identical terminations are mounted to a single short (to avoid buckling) composite laminate, all in circular configuration. The terminations are in turn tied to the load cell and moving crosshead of a standard 50,000 lb. Instron testing machine.

Key metallic portions of the hardware include the two entrapment rings, the two outer and two inner backing rings (segmented), the two end plates, and two categories of bolts (some to tie the entrapment plates together, and some to tie the entrapment plates to the thick end plates).

For this small initial test, the entrapment "inclusions" that help trap the composite against the metal entrapment element were conveniently formed by winding from wire. As this concept is scaled up, these will become metallic strips machined to the proper profile and roll-formed to circular shapes.

The vent holes at the base of each trap are for the VARTM process, and allow vacuum to pull resin into the fabric in each trap.

5.4.1.2 Predicted Performance of 7 inch Axial Specimen

Figure 78 shows the model-predicted displacement distribution (uniform across all 3 traps) and stress distribution (within the fatigue limit of the 6061-T6 aluminum used in this development hardware).

5.4.1.3 Fabrication of 7 inch First-Generation Termination Specimen

Figure 79 shows the machined metallic components of this 1st generation test hardware.

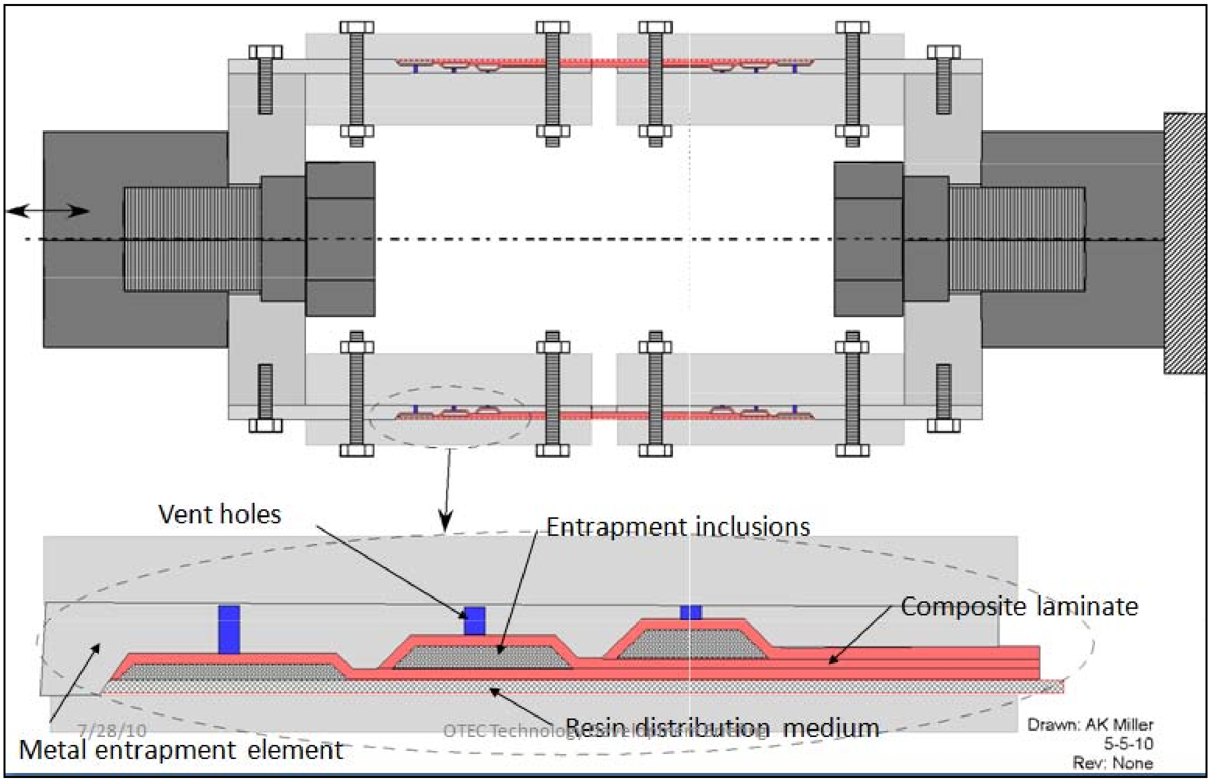
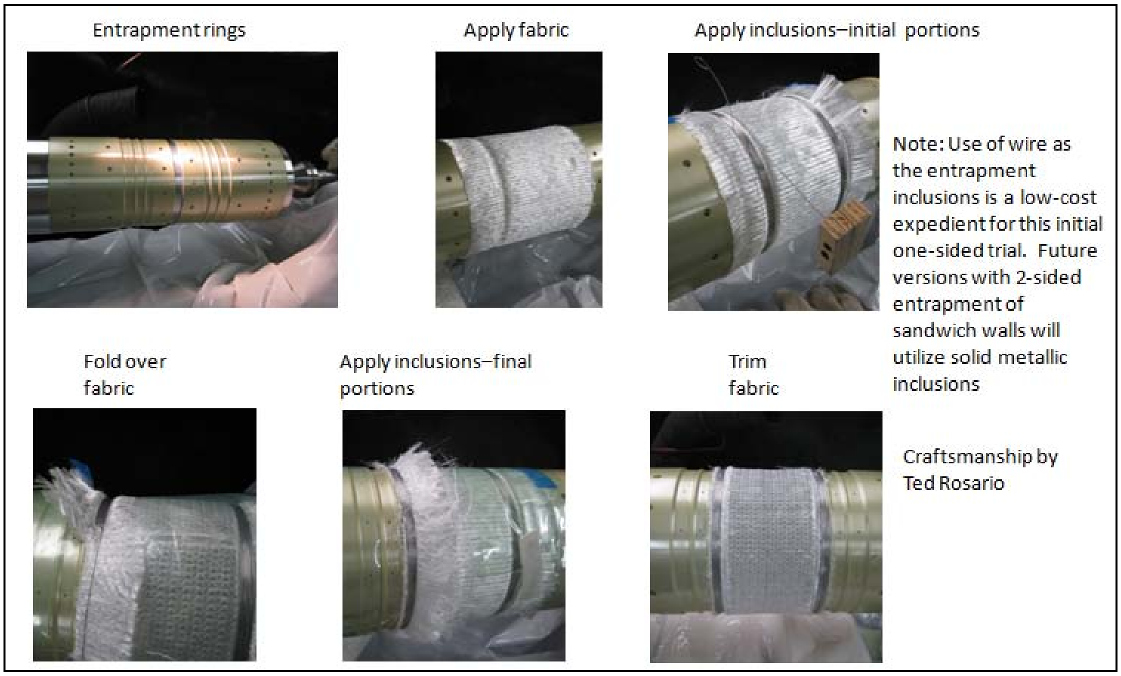


Figure 79. 7 inch OD Fatigue Specimen

5.4.1.4 Addition of Dry Composite Elements

Figure 80 through Figure 84 show the addition of the dry composite elements of the termination.



Note: Use of wire as the entrapment inclusions is a low-cost expedient for this initial one-sided trial. Future versions with 2-sided entrapment of sandwich walls will utilize solid metallic inclusions

Craftsmanship by Ted Rosario

Figure 80. Place Fabric Layer #

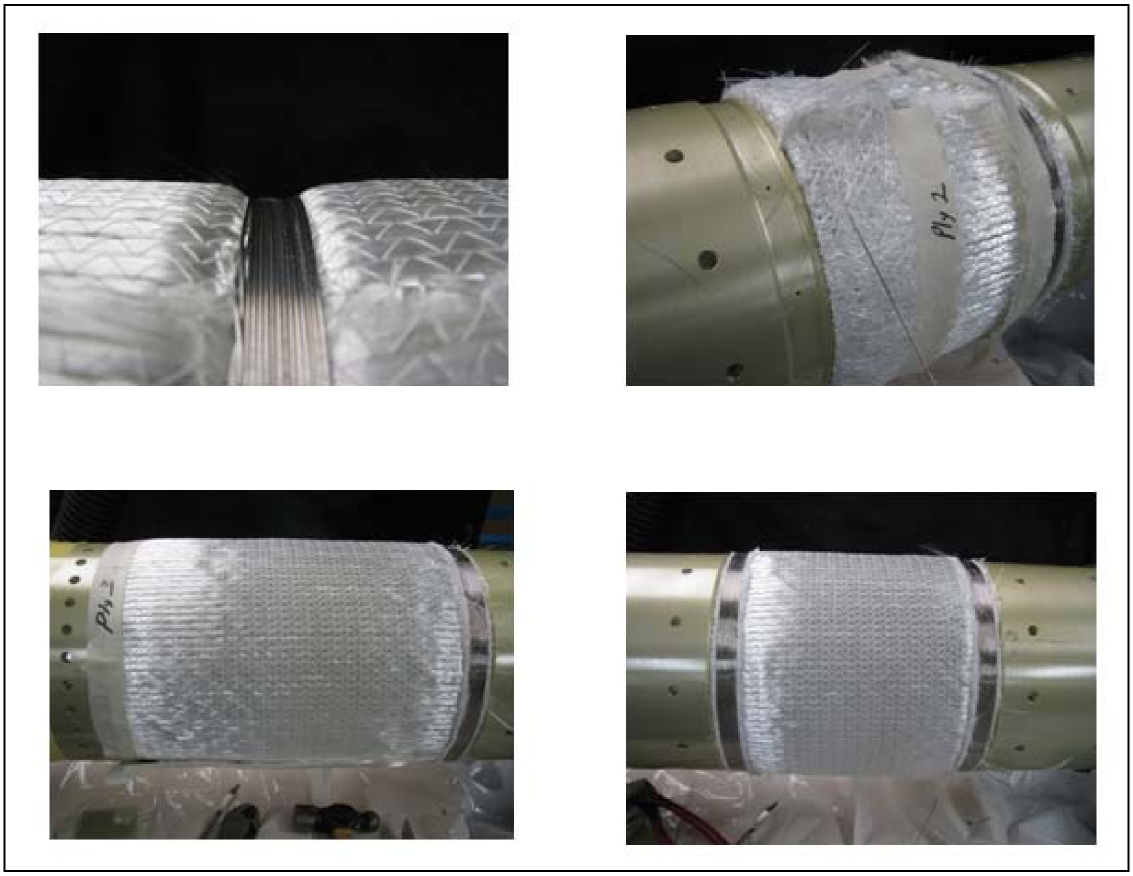


Figure 81. Place Fabric Layers #2, 3

Figure 82. Add Resin Distribution Medium (RDM)

Figure 83. Add Outer Backing Plates, Remove from Layup Mandrel

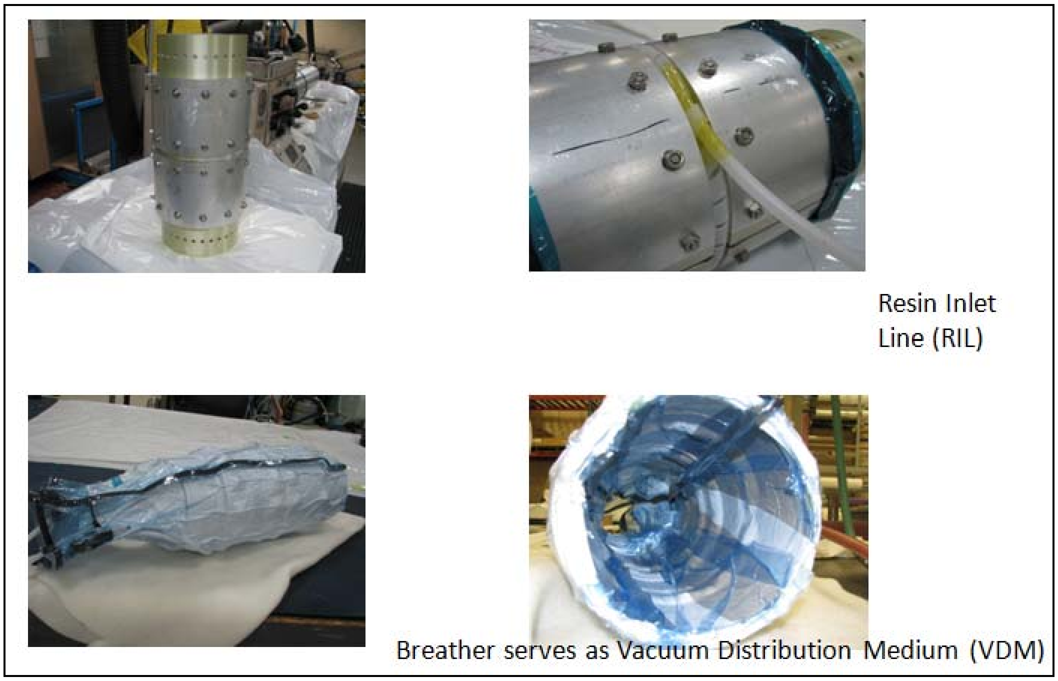


Figure 84. Add Resin Distribution Line (RDL) and Resin Inlet Line (RIL)

5.4.1.5 Resin Infusion

Figure 85 shows the infusion of the composite fabric with vinyl ester resin, using the VARTM (Vacuum Assisted Resin Transfer Molding) process. The resin came through the vent holes at the base of each trap as expected, and at least based on all evidence available for examination at this point, all of the fabric wet out with resin just fine.

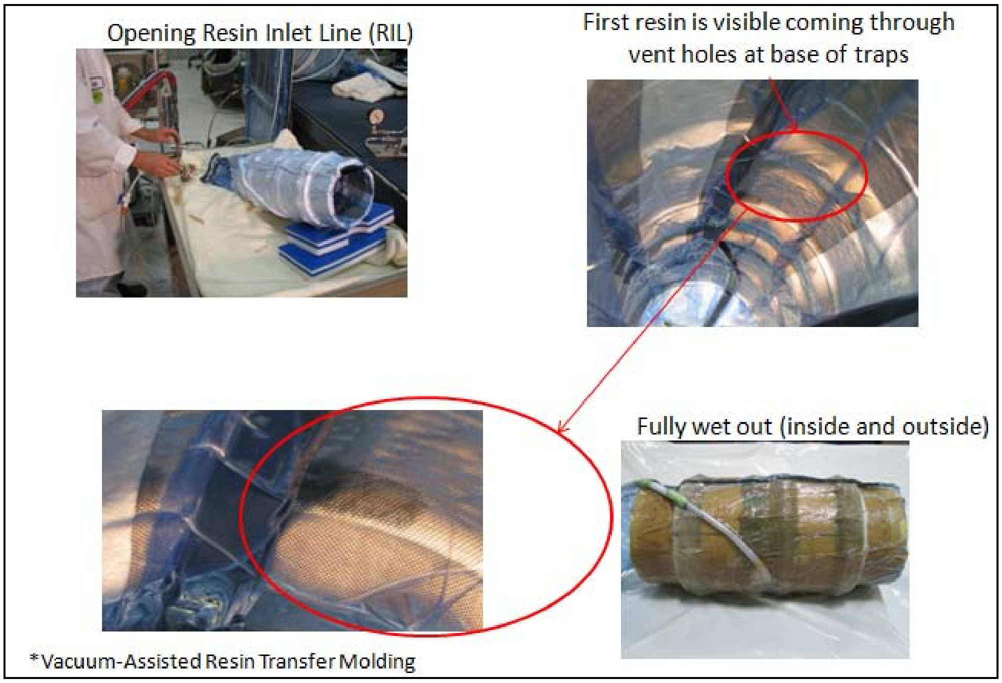


Figure 85. Resin Infusion using the VARTM Process

Figure 86 shows the “de-tooling,” and Figure 87 shows the fabricated test specimen.

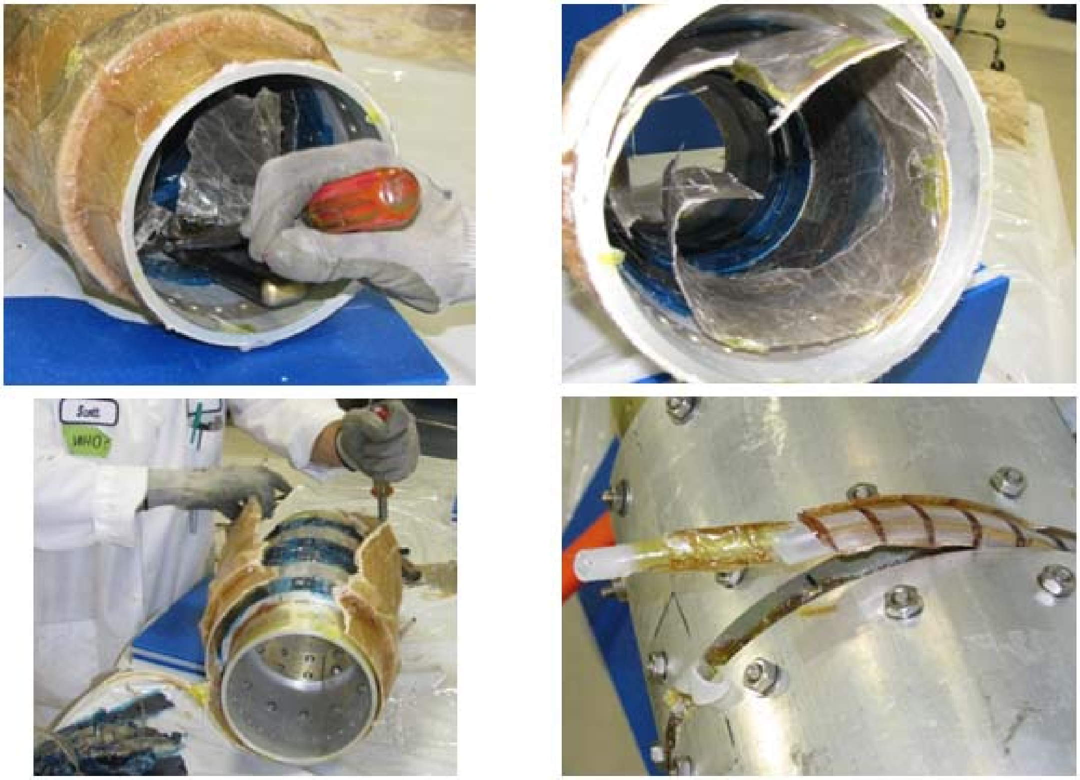


Figure 86. De-tooling

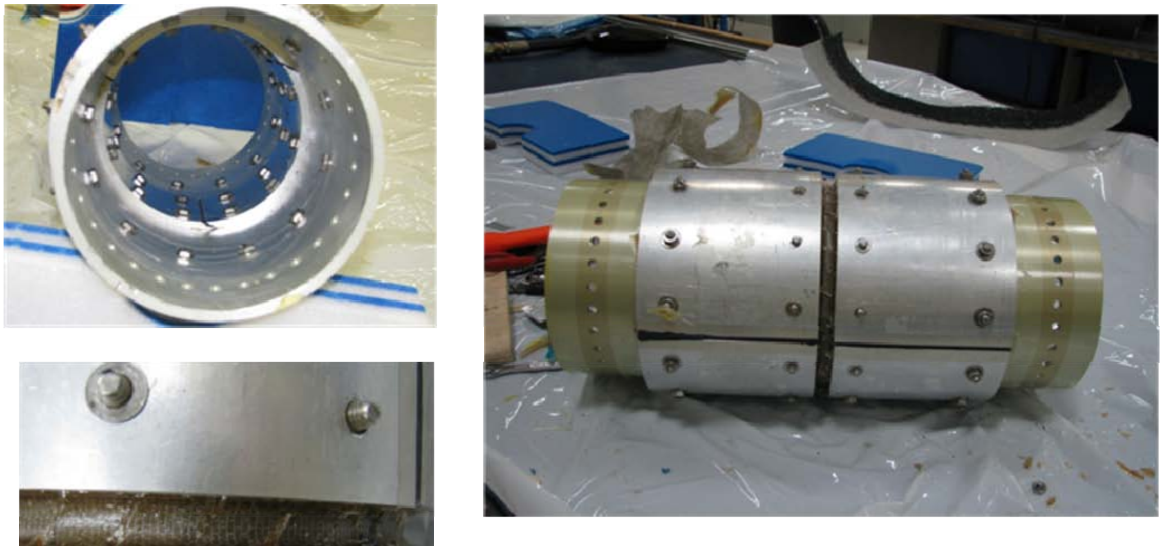
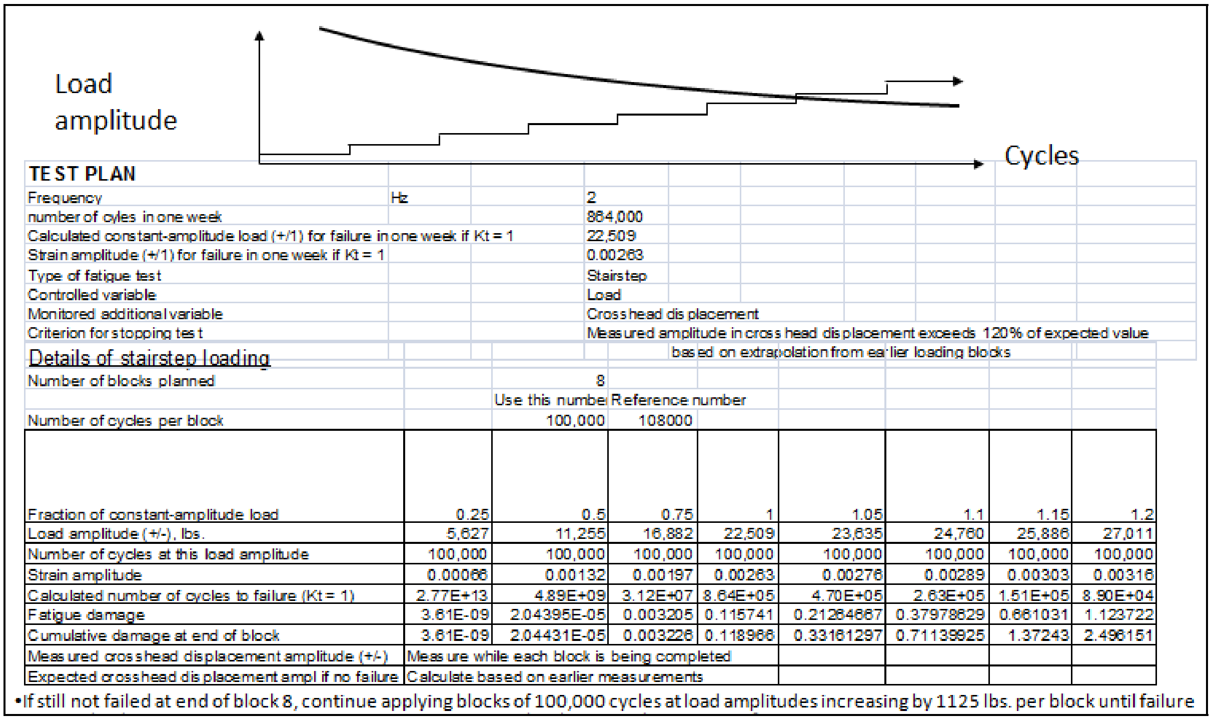


Figure 87. Fabricated Test Specimen

5.4.1.6 Test Plan

Figure 88 shows the test plan, imposing “stairstep loading” to help ensure getting a meaningful result on this initial test.



TEST PLAN		
Frequency	Hz	2
number of cyles in one week		864,000
Calculated constant-amplitude load (+/1) for failure in one week if Kt = 1		22,509
Strain amplitude (+/1) for failure in one week if Kt = 1		0.00263
Type of fatigue test		Stairstep
Controlled variable		Load
Monitored additional variable		Crosshead displacement
Criterion for stopping test		Measured amplitude in crosshead displacement exceeds 120% of expected value based on extrapolation from earlier loading blocks

Details of stairstep loading								
Number of blocks planned		8						
		Use this numbe	Reference number					
Number of cycles per block		100,000	108000					
Fraction of constant-amplitude load	0.25	0.5	0.75	1	1.05	1.1	1.15	1.2
Load amplitude (+/-), lbs.	5,627	11,255	16,882	22,509	23,635	24,760	25,886	27,011
Number of cycles at this load amplitude	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000
Strain amplitude	0.00066	0.00132	0.00197	0.00263	0.00276	0.00289	0.00303	0.00316
Calculated number of cycles to failure (Kt = 1)	2.77E+13	4.89E+09	3.12E+07	8.64E+05	4.70E+05	2.63E+05	1.51E+05	8.90E+04
Fatigue damage	3.61E-09	2.04395E-05	0.003205	0.115741	0.21264667	0.37978629	0.661031	1.123722
Cumulative damage at end of block	3.61E-09	2.04431E-05	0.003226	0.118966	0.33161297	0.71139925	1.37243	2.496151
Measured crosshead displacement amplitude (+/-)	Measure while each block is being completed							
Expected crosshead displacement ampl if no failure	Calculate based on earlier measurements							

- If still not failed at end of block 8, continue applying blocks of 100,000 cycles at load amplitudes increasing by 1125 lbs. per block until failure

Figure 88. Stair Step Loading Test Plan

5.4.2 Test Results

5.4.2.1 Test Results and Observation

The test plan illustrated in Fig. 88 was carried out through the 4th block with no changes. However, difficulties were encountered with the bolts that attach the entrapment rings to the thick end plates. They were vibrating loose under the fatigue cycling. This required constant manual attention to keep tightening the bolts. To avoid excessive test time and labor costs, a decision was made to shorten the 5th block to 10,000 cycles and to continue in the same pattern until an obvious failure occurred.

The 5th block was completed successfully to 10,000 cycles, but with some increase in maximum displacement as shown in Figure 89. It is not clear at this writing whether this was from enlargement of the bolt holes due to bolt loosening and slippage or whether it indicated the beginnings of failure.

The 6th block was begun, and at about 3,000 cycles a crack was seen in the composite laminate exposed to view between the upper and lower outer backing plates. Opening and closing of this crack was seen as the load cycled, and was recorded in a video. At this point, the test was declared completed. Figure 90 taken from the video shows extremes in the crack appearance, at the maximum tensile and compressive loads.

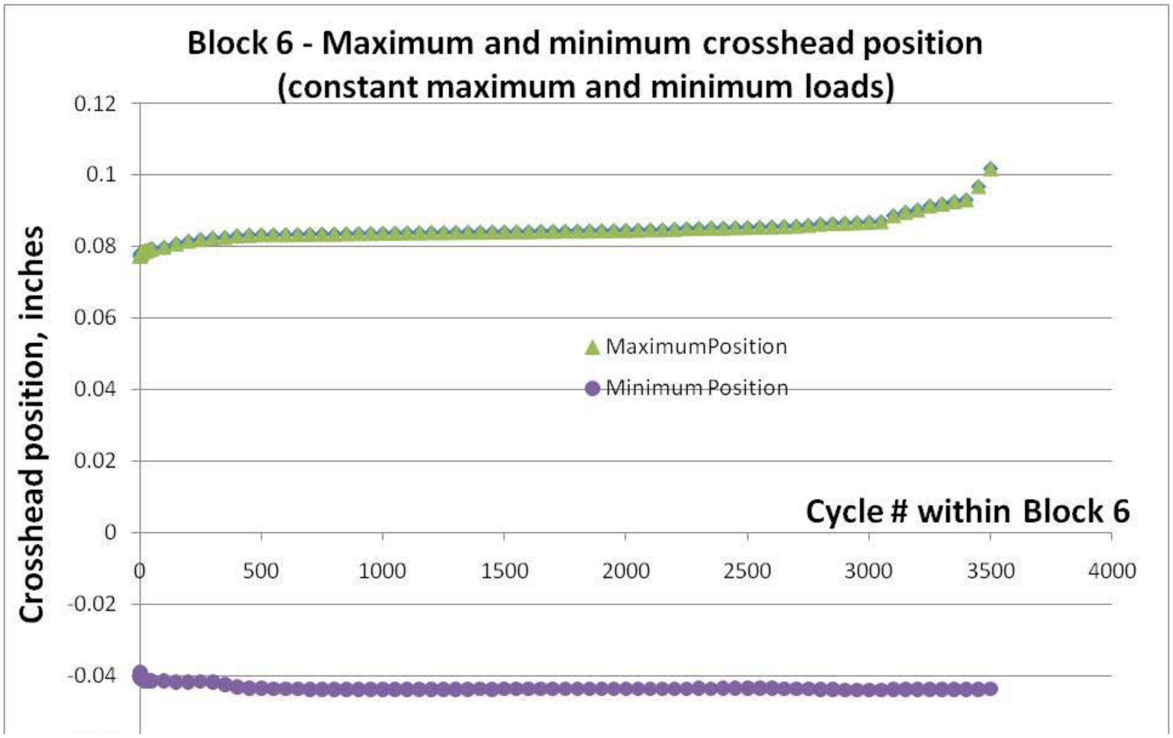


Figure 89. Peak Loads Within Block 6

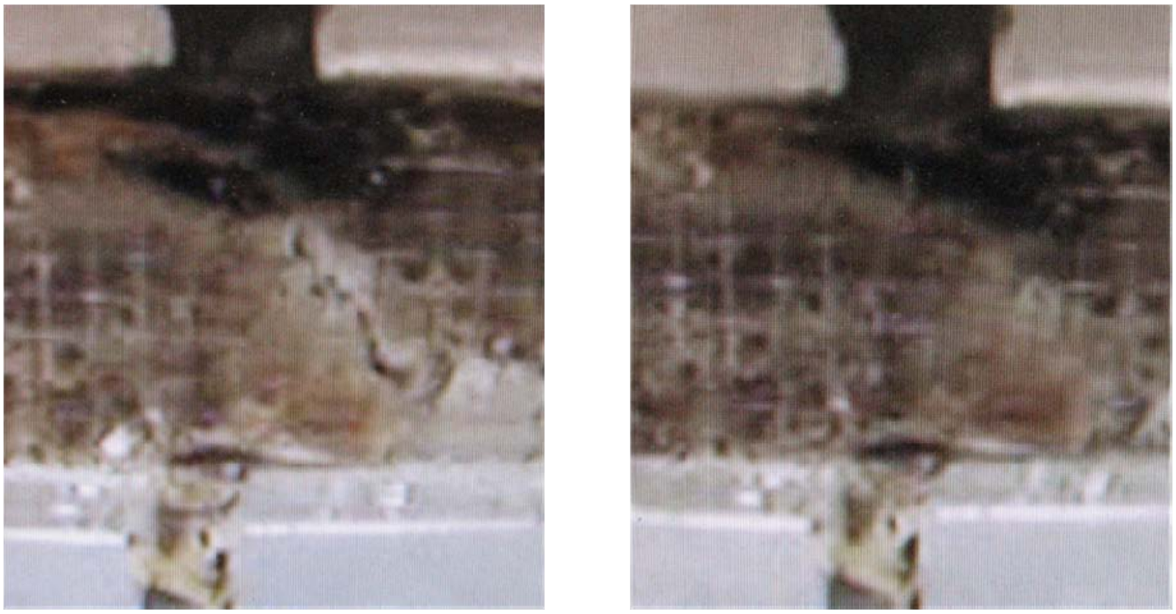


Figure 90a (at maximum tensile load)

Figure 90b (at maximum compressive load)

Figure 90. Fatigue Crack

5.4.2.2 Specimen Disassembly

The test specimen was disassembled without difficulty. The bolts holding the two backing plates together were readily removed and the backing plates fell off without any force required. This verified that there was no bonding of laminate to backing plates and therefore no load transfer through the backing plates. The shrink tape covering the wire screen RDM was easily unpeeled, revealing the RDM and laminate under it. Figure 91 shows the disassembled specimen. Disassembly verifies that all of the dry fabric wet-out completely during the VARTM resin infusion process which is significant for termination fabrication process risk mitigation.

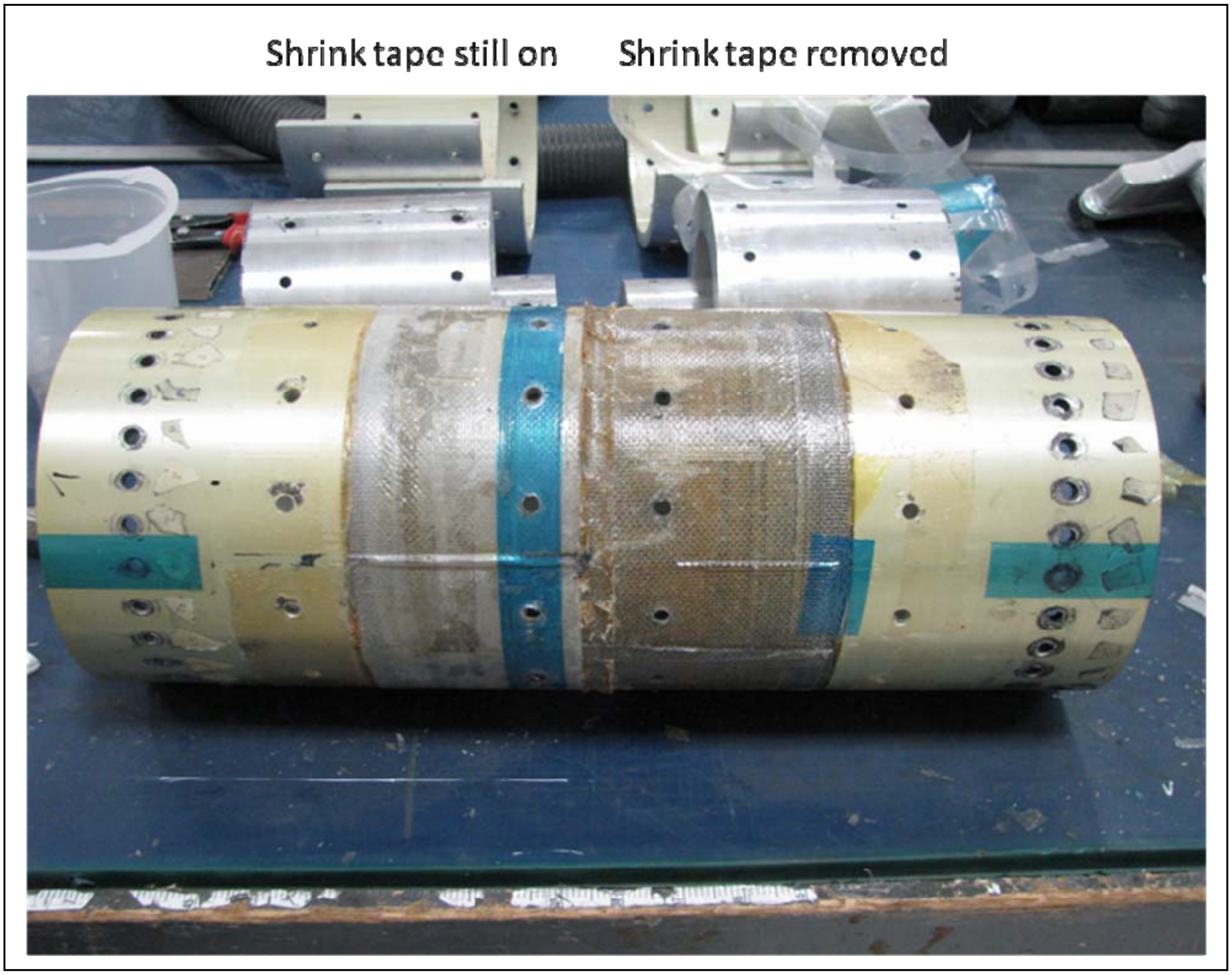


Figure 91. Dissembled Fatigue Test Specimen

5.4.2.3 Failure Locations within the Composite Laminate

Upon disassembly, it was seen that the crack that had been seen during load block 6 was at a central location within a much larger single dominant crack encompassing roughly 90 degrees of the specimen. Figure 92 shows this crack, with insets showing its more significant regions. At the left (in this figure) the crack has a backwards-F appearance. The two crossbars of the “F” run along two of the three entrapment regions in the upper termination, the two closest to the loaded end of the laminate. The two crossbars intersect a slanted, mostly-vertical crack running down through the full-thickness portion of the laminate. This crack changes direction to horizontal in two places and passes through two of the bolt holes in the full-thickness laminate. At the right of this dominant crack, it appears to run somewhat diffusely down to reach two of the entrapment regions in the lower termination.

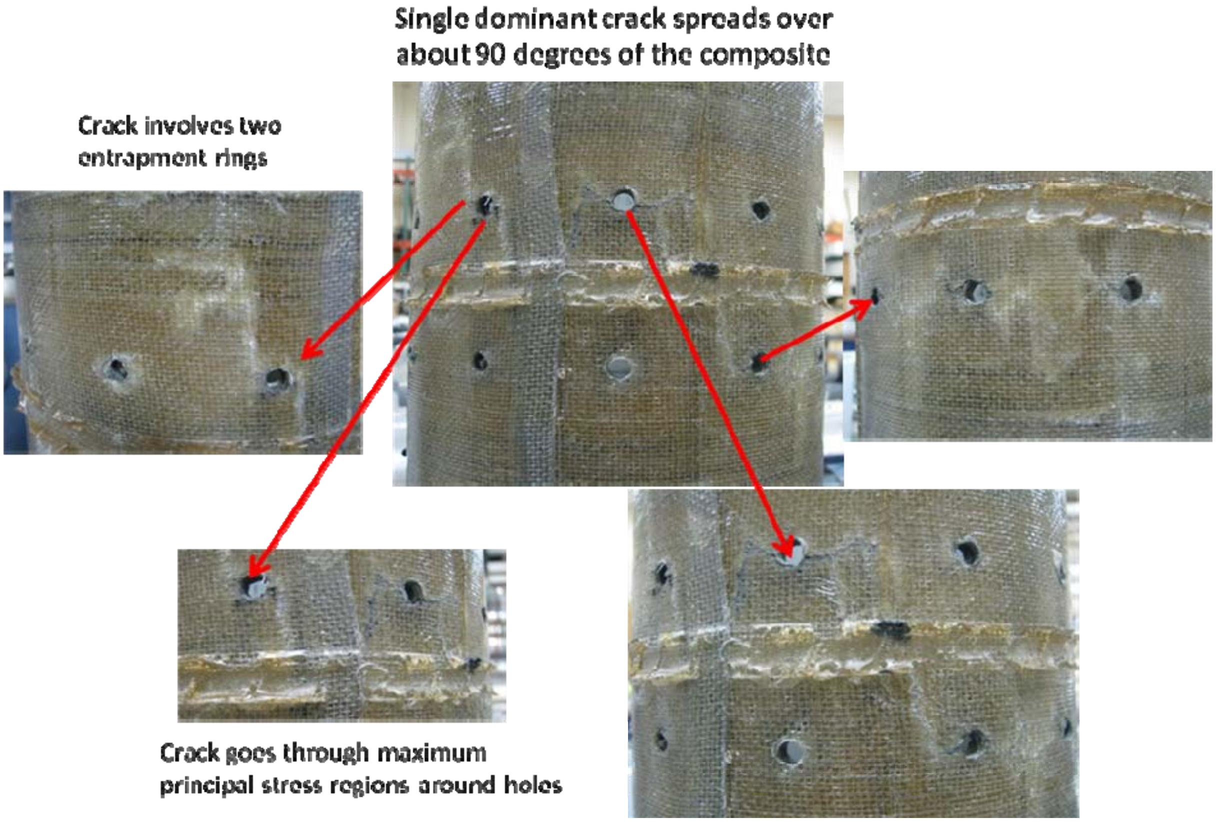


Figure 92. Test Specimen Crack

The significance of the failure locations is that they involve the entrapment regions. This is good, because it means that the fatigue generated is characteristic of the composite laminate in the entrapment regions as opposed to other non-composite portions of the specimen that might have failed, creating test artifacts.

5.4.2.4 Data Analysis

Table 24 shows the data and data analysis. The goal of the analysis is to back out an effective fatigue stress concentration factor characteristic of the multiple-entrapment termination. The analysis is structured to do that.

Table 24. Data Analysis for 7 inch Single-sided Termination Fatigue Test

Block #	1	2	3	4	5	6
Fraction of constant-amplitude load	0.25	0.5	0.75	1	1.05	1.1
Load amplitude (+/-), lbs.	5627.322	11254.64436	16881.97	22509.29	23634.7532	24760.2176
Number of cycles at this load amplitude	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+04	3.00E+03
Cumulative number of cycles at start of block	1.00E+00	1.00E+05	2.00E+05	3.00E+05	4.00E+05	4.10E+05
Cumulative number of cycles at end of block	1.00E+05	2.00E+05	3.00E+05	4.00E+05	4.10E+05	4.13E+05
Strain amplitude	0.000658	0.001315329	0.001973	0.002631	0.00276219	0.002893724
Strain amplitude	0.000658	0.001315329	0.001973	0.002631	0.00276219	0.002893724
Calculated number of cycles to failure for smooth, dr	1.05E+14	1.86E+10	1.19E+08	3.28E+06	1.79E+06	1.00E+06
Fatigue damage	9.50E-10	5.38E-06	8.44E-04	**3.05E-02**	5.60E-03	3.00E-03
Cumulative damage at end of block	9.5E-10	5.3812E-06	0.000849	0.031315	0.0369128	0.03991192
Total number of cycles applied						4.13E+05
Effective strain amplitude to get failure in this number of cycles (smooth dry laminate)						3.11E-03
Product of strain amplitude x fatigue damage (using equation for a smooth dry laminate)	6.25E-13	7.08E-09	1.66E-06	8.01E-05	1.55E-05	8.68E-06
Total strain amplitude x fatigue damage						1.06E-04
Fatigue damage (using equation for a smooth dry laminate)	9.50E-10	5.38E-06	8.44E-04	3.05E-02	5.60E-03	3.00E-03
Total fatigue damage						3.99E-02
Effective strain amplitude [Product of strain amplitude x fatigue damage / fatigue damage]						**2.65E-03**
Effective strain amplitude relative to smooth laminate for same # of cycles to failure						85%
Strain amplitude reduction relative to smooth laminate in air for same # of cycles to failure						**15%**

The top half of the table shows the raw data in terms of the load amplitude and number of cycles applied within each block. Load amplitude was converted to strain amplitude using the material modulus and laminate thickness. Using the known fatigue equation for smooth, unconditioned, dry X-Strand, vinyl ester laminate developed from Lockheed Martin-sponsored tests run at West Virginia University, the fatigue damage for each block was calculated, in terms of the number of cycles applied and number of cycles to failure at that strain amplitude. Note that over 75% of the fatigue damage was induced by block 4.

The bottom half of the table shows the calculated effective strain amplitude for the stair-step loading. For each block, the product of the strain amplitude times the calculated fatigue damage was calculated and these products were summed. Dividing this sum by the total fatigue damage generates the effective strain amplitude for the test sequence which is 0.00265. Note that this is close to the strain amplitude for the dominant block 4, as would be expected.

Finally, dividing this actual effective strain amplitude which caused the termination to fail in 413,000 cycles by the strain amplitude (0.00313) at which an average smooth dry laminate of the same material would fail in 413,000 cycles, we find that the termination reduces the fatigue strain amplitude to 85% of the smooth laminate value. Therefore there is a strain amplitude reduction of 15% or in effect a fatigue stress concentration factor of 1.15.

Figure 93 pulls together the analysis, showing the actual stair-step loading blocks imposed, the effective strain amplitude for this sequence, the smooth, dry laminate behavior, and the way in which the preliminary stress concentration factor was calculated.

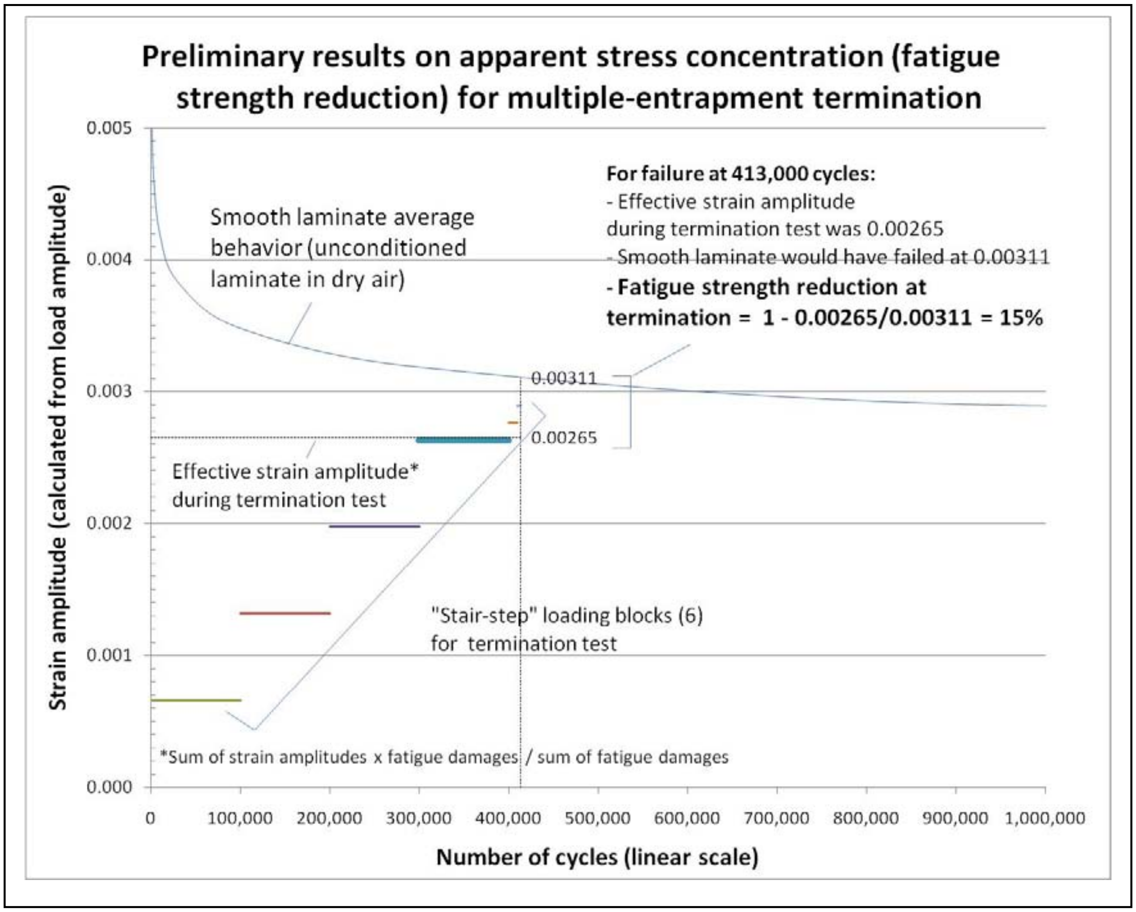


Figure 93. Summary of Test Results and Analysis, 7 inch Termination Specimen

This is a preliminary result based on a single test. Other reasons for caution include the fact that the termination was made from stitched fabric by VARTM with RT cure only, whereas the smooth-specimen test data was generated earlier on filament-wound, hot-press cured laminates. However it is a very encouraging preliminary result. If further substantiated by additional testing, scale-up, etc. it indicates that the effective stress concentration for actual fatigue failure of this type of termination is fairly small, and perhaps even within the 1.2 value that is commonly assumed for fatigue analysis of offshore structures.

5.4.3 Conclusions

A summary of conclusions follow:

- Metallic parts of the traplock termination achieved good fit with standard machining
- Dry fabric composite elements of the termination were successfully placed with simple operations

- The termination was successfully and completely infused with resin using thin aluminum screen as the RDM
- The completed specimen was successfully mated to the 50,000 lb Instron testing machine
- Stair-step fatigue testing was successfully completed with laminate failure observed during the 6th loading block
- Failure occurred within the composite laminate, and portions of the single dominant crack are within the entrapment regions.
- Comparison of the calculated effective strain amplitude for failure of the termination against the strain amplitude for failure of a smooth, dry laminate at the same Nf indicates a preliminary value for the effective fatigue stress concentration factor of 1.15.
- This is a very mild stress concentration factor and if substantiated by further testing including scale-up, would indicate that the multiple-entrapment type of termination is a very effective means for securing our Cold Water Pipe to the OTEC platform.

5.5 Fatigue Tests

5.5.1 Expanded 7 inch Fatigue Design

5.5.1.1 Purpose of the Tests

The purpose of the expanded 7 inch fatigue design testing was to:

- Extend the traplock concept to a 2-sided trap suitable for the sandwich CWP
- Do a more rigorous finite-element stress analysis as part of the design, to quantify the maximum stress concentration factor and its origins
- Optimize the configuration for best load sharing among the traps and minimum stress concentration factor.
- Test the final specimen design experimentally

5.5.1.2 Configuration

The number of traps on each side, and distribution of thicknesses and lengths for each trap is similar to the 1-sided specimen described previously.

A solid model (Pro-E) of the 2-sided 7” diameter tension-compression has been created and an axisymmetric stress analysis of the initial configuration performed. The stress analysis included all of the advanced methodologies required for this class of problem. This also included modeling of the fiber composite regions as orthotropic materials with properties rotated into the local plane of the laminate, and (most difficult) modeling of the contact boundary conditions between the composite and metallic elements.

5.5.1.3 Results of Finite-Element Stress Analysis

The finite element results are shown in Figure 94 through Figure 99.

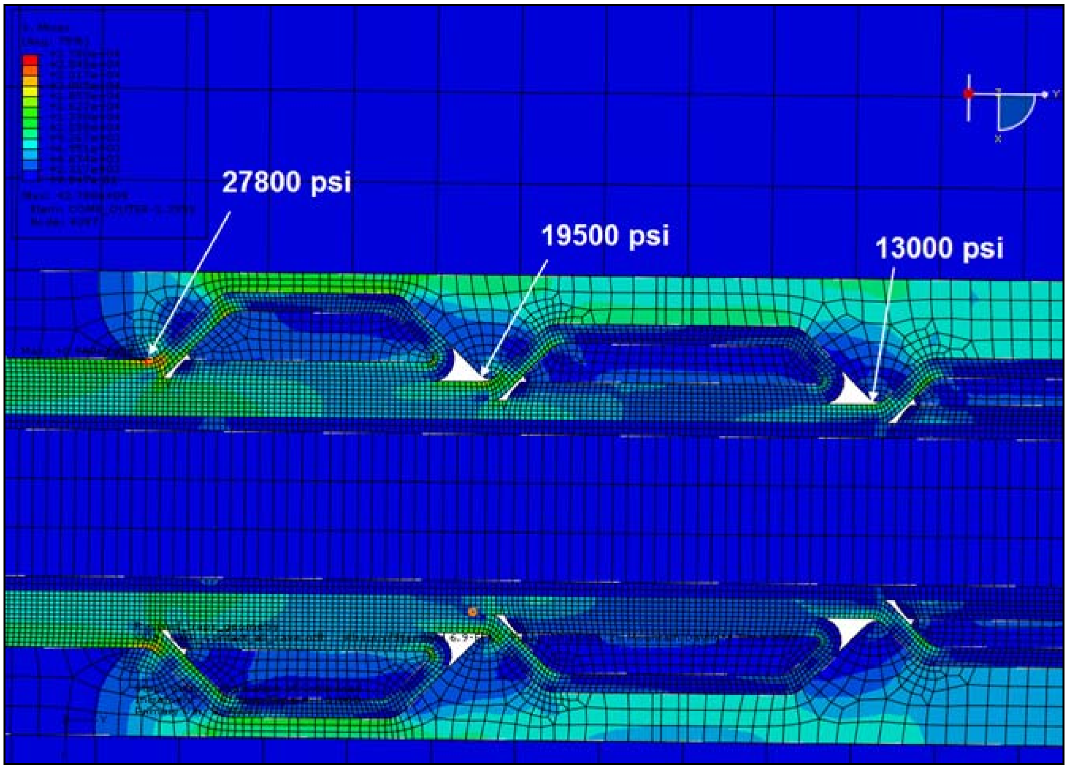


Figure 94. Von Mises Stress Plot, Three Trap Regions, 7inch CWP Test Specimen

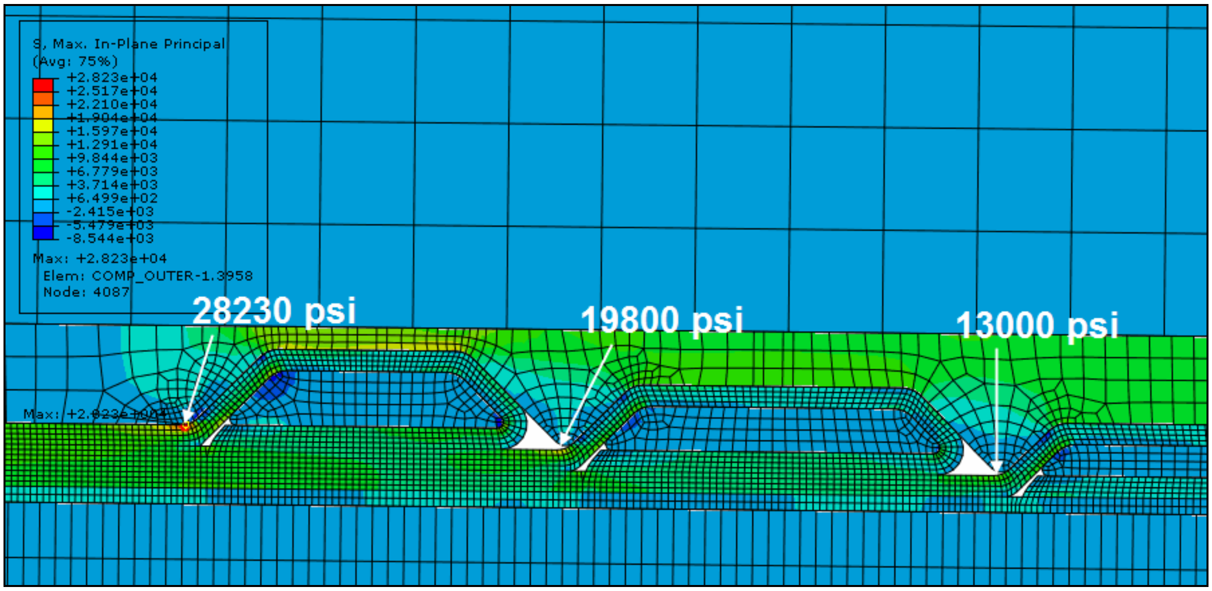


Figure 95. Principal Stress Plot, Three Trap Regions, 7inch CWP Test Specimen

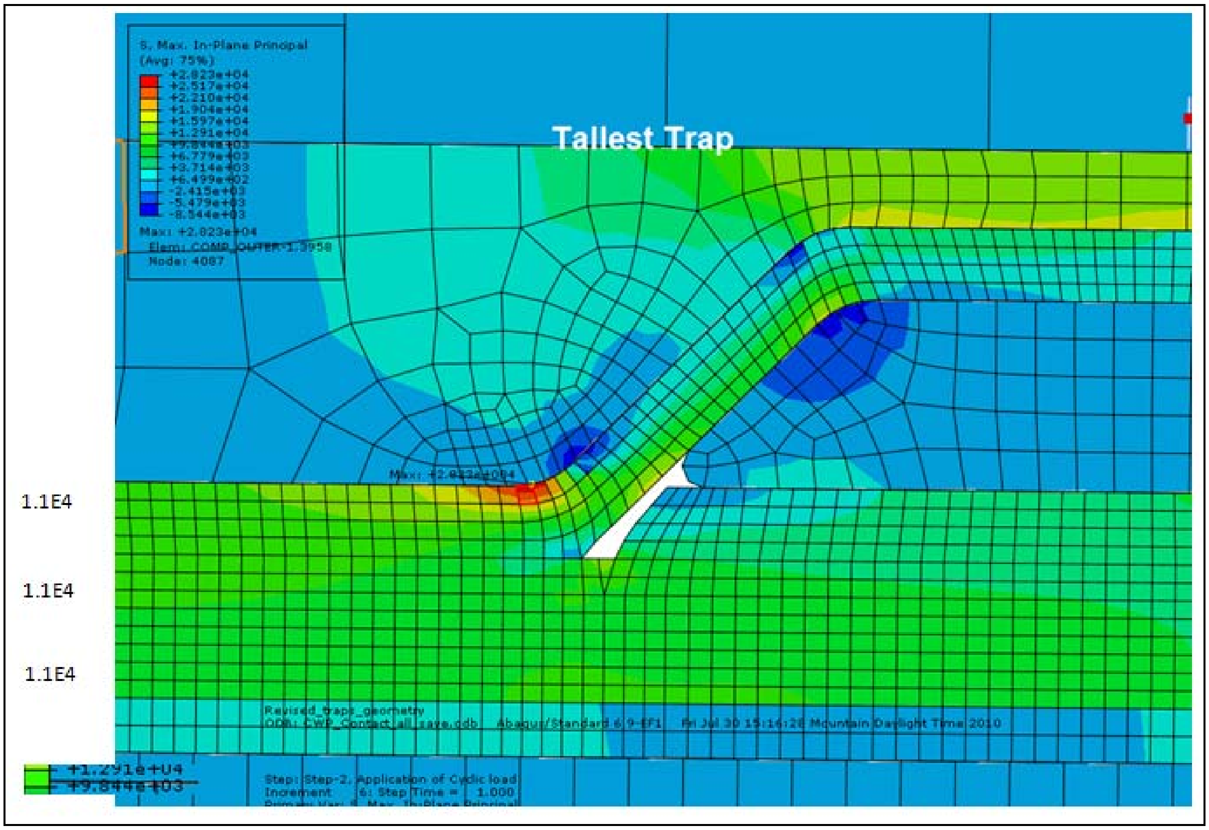


Figure 96. Enlarged View, Tall Trap Region Showing Principal Stresses

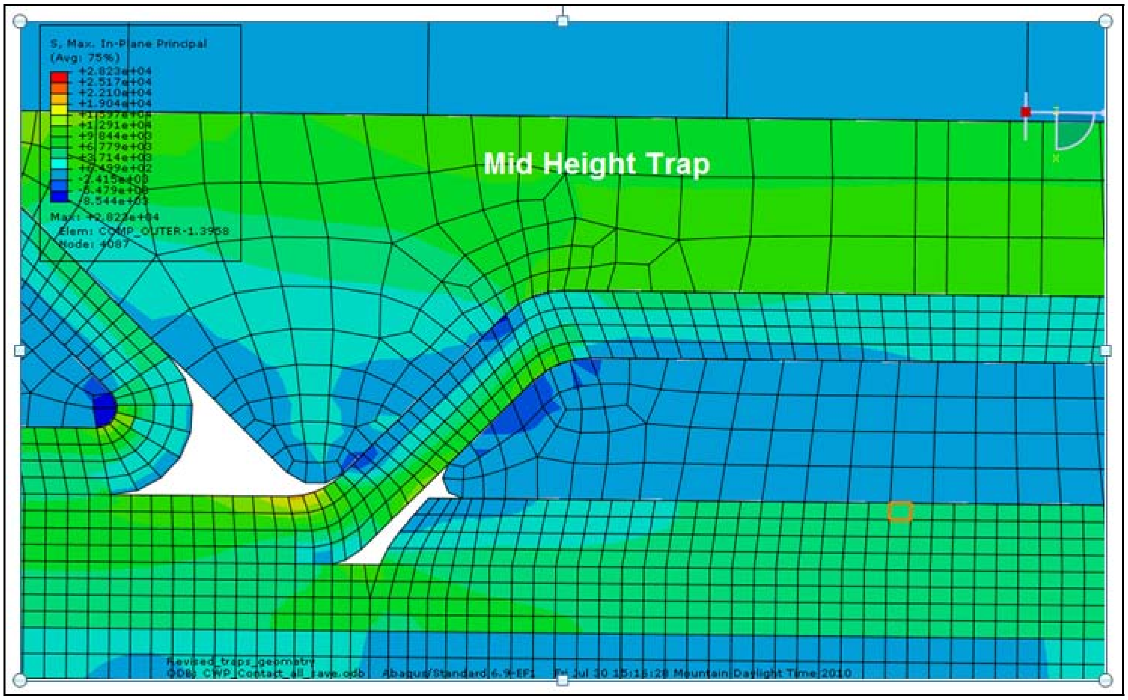
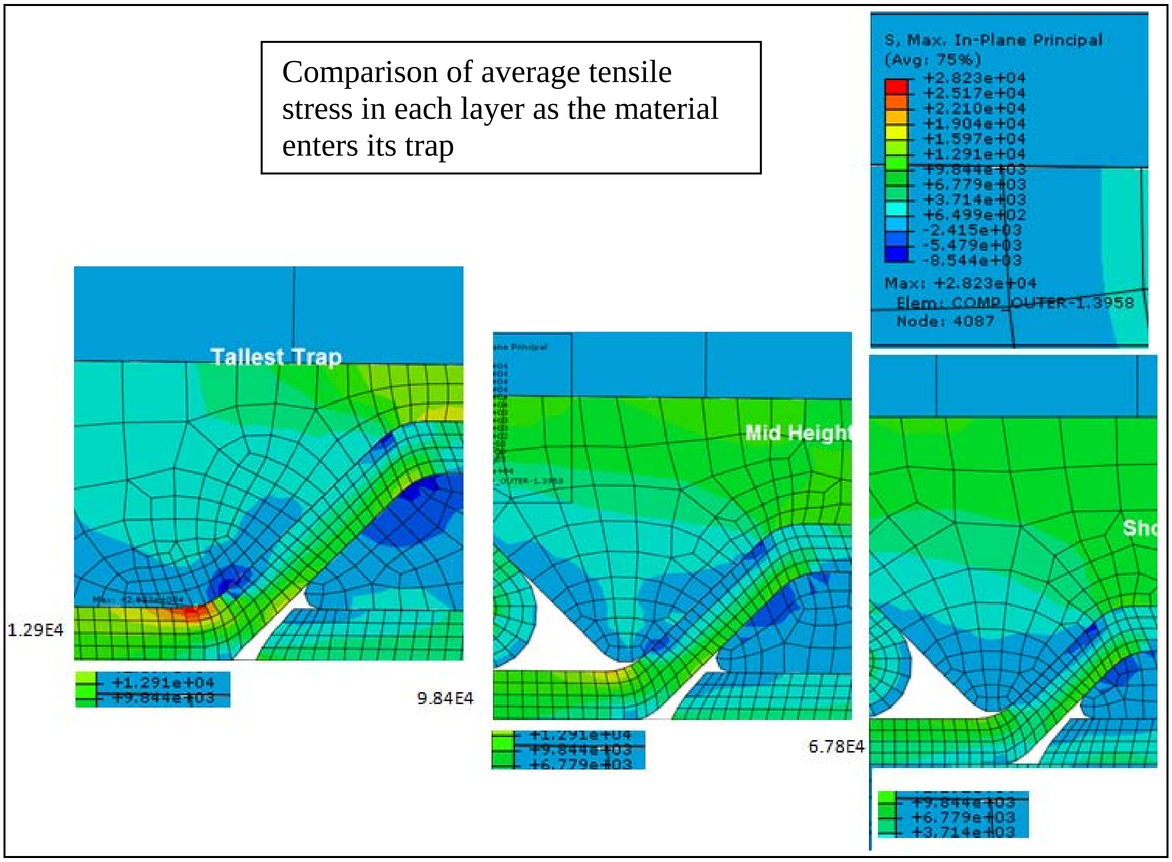


Figure 97. Enlarged View, Mid Height Trap Region Showing Principal Stresses



Comparison of average tensile stress in each layer as the material enters its trap

Figure 98. Average Tensile Stress Comparison

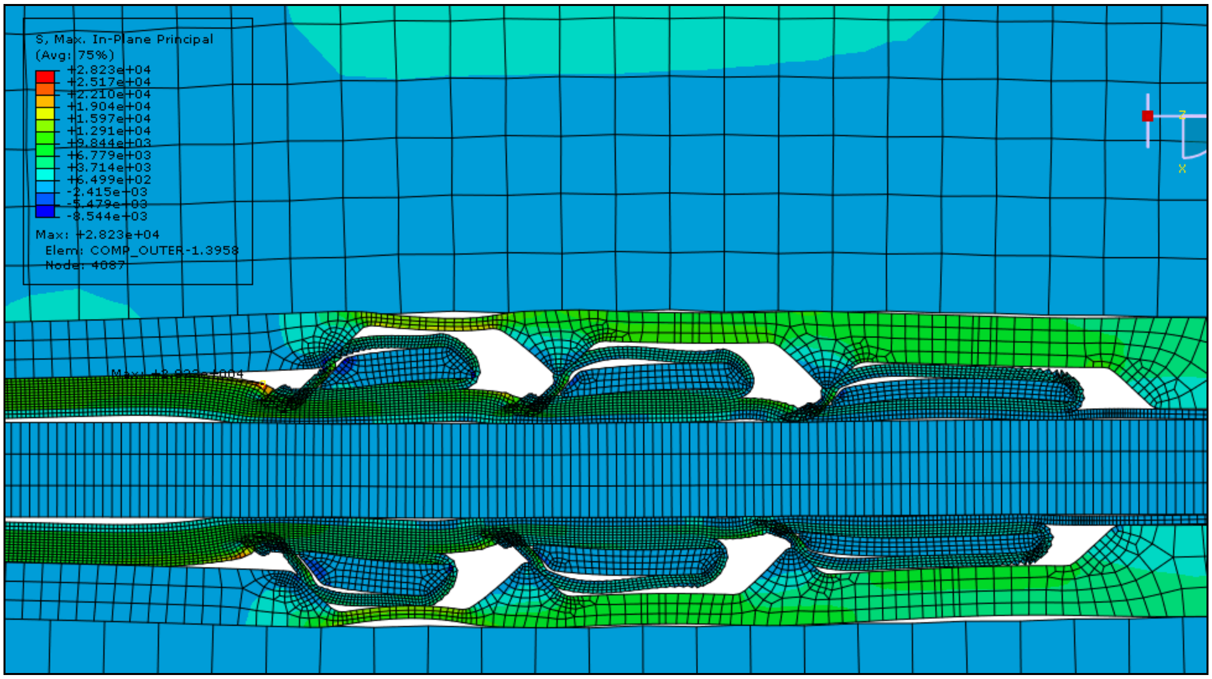


Figure 99. Exaggerated Deformations of the Loaded Cold Water Pipe Test Specimen

5.5.1.4 Interpretation of Finite Element Analysis Results

The elastic finite element results show strong but very localized stress concentrations at the point where each ply departs from the laminate and starts to enter its own entrapment region. For example, compared to a far-field laminate stress of about 8,000 psi, Figure 94 shows that the maximum principal stress at the tallest trap is about 28,000 psi. Figure 95 shows that the maximum principal stress at the mid-height trap is about 18,000 psi. These worst-case local stresses would indicate a stress concentration factor of three to four.

Evidently, in the light of the initial fatigue test results reported in section 5.4, these highly localized predicted stress concentrations do not dominate the macroscopic behavior of the termination, at least in this initial test. Those results indicate that for overall failure, the effective stress concentration factor is about 1.15.

It is not unusual for a high localized theoretical stress concentration factor to be mitigated by real material behavior. For example, an initial crack that originates in a highly stressed location can run into a lower stress field as it propagates, leading to so-called progressive damage behavior that is more benign than one would expect from the elastic calculations alone.

This behavior certainly warrants further study and testing as this work matures. The initial results suggest that reliance on only a calculated stress concentration factor could be very conservative

5.5.2 Test Results and Conclusions

Orthotropic finite element analysis of a composite entrapment-type termination, including representation of contacting surfaces, can be used to study the predicted maximum stresses. However, other factors appear to be interceding in the real behavior and are making the actual effective stress concentration factor in the termination substantially milder than the finite-element work would indicate.

5.6 Pilot Plant Platform Connection

5.6.1 Logic Flow for 4 meter Cold Water Pipe Connection

Due to the increased flexibility of the 4m CWP relative to the platform, the flow logic for the 4m gimbal / no-gimbal decision is different than for the 10m analysis, see Figure 100. Even with a direct connection to the pilot plant platform, the 4m CWP has a satisfactory lifetime. Therefore, a gimbal is not required. This decision has two qualifiers:

a. That the strain concentration in the termination fatigue stress is satisfactory, and
b. That the dynamic analysis of the coupled CWP/Platform is correct. While several programs have provided similar results, it will require at model test in a wave tank to finally validate these results.

During the course of this program, it was not certain that a gimbal would not be needed. Design work had to proceed on the pipe handling equipment during fabrication and on the platform. Therefore, early in the design phase it was decided to leave room for a gimbal and design the pilot plant for an optional gimbal.

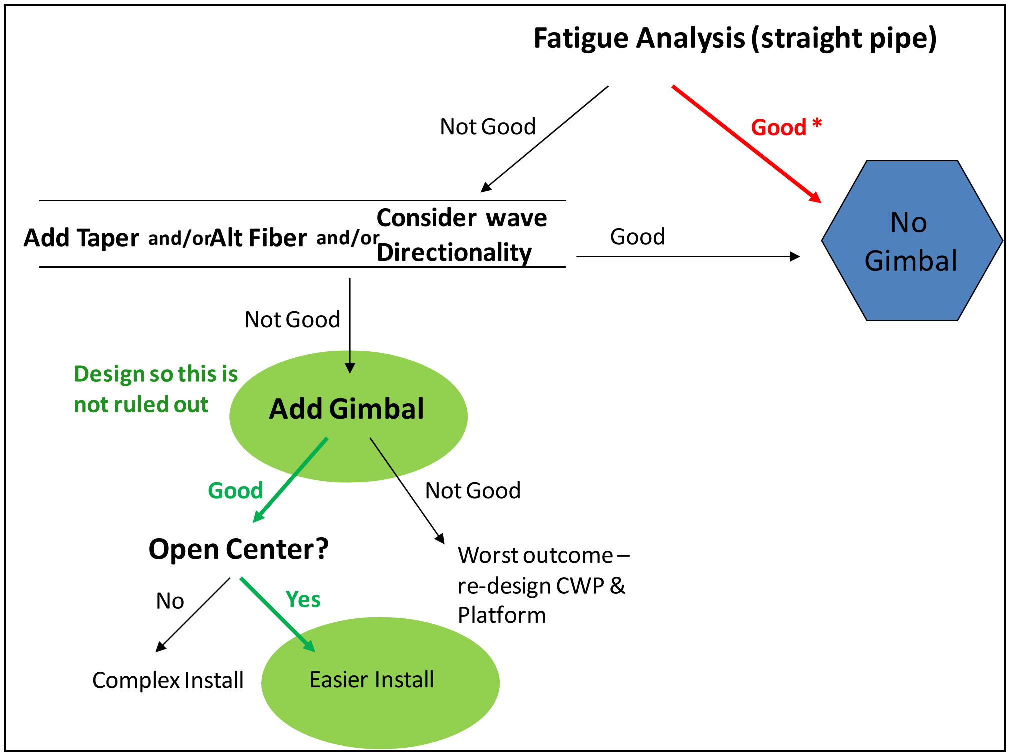


Figure 100. Logic Tree for the 4m Gimbal Decision

The current pilot plant design for the platform and for the pipe handling equipment includes a conceptual gimbal design, shown in Figure 101. Details are not provided on this gimbal concept as these details were not part of this contract.

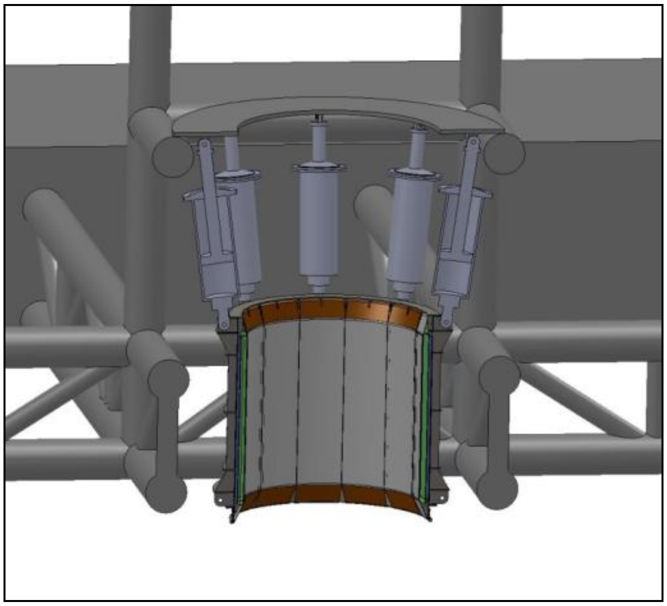


Figure 101. Conceptual Gimbal for the Pilot Plant

Left with the conclusion that a gimbal is needed for the commercial OTEC plant but not necessarily needed for the pilot plant begs the question: Should a gimbal be added to the pilot plant? Gaining the experience of designing, fabricating, and handling the gimbal plus the added CWP dynamic experience with the gimbal (and without if the gimbal could be locked) would be a valuable addition to the Pilot Plant. It is therefore recommended that a gimbal be included in the pilot plant, if affordable. Cost is the only disadvantage identified with this option.

5.6.2 Platform Connection

To be added later.

5.7 Conclusions and Recommendations

To be added later.

6. PIPE HANDLING DURING FABRICATION

6.1 Introduction

This chapter is focused on the design of the CWP handling system during the pipe fabrication phase. The CWP is fabricated vertically on board the OTEC platform. The equipment discussed in this chapter supports the CWP during this fabrication. Through the trade studies and design of this system, this equipment acquired the names of “Gripper” and “Guides”.

This chapter discusses two different OTEC systems: The first is a commercial 100MW OTEC plant with a 10m diameter CWP and the second is a pilot 10 MW OTEC plant with a 4m CWP. A pipe handling system for the 10m CWP was conceptually developed first and then a handling system for the 4m CWP was more fully developed for the pilot plant.

6.2 Requirements

The purpose of the pipe handling equipment is to support the CWP during pipe fabrication. Figure 102 shows the OTEC platform with the pipe fabrication tower installed. The CWP is fabricated vertically in 11-m segments within this tower and cured just above the deck of the platform. As each segment is fabricated, the pipe is lowered, and a new section is added.

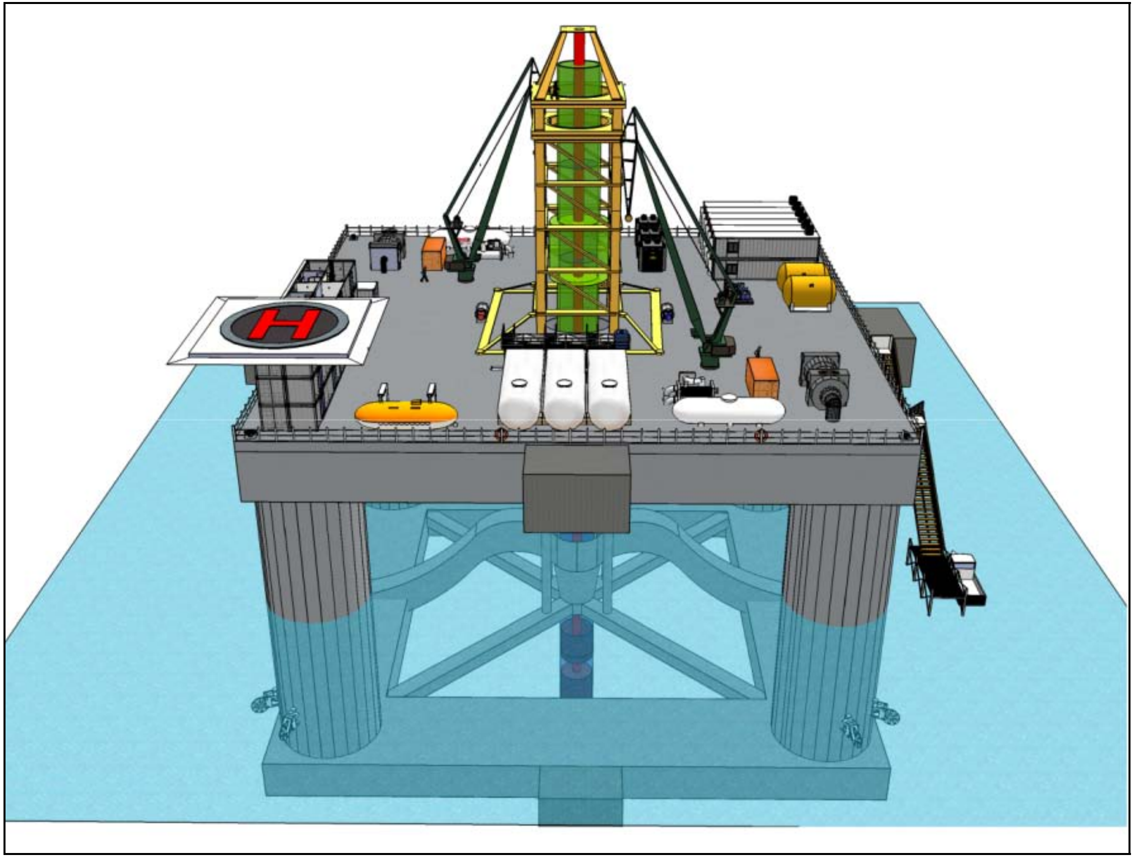
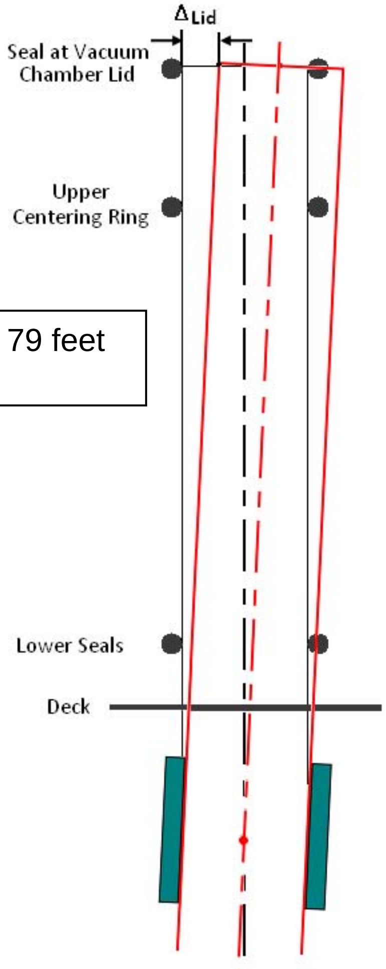


Figure 102. OTEC Platform with Pipe Fabrication Tower

The Pipe Handling Equipment is required to:

a. Reliably support the CWP weight during all stages of fabrication.
    (1) The final CWP length is 3280ft (1000m)
b. Reliably hold the CWP in shear currents, wave loads, and bending moments due to platform motion.
    (1) Survive a 10-year storm
    (2) Support CWP fabrication operations in 90% swell and wave conditions
c. Accurately control the vertical placement of the CWP
    (1) Fabricate incrementally in ~11m segments
    (2) Raise or lower and adjust pipe position accurately
    (3) Hold, raise and lower the CWP from any point along its length
d. Accommodate CWP irregularities both inside and outside the pipe
    (1) Accommodate ID and OD irregularities
e. Not damage the CWP
    (1) Not crush or collapse the CWP.
    (2) Contact CWP at a uniform pressure; nominally 50 psi or below
f. Set the CWP in its final termination location on the platform.
    (1) The pipe is fabricated above the platform, 66 feet (20m) above the water.
    (2) The pipe termination ends up at a location approximately 59 feet (18m) below water.
g. Minimize above deck CWP motions; hold the CWP stationary for the above-deck fabrication process
    (1) Max Displacement 79 feet (24m) above the deck is at the vacuum chamber top lid seal with an allowable ΔLid<1.3in (Figure 103) during operations.
h. Accommodate contingencies
    (1) Accommodate a hand-built pipe splice
    (2) Be reversible
i. Convert to an OTEC plant
    (1) Be able to transform from a CWP factory to an operating OTEC plant.
    (2) Remove fabrication equipment when complete



Most severe restraint is 79 feet above the deck.

Figure 103. Movement of the CWP above Deck

6.2.1 CWP Characteristics for Handling

The driving challenge for the CWP handling equipment is the size and flexibility of the CWP. Table 25 provides the primary dimensions for the 10m (commercial) and 4m (pilot phase) CWPs. These CWPs are massive structures that are designed for a maximum flexibility and ideal performance as a dynamic OTEC CWP. The 10m CWP has an outer circumference of 35 feet and has a wet weight of 2,300 tons. Gripping equipment must support 3500 lbs per inch of circumference.

Structures of this size and weight are beyond our everyday experience. One can make a comparison to a simple everyday structure: a common plastic soda straw. A scale model of the 10m CWP with a straw would be at 1/1500 scale and would be 2.2 feet long; a slenderness ratio of 95. The wall thickness of the straw is proportional but the weight of the straw is 2x what it should be to be an accurate scale model. In addition, the axial stiffness of the straw is 140 times greater and the oval stiffness (stiffness by pinching the straw between two fingers) is 270 times greater. Holding this model pipe straw with the proper weight and stiffness while avoiding crimping or collapse would be a significant challenge.

Table 25. CWP Dimensions for Handling, 10m and 4m Pipes

Summary CWP Characteristics	10m CWP, version 5				4m CWP version 5			
	US units		Metric		US units		Metric	
Inside diameter inlcuding Resin Distribution Layer	394.0	in	10.01	m	157.3	in	3.99	m
Outsude Diameter including Resin Distribution Layer	412.9	in	10.49	m	165.9	in	4.21	m
Length	39400	in	1,000.8	m	39400	in	1,000.8	m
Bottom Weight, wet weight	-	lbs	-	kN	91,000	lbs	405	kN
Mass, CWP - no bottom weight - no internal water	10,599,405	lbm	4,807,809	kg	1,741,782	lbm	790,059	kg
% wall that is void inc RDL	65.3	%	65.3	%	67.3	%	67.3	%
Total wet Weight includng bottom weight	4,579,592	lbs	2,077.3	tonnes	800,555	lbs	363.1	tonnes
EA	1.65E+10	lbs	7.35E+07	kN	2.40E+09	lbs	1.07E+07	kN
EI	3.31E+14	lb-in^2	9.50E+08	kN-m^2	7.71E+12	lb-in^2	2.21E+07	kN-m^2
Wet Weight per unit length of circumference:	3530.8	lb/in	0.63	tonnes/cm	1536.0	lb/in	0.27	tonnes/cm
Air Pressure to float:	37.9	psi	2.58	atm	41.5	psi	2.83	atm

The CWP does not have a smooth outer wall. The outer surface is rough due to the resin distribution medium used in the fabrication. The arithmetic average is 351 microns. The typical profile of CWP samples are shown in Figure 104. During the fabrication process, surface irregularities are added to the inside and outside walls. The types of irregularities are shown in Figure 105 and the maximum height and dimensions of these are given in Table 26.

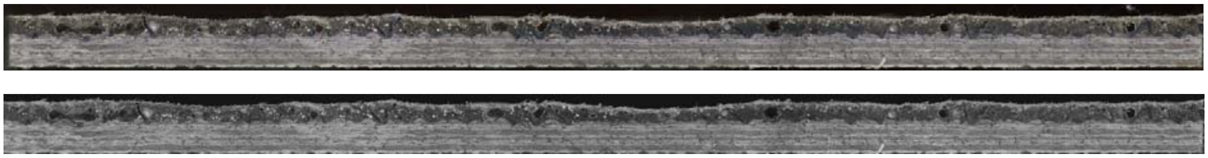


Figure 104. Image of a Pipe Section Before and After Image Processing

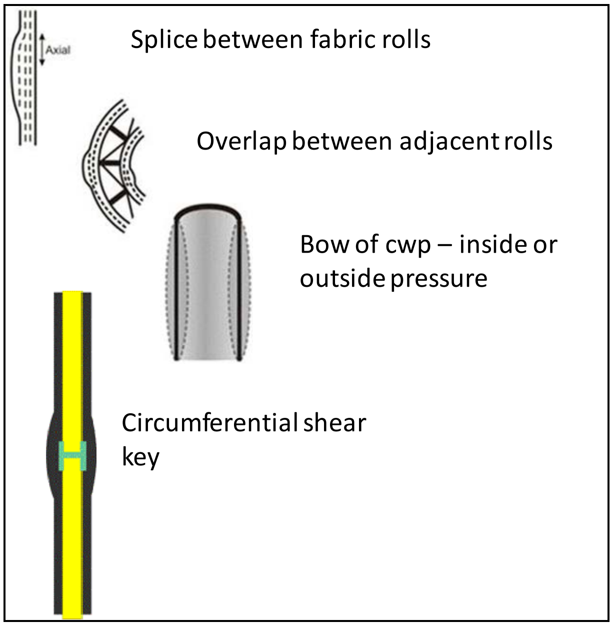


Figure 105. Varying Types of Pipe Irregularities and Distortion

Table 26. Size of Pipe Irregularities on the 4m CWP

bumps:						
Shear Key OD		166	in		4216	mm
Shear Key ID		157.24	in		3994	mm
Shear Key with face sheet OD		166.8	in		4237	mm
Shear Key with face sheet ID		156.44	in		3974	mm
Vertical Strip-like bumps adjacent rolls		0.04	in		1.0	mm
horizontal strip-like lumps - shear key		0.50	in		12.7	mm
horizontal overlaps splices between fabric rolls		0.125	in		3.2	mm
emergency splice thickness outside - full circumference:		0.22	in		0.006	mm
emergency splice elevation outside - tapered ends: (estimate)		39.4	in		1.0	m

6.2.2 Operational and Survival Mode

The team established two standards, operational and survival, for Gripper performance as a design guideline. In the Operational mode, when CWP fabrication is in process, the Grippers need to accurately hold and move the pipe as needed for the fabrication process. In the Survival mode, when CWP fabrication ceases, the Grippers need to simply hold the pipe securely, no pipe movement is needed.

Operational mode was selected at 90% seas or 90% swell conditions for 12 month operations off Barbers Point, Oahu. Survival mode was based on a 10-year storm at the same location.

For Operational mode, vertical movement and accuracy was selected at 0.25 inch vertical movement resolution and for horizontal positioning: <1.3” at 79’ above the deck. The CWP fabrication process was being developed concurrent with this handling system design, so final testing and verification that these goals are adequate have not been completed on the fabrication side. However, these values were agreed upon by the CWP development team and the CWP handling team as reasonable. During the design, the maximum movement of the pipe was kept at 1.3” or less even during 10-year storm conditions. Theoretically, pipe could be manufactured during any weather condition. In practice, fabrication would be terminated at some level of platform movement, but that level was not defined in this study. The upper sea state for operations will be determined by the maximum movement of the CWP allowable while still maintaining an adequate vacuum seal against the pipe and the safe handling of CWP materials on board a moving deck.

6.3 Trade Studies

A variety of methods were considered for supporting the vertical and horizontal loads on the CWP and for moving the CWP up and down. This section summarizes the various methods considered and provides the logic that lead to the final selection of the grippers and guides.

6.3.1 Holding Mechanism

This section briefly reviews the various techniques that were considered for supporting the weight of the CWP during manufacture. In the case of the 10m diameter CWP, the total wet weight is 2,300 tons and this translates into a vertical load of 3,500 lbs per inch of external circumference of the CWP. In the case of the 4m diameter CWP, the total wet weight is 400 tons and this translates into a circumferential load of 1,550 lbs per inch of external circumference.

The following illustrations and paragraphs describe the various techniques that were considered to support these loads.

Friction: A simple frictional contact with the CWP was first considered. The frictional surface could be either on the inside or on the outside of the CWP as illustrated in Figure 106. Considerations for the friction approach were the reliability of the coefficient of friction and how that coefficient would change if the CWP were wet or coated with hydraulic fluid. In order to use friction reliably, it was quickly computed that very large areas of the CWP would have to be engaged to have a practical frictional grip.

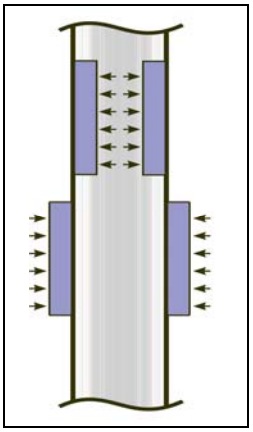


Figure 106. Internal or External Friction

Pins: Pins could be inserted into holes placed either in the internal or external face sheets of the CWP. This concept was dismissed because of the very high loads per pin or alternatively the very large number of pins that would have to be accurately inserted at any given time. Secondly, penetrating the face sheet would expose cut glass fibers which would have to be coated to protect them from seawater exposure.

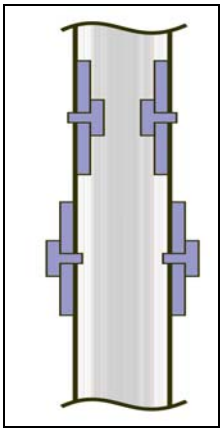


Figure 107. Internal or External Pins

Ridges: Ridges could be incorporated as part of the inner facesheet or external facesheet and be used to support the entire CWP weight. One of the disadvantages of these ridges is that they would have to be inserted at multiple locations on the CWP and the fiberglassing requirements would not be trivial. This would increase the cost of the CWP and that added cost would be for each CWP. In addition ridges on the outside of the CWP would have difficulty passing through any guides or restraints that were placed for lateral loading. Alternates to the ridges were internal grooves. These also had the difficulty of CWP complications and having to place them at specific locations along the CWP length.

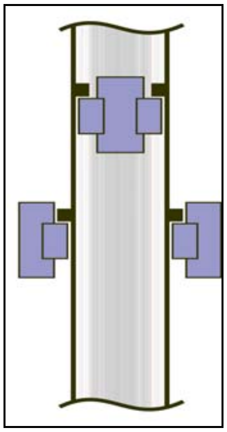


Figure 108. Internal or External Ridges

Velcro: Even the hook and fastener concept was considered as a means of supporting the CWP. Velcro Corporation was contacted and the cost of coating a CWP with Velcro® tape was reasonable. The difficulty with Velcro® was the driving mechanism for moving conveyor belts or large pads and the means of attaching the Velcro® onto the CWP. Furthermore, shear loads are in the order of the shear capacity that we expected to achieve by friction alone and therefore the hook and fastener approach did not present any significant gripper size reduction over a frictional gripper.

Figure 109. Velcro®

Kellem Grip: Finger grips or Kellem Grips are frequently used to pull on pipes and cables. These grips have a natural tendency to squeeze on the outside of these circular structures and they hold by friction. The difficulty with these grips is that they hold at a fixed point and they do not normally translate up or down a pipe or cable. Makai considered a variation of the finger grip that consisted of an endless finger grip where the woven fabric at the top rolled over and was connected to the bottom. Thus it is endless. By carefully handling the netting at the top of the grip, net could be removed from the bottom and continuously fed into the top thus lowering the CWP. A model was built of this configuration but there were two major difficulties. The net handling mechanism at the top of the gripper would be rather complex and would have to be flawless in terms of gripping each netting intersect in each section. Secondly, the finger grip can be easily released by pushing up on the netting at the bottom of the grip region. Thus it could very suddenly and catastrophically drop the CWP. This concept was considered too risky and would require too much development.

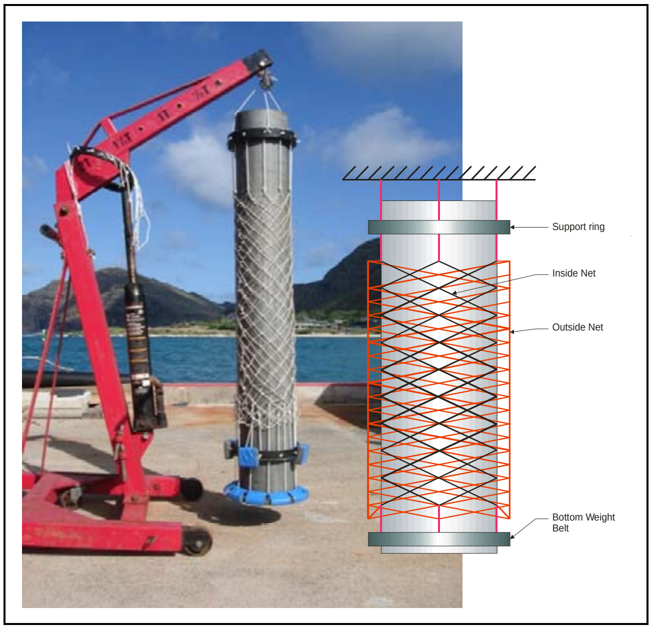


Figure 110. Finger Grip

Internal Lever Lock: An internal locking mechanism was also considered as shown in Figure 111. This system shows a series of pads and levers that wedge themselves inside the CWP. The weight of the CWP presses the pads firmly against the inside of the CWP. This configuration introduced the concept of using the weight of the CWP as a means of providing the normal pressure for a friction grip and demonstrated that power was not needed to hold the CWP. The disadvantage of this concept was that the CWP was supported from the inside and thus the vertical load had to be carried up through the fabrication tower and back to the OTEC platform deck. The impracticality of that load path and the limited space inside the fabrication tower made this concept infeasible.

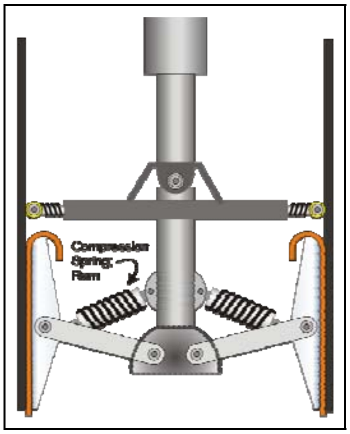


Figure 111. Internal Lever Lock

External Wedge: An external wedge concept is shown in Figure 112. A wedge with a 4:1 slope could be driven between the CWP and a cone surface in order to hold the CWP by friction. With the 4:1 ratio wedge, a normal force would always be applied to the CWP and a coefficient of friction of 0.25 or greater would support the weight of the CWP. The hydraulic ram show in Figure 18 is for setting and retracting the wedge.

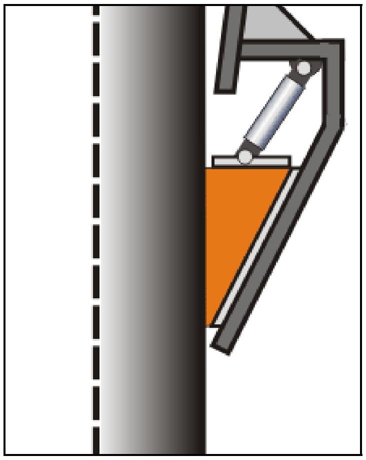


Figure 112. External Wedge

External Wedge with Guides: Variations of the external wedge discussed above were considered. Figure 113 shows a wedge concept on rollers such that also provides lateral support while moving up and down.

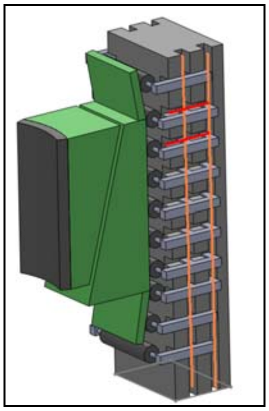


Figure 113. External Wedge with Guides

External Sand Wedge: The team considered using a material such as sand to develop a frictional bond with the outside of the CWP. In this concept a sand wedge would be formed around the outside of the CWP. By covering the top of the sand wedge and pressurizing the sand area, the CWP would shrink slightly under the external pressure. The sand would settle around the CWP and as the hydrostatic pressure is slowly released, the sand would be wedged in place providing an external frictional load to the CWP. This system could be easily released by simply pumping water at the base of the sand wedge and fluidizing the sand. The additional advantage that the sand wedge has is that it could take the shape of any irregularities on the CWP. The radial elasticity of the CWP provides the uniform normal force on the sand. The disadvantage of this concept is that the CWP must be preloaded hydrostatically and the CWP does not have the capability to takes these loads without buckling.

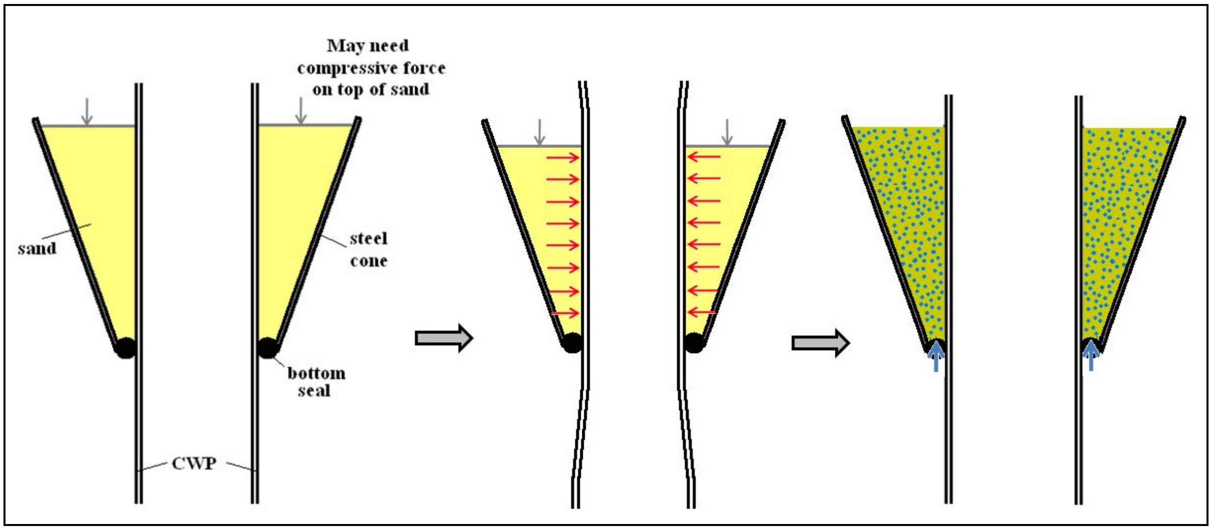


Figure 114. External Sand Wedge

6.3.2 Moving Mechanism

In addition to holding the considerable weight of the CWP, the pipe must be moved both up and down as the CWP is being fabricated. A variety of moving concepts were considered and these are discussed in the following paragraphs.

Conveyors: Conveyor tracks were considered for loading the CWP both inside and outside as shown in Figure 115 Although conveyors are standard moving mechanisms they provide only limited contact surface with the CWP. Considering the total weight of the CWP and working with a nominal coefficient of friction of 0.25 coupled with a normal pressure of about 50 psi, one could only develop a shear load of 12.5 psi on the wall of the CWP. This small shear force translates into a very large contact area with the CWP which proved to be impractical.

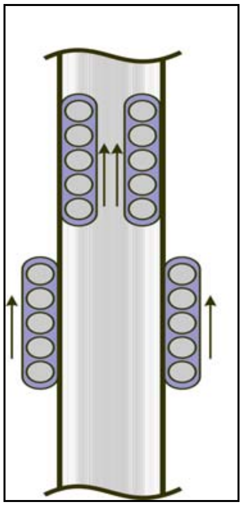


Figure 115. Internal or External Conveyors

Cables: A conventional means of handling heavy loads is with a winch and cable combination as shown in Figure 116. In the case of the 10m diameter CWP, however, as many as ten synchronized winches handling ten 3 inch diameter wire ropes would be needed to reliably support the total wet weight of the CWP. Synchronizing these ten winches to evenly share the load would be a difficult operation and was considered a very high risk. In addition, the cables would be attached to the bottom of the CWP and thus the pipe would be held from the bottom: The entire CWP would be in compression. The 1,000m CWPs is not sufficiently stiff in bending to be supported at the bottom only without buckling. To overcome the buckling an intermediate attachment between the CWP and the ten cables would have to be placed somewhere at mid length and that was considered impractical.

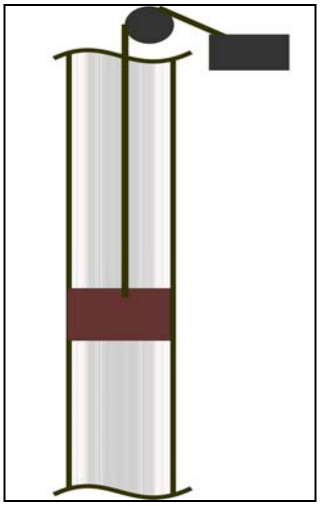


Figure 116. Cables

Built-In Cables: The team considered cables built into the CWP as longitudinal strength members and also as means of supporting the CWP during fabrication as shown in Figure 117. This concept was considered problematic because of the difference in elasticity between the cables and fiberglass. Also, the cables or rods are lengthened incrementally as the CWP grows requiring a large number of mechanical links which was considered unwieldy.

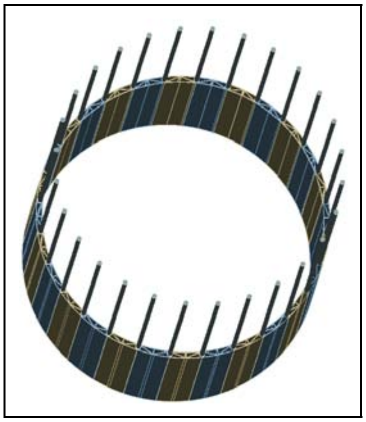


Figure 117. Built-in Cables

Hydraulic Rams: One or more hydraulic rams could very easily accommodate the large loads required as shown in Figure 118. Rams have the disadvantage that they have a finite stroke, and many strokes would be required for the full CWP length. This would require multiple attachments and removal of the rams to the CWP during the fabrication process.

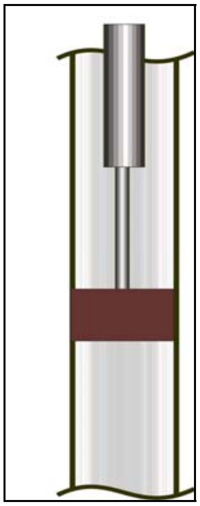


Figure 118. Hydraulic Ram(s)

Tire Drives: Inflated rubber automobile or truck tires are commonly used in marine cable or pipe engines to deploy cables and pipe overboard. A concept using tire drives is shown in Figure 119. Tire drives are generally favored because they distribute the loads over a long length. Tire drives have the same practical limitations as the conveyor belts: the contact surface area is limited and a huge number of tires would be required for these very large CWPs. The drive mechanisms for these tires would be prohibitively expensive.

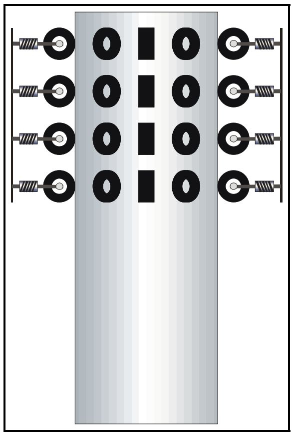


Figure 119. Tire Drives

6.3.3 Guide Concepts – Horizontal Loads

In addition to the vertical loads described above and the moving mechanisms, the CWP handling equipment must carry the lateral loads in the CWP due to platform motions, wave loads and current loads. Shear and bending moments in the CWP just below the platform require lateral supports to take bending and shear. Several of the concepts considered are shown in Figure 120.

Most of these concepts are variations about guides or bushings that snuggly fit on the outside of the CWP. Two or more guides can be used to take both the lateral and bending moments. Sets of two, three and even continuous guides were considered. The primary driving constraint was the allowable motion of the CWP above the main deck. The more firmly the pipe is held below the deck, the more stationary the pipe above the deck is. Some of CWP guide concepts were moveable as shown in Figure 121. Pads and wedges could be adjusted for the diameter of the CWP and even rollers, designed to minimize the frictional components, were considered.

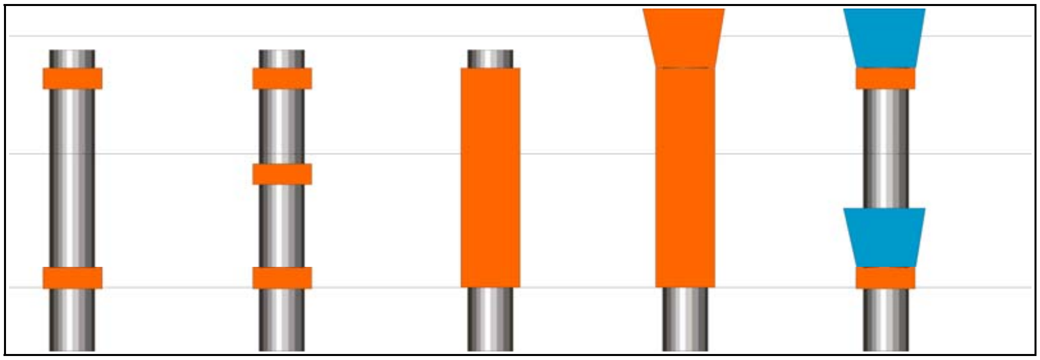


Figure 120. CWP Guide Concepts

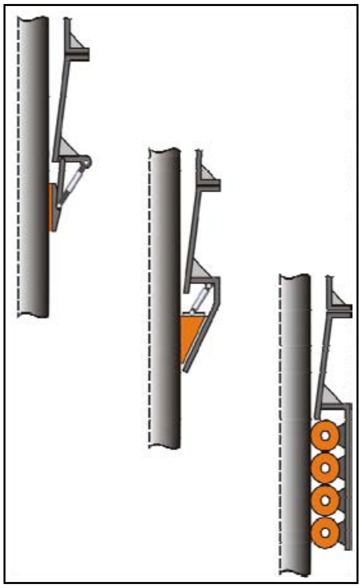


Figure 121. CWP Guide Concepts

6.3.4 Basis for Selecting the Final Approach

The paragraphs below describe the logic used to select the final baseline configuration taken for further design development.

6.3.4.1 External vs. Internal Gripper

Initially the team considered a concept applying pressure to the inside of the CWP as there seemed to be less pipe collapse issues. This turned out to be wrong as analysis showed the pipe buckles at nearly the same pressure if applied externally or internally. Applying a hydrostatic pressure on the outside of the pipe can cause the pipe to buckle under a fairly low pressure. However, a series of pads or wedges in an external gripper device provides more than enough hoop strength to the gripper and CWP structure that this form of collapse is not possible (an exception is the sand wedge which required hydrostatic loading as a pre-set). The limiting pressure is determined by the ribs within the core structure. These ribs collapse at some wall pressure and they are nearly equally loaded if the pressure applied is on the inside or the outside. Thus there is no significant pressure advantage to gripping from inside the CWP.

There are several disadvantages of gripping inside the CWP. As mentioned earlier, carrying the considerable vertical load would have a load path up through the center of the fabrication apparatus and down through the fabrication tower to the deck. This is long, elastic, and expensive. Alternately, the team considered carrying the vertical load to a buoy floating inside the CWP but this presented access, visibility, and dynamic issues. A complex apparatus inside the pipe without good visibility and with the possibility of oil leaks coating the inside wall made this alternative undesirable.

One advantage of an inside the CWP concept was the possibility of having a lowering system that could lower the pipe all the way to the lower pontoon with the same handling device. This issue was viewed as a difficulty with any external device that had to pass a CWP termination. Any external gripping mechanism had to be coupled with a concept for this final lowering.

In the final selected arrangement, a combination of the two methods was selected. An external gripper was used for most of the CWP holding and lowering. For the final lowering, it was realized that the terminated pipe could provide buoyancy by capping inserting air at ~40 psi. Thus it could be lowered in place with a small heave-compensated winch. This approach is further described in sections 6.4.5 and in 6.14.4

6.3.4.2 Load Distribution

The CWP is a massive structure being extremely heavy and yet rather delicate. It can only be supported by distributing support loads over a very large surface. This fact eliminated concepts such as pin holes, conveyors, and tire drives. Early numbers applied to the CWP were 3500 lbs of support per inch of circumference for the 10m CWP. This load had to be well distributed with no load concentrations to engage the face sheets evenly. This limitation favored a frictional attachment.

6.3.4.3 Guide Pressure

The guide structure must contact the CWP on the outside and large forces are inevitable. Early load analysis indicated that large pads would be needed with a length of one to one-half the pipe diameter to resist the moments and lateral loads. Therefore elevated external CWP pressures were necessary and would be part of the CWP design thus favoring a frictional gripper operation. Therefore, requiring a large external pressure capability for the grippers was not an additional CWP expense.

6.3.4.4 Surface Texture

The CWP must slide through the guides and thus they have to be smooth. This eliminated ridges or any other protrusions from the CWP wall.

6.3.4.5 Pipe Structure

The pipe is a well-designed structure to operate efficiently as an OTEC intake structure. It is highly flexible and with suitable fatigue life. The design team did not want to compromise this design for a relatively short fabrication time. The team avoided built up ridges and holes. In a more subtle way, this pipe survives well because it is flexible and can move with water movement. By allowing the pipe the maximum amount of flexibility (between guides, for example), we could minimize point strains in the CWP.

6.4 Gripper and Guide Concept Summary

The selected base configuration is based on the external wedge and guide as shown in Figure 122. One fixed gripper and one moveable gripper, each consisting of a series of external wedges operated by hydraulic rams, externally support the CWP below the main deck. Two independent guides fit snugly around the outside of the CWP and provide lateral force and moment resistance.

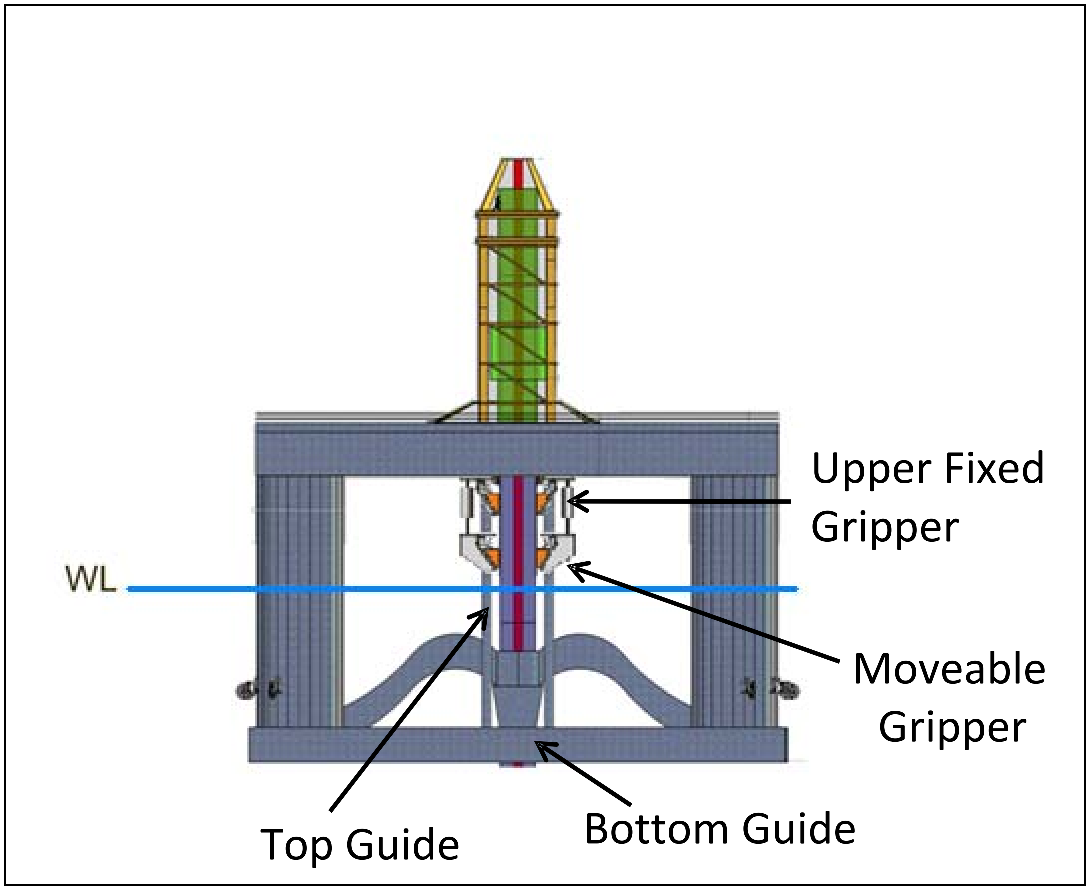


Figure 122. Selected Baseline Configuration

6.4.1 Nomenclature

Throughout this chapter we are discussing the grippers and guides that hold and move the CWP during fabrication. The following nomenclature is used to describe these devices:

- **Gripper**: A device for holding and lowering the CWP.
- **Gripper Pads**: These are segmented external collar sections that contact the CWP. The gripper pads consist of the following:
  - **Friction Layer**: This is the rubber layer in direct contact with the CWP. It has a high coefficient friction.
  - **Tension Layer**: The tension layer is immediately outside the friction layer and supports the weight of the CWP. The tension layer is attached at the top to the structural frame of the gripper.
  - **Gel Bag**: This is a large soft bag behind the tension layer that evenly distributes the squeeze pressure to the CWP.
- **Wedges**: The wedges are the inclined plane structure that moves the gripper pads towards and away from the CWP. The incline of the wedges is a means of transferring the weight of the CWP to a radio pressure on the CWP.
- **Guides**: The guides are a pair of external sleeves that hold the CWP horizontally and resist the lateral loads due to currents and platform motions. The CWP can move vertically through the guides.
- **Guide Pads**: These are segmented external collar sections that contact the CWP in the guides. These pads consist of the following:
  - **Slide Layer**: This is in contact with the CWP and has low friction.
  - **Tension Layer**: The tension layer transfers any sliding friction forces from the slide layer into the guide structure.
  - **Water Bag**: The water bag is sandwiched between the guide structure and the tension layer. It evenly distributes the guide pressure over the surface of the CWP.

6.4.2 Grippers

The grippers hold onto the CWP by friction. See Figure 123. A nominal squeeze on the CWP of 50 psi and a minimum coefficient of friction of 0.25 provides 12.5 psi shear over the surface of the CWP. A gripper pad 120 inch (3m) tall supports the 1500 lbs/inch of circumference load of the 4m CWP and a gripper pad 280 inch (7m) tall supports the 3500 lbs/inch of circumference load of the 10m CWP. The gripper normal pressure is mechanically achieved through the gripper wedges. The slope of the wedge is 4:1, thus maintaining a squeeze on the pipe that is 4 times the weight of the CWP. The wedge does not require hydraulic power to hold the pipe so the system will securely support the CWP even in power failure. The hydraulic rams on the wedges set and retract the wedges.

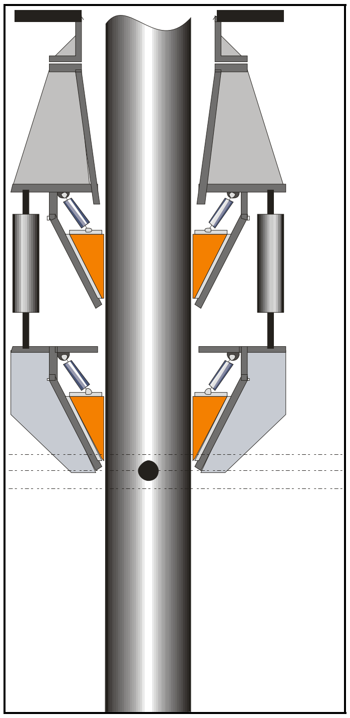


Figure 123. Gripper Hydraulic Wedge Final Concept

The complete system is comprised of two grippers. The upper gripper is stationary and simply holds the CWP in place. It also centers the CWP for the fabrication apparatus and helps prevent lateral movement. The lower gripper can move up and down and is suspended by hydraulic rams with a 19.7’ (6m) throw. The lower gripper does not provide lateral support – it “floats” about the CWP. Each gripper can support the entire CWP weight. At all times, except when moving the CWP, both grippers are attached to the CWP.

Movement of the CWP is an alternating hand-off process between the two grippers. Figure 124 shows the sequence schematically. Normally, both grippers support the CWP. When the CWP is lowered, the lower gripper lifts the pipe slightly checking that it is carrying the entire load by monitoring the lifting ram pressure and the upper gripper wedges are retracted. The pipe is lowered just short of the length of the lowering rams and the upper gripper is engaged. The lower gripper lowers a few more inches checking that the load of the CWP is being carried by the upper gripper by monitoring the lifting ram pressure. The lower gripper disengages and is raised to grab onto the pipe again. This process is repeatable and reversible.

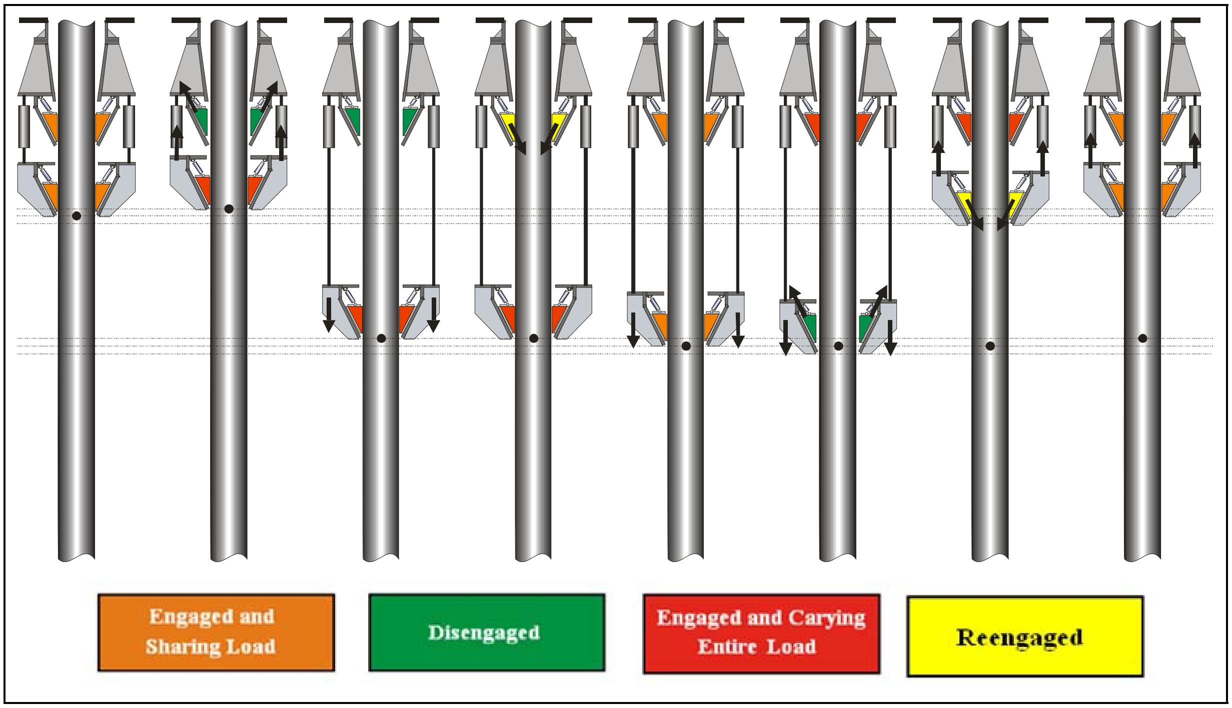


Figure 124. Gripper Movement Sequence

6.4.3 Pads

A concept that was developed early in the trade studies was the "waterbed" concept for applying uniform pressure over the surface of the CWP. It was realized that the pipe structure is sensitive to point loads and that the success of the frictional gripper would be dependent upon achieving a reasonably uniform pressure over the entire surface of the CWP in the gripper region. A waterbed approach can achieve this goal as the water pressure is uniform (ignoring hydrostatic gradient) and the waterbed would conform to pipe irregularities. Figure 125 shows the initial concept for the waterbed. A friction layer on the CWP side of the pad is in direct contact with the CWP. Behind the friction layer is a tension layer that holds the vertical load of the CWP. The friction layer shear is transferred to the tension layer which hangs from the top of the pad. Behind the tension layer is the waterbed which is either gel or water filled. Sand was considered for the medium during the concept development but was dropped as less desirable. The gel or water more evenly distributes the normal pressure over the surface of the CWP.

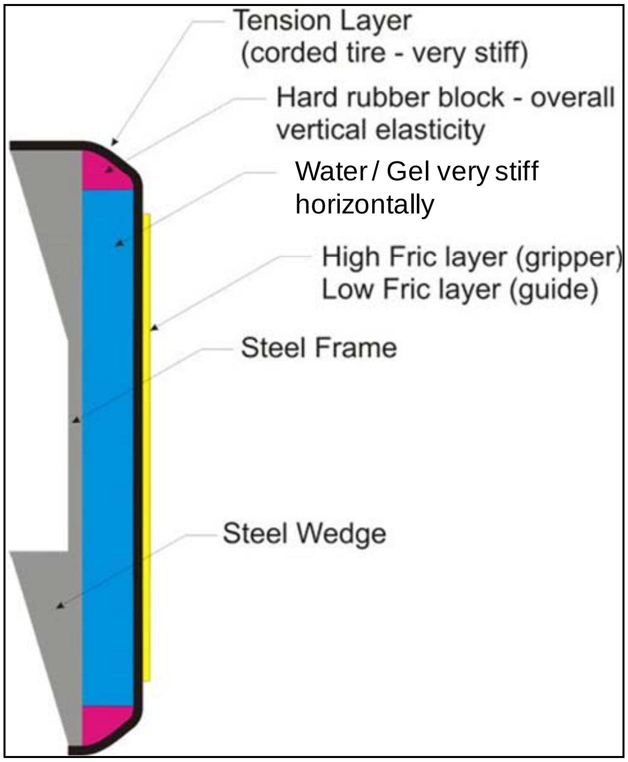


Figure 125. Baseline Pad concept

6.4.4 Guides

The baseline concept has two guides, one at the level of the lower pontoon and one just below the waterline. The upper guide can be as high as the lowest position of the lower gripper. The guides have similar pads as the grippers, keeping the pressure evenly distributed over the surface of the CWP, except that the surface layer is low friction, not high friction.

6.4.5 Final Lowering

Figure 126 illustrates the final lowering sequence for the CWP. Once the pipe fabrication is completed, a termination is manually added to the top of the CWP. In this illustration, this termination is envisioned as a tapered cone. The top of the CWP can be sealed with a domed cap and the pipe is pressurized with air. At a nominal 40 psi, both the 10m and the 4m CWPs can be floated. A heave-compensated winch is used to lower the CWP to its final location in conjunction with ballast control during the lowering. Prior to this lowering, the grippers or the gripper pads are removed to allow clearance for the end termination.

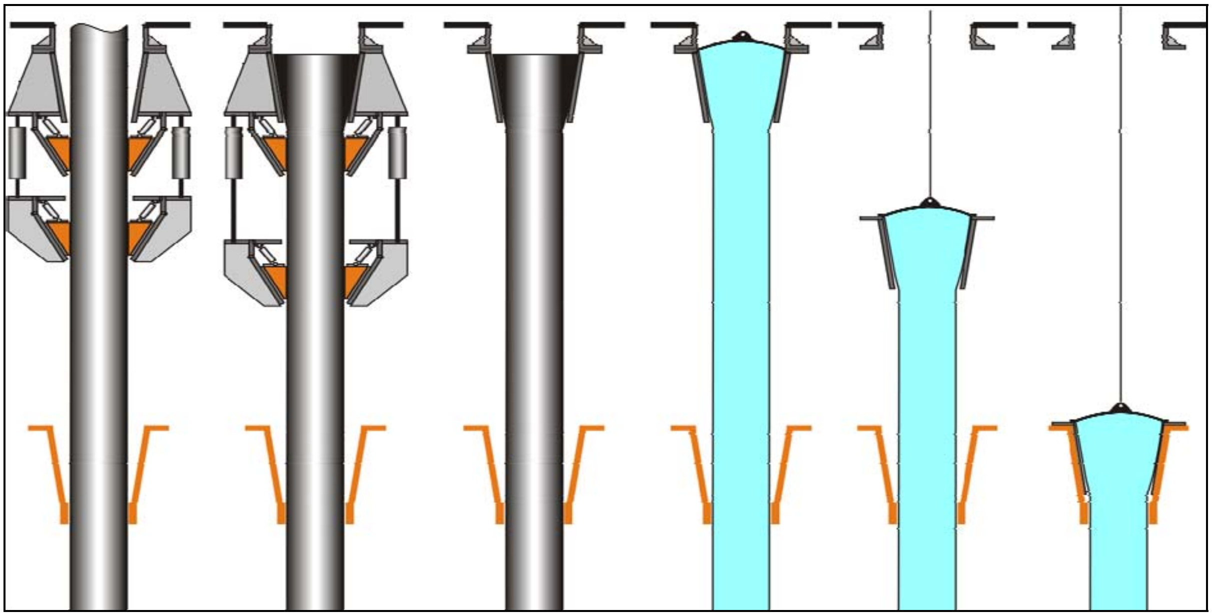


Figure 126. Final Lowering Concept

6.5 CWP and Platform Dynamics during Fabrication

6.5.1 Effect of Dynamics on Pipe Fabrication

During CWP fabrication the pipe movement is driven by platform motions, currents, and waves. The dynamics of the CWP and Platform interaction play a major role in the design constraints during the pipe fabrication. The design of the handling system and CWP during fabrication was driven by maximum pressure exerted by the guides and grippers. The design of the permanent attachment was driven by the fatigue life of the CWP.

The final gripper design is a function of maximum pressure capacity of the CWP, the friction and pressure distribution exerted by the gripper and guide pads, and the allowable motion of the CWP during fabrication. Figure 127 illustrates the iterative design process that impacted each of these elements. In the center of the figure is the gripper and guide arrangement. The platform and CWP coupling is driving the motions and pressures on the CWP and these in turn are being driven by the wave and current conditions.

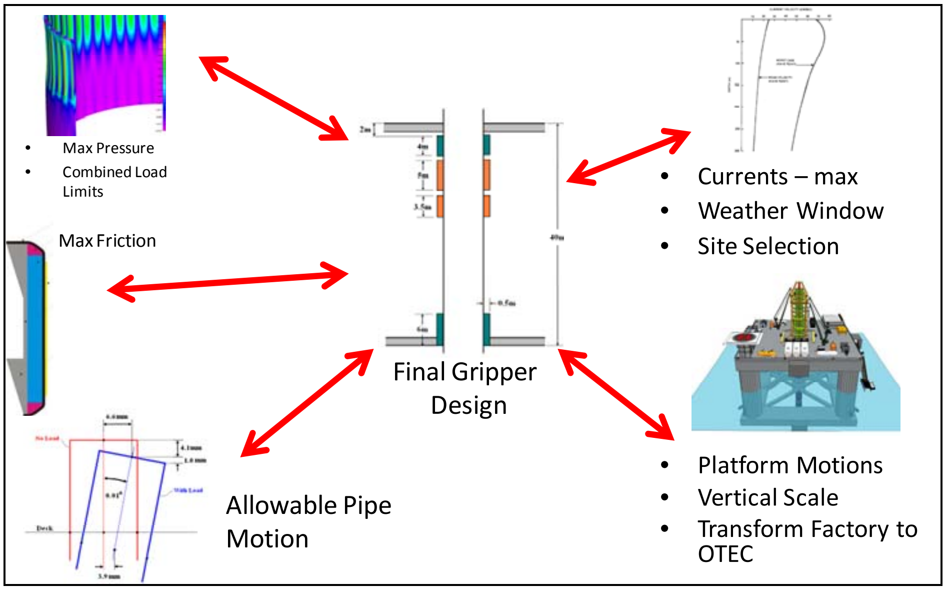
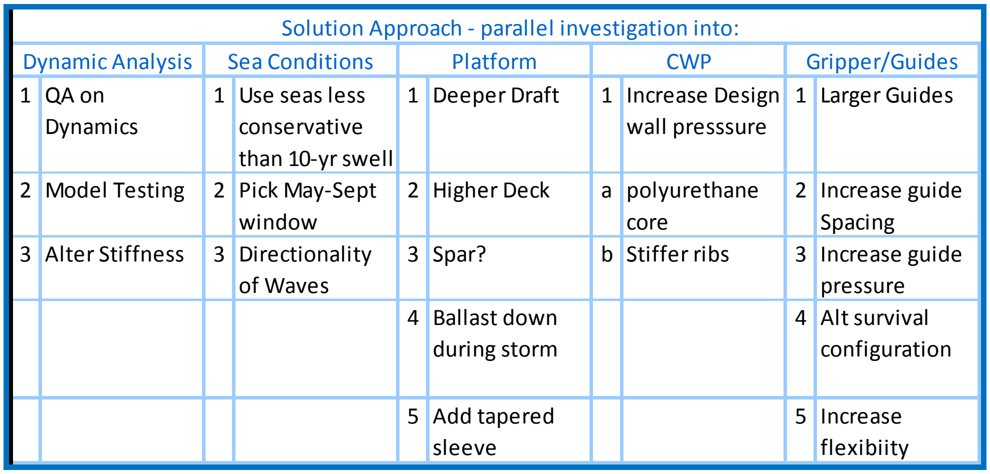


Figure 127. Iterative Design of the Gripper, Guides, Platform and CWP

The dynamic loads for both the 10m and the 4m CWP were determined to be high. Several approaches were investigated for reducing these loads as summarized in a matrix in Table 27.

- The accuracy of the Dynamic Analysis was questioned. A detailed analysis was performed on the analytical procedures applied. The results of this quality assurance program are reported in Section 5.
- The fabrication process assumes maximum conditions based on 90% swell and waves plus a 10-year swell or storm event. A reduction in wave induced forces can be achieved by narrowing the fabrication timeframe. For example, the significant seas are reduced by 50% by narrowing the fabrication window to the May-September region.
- The team considered variable platform configurations including a deeper draft, higher decks (allowing a greater distance between guides), other platforms such as spars, ballasting down during fabrication, and adding a tapered sleeve to the pontoons through which the pipe would be deployed (thus a wider guide).
- The team considered increasing the pressure capability of the CWP by changing the design of the core or by adding polyurethane in the voids of the core.
- There was considerable re-arrangement and sizing of the guides and grippers. Softening the connection was one way of minimizing maximum strains in the CWP however, this did little to reduce pressure.

Table 27. Alternatives for Lowering the CWP Pressure



Solution Approach - parallel investigation into:									
Dynamic Analysis		Sea Conditions		Platform		CWP		Gripper/Guides	
1	QA on Dynamics	1	Use seas less conservative than 10-yr swell	1	Deeper Draft	1	Increase Design wall presssure	1	Larger Guides
2	Model Testing	2	Pick May-Sept window	2	Higher Deck	a	polyurethane core	2	Increase guide Spacing
3	Alter Stiffness	3	Directionality of Waves	3	Spar?	b	Stiffer ribs	3	Increase guide pressure
				4	Ballast down during storm			4	Alt survival configuration
				5	Add tapered sleeve			5	Increase flexibiity

The design approach is illustrated in the logic tree shown in Figure 128. If, after analysis and re-arranging the guides, the pipe pressure still exceeds 50 psi, then alterations to the platform arrangement and weather window would be considered. If these are unsuccessful, then the CWP would be modified for a higher pressure. If this were unsuccessful, then a new platform or a new CWP would have to be considered.

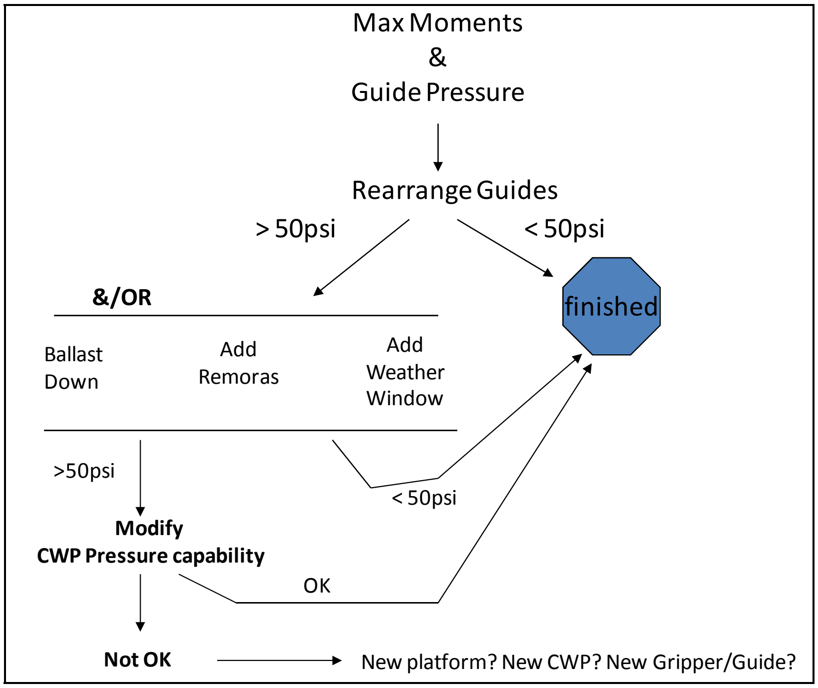


Figure 128. Logic Tree for Design of the Pipe Handling Dynamics

The following sections provide the results of the dynamic CWP/Platform analysis during fabrication.

6.5.2 Results of Dynamic Analysis during Fabrication

Figure 129 shows a schematic arrangement of the gripper and guide components for the 10 m pipe. Figure 130 shows the geometry for the pilot plant, 4 m pipe[xiv].

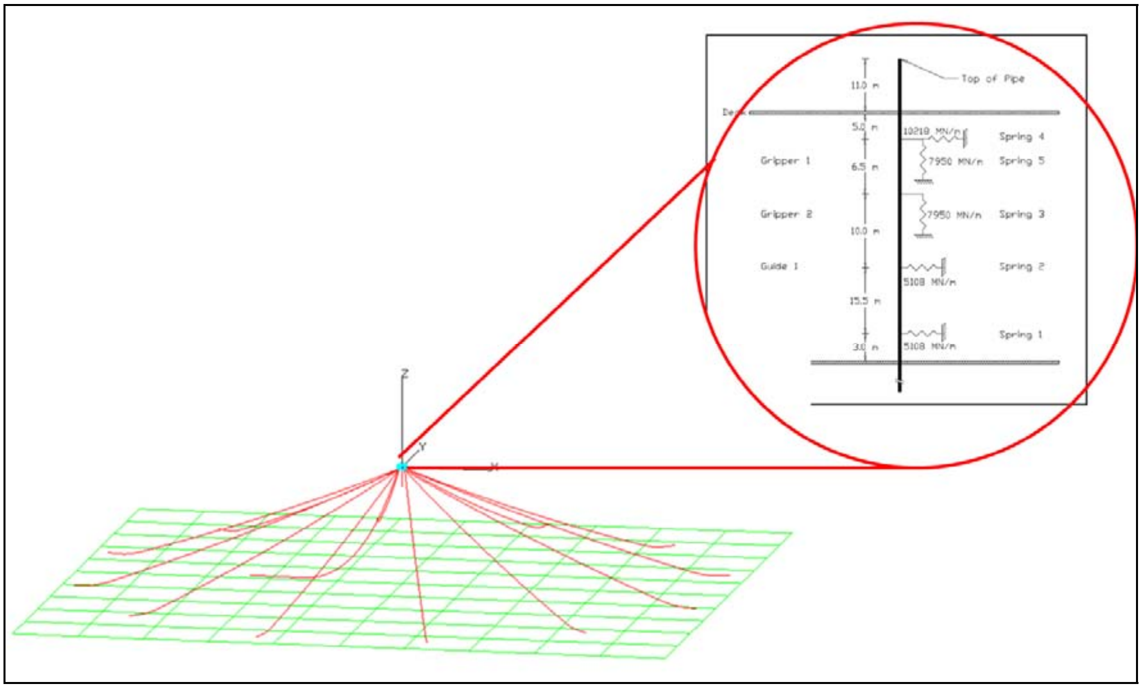


Figure 129. Gripper and Guide Schematic – 10 m Pipe

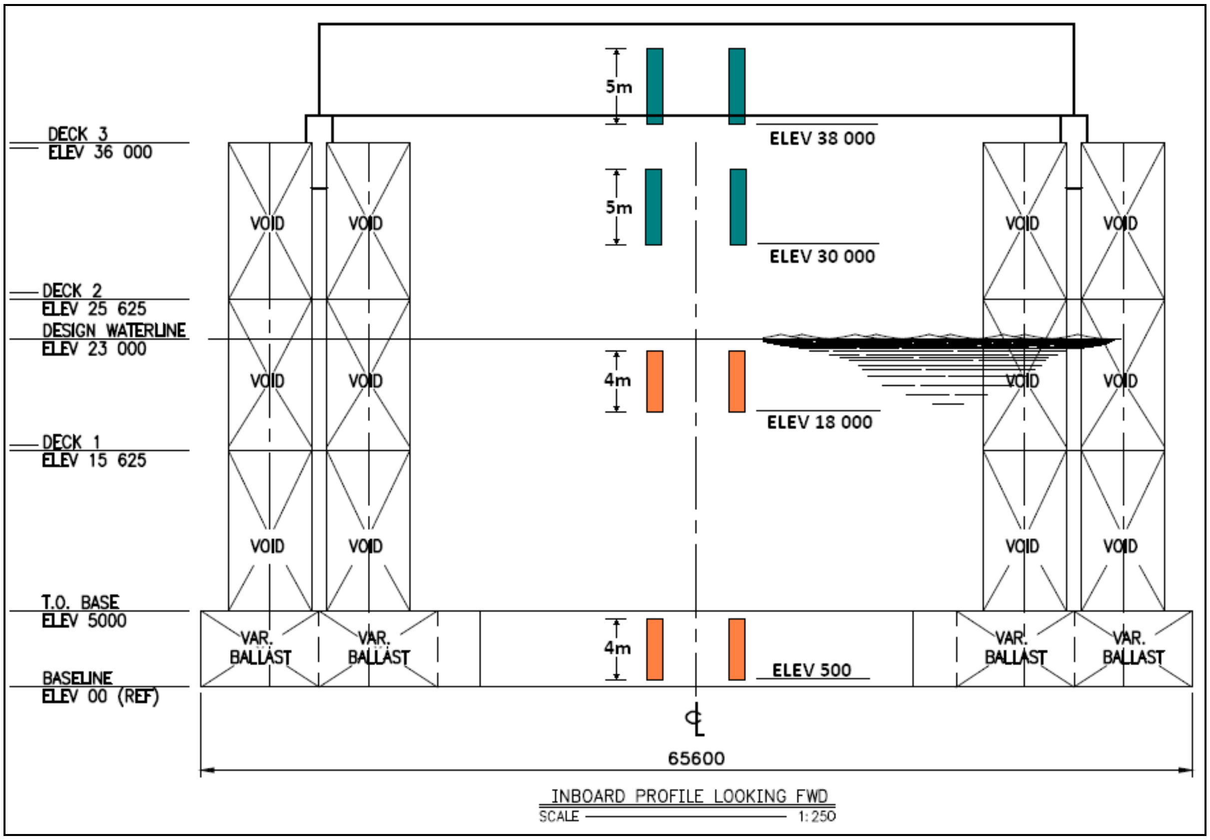


Figure 130. Gripper and Guide Dimensions – Pilot Plant (4 m Pipe) [xiv]

The loads and strains on the pipe are concentrated at the lower guide during CWP fabrication, and they cannot be mitigated by a gimbal or tapers. Also, the deflection of the pipe above the gripper must be restricted in order for the Vacuum Assisted Resin Transfer Molding (VARTM) process to succeed.

CWP fabrication is, therefore, a weather sensitive process. In order to evaluate the loads and deflections a number of cases were analyzed for the 90% and 10-yr swell conditions as shown in Table 7. The 90% condition is selected as an operational target, so that fabrication can precede a high percentage of the time. The 10-yr swell is a standby survival condition for the pipe fabrication phase. Fabrication would be halted if this event occurs, but the pipe would need to survive.

The calculations summarized in Table 28 were performed with HARP. Version 2 of the 4m cold water pipe design presented in Table 6 is modeled for the guide loads calculation. The rotational stiffness at the attachment to the platform is $2.0\text{x}10^9$ N-m/rad based on an FEA model of the pipe reactions above the guide[2].

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[2] Stiffness values provided by Makai. See Section 6.3.4 on guide design.

Table 28. Summary of Results for Pipe Guide Loads during Fabrication

		Shear (N)			Tension (N)			Moment (N-m)			Strain		
Case #	File Name	Max	Min	Stdev	Max	Min	Stdev	Max	Min	Stdev	Max	Min	Stdev
1	CWP_4mOD_500m_10yrSwell_0deg.xls	713,804	-1,193,290	332,263		879,192	60,459	50,097,900	-27,505,600	14,030,247	0.03%	-0.02%	0.01%
2	CWP_4mOD_500m_90Sea_0deg.xls	69,727	-432,674	78,723	1,773,570	879,192	11,971	13,897,000	-2,855,460	2,351,292	0.01%	0.00%	0.00%
3	CWP_4mOD_1000m_10yrSwell_0deg.xls	482,240	-964,083	248,232	3,255,980	1,461,120	114,082	37,036,400	-19,391,500	9,935,269	0.02%	-0.01%	0.01%
4	CWP_4mOD_1000m_90Sea_0deg.xls	63,095	-558,176	90,447	2,957,110	1,461,120	20,868	14,451,800	-3,667,480	2,596,098	0.01%	0.00%	0.00%
5	CWP_10mOD_500m_10yrSwell_180deg.xls	8,151,780	-6,423,350	2,117,223	10,348,900	4,447,200	477,313	581,237,000	-666,483,000	184,871,514	0.36%	-0.41%	0.11%
6	CWP_10mOD_500m_90Sea_180deg.xls	4,625,360	-3,679,490	1,344,495	9,170,760	4,447,200	92,537	177,144,000	-229,722,000	67,335,924	0.11%	-0.14%	0.04%
7	CWP_10mOD_1000m_10yrSwell_180deg.xls	6,272,440	-4,575,060	1,620,581	20,684,800	8,887,110	906,175	540,804,000	-598,799,000	187,798,916	0.34%	-0.37%	0.12%
8	CWP_10mOD_1000m_90Sea_180deg.xls	3,071,900	-1,760,940	744,287	18,512,000	8,887,110	193,705	76,959,800	-105,765,000	25,742,177	0.05%	-0.07%	0.02%

6.5.3 Logic Tree for Gripper and Guide Handling

Figure 131 shows the final logic tree for the 10m analysis. After re-arranging the guides and grippers, and selecting the proper interface stiffness between the CWP and the platform, the maximum pressures on the CWP can be kept very near 50 psi. Considering that the 100MW platform is only conceptual, it was not possible to carry this analysis further. We believe that a gripper and guide system can be built that will keep the maximum pipe pressures at 50 psi. We have not yet considered ballasting down, adding the remoras during fabrication, or narrowing the operations to a narrower weather window. If, after final analysis, the pressure exceeds the CWP capacity, these other options are available with improvements in the order of 20% to 30% each.

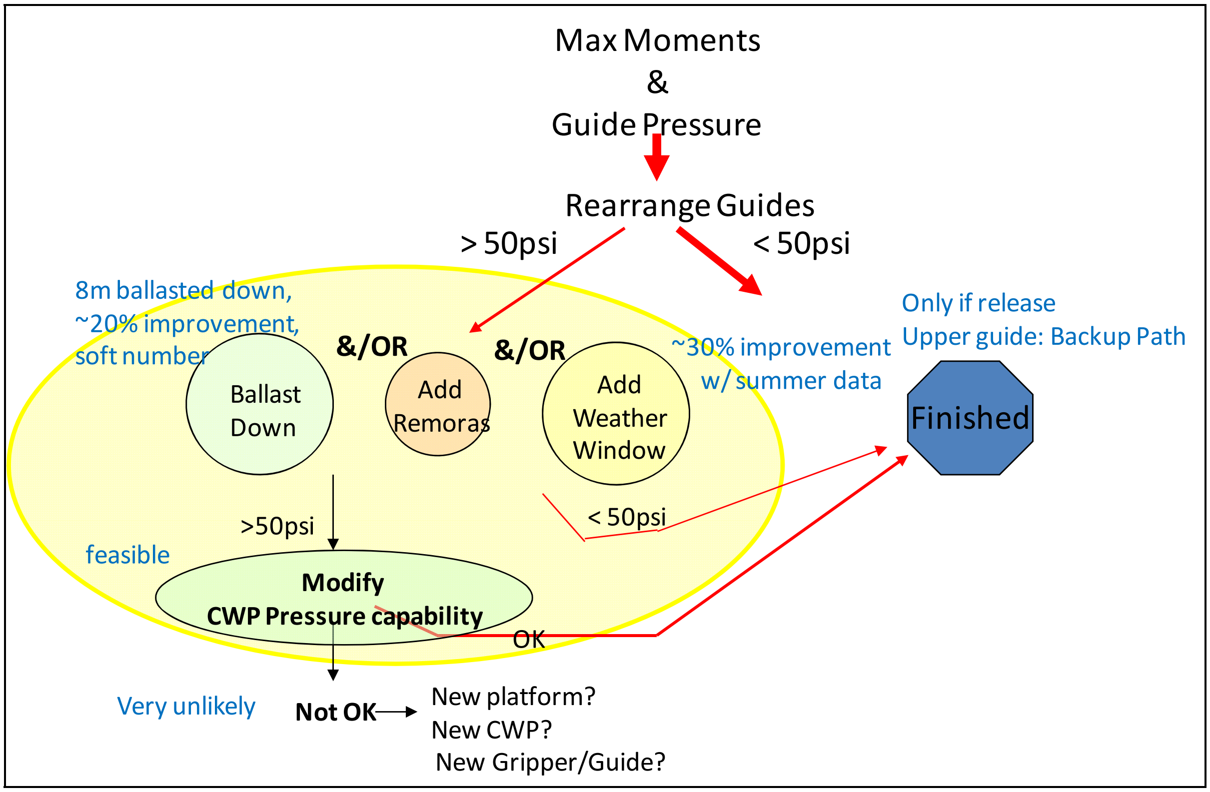


Figure 131. Final Logic Tree for the 10m CWP Fabrication Handling

Two Gripper and Guide adaptations were needed to lower the CWP external pressures for the 10m CWP as shown in Figure 132. First, the lower guide was lowered and increased in size. This involved having the lower guide well below the bottom pontoon. That lowering has to occur once the platform has moved to its permanent location. Secondly, during storms, the upper guide needs to be disengaged. The high moments in the pipe are then taken by the lower guide and the upper gripper. With the larger moment arm, the loads and pressure on the CWP is reduced.

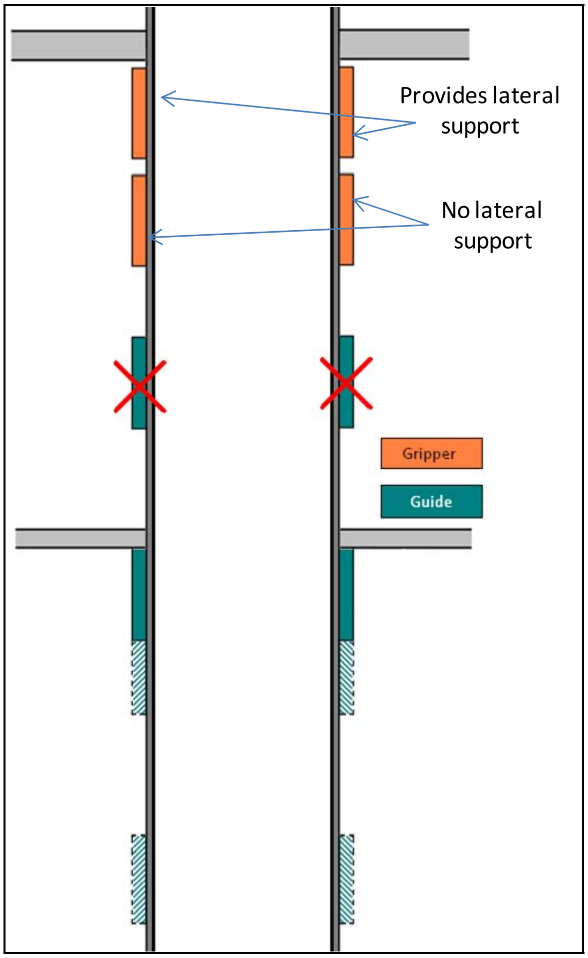


Figure 132. Methods for Minimizing Pressure for the 10m CWP

Figure 133 shows the final logic tree for the 4m CWP. In this case, the loads could be easily reduced by re-arranging the grippers and guides. The 4m CWP is easier to handle because the pipe is smaller and the loads are reduced and the vertical distance available on the platform is the same.

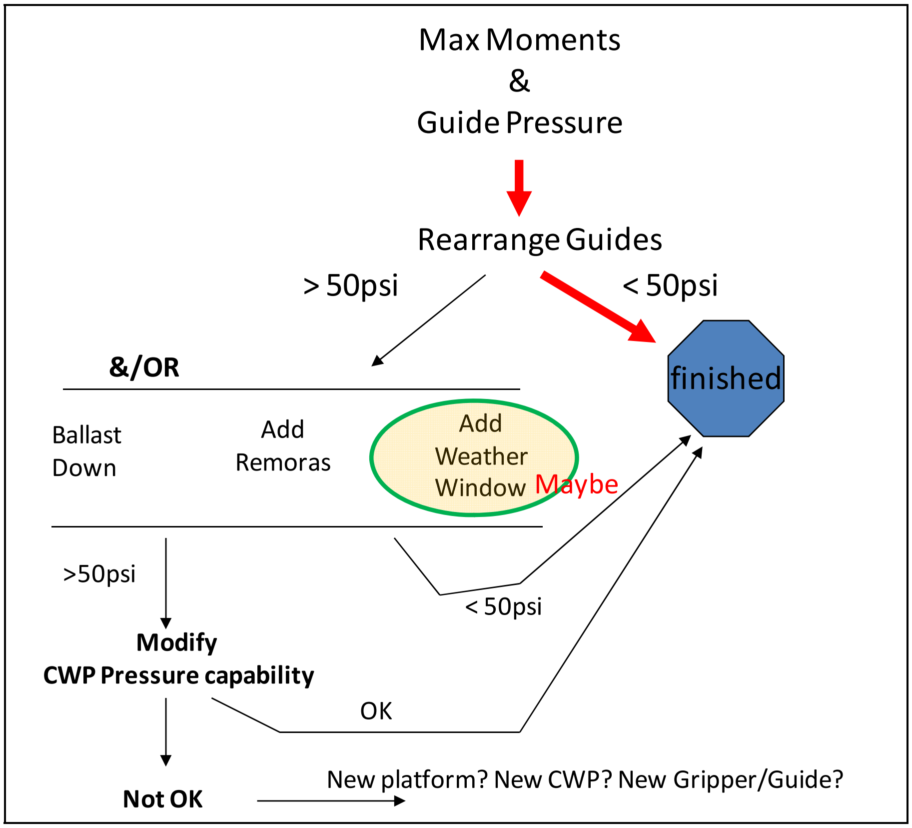


Figure 133. Final Logic Tree for the 4m CWP Fabrication Handling

Figure 134 shows the maximum pressures and the relative geometry of the grippers and guides for the 10m and 4m CWPs. Table 29 shows the maximum shear, tension and bending moments in the 10m and 4m CWPs during the 10-year swell event which is the worst case loading condition.

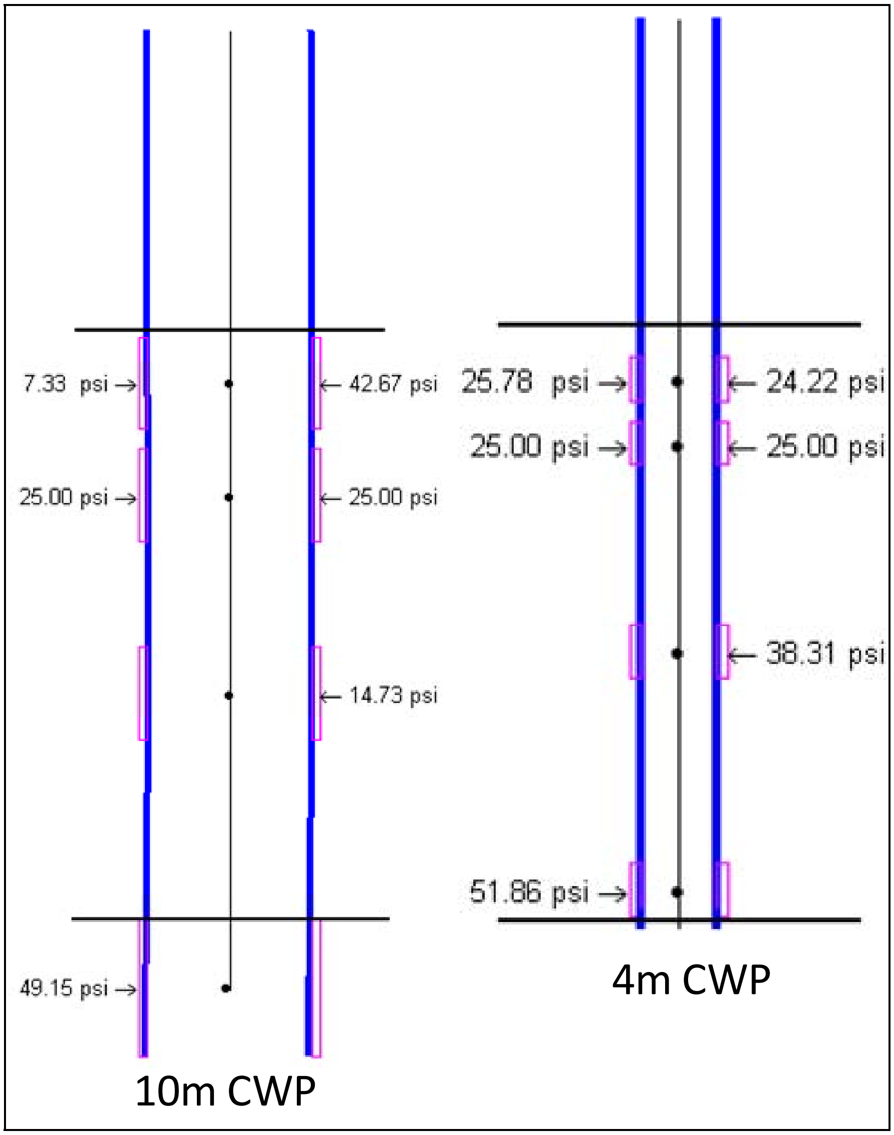


Figure 134. Final Arrangement of the Grippers and Guides to Minimize CWP Pressure

Table 29. Max Loads from Dynamic Analysis 10yr Swell Condition

	10m CWP	4m CWP
Shear	8.2 MN	1.2 MN
Tension	20.7 MN	3.3 MN
Bending	666.5 MN-m	50.1 MN-m

6.6 CWP Squeeze Pressure

CWP squeeze and maximum CWP pressure was a major design driver in this program. Buckling of the CWP was a major concern. A Finite Element Analysis (FEA) of the CWP was used to determine the overall distortion of the CWP under pressure (Figure 135) and to determine the point at which the CWP ribs buckle (Figure 136). The core structure is shown in Figure 137. When applying an external load to the CWP, half of the compression resistance is provided by the outer face sheet and about half by the inner face sheet. Therefore, half the total radial inward pressure is transferred to the inner face sheet through the core ribs. If this pressure is too great, these ribs will buckle. By increasing the number, the thickness and the angle of these ribs, their buckling strength can be changed.

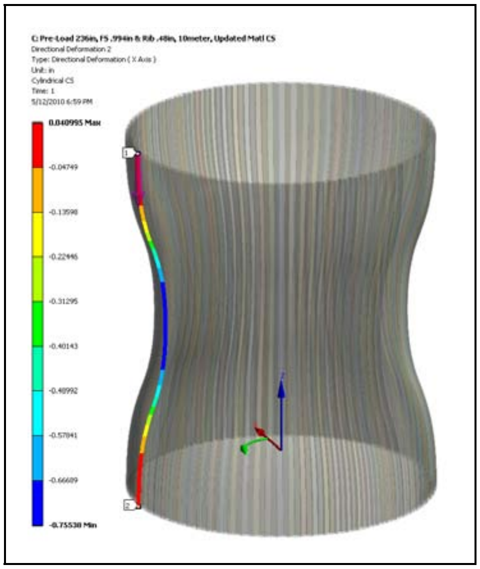


Figure 135. CWP Deformation under External Pressure

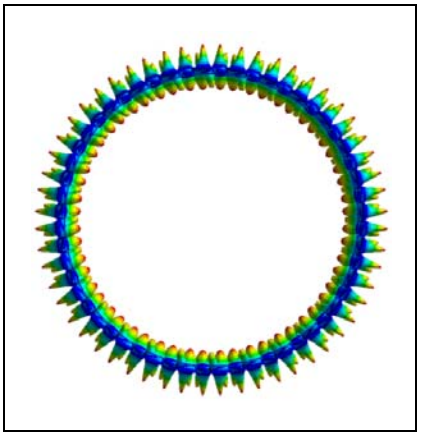


Figure 136. FEA of the Local Buckling of the CWP at the Core Ribs

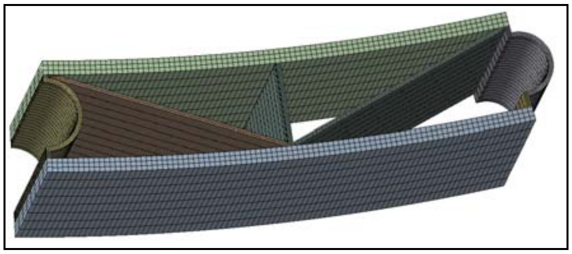


Figure 137. CWP Core Ribs

An early FEA of the CWP concluded that the original design would fail at about 28 psi and have a working pressure of 14 psi. The successful application of the gripper required a much higher working pressure (about 50 psi) so the design was altered to increase the number and size of the ribs. This resulted in a CWP version 2 design.

A review of the FEA showed that ANSYS was providing incorrect numbers and that the program was incorrectly using the CWP properties. This turned out to be an ANSYS program fault. Working out the problems with ANSYS resulted in a much stronger CWP. These results were close to the original predictions. After several iterations, a CWP version 5 design is the current version with a predicted collapse pressure of 140 psi (working 70 psi). A large safety factor was used prior to having testing results on the actual collapse pressure. The gripper and guide design throughout this report focuses on 50 psi although CWP version 5 could be safely handled at 70 psi.

As a result of these iterations it was realized that the pressure capacity of the CWP could be altered at fairly low cost to the CWP. There would be no difference in CWP manufacturing complexity, just slightly more weight in the core section.

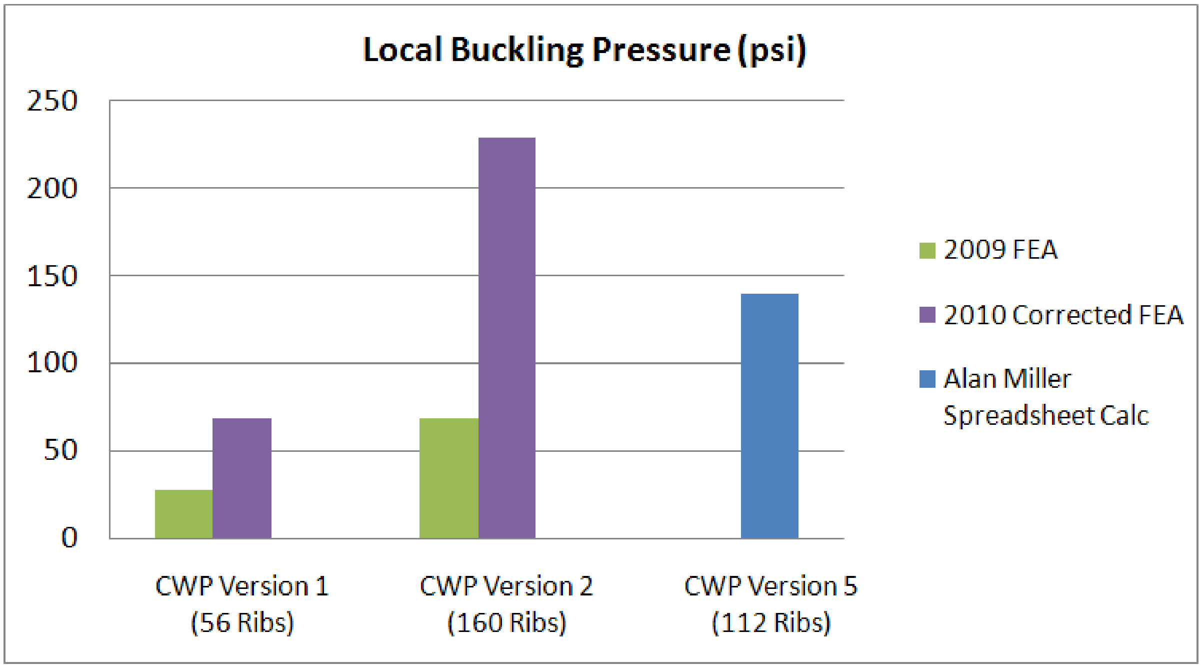


Figure 138. Local Buckling Pressure of the Core Ribs

6.7 General Arrangement – 10 meter

This section summarizes the methodology used to size, arrange and select the functions for the grippers and guides in order to meet the pressure and movement criteria for the CWP handling system. The typical arrangement is shown in Figure 139. The team needed to resolve the optimal arrangement of the grippers and guides in order to properly and reliably hold the CWP and to minimize pipe movement above the deck and without applying excessive pressure to the CWP wall. They also had to resolve the optimal size and characteristics of each gripper and guide pad. This turned out to be a fairly complex optimization process because of the very high number of variables that were involved.

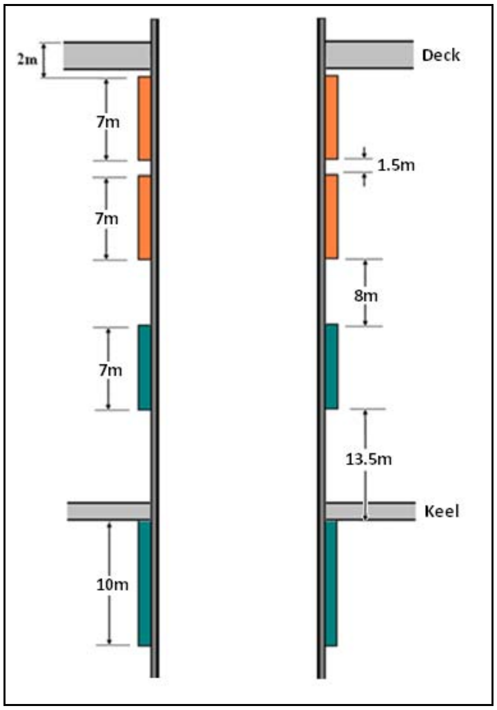


Figure 139. Typical Arrangement of Grippers and Guides

6.7.1 Pad Pivot, Tilt and Stiffness Functions

The pads within the grippers and guides have the following functions:

- **Pivoting**: Pivoting is when an individual gripper or guide pad rotates vertically with the wall of the CWP. In Figure 140, the pad on the left does not rotate with the CWP and the result would be an uneven pressure distribution from top to bottom of the pad. The pad on the right rotates with a tilting pipe and the result is a more uniform pressure distribution on the wall of the pipe. Pivoting could be achieved by a hinged pad or, alternatively, the gel or water filled bags previously described could provide the pivoting function.

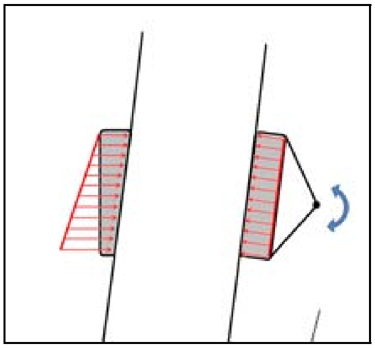


Figure 140. Pivoting

- **Tilting**: Tilting of pads occurs when the entire guide or gripper structure rotates with a rotating CWP as shown in Figure 141. If the entire gripper were gimbaled, the structure would rotate with the CWP. The pads in a tilting gripper or guide have an affective even pressure distribution over the surface of the pipe and thus they are affectively pivoting. A tilting structure, however, has the additional advantage in that as a pipe rotates the wall on one side of the pipe moves down slightly and the wall on the opposite side of the pipe moves upward. With a tilting structure, there is no relative vertical movement between the pad and the CWP. On pads that simply pivot but do not tilt, there is slight vertical movement between the wall of the CWP and the surface of the pads as the pipe rotates.

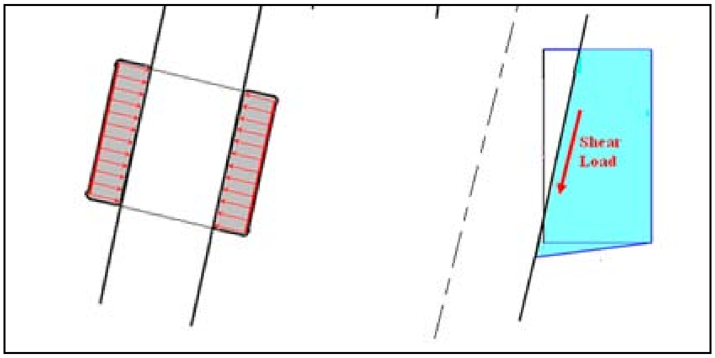


Figure 141. Tilting

- **Floating**: A floating gripper structure is one that does not provide any lateral support as shown in Figure 142. Therefore when a floating gripper attaches itself to the CWP, the pressure is uniform around the full circumference of the CWP. If a gripper does not float, and there is a lateral load on the CWP, then the pressure distribution around the CWP is not uniform. Only grippers could potentially float. Since guides are there to support lateral loads, the floating guide would not be functional.

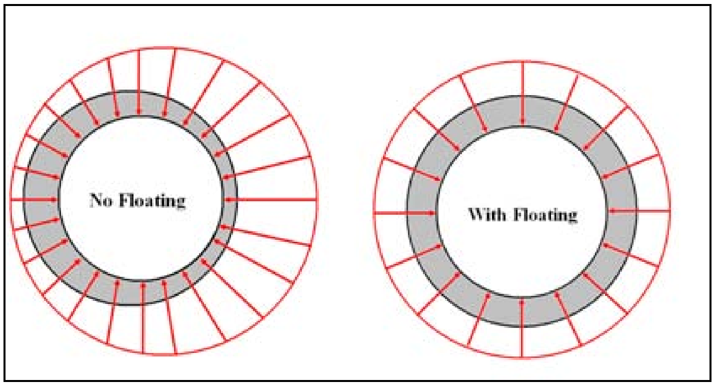


Figure 142. Floating

6.7.2 Methodology

In order to evaluate the performance of these grippers and guides, a finite element model was developed in MATLAB which modeled a flexible CWP supported at numerous points by grippers and guides. The physical arrangement of the MATLAB model is shown in Figure 143. Each guide and gripper has a vertical and horizontal stiffness. The horizontal stiffness is broken into two parts: the stiffness associated with the gripper pads themselves and the stiffness associated with the platform. Each gripper and guide also has a rotational stiffness.

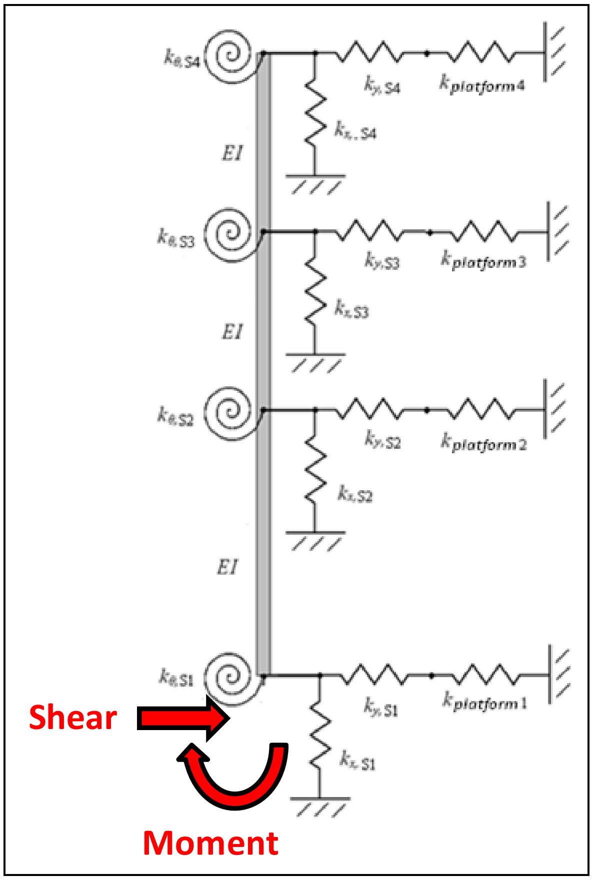


Figure 143. MATLAB Model of the Gripper and Guide Arrangement

The input to the MATLAB model consisted of the gripper and guide pad properties, the locations of the pads and the sizes of the pads. In addition there are the platform stiffness and the input loads at the base of the platform which are the maximum shear and moment loads in the CWP. Early in the program these maximum loads were estimated independently by wave and current calculations. Later in the program, these values were derived directly from the dynamic analysis of the coupled CWP and platform discussed above. The maximum shear and moment loads that were used in this model were for two different conditions: maximum operating conditions which were for the 90 percent swell and the maximum survival conditions which were for the ten year swell. One of the goals of this analysis was to determine how the CWP should be held during pipe manufacturing and whether the CWP should be held differently during storm conditions.

In addition, the MATLAB program could assign the pivoting, tilting and floating functions to any of the grippers and guides.

Figure 144 shows a typical output configuration from the MATLAB simulation. On the far left are the loading conditions at each of two grippers and two guides. The diagram in the middle shows the maximum pressures and the diagram at the right shows the shape of the CWP. Note that the horizontal scale is 100 times the vertical scale and therefore the distortion is greatly exaggerated..

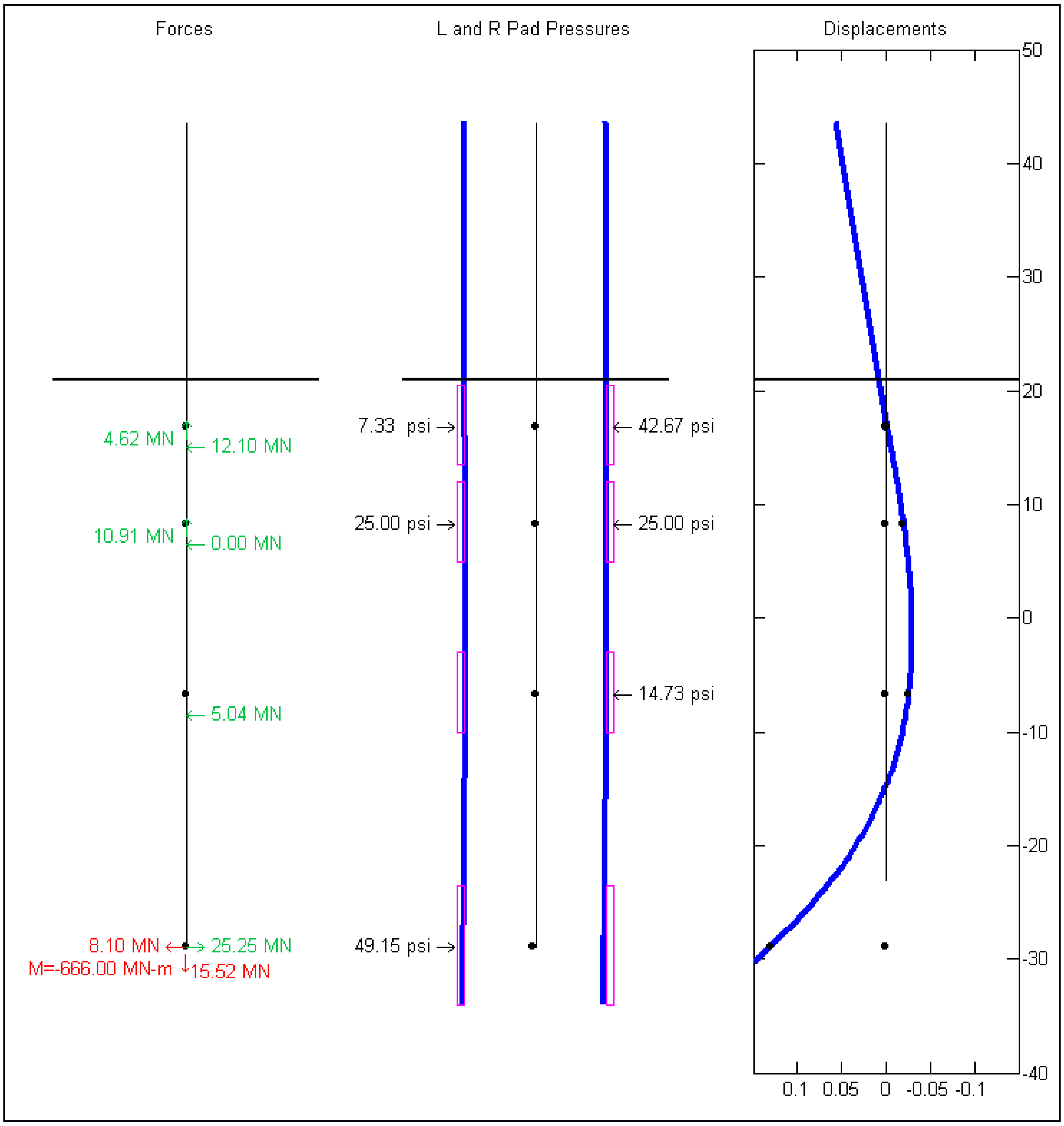


Figure 144. Typical Output from the MATLAB Simulation

6.7.3 Component Characteristics

The following is a list of the primary dimensional characteristics that were input to the MATLAB analysis. These dimensional variables are also shown in Figure 145.

a. Distance from top guide to deck
b. Length of gripper 1 pad
c. Length of gripper 2 pad
d. Preload gripper pad pressure
e. Distance between gripper pads
f. Distance gripper 2 is lowered
g. Shear modulus of gripper pads
h. Young’s modulus of gripper pads
i. Thickness of gripper pads
j. Length of bottom guide
k. Young’s modulus of bottom guide
l. Thickness of bottom guide
m. Size of gap at bottom guide
n. Length of top guide
o. Thickness of top guide
p. Size of gap at top guide
q. Young’s modulus of top guide
r. Platform Height
s. Applied shear and moment loads

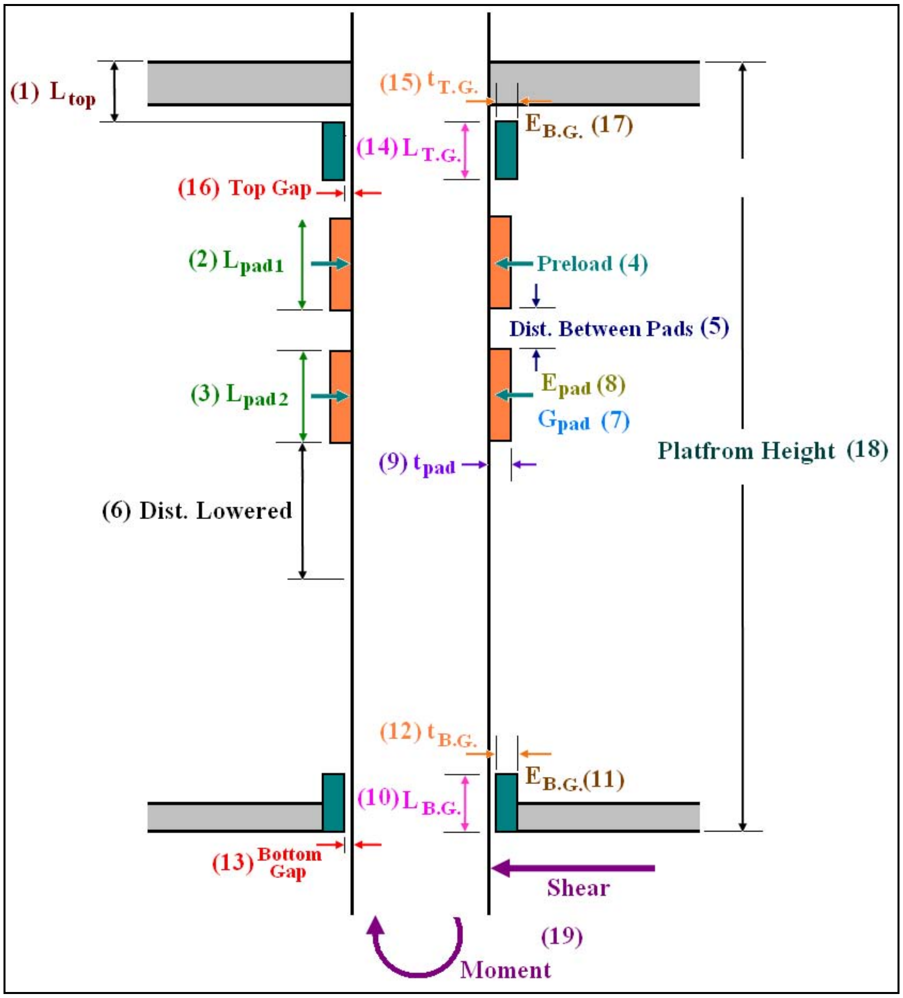


Figure 145. 19 Variables in the MATLAB Analysis

In addition to the above variables, the MATLAB program could analyze a wide variety of gripper and guide configurations. For instance, the arrangement shown in Figure 145 shows a guide-gripper-gripper-guide arrangement. We also considered gripper-gripper-guide-guide, guide-gripper-guide-gripper-guide and many other configurations. In addition, the functions such as tilt, pivot and float could be assigned to any of the grippers and guides. Analysis was performed for maximum operating conditions and also for maximum survival conditions.

Because of the large number of variables and almost infinite configurations, the optimization process was highly iterative. Makai defined a number of success criteria such as maximum pad pressure, pipe movement above the deck and pipe slipping within the gripper pads. A safety factor was assigned to each of these desirable characteristics and then a wide number of configurations were evaluated. With each round of evaluations a sensitivity analysis was performed based on primary pad characteristics and geometry. The result was a large number of graphs that are typical of those shown in Figure 146 and Figure 147. Figure 146 shows the safety factor on a number of desirable gripper and guide characteristics as a function of the stiffness of the gripper pad. Figure 147 shows the change in safety factor as a function of the pivoting, tilting and floating characteristics of various components. Note that many of the safety factors are below one, meaning that this is an undesirable configuration.

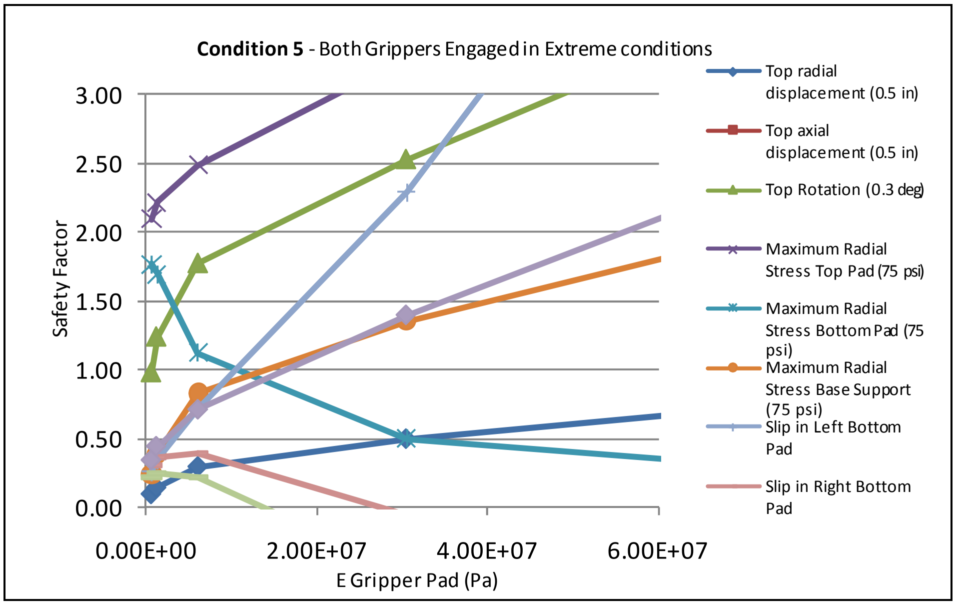


Figure 146. Typical Sensitivity Analysis as a Function of Elasticity

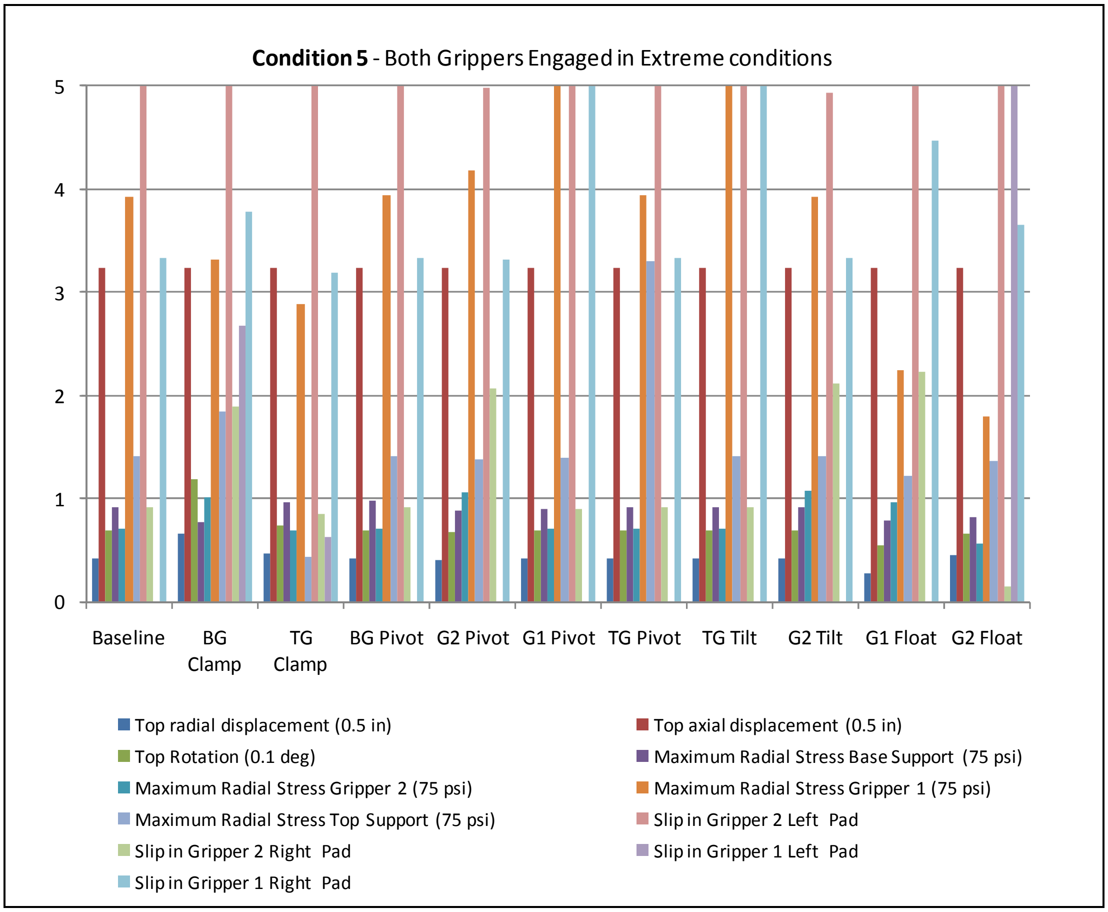


Figure 147. Typical Analysis Output for Gripper and Guide Functions

Through this analysis we came to the following conclusions:

a. The performance of most gripper and guide configurations are well below performance goals.

b. The parameters with the greatest influence on performance are:

    (1) Size of the gap at guides: Guides with any gap tolerance greatly affects the movement criteria above the deck. It was concluded that this variable had to be set to zero. In other words, the guides must fit snugly to the CWP.

    (2) Preload: Increasing the preload improves the gripping of the CWP but also increases the pressure on the CWP.

    (3) Horizontal elasticity of the grippers: The stiffer the gripper pads, the smaller the displacement of the pipe above the platform. However, very stiff pads can result in slipping of the CWP on grippers that do not pivot or tilt.

    (4) Shear modulus of the grippers: The rubber friction pad must be compliant enough to move with the CWP but not too compliant that vertical displacements become large.

c. The pivoting or tilting of the guide and gripper pads is necessary to reduce the pressure on the CWP.

d. Floating of the second gripper improves its holding ability.

e. Clamping onto the CWP with top and bottom guides will reduce motions above the platform but increase pressure on the CWP.

The optimization process also incorporated practical considerations. For instance, it would be advantageous to hold the CWP immediately below the main deck but a 2m gap was reserved between the bottom of the CWP fabrication and the uppermost part of the highest gripper or guide. This gap allowed the inspection of the CWP as it immerges from the fabrication process and allowed room for repairs or modifications to the CWP. In addition, it was not advisable to have grippers operating below water where they could not be observed, inspected and repaired. Guides, however, below the water could make use of the water lubrication. Guides below the keel would be operationally more difficult and were avoided, where possible.

6.8 10 meter Configuration Results

Figure 148 shows the optimized arrangement for the grippers and guides for the 10m CWP. The upper and lower grippers are each 7m tall with the upper gripper located 2m below the main deck. The upper guide is 7m tall and is located just below the water line. The lower guide is a full 10m tall because of the high lateral loads on the CWP and this guide must be located below the keel of the platform. This will require that the lower guide be retractable to move the platform into a harbor and then dropped below the keel once the platform is on site.

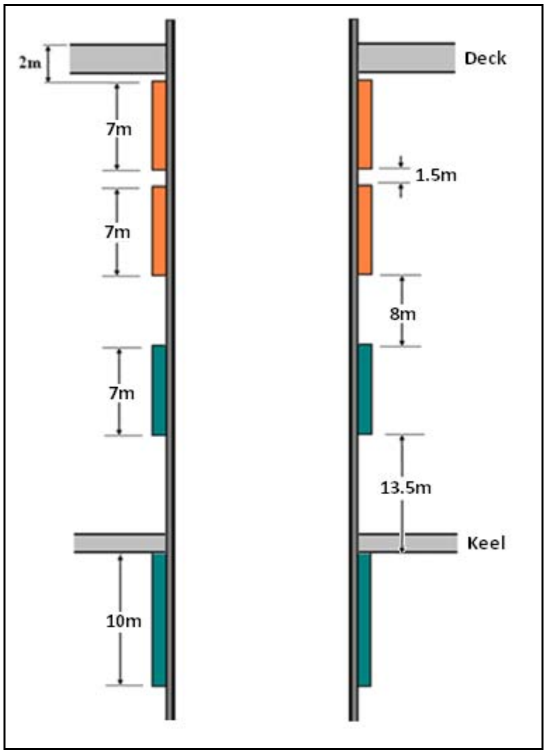


Figure 148. Arrangement of the 10m Gripper

All the pads in both grippers and guides are either water or gel filled and thus they effectively pivot. The bottom gripper both floats and tilts.

In a case of very severe loads from the 10-year storm, the upper guide is disengaged by deflating the water bags and the large moments on the CWP are carried by the upper gripper and the lower guide; pressures are reduced because of the larger moment arm. Once the storm passes, the upper guide is reengaged and the motions in the CWP above the deck again become manageable.

Table 30 shows the primary characteristics of the 10m gripper and guide arrangement.

Table 30. 10m Gripper/Guide characteristics

Resolved Characteristics of the 10m Gripper/Guide

1	Distance from top guide to deck	2 m
2	Length of gripper 1 pad	7 m
3	Length of gripper 2 pad	7 m
4	Preload gripper pad pressure	50 psi
5	Distance between gripper pads	1.5 m
6	Distance gripper 2 is lowered	5.5 m
7	Shear modulus of gripper pads	2 Mpa
8	Young’s modulus of gripper pads	6 Mpa
9	Thickness of gripper pads	.05 m
10	Length of bottom guide	10 m
11	Young’s modulus of bottom guide	6 Mpa
12	Thickness of bottom guide	.05 m
13	Size of gap at bottom guide	0 m
14	Length of top guide	7 m
15	Thickness of top guide	.05 m
16	Size of gap at top guide	0 m
17	Young’s modulus of top guide	6 MPa
18	Platform Height	44 m
19	Applied Shear Load	8.1 MN
20	Applied Moment Load	666 MN-m
21	Platform Stiffnesses	2E8 N/m

The motions of the 10m CWP under the most extreme 10m swell conditions are shown in Figure 149 and in Table 31. Depending upon the eventual height of the CWP fabrication apparatus, the motions of the CWP at 44m above the deck are 2.25 inches. During maximum operational conditions this movement is considerably less.

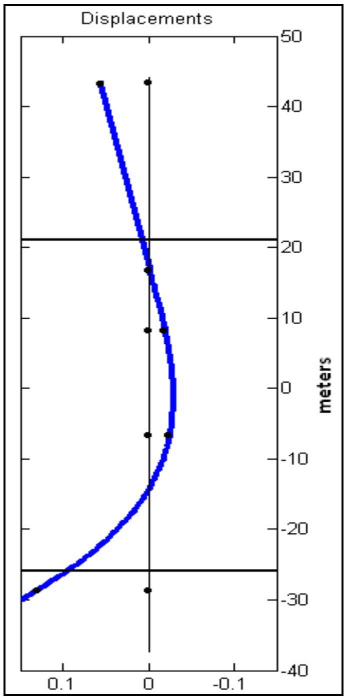


Figure 149. Maximum Movements of the 10m CWP

Table 31. Maximum Movement and CWP Angle for the 10m CWP

	Lateral Movement (m)	CWP Angle (deg)
Top of Apparatus	0.0571	0.14
Upper Gripper	-0.001	0.14
Lower Gripper	-0.020	0.10
Top Guide	-0.025	-0.09
Bottom Guide	0.129	-0.80

The 10m gripper and guide design was not further optimized because the fabrication apparatus has not been designed and the platform configuration is only conceptual. The conclusions from the 10m design and optimization process is that a 10m gripper and guide can most likely be built and the performance as presently configured is most likely acceptable. Further optimization of the pipe handling equipment can occur once the 10m CWP design and the 100 megawatt platform design are more mature.

6.9 General Arrangement and Component Functions – 4m

The optimization process described in the sections above was also used to size and configure the 4m gripper and guide arrangement. The final arrangement is shown in Figure 150. The two grippers are each 3.25m tall and the two guides are each 4m tall. The upper guide is just below the water surface and the lower guide is within the lower pontoon. Unlike the 10m design, the 4m design does not need to protrude below the keel.

There is a gap between the upper deck and the upper gripper that is 2m wide. This allows inspection and repair of the CWP as needed. All the grippers and guides in this arrangement have water or gel filled pads and therefore they effectively pivot.

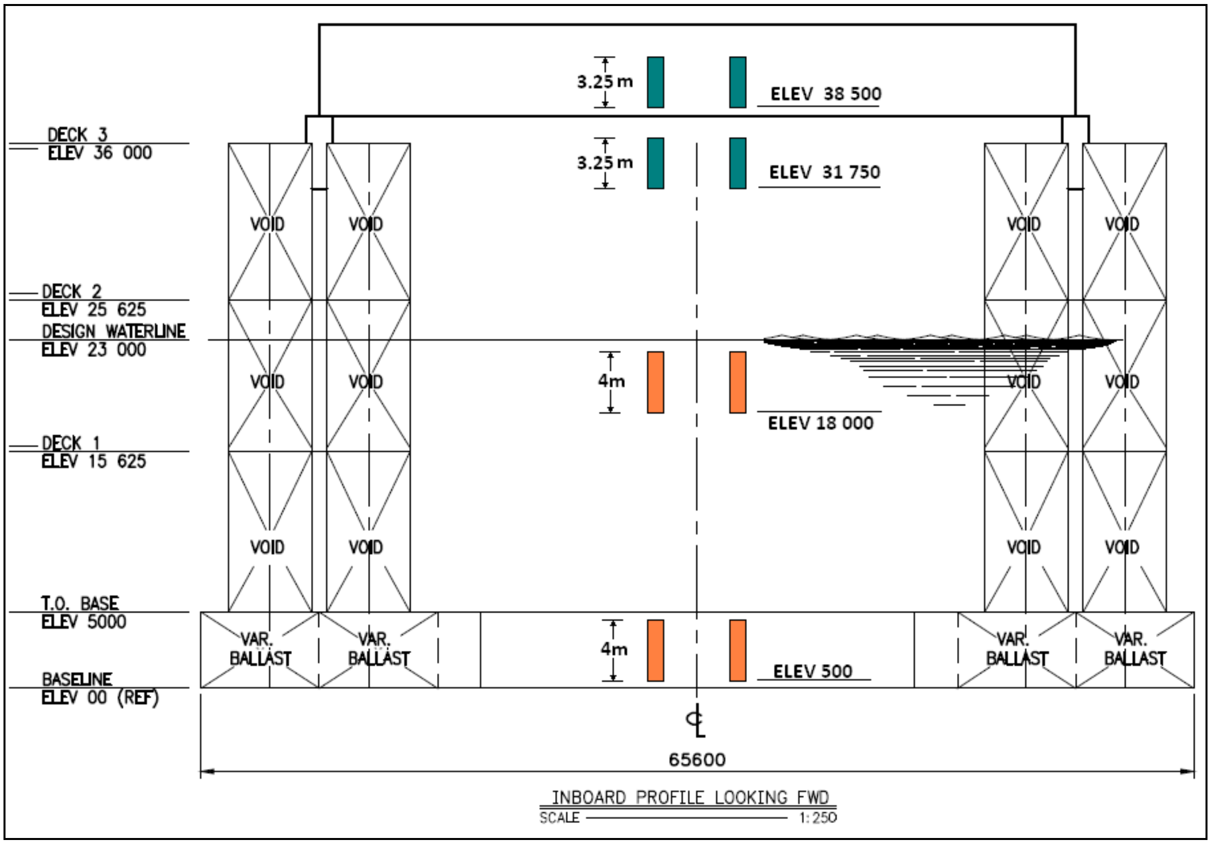


Figure 150. 4m Gripper/Guide Arrangement

The dimensions and characteristics of the 4m grippers and guides are shown in Table 32.

Table 32. 4m Gripper and Guide Characteristics

Resolved Characteristics of the 4m Gripper/Guide

1	Distance from top guide to deck	2 m
2	Length of gripper 1 pad	3.25 m
3	Length of gripper 2 pad	3.25 m
4	Preload gripper pad pressure	50 psi
5	Distance between gripper pads	1.5 m
6	Distance gripper 2 is lowered	5.5 m
7	Shear modulus of gripper pads	2 Mpa
8	Young’s modulus of gripper pads	6 Mpa
9	Thickness of gripper pads	.05 m
10	Length of bottom guide	4 m
11	Young’s modulus of bottom guide	6 Mpa
12	Thickness of bottom guide	.05 m
13	Size of gap at bottom guide	0 m
14	Length of top guide	4 m
15	Thickness of top guide	.05 m
16	Size of gap at top guide	0 m
17	Young’s modulus of top guide	6 MPa
18	Platform Height	44 m
19	Applied Shear Load	1.2MN
20	Applied Moment Load	50 MN-m
21	Platform Stiffnesses	1E8 N/m

6.9.1 Platform Stiffness

As with the 10m design, the stiffness of the individual pads and the platform are critical to meeting the pipe movement criteria above the deck. Figure 151 shows the MATLAB model of the CWP movement and the equivalent stiffness of the gripper, guide pads and platform. Note that there are only three lateral support contact points with the CWP. The lower gripper floats and therefore is unable to provide lateral support.

Figure 152 shows the required stiffness for the platform. These data have been provided to the platform group as a platform design criteria. These values were determined by evaluating pipe movement with a variety of platform stiffness values. Results of these analyses are shown in Figure 153 for conditions when the top gripper is engaged or the top gripper is disengaged. The top gripper is disengaged and the CWP is held laterally only by the two guides at the point when the lower gripper is lowering the CWP. The design stiffness is shown as a vertical green line in Figure 153. In this analysis it was assumed that the platform at the lower guide is twice as stiff at the upper guide and that the stiffness at the main deck is infinite. Since the main deck is the reference position, everything moves relative to that location and all the other stiffness values are relative to this position.

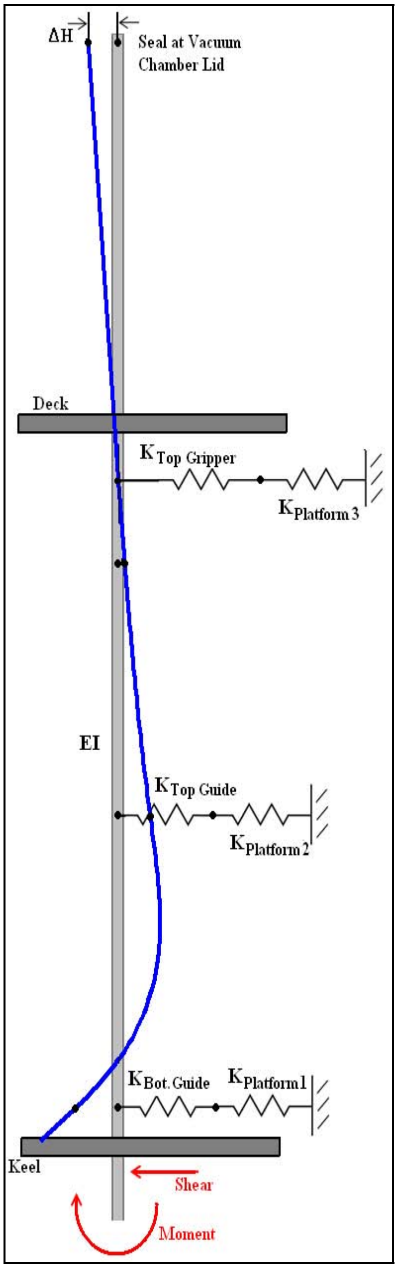


Figure 151. Movement Analysis Including Platform Stiffness

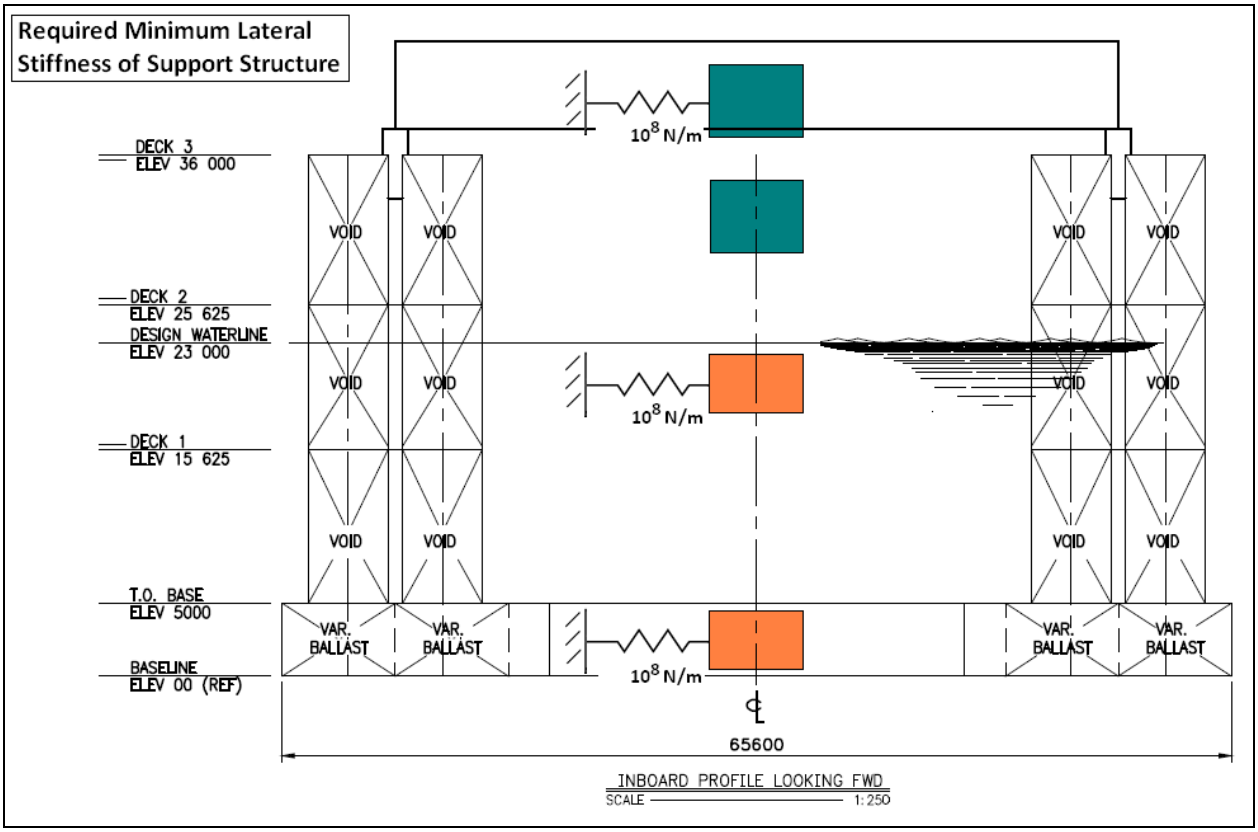


Figure 152. Required Platform Stiffness, 4m Gripper/Guide

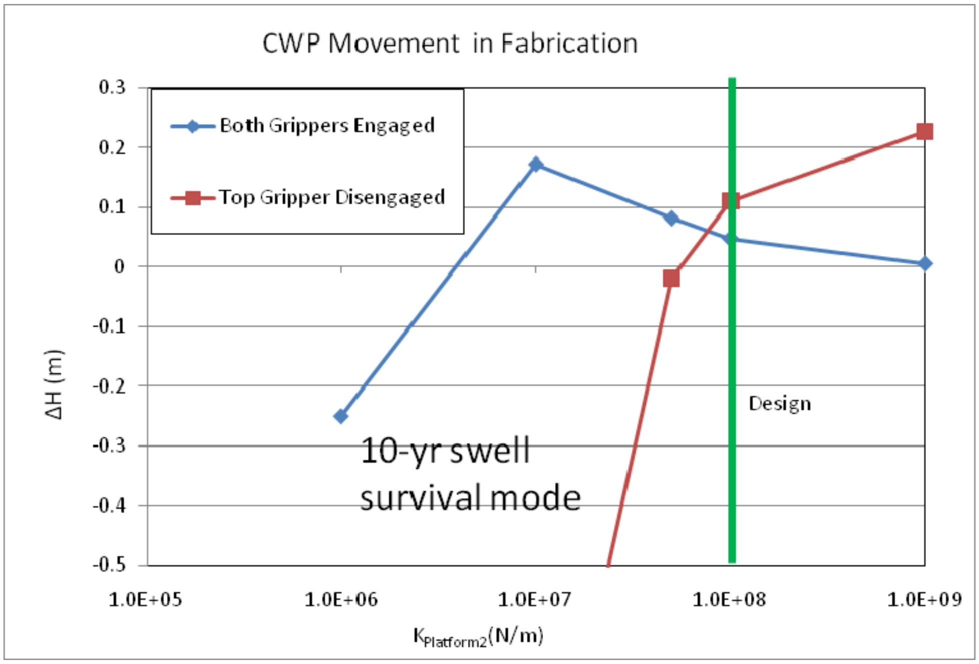


Figure 153. CWP Movement vs. Platform Stiffness

6.9.2 Pipe Movement

Table 33 and Figure 154 illustrate the maximum movement of the 4m CWP in the gripper-guide arrangement. The maximum movement at the top of the fabrication apparatus is 2.25 inches or 3.2 cm referenced to the upper gripper. There is similar movement at the two guides; the relative movement at the upper gripper is zero because this is the reference point. This conceptually meets the needs of the CWP fabrication process constraints although at this time, the ability to dynamically seal on the moving pipe has not been demonstrated.

Figure 154 shows the maximum distortion of the pipe within the grippers and guides. Note that the horizontal scale is 100 times the vertical scale and therefore the distortion is greatly exaggerated.

Table 33. CWP Movement and Angle in 4m Gripper/Guide

	Lateral Movement (m)	CWP Angle (deg)
Top of Apparatus	0.0322	0.07
Upper Gripper	0	0.07
Lower Gripper	-0.0062	0.08
Top Guide	-0.033	0.13
Bottom Guide	0.0446	-1.08

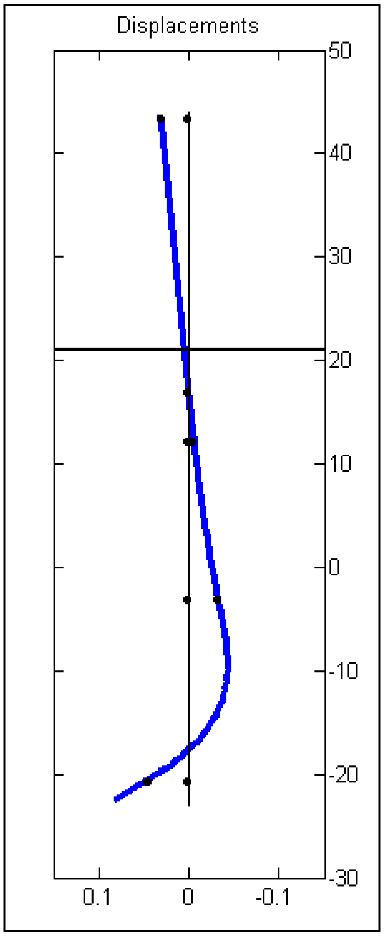


Figure 154. 4m CWP Movement

6.9.3 Dynamic Analysis

The above sections discuss the maximum movement within the gripper and guide arrangement due to the maximum shear and moment loads that have been provided from the CWP and platform dynamic analysis. All of the above have been the result of a static analysis. Makai also performed a dynamic analysis of the 4m CWP within the grippers and guides. A time series of moments and shear values from the platform dynamic analysis was used as the time-varying driving forces within an ABAQUS dynamic model. The comparisons between the static and dynamic models are shown in Figure 155 and Figure 156. The two models agreed very well. The analysis illustrates that the inertial mass of the CWP within the gripper and guide geometry does not play a major role as the accelerations are small and the stiffness of the CWP dominates.

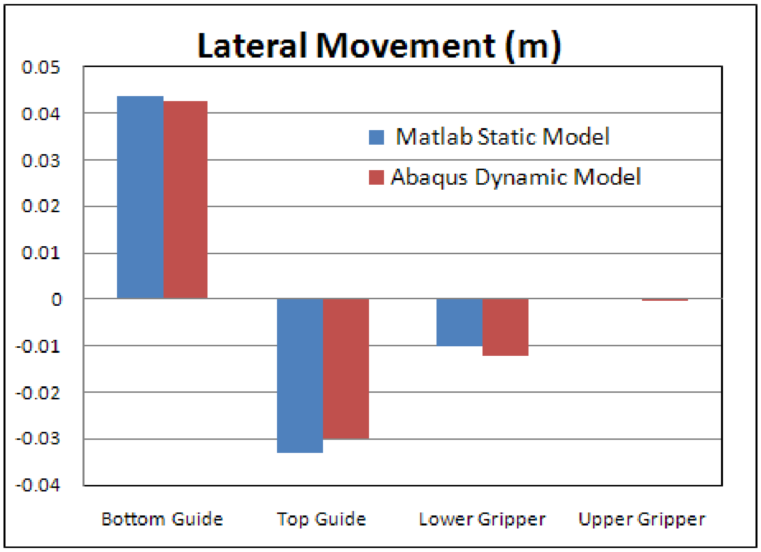


Figure 155. Check between Dynamic and Static Models

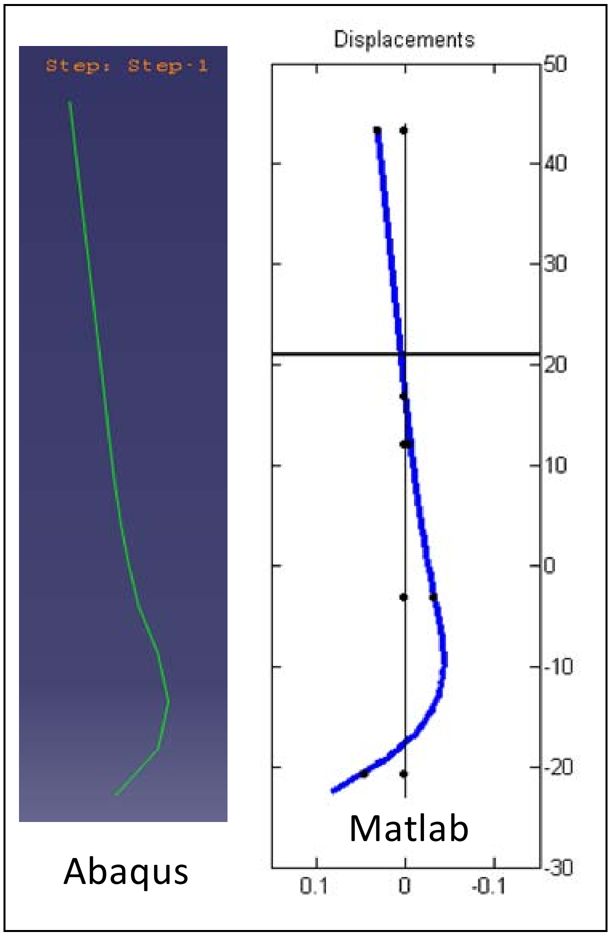


Figure 156. CWP Shape Comparison for the Dynamic and Static Models

6.10 10 meter Gripper and Guide Preliminary Design Summary

A conceptual design was developed for the 10m gripper and guide. This design was used to investigate the challenges and opportunities associated with handling the 10m CWP and to assure that the 4m pilot plant gripper and guide addressed the major issues associated with the commercial pipe handling. This design was only carried through the preliminary design phase and much of the analyses performed is provided in previous sections of this report.

A 10m gripper and guide was developed within SolidWorks in order to investigate the geometry and interfacing with the CWP. This section presents multiple views from that SolidWorks design.

Figure 157 shows the overall configuration of the 10m grippers and guides. Each of the grippers is 7m tall and are located above the water line. The upper guide is also 7m tall and the top of that guide is just below the mean water line. The lower guide is 10.5m tall and must be located below the keel in order to accommodate the very large moments and shear loads on the 10m CWP and to keep the CWP contact pressure at or below 50 psi.

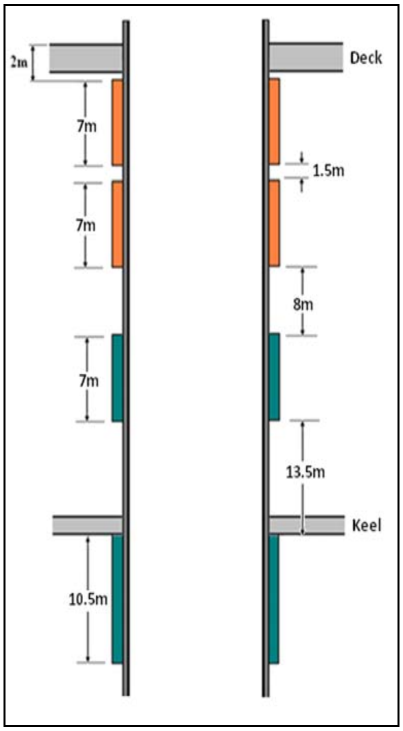


Figure 157. 10m Gripper and Guide Configuration

Figure 158 shows this arrangement within the SolidWorks model. The upper gripper is 2m below the main deck and is nearly centrally located on the second deck. The lower gripper is moveable and hangs by hydraulic rams from the platform. The top and bottom guides in this model are floating relative to the platform. The detailed structure for supporting these guides within the platform has not been designed.

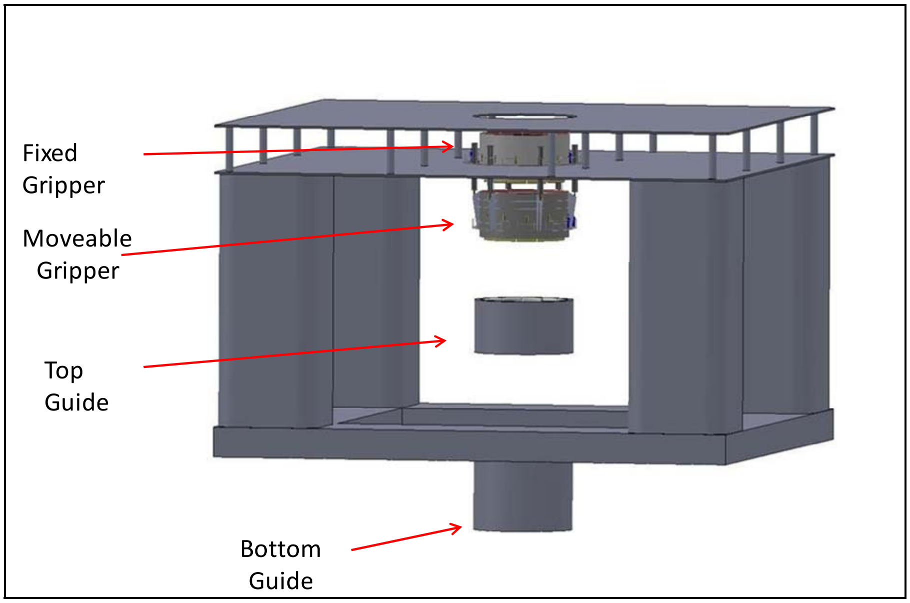


Figure 158. 10m Gripper and Guides on the Commercial 100MW Platform

Figure 159 shows a cross section of the two grippers. Note that the upper gripper is centrally located on the bottom deck and the lower gripper is hanging by six hydraulic lifting rams. These rams have swivel joints at either end and thus the lower gripper is allowed to freely swing laterally. The lower gripper thus floats. This sectional view also shows the multiple wedges and pads.

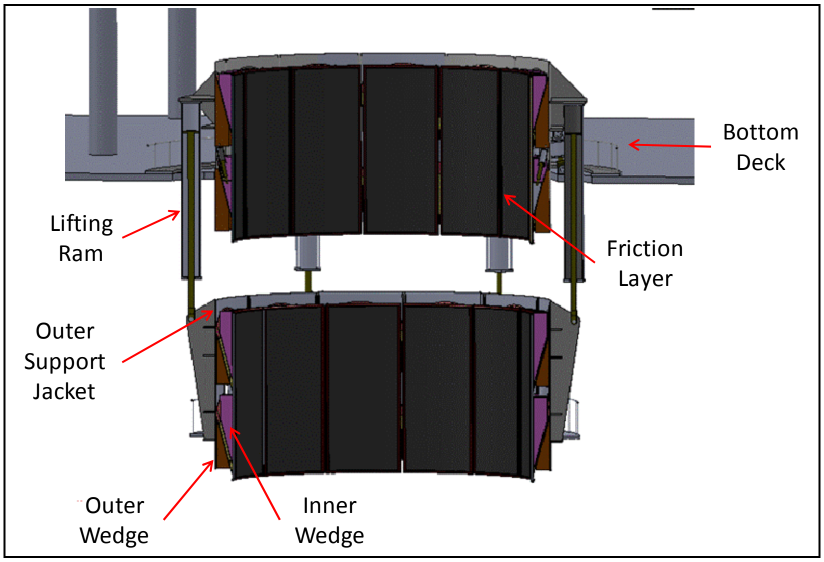


Figure 159. Cross Section of the 10m Upper and Lower Guides

Figure 160 is a top view of one of the grippers. There are twelve wedge and pad assemblies within the gripper outer support jacket. As these wedges move up and down, the friction layer and pads move in and out regularly much like a blocking chuck on a lathe.

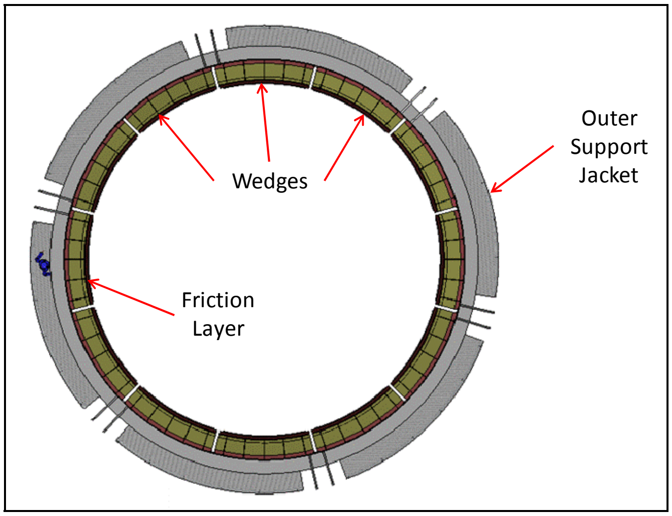


Figure 160. 10m Gripper End View Showing Array of 12 Pads and Wedges

The operations of the inner and outer wedges are illustrated in Figure 161. Because of the very large 7m height of the 10m grippers, the wedge structure is broken into two individual wedges. This minimizes the ratio thickness of the wedge assembly. The inner and outer wedges are connected via a wedge ram that is located near the center of the assembly. The wedge ram is used to move the inner wedge up and down and to engage and disengage the CWP.

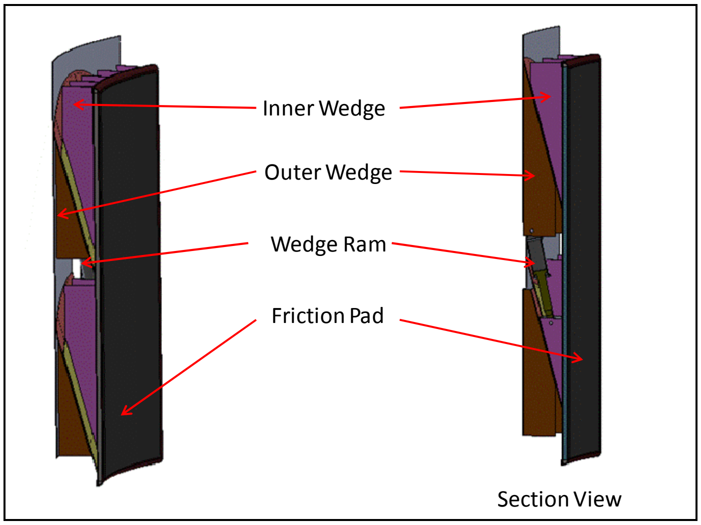


Figure 161. End and Sectional Views of 10m Gripper Wedges

The outer structure of the lower gripper is shown in Figure 162. Note the large scale of this structure as seen by the man standing on the catwalk. The hydraulic wedge rams are accessible through cutouts in the outer support jacket. The lower gripper hangs from the lower deck of the platform and is suspended by six lifting rams. These lifting rams are the means of lowering and raising the CWP.

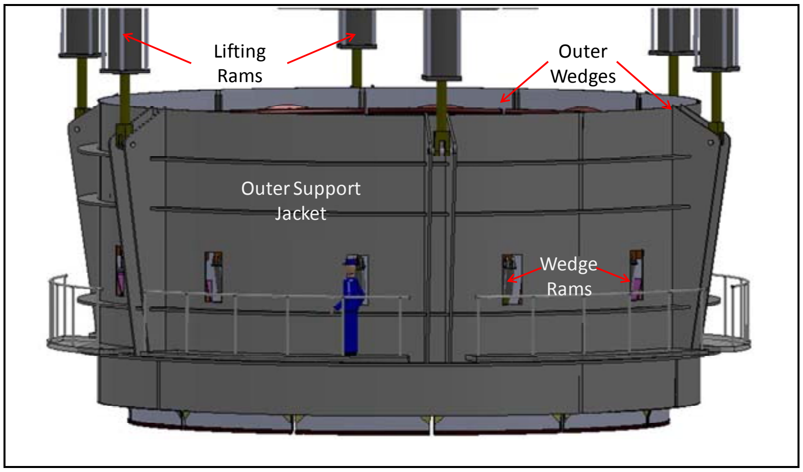


Figure 162. 10m Lower Gripper Outside View

A similar view of the upper gripper is shown in Figure 163. Because of the very large diameter of the commercial CWP, any twisting of the pipe within the upper gripper causes the wall of the pipe to move either upward or downward relative to the gripper pads. With a large 5m radius, this movement is significant even at very small angles. Therefore the upper gripper is mounted on short hydraulic rams to the bottom deck and is allowed to pivot very slightly with the CWP. The CWP rotates a maximum of 0.14 degrees and by allowing the upper gripper to gimbal 0.5 degrees this relative motion between pipe and pad is eliminated. See a more detailed discussion in Section 6.11.5.2.

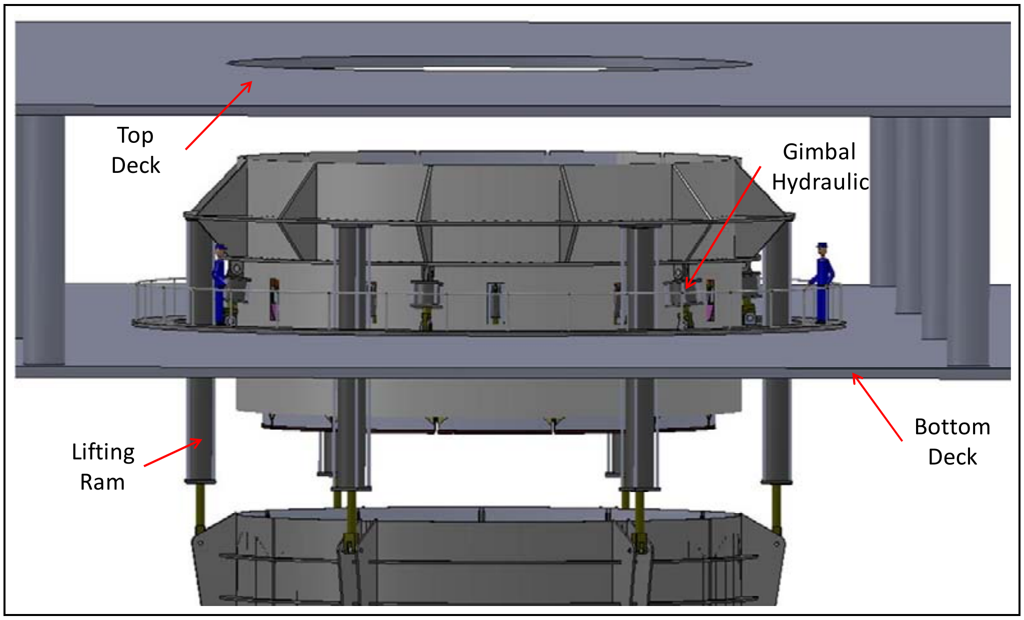


Figure 163. 10m Upper Gripper External Mounted on Deck

It is necessary to be able to remove the pad and wedge assemblies from both the upper and lower grippers. This is desirable in case any repair is necessary during pipe fabrication and it is necessary at the end of the fabrication to lower the final CWP termination through the gripper outer frames. In addition, since many commercial OTEC plants are envisioned, these gripper components can be reused for other OTEC plants. Removal of the Gripper Pads and Wedge assembly is shown in Figure 164.

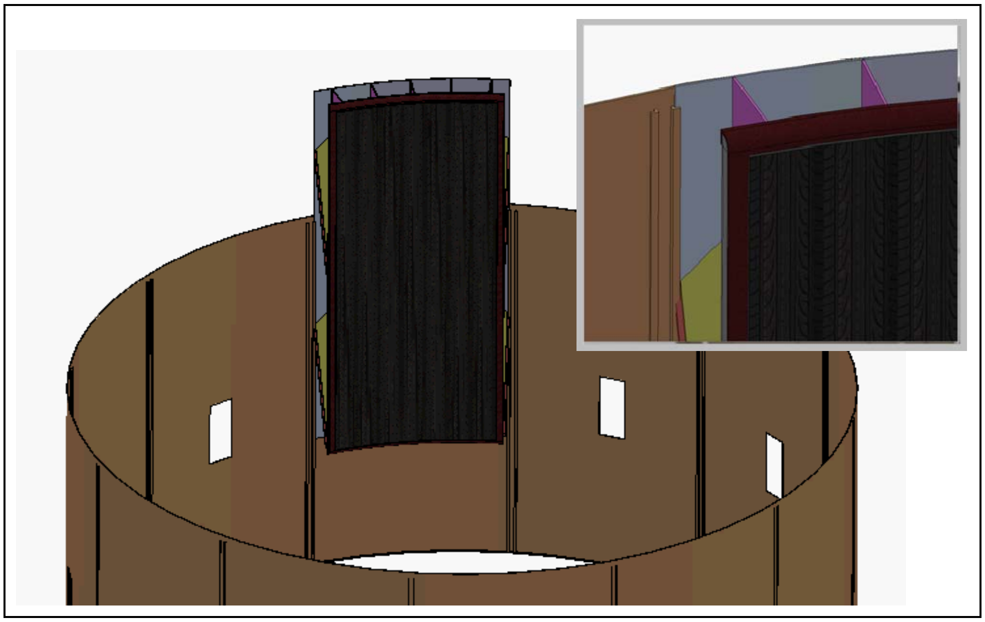


Figure 164. Removal of Wedge and Pad Assembly from 10m Gripper –

The motion of the inner wedge is illustrated in Figure 165. As the wedge ram elongates, the inner wedge is moved downward and inward thus engaging the CWP.

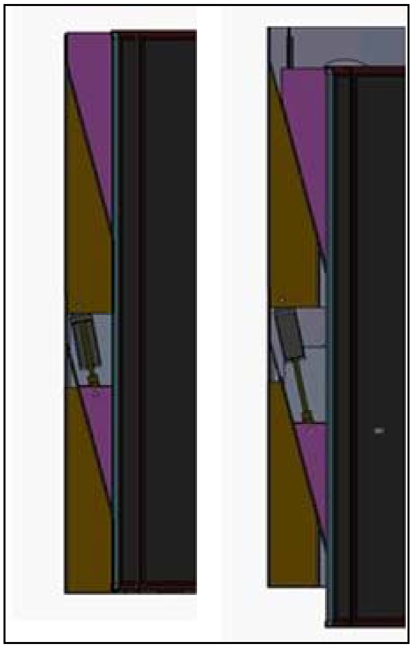


Figure 165. 10m Wedge Movement

6.11 4m Gripper Detailed Design

A final detail design has been completed for the 4m grippers and guides. The detailed drawings and specifications are provided in the appendix. This design was developed in SolidWorks in three dimensions. This section gives a tour of the SolidWorks model and points out the features and functions of both grippers and guides.

A profile of the platform as the CWP is being fabricated is shown in Figure 166. On the deck of the platform is the fabrication apparatus. The two grippers are located below the top deck and the two guides are located below the water line. For scale, note the man standing just to the left of the upper gripper. The following sections provide details on the grippers and guides.

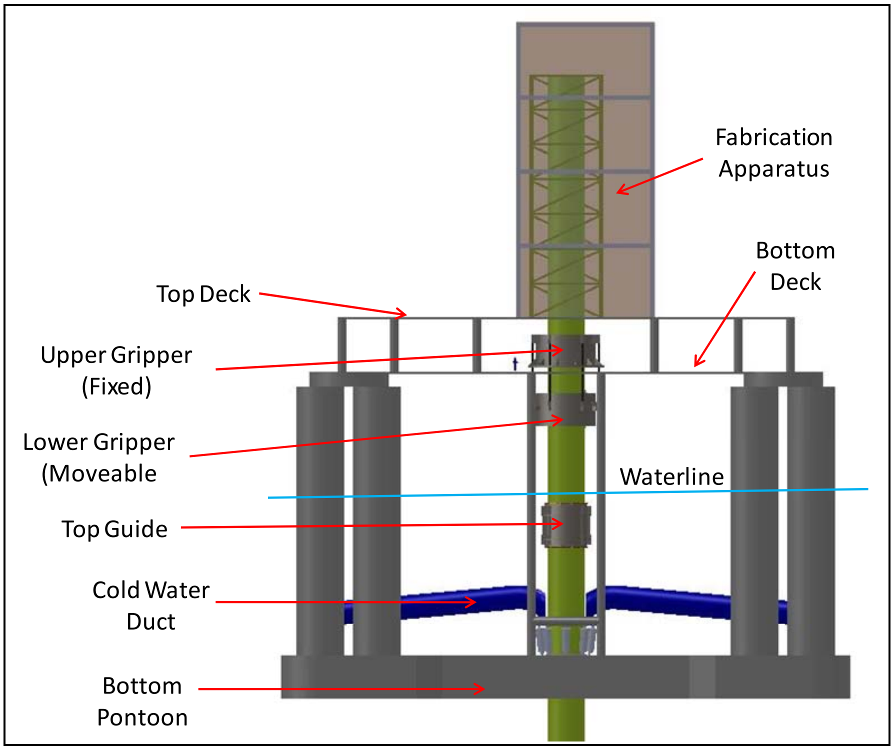


Figure 166. 4m CWP Fabrication and Pipe Handling Equipment

The upper and lower grippers are shown in Figure 167. The upper gripper sits on the bottom deck of the platform and the lower gripper is suspended below on six hydraulic lifting rams. Spherical rod ends are used at either end of the lifting ram to allow slight angular movement (see insert). Therefore the lower gripper is free to float and does not provide any lateral support. All the lifting rams are on a common hydraulic manifold when the lower gripper is attached to the CWP. In this state the lower gripper acts as a gimbal as it can freely move laterally and rotate with the CWP (floats, tilts and pivots). When the lower gripper is not engaged on the CWP, the rams are all independently controlled such that the lower gripper cannot tilt,

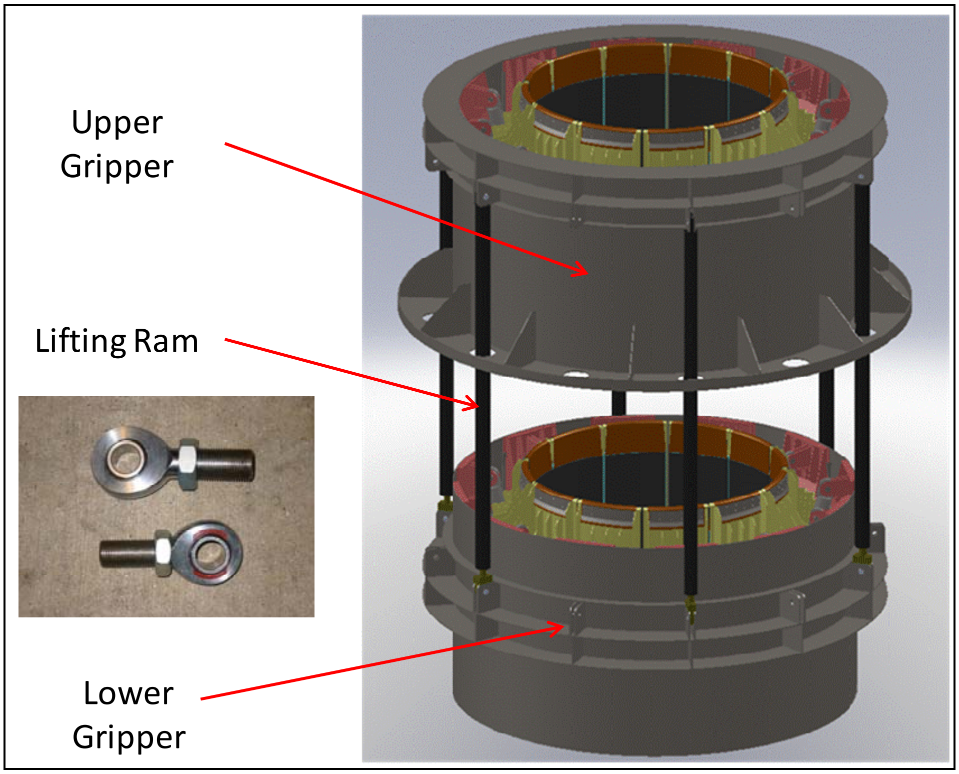


Figure 167. External View of the Upper and Lower 4m Grippers

6.11.1 4 meter Gripper Design Overview

A cross sectional view of the two grippers is shown in Figure 168. The wedge and pad design for the two grippers are identical. The primary difference between the two grippers is that the top gripper is stationary and lower gripper moves up and down on the lifting rams.

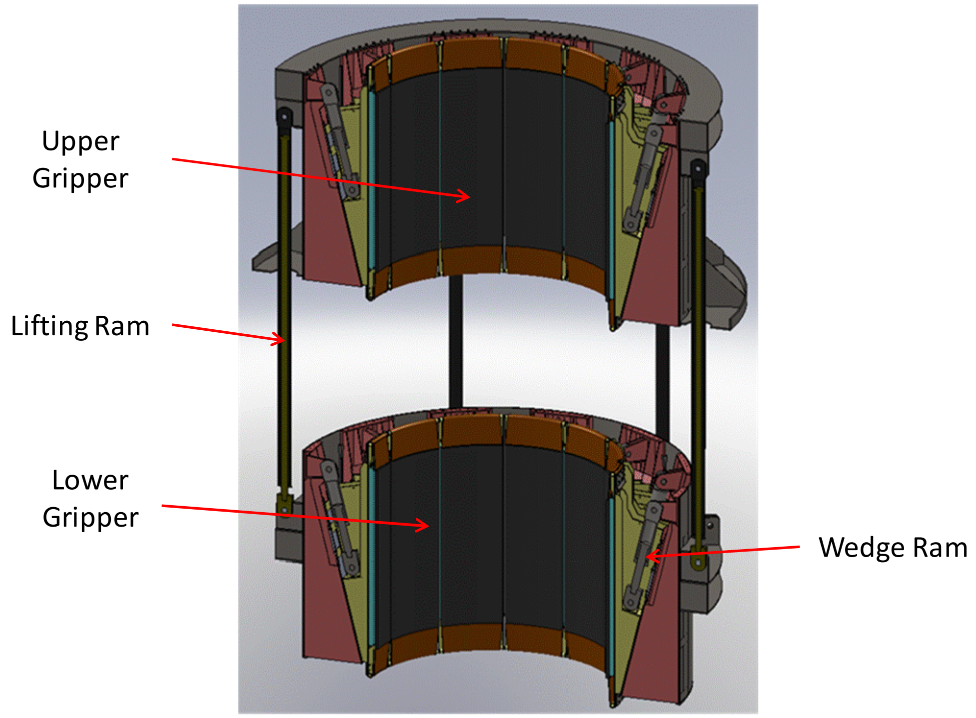


Figure 168. 4m Upper and Lower Gripper Cross Sectional View

Figure 169 through Figure 172 show details on the wedges and pads in these two grippers. There are twelve wedge and pad assemblies in each gripper evenly spaced circumferentially around the CWP. When engaged on the CWP, the gap between the gripper pads is minimal. Each wedge assembly consists of a stationary wedge that is fixed to the outer frame and an inner wedge that moves up and down the inclined plane. The inner surface of the inner wedge remains vertical and parallel to the CWP. The wedge is moved up and down (and thus in and out) by the hydraulically controlled wedge ram.

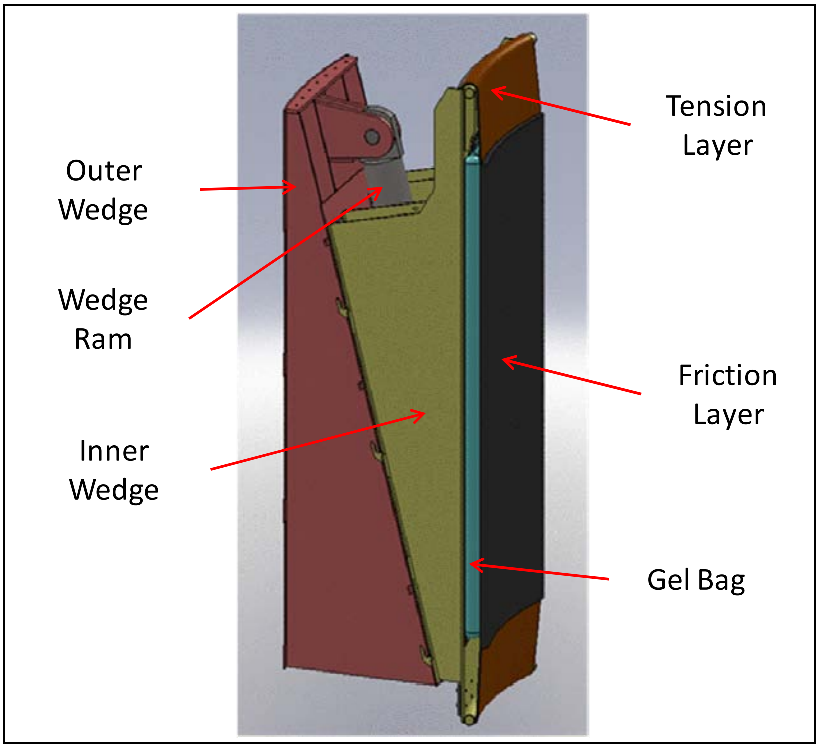


Figure 169. 4m Wedge and Pads Assembly Structural View

Figure 170 is an exploded view of the components in the wedge and pad assembly. Between the two wedges there is a Ultra High Molecular Weight (UHMW) polyethylene layer which provides a low friction bearing surface for these components. The gel bags and the tension and friction layers are on the inner surface of the inner wedge.

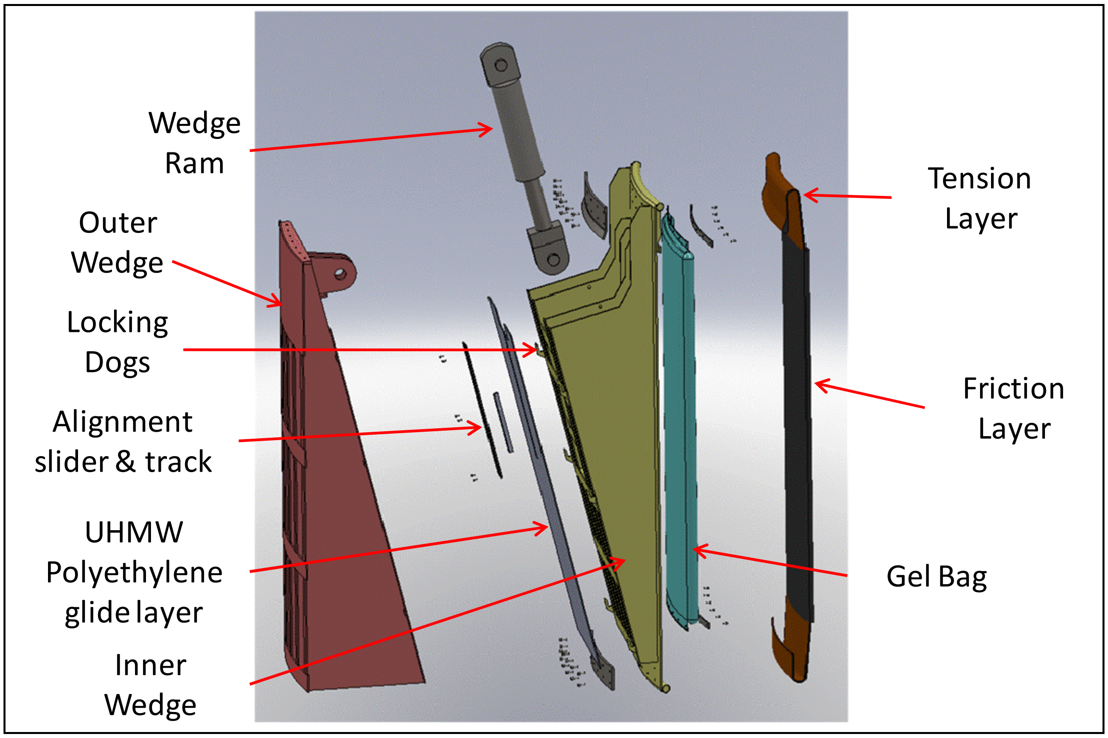


Figure 170. 4m Wedge and Pad Components Exploded View

Figure 171 shows a cross section of the assembled wedge and pad assembly. The wedges stay in contact with each other primarily through gravity but a slider and track is centrally located between the two wedges to keep it sliding along the axes of the ram. This slider and track assembly is shown in more detail in Figure 172.

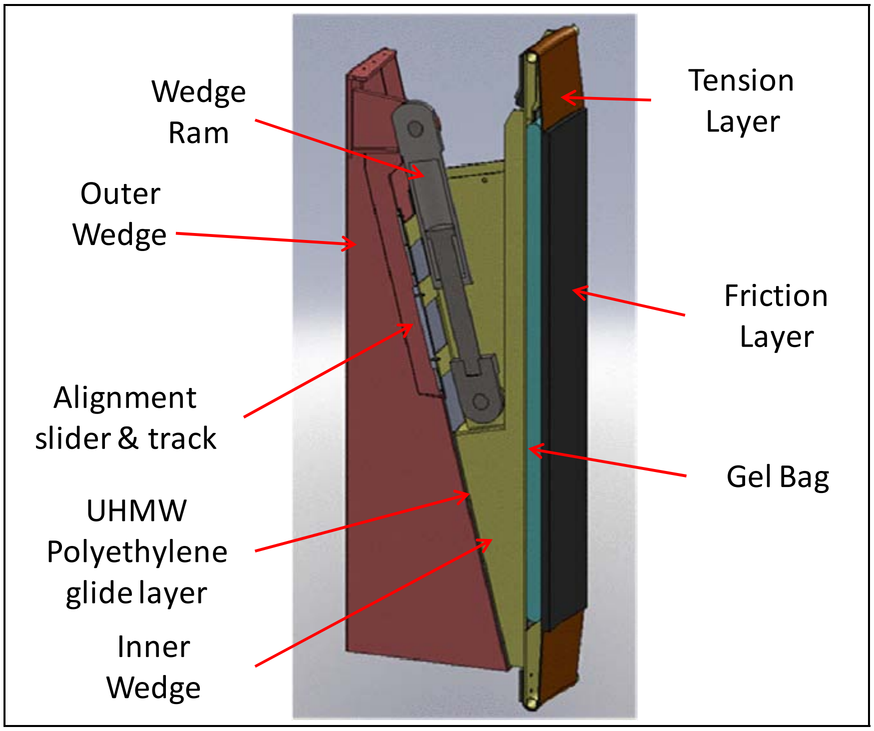


Figure 171. Cross Section of Assembled Wedge

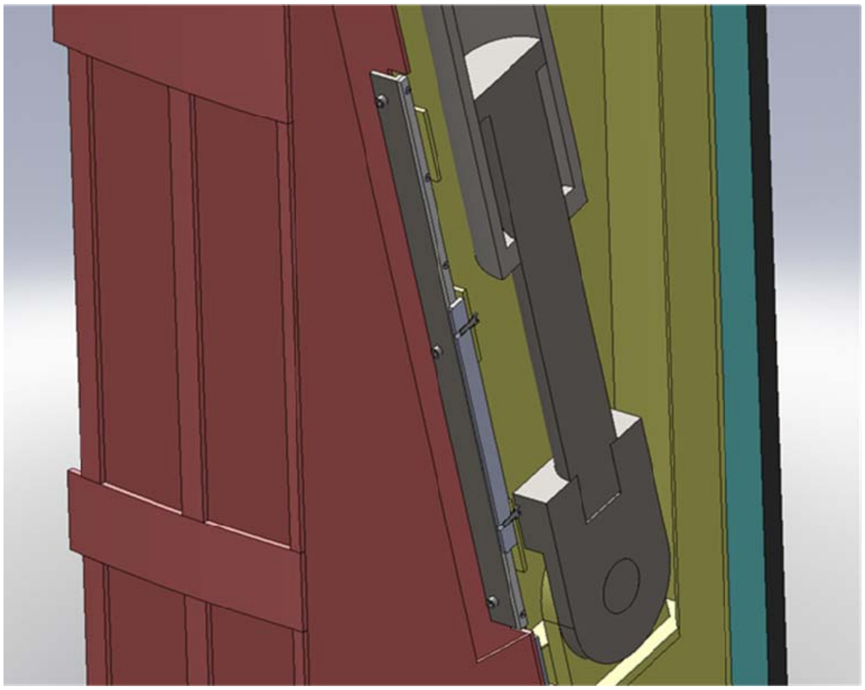


Figure 172. Wedge Ram, Alignment and Slider Track Details

The gel bags and tension layers hang on the inside of the inner wedge. The details of the attachment are shown in Figure 173. The tension layer rolls over the top of the inner wedge and is clamped to the inner wedge structure. The gap shown in the tension layer in Figure 173 is the gap between two adjacent wedges. The gel bag is hung inside the tension layer. The gel bag support only needs to support its own weight. There is a similar attachment for the tension layer and gel bags at the bottom of the wedge.

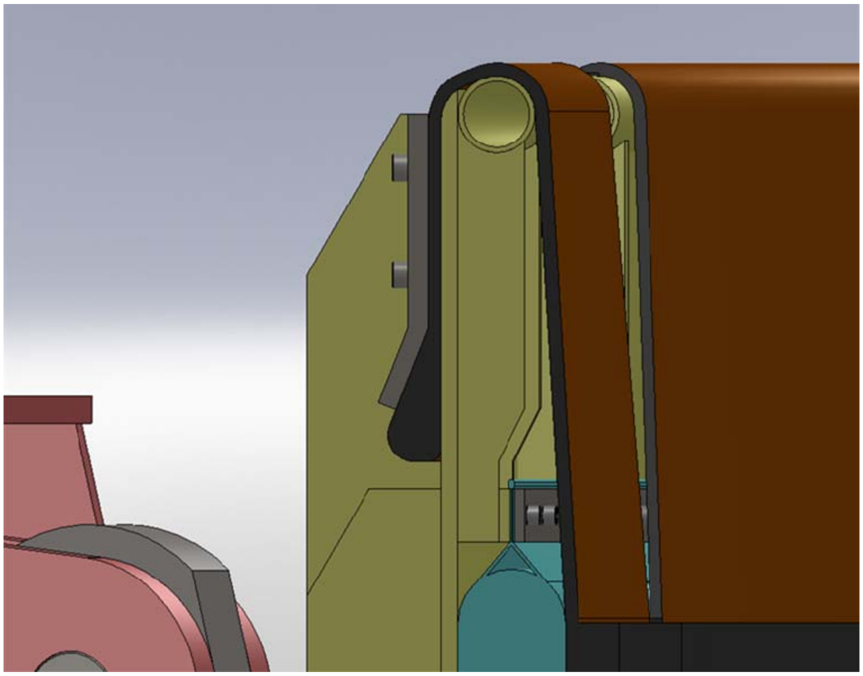


Figure 173. Tension Layer and Gel Bag Attachment Details

There is a set of locking dogs, the two wedges that lock the inner and outer wedges together when the upper wedge is in its upper most position. The wedge assembly can be removed from the gripper ring by lifting it out as an entire assembly. This can be conveniently done when the two wedges are firmly locked together. The locking dogs are shown in Figure 174. There is also a lifting eye just above the center of gravity for this structure for properly lifting, inserting and removing this assembly.

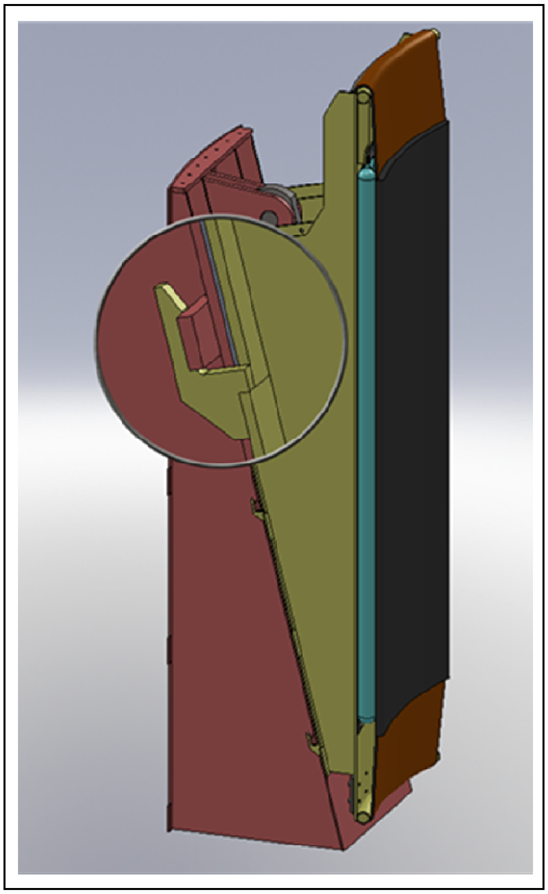


Figure 174. Wedge Detail Showing Locking Dogs

6.11.2 4 meter Guides Design Overview

The two below water guides are shown in Figure 175. These guides provide lateral support for the CWP but do not provide vertical support. The goal is to be a snug but firm bushing through which the CWP is deployed. By firmly restraining horizontal movement at the guide locations, the movement of the CWP above the deck during fabrication is minimized.

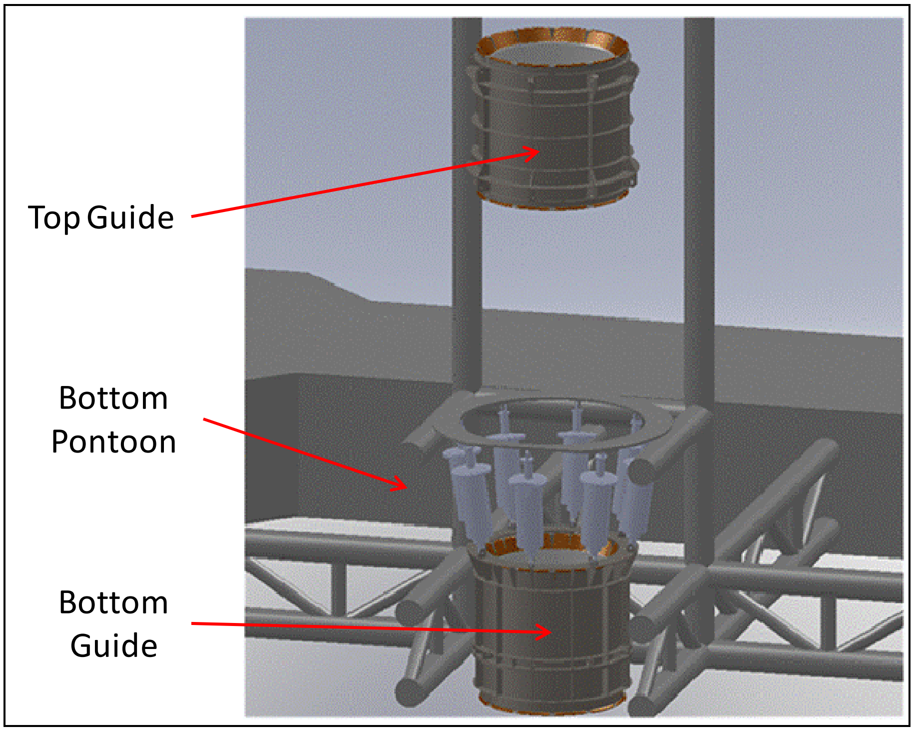


Figure 175. 4m Guides Relative to the Platform Structure

Figure 176 shows a cross sectional view of the two guides. These guides are similar to the grippers in that they contain fluid filled bags to equalize the pressure on the CWP. The guides also have twelve pads such that there are twelve distinct but independent contact points around the circumference of the CWP. Each one of these contact points is very rigid radially and therefore supports the CWP and prevents its collapse. There is a tension layer coated with a low friction glide layer over the surface of these pressure-equalizing bags. Because there can be a large contact force between these pads and the CWP during lowering, the tension layer is required to resist this friction.

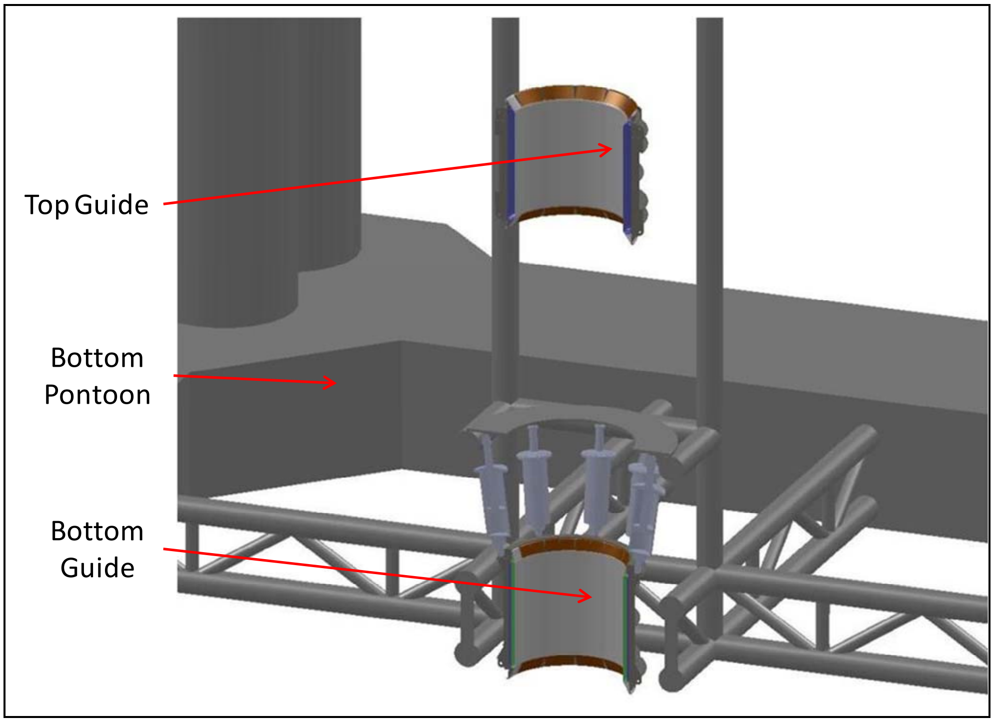


Figure 176. 4m Guides and Platform Cross Section

Figure 177 shows a cross section of the upper guide. The upper guide consists of a rigid circular frame and twelve water filled bags for the pressure equalizing medium. Each of these bags is 8 inches thick and the amount of water can be independently controlled in every bag. When the bags are inflated at low pressure the slide and tension layers will be pressed snugly against the outside of the CWP. Thus the CWP is held firmly without any gaps. If there are variations in the diameter of the CWP, the amount of water in these compensation bags can be adjusted.

Water filled bags in the upper guide are 8 inches thick; they can be completely drained and the slide layer can be retracted 8 inches from the surface of the pipe. Guide retraction is required at the end of the pipe fabrication process when a larger-diameter pipe termination must be dropped down through this upper guide. The 8 inch retraction provides adequate space for this operation.

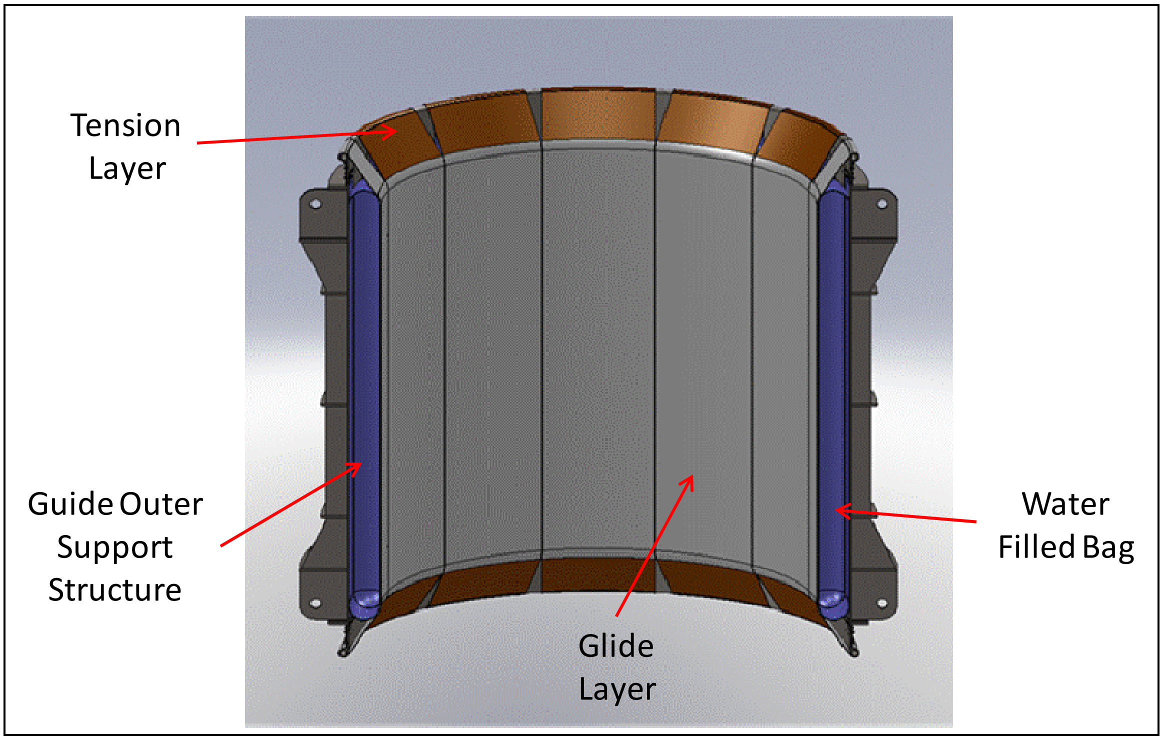


Figure 177. 4m Upper Guide Cross Sectional View

The details of the connection between the water bag glide layer, tension layer and the upper guide structure is shown in Figure 178. The glide layer is a Kevlar coated fabric. The coating is urethane with a relatively low coefficient of friction. Both guides are below water and therefore the glide layer is lubricated with water at all times.

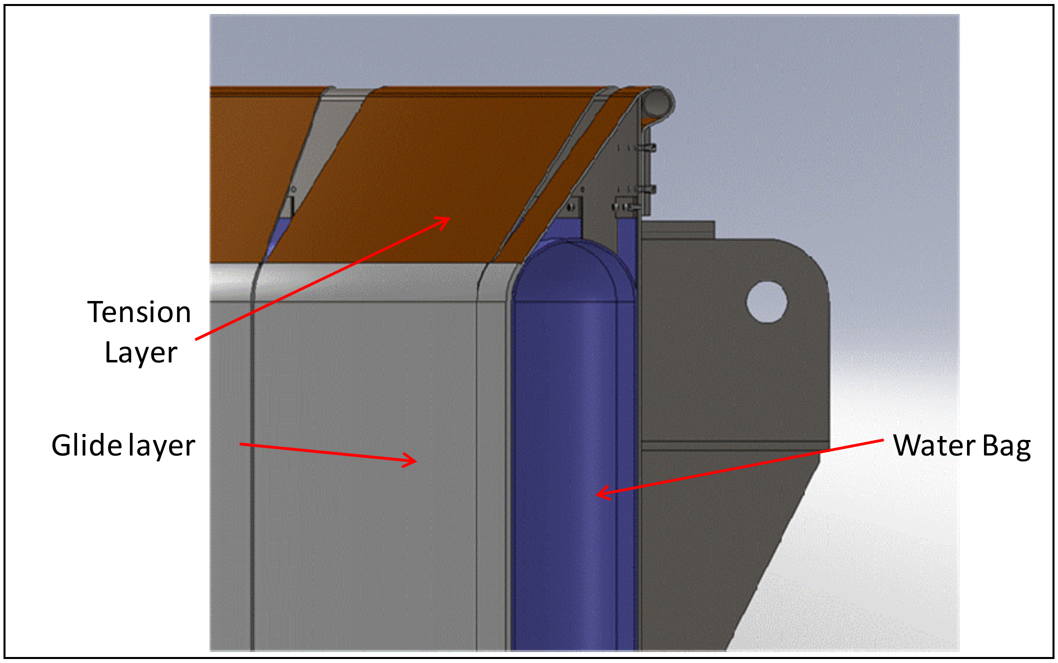


Figure 178. Upper Gripper Bag and Tension Layer Attachment Detail

The lower guide is slightly different and is shown in Figure 179. The upper frame of the lower guide is the mating flange for the final placement of the CWP. The CWP termination does not need to be dropped through this guide and therefore the thick retractable water bag of the upper guide is not needed here. Also, a single water filled bag would be a risk. The lateral loads in this lower guide are higher and if a water filled bag were to fail, the CWP would likely contact steel and be damaged. Therefore on the lower guide there are two separate bags as shown in Figure 180. An inner bag is a gel filled bag. This is backed by an adjustable thin 1 inch thick water bag. If the water bag ruptures, the gel bag is there to protect the CWP from damage. Because CWP deflections are not that large in the upper guide the CWP will never be able to contact the guide structure if a water bag ruptures.

The lower guide, as shown in Figure 179, is supported by a gimbal arrangement. A gimbal is notionally shown in this figure since the gimbal has not been a design deliverable in this study. However, because a gimbal is needed for the commercial OTEC plant with a 10m CWP, a gimbal may be desirable for this pilot plant. In that case, the gimbal is attached to the lower guide and the CWP is finally docked at the top of the guide as shown in Figure 181. During the fabrication process, the gimbal is locked such that the guide cannot rotate. Once the CWP is in place and bolted to the lower guide, the gimbals are then freed to rotate.

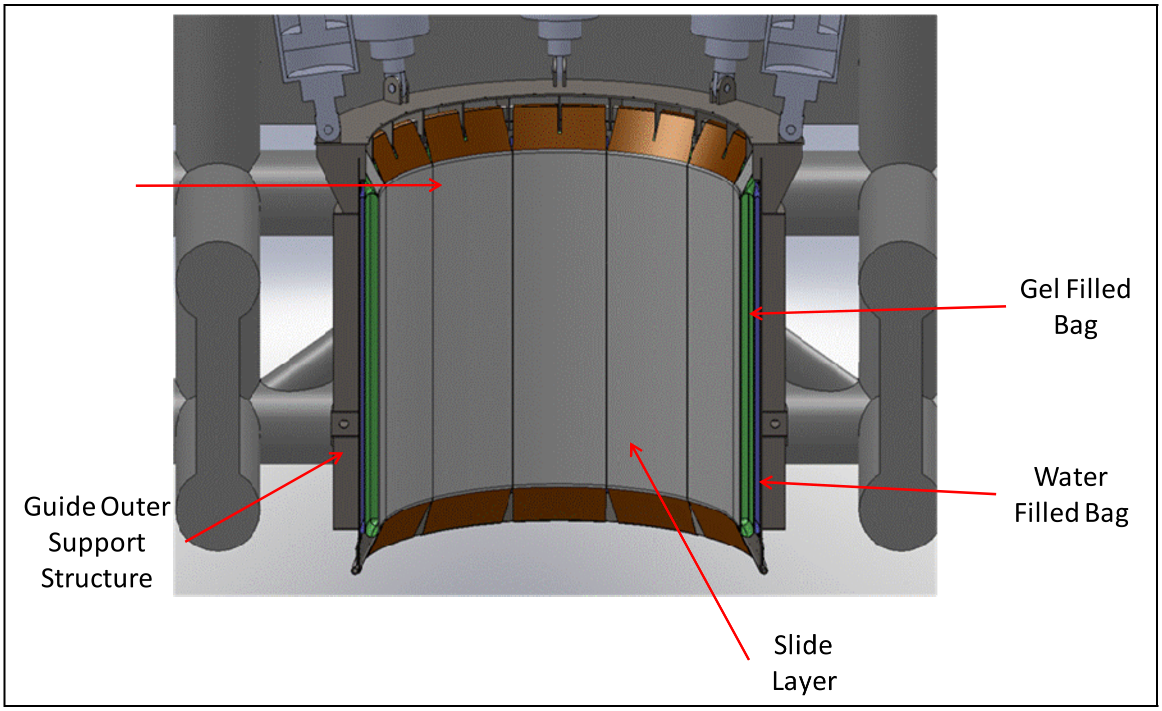


Figure 179. 4m Lower Guide Cross Sectional View

Details of the attachment of the two bags and the tension layer for the lower guide are shown in Figure 180. Because of the heavy structure at the top of the guide for the final docking of the CWP, there are multiple gussets that penetrate the middle of the tension layer on each of the twelve pads.

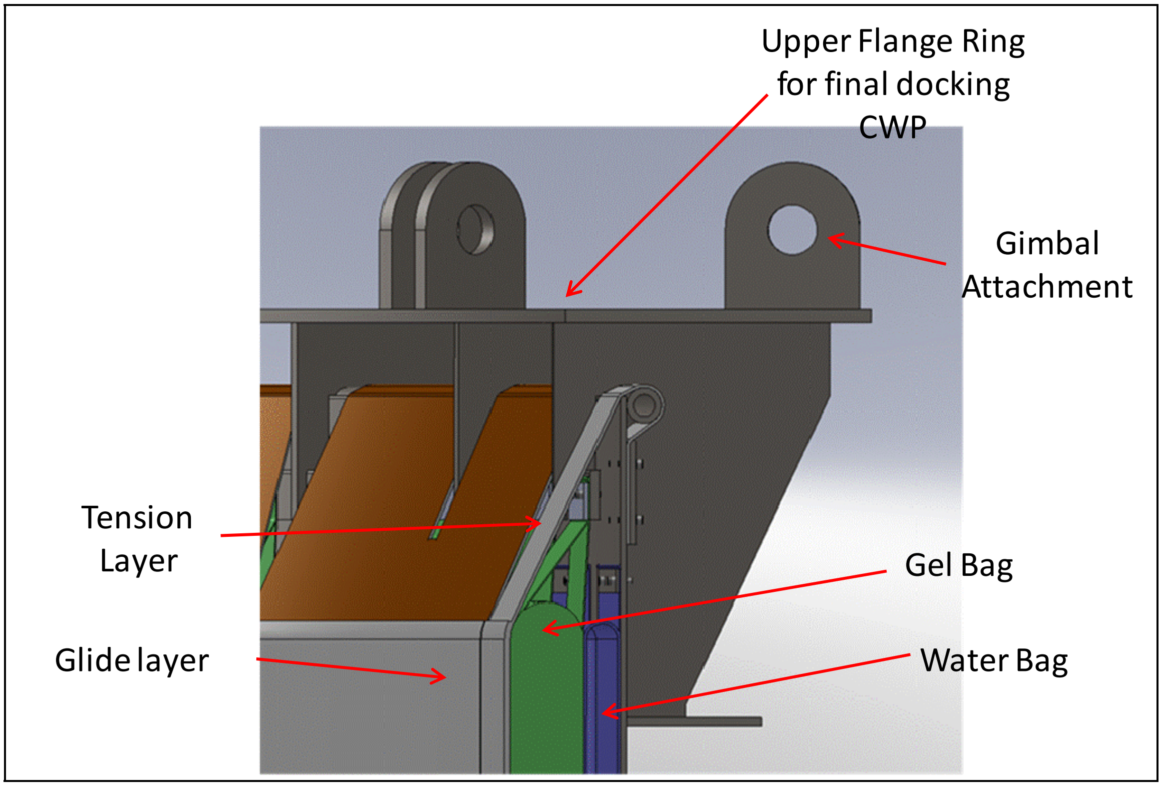


Figure 180. Lower Guide Details of Bag Attachments and CWP Flange

The final docking of the CWP in the upper guide is shown in cross sectional view in Figure 181 and the exterior of the connection is shown in Figure 182. In the latter view, the final manifold closure has been dropped in place and the bellows for the gimbal is shown to complete the water connection to the remoras.

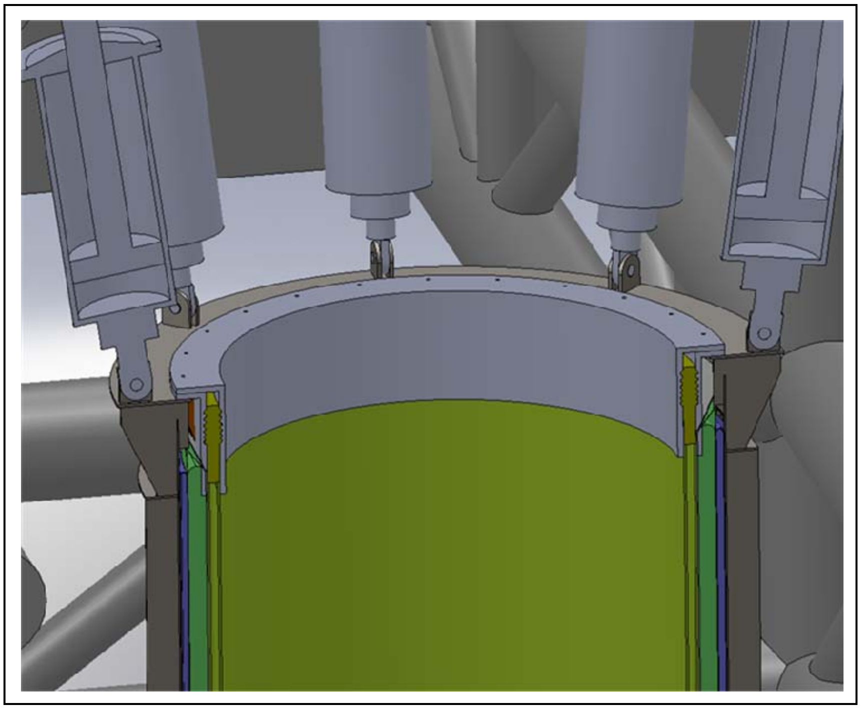


Figure 181. Lower Guide Cross Section with CWP Set in Place

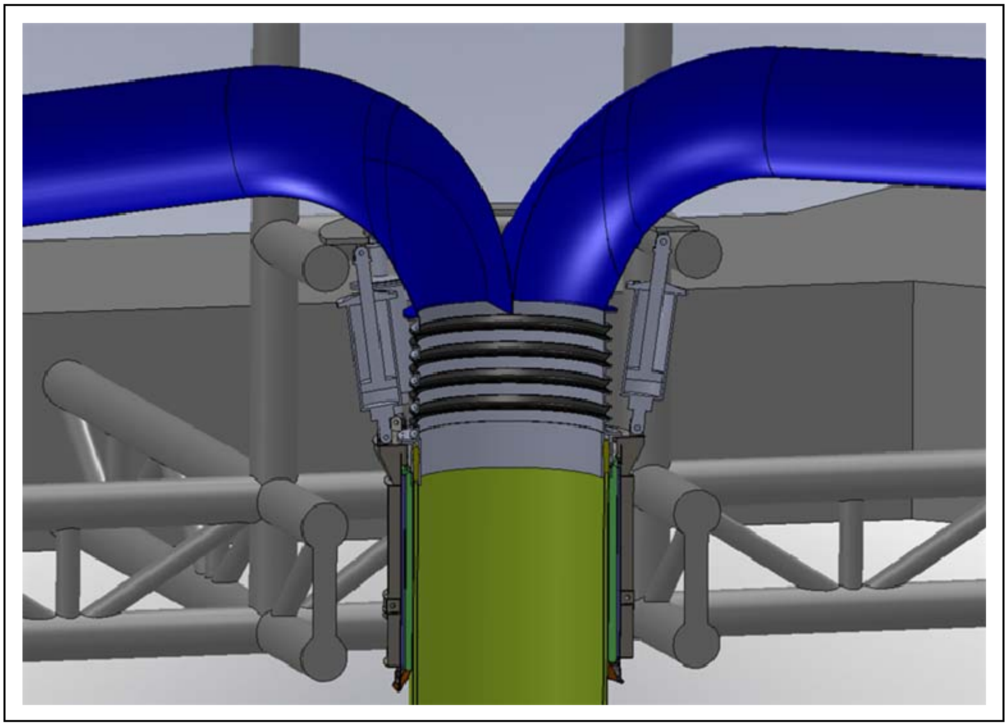


Figure 182. CWP in Place and Attached to Lower Guide

6.11.3 Pad Friction

6.11.3.1 Requirements

The grippers support the CWP through friction and this was a critical concern throughout this development. It was necessary to select appropriate pad materials and to test the coefficient of friction between these materials and a representative pipe. The nominal design for the gripper assumes an external uniform pressure on the CWP of 50 psi. If a pad could provide a reliable coefficient of friction of 0.25, then the pads could support the pipe through friction at 12.5 pounds for every square inch. We therefore entered into a testing program to search for a reliable friction layer material that would have a coefficient of friction of at least 0.5 giving us a minimum safety factor of 2.0.

The objective of the testing program was to identify a material for the friction layer with the following characteristics:

a. A coefficient of friction of at least 0.5.
b. No significant difference between the static and dynamic coefficients of friction. In other words, a material does not chatter once it starts to slip.
c. Compatible with seawater and sun.
d. Can be attached to or reinforced with a tension layer.
e. Compatible with hydraulic fluids.
f. Once cleaned of hydraulic fluids, the coefficient of friction remains high.
g. Readily available.

The details of the testing program are included in the appendix.

6.11.3.2 Testing Program

A test apparatus was designed and built for testing the coefficient of friction between a friction layer sample and a representative piece of CWP. See Figure 183. Samples of CWP wall were provided by Lockheed Sunnyvale. These pieces were made using the VARTM process and with identical molds and without mold release as planned for the CWP. The surface of these samples is a rough and somewhat fibrous surface, see Section 6.2.1.

Figure 183. Friction Test Apparatus

The test samples were 4 inch by 4 inch and were pressed uniformly against the CWP sample by a pneumatic ram. Contract pressure could be varied between 10 psi and 100 psi. Most testing was done at 50 psi contact pressure.

The test apparatus pressed the two samples together at the desired pressure. With one sample being held, the other was pulled laterally developing a shear between the two samples. Displacement and shear loads were continuously measured and the coefficient of friction between the two samples could be calculated. shear distortion of the rubber sample could be determined from the shear vs. displacement curve.

6.11.3.3 Candidate Materials

Makai contacted more than a dozen rubber suppliers and received more than 50 samples of friction layer candidates. Some were special formulas developed by the suppliers for our particular application and others were formulas developed specifically for high friction in other applications. In one case a rubber developed for high friction shoe soles was tested. Table 34 is a partial listing of samples that were tested in the friction testing machine.

Table 34. Representative Friction Material Samples

Sample number	Source	Size (in)	Type of Rubber	Shore A Durometer	Dry μ	Description
1	Burke	5.5x5.5x1	SBR	80	0.34	rubber
2	Burke	5.5x5.5x1	SBR	80		rubber on steel
3	tire	3.125x4.375	SBR/NR	70	0.51	newest
4	tire	3.5x4.25	SBR/NR	70		tread other direction
5	tire	3.625x5	SBR/NR	70		old tread
6	shoe rubber	4x4			0.58	plain rubber
7	shoe rubber	4x4				amph
8	shoe rubber	4x4				hydro
9	shoe rubber	4x4				aqua
10	VIP Rubber	4x4			0.36	
11	Stockton Rubber	4x4x1	Neoprene	55-60	0.56	4392C
12	Stockton Rubber	4x4x1	Nitrile	55-60	0.74	3193C
13	Stockton Rubber	4x4x1	Natural Rubber	55-60	0.64	1195D
14	Stockton Rubber	4x4x1	SBR	70-75	0.44	2180C
15	Burke	4x4x1	Natural Rubber	50		2nd shipment
16	Stockton Rubber	4x4x1	Natural Rubber	50		1199C
17	Stockton Rubber	4x4x1	Natural Rubber	55	0.43	1201C
18	Stockton Rubber	4x4x1	Natural Rubber	70	0.39	1307C
19	Stockton Rubber	4x4x1	Natural Rubber	70	0.38	1308C

6.11.3.4 Results

Figure 184 shows the results of a typical friction test. The effective coefficient of friction is plotted as a function of shear displacement. The maximum coefficient of friction of this sample is 0.65 and this is achieved when the material starts to slip over the CWP sample. The rubber shown in Figure 184 is the final selected friction layer compound.

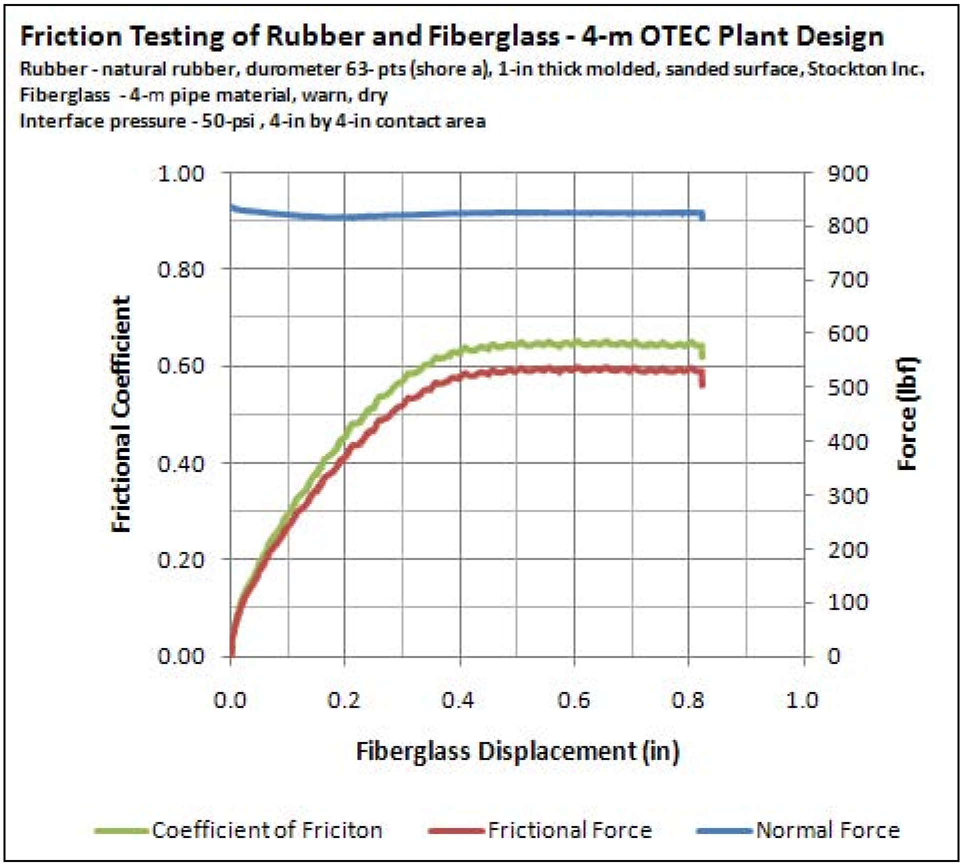


Figure 184. Example of Friction Test Results

Figure 185 and Figure 186 show the maximum coefficient of friction for several candidate materials both in the dry and wet conditions. Stockton Rubber 13 exceeded our criteria both in dry and wet conditions. Another rubber provided by Stockton, number 12, actually had higher performance with coefficient of friction exceeding 0.7. This was a Nitrile rubber and was not recommended for prolonged exposure outside. The Stockton number 13 is a natural rubber with the characteristics shown in Table 35.

Table 35. Stockton Rubber 13 Characteristics

TEST	TEST NAME	TYPICAL RESULTS
ASTM D-412	Tensile Strength	3400 psi
ASTM D-412	Elongation	580%
ASTM D-412	300% modulus	1375psi
Durometer		63+/-5 Shore A Scale

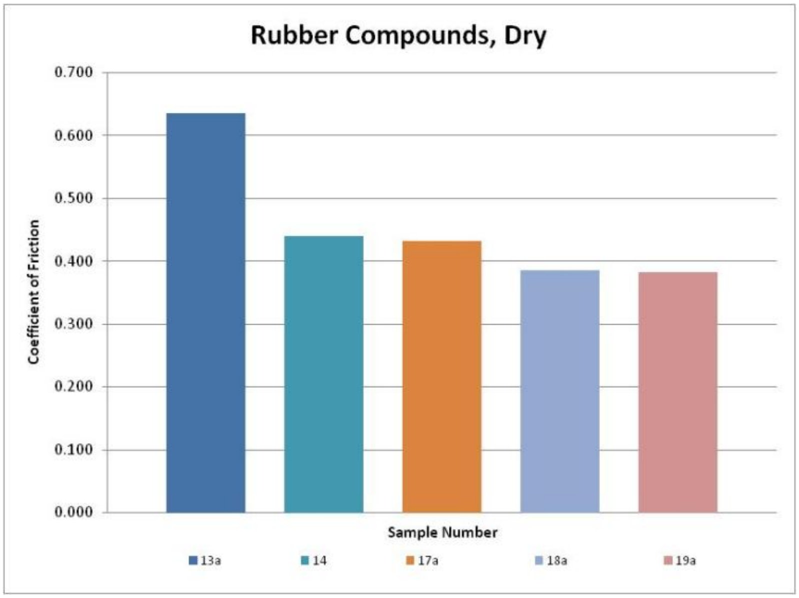


Figure 185. Rubber Compound Variation in Dry Tests

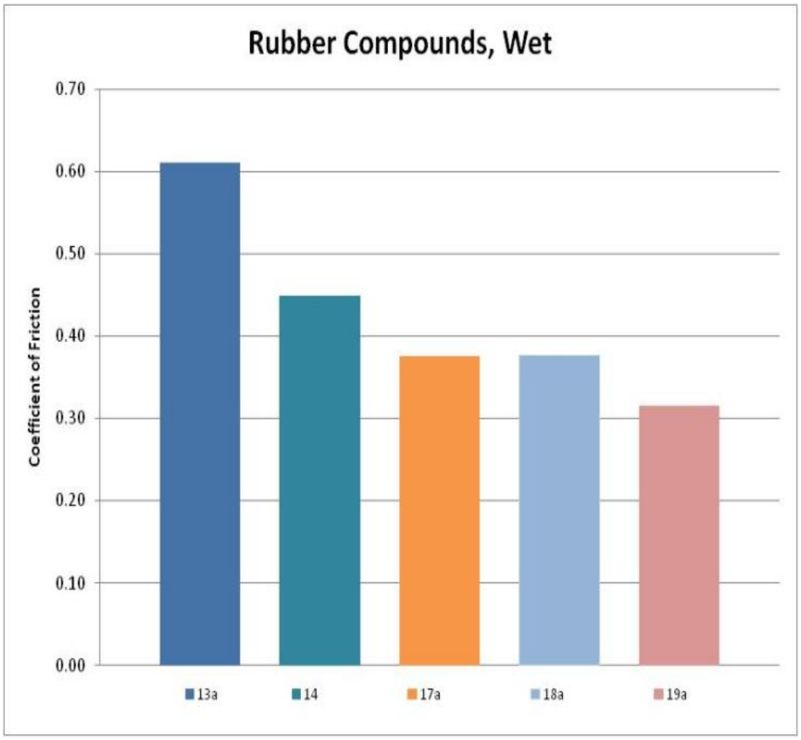


Figure 186. Rubber Compound Variations in Wet Tests

6.11.3.5 Contamination

One concern was inadvertent lubrication of the surfaces with hydraulic fluid from a leaking hydraulic ram. If there were a hydraulic spill, it was important to be able to easily clean the hydraulic fluid off the CWP and pads and still maintain a high coefficient of friction. Several water soluble and environmentally compatible hydraulic fluids were tested.

shows the results of testing four different water soluble hydraulic fluids on the Stockton natural rubber #13 samples. There are four sets of bar graphs, one set for each hydraulic oil candidate. The left bar of each pair shows the maximum coefficient of friction with a lubricated contact between the rubber and the CWP sample. The bar on the right shows the maximum coefficient after the lubricant had been washed off with fresh water. Two of the hydraulic fluids behaved very well with only a slight degradation in friction with the lubricant and complete restoration of friction after the oil had been washed off. Those two hydraulic candidates are Lubritherm and PowerFlo. Lubritherm by Lubecorp Manufacturing Inc. is a water-based synthetic oil that is suited for severe hydraulic service. PowerFlo by Tapco is a synthetic glycol-based water soluble oil and is fire retardant.

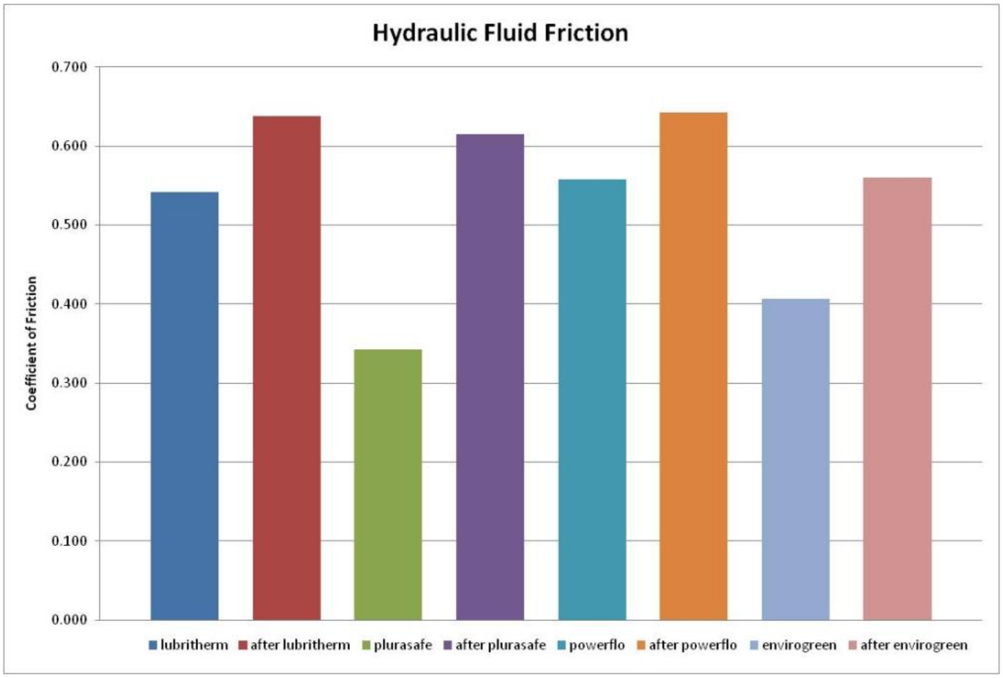


Figure 187. Friction Coefficients, Stockton Natural Rubber,4 Oils

6.11.4 Pads

The pads in the gripper are the friction layer contacting the CWP, the tension layer carrying the CWP weight and the gel bag acting as a pressure equalizer behind the friction and tension layers as shown in Figure 188. These pads coupled with the CWP were a challenge to analyze. The main analytical issues were:

a. What is the pressure distribution over the surface of the CWP considering the distortion of the CWP, bumps on the CWP and resistance to gel movement within the gel bag?

b. What is the final radial stiffness of the various layers and the gel bag? The desired goal is to have an extremely high, nearly incompressible, stiffness.

c. What is the shape of the gel bag both when engaged and when disengaged?

d. How should the tension layer be supported? The support point needs to be rigid yet have an adequate clearance from the surface of the CWP.

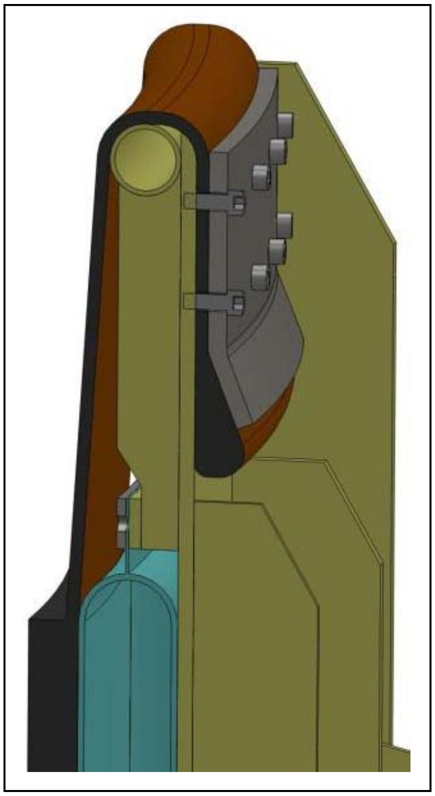


Figure 188. Upper Pad Notional Configuration

6.11.4.1 Pad Finite-Element Analysis

Makai used a non-linear, finite element ANSYS tool to model the pad components. This proved to be a challenge for ANSYS because of the very large deflections and the wide range of materials used in the CWP and pad.

a. The gel bag is a nylon fabric bag filled with a very low shear modulus material. As the bag is pressurized the nylon fabric stretches and gel moves throughout the bag. There are large displacements of material.
b. The tension layer is comprised of a woven Kevlar fabric which is elastic and unevenly loaded.
c. The rubber friction layer is compressed during engagement and when carrying the CWP weight the rubber goes into large shear distortions.
d. The loading is a two step process: the pipe is first radially engaged and the pressure is set in the gel bags and then the CWP load is transferred to the gripper.

It was possible to build an ANSYS model to duplicate most functions and properties of the gripper. The major challenge was the gel bag because ANSYS was not able to accurately model an extremely low shear strength gel within a solid boundary (the nylon fabric bag). ANSYS was only able to converge by allowing the gel to mathematically penetrate the fabric layer, a condition that was unsatisfactory for a proper gripper analysis. As a work around, the ANSYS bags were filled with water and ANSYS would then report the “distortion” of the water within the bag. A separate and independent calculation was made to translate this level of distortion into a gel bag pressure distribution. See the following section, 6.11.6 on the gel development.

A major driver in the ANSYS model was the distortion of the CWP under pressure. The CWP wall moves readily inward and it moves more at the center of the gripper than at the edges. As a result, the gel bag must compensate for this change in displacement. Because modeling the gripper and pads was a computational intensive analysis, it was necessary to simplify the CWP to minimize processing time. Figure 189 shows the radial deflection of the 10m CWP computed by Lockheed on an independent and complete CWP FEA analysis. The “model” pipe used in the pad FEA analysis is a close approximation.

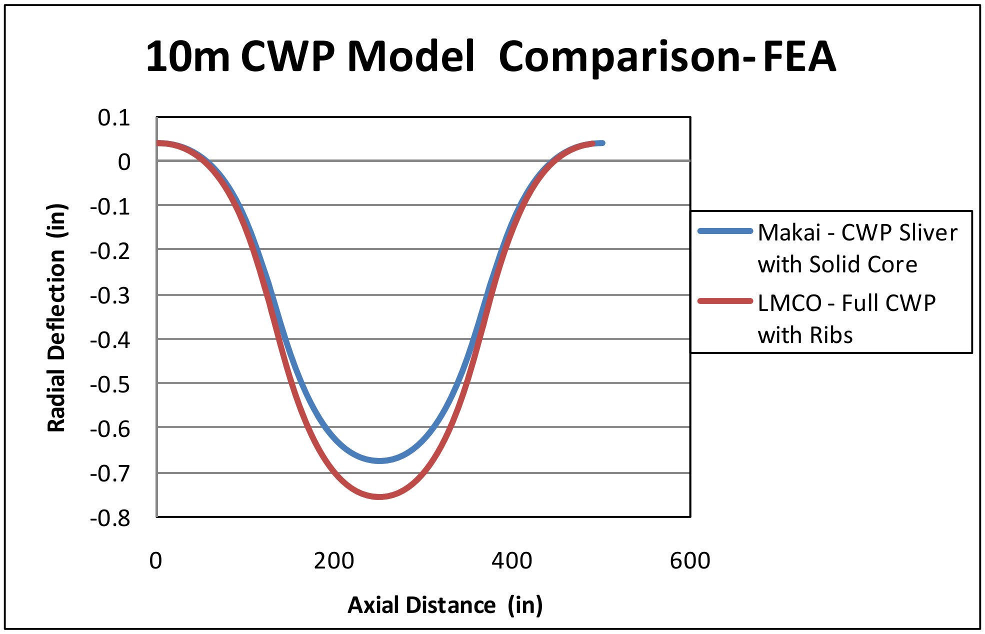


Figure 189. Radial Deflection of the 10m CWP in ANSYS Model

The ANSYS model was then used to develop the final configuration of the pads and was used to determine the hanging point and elevation of the tension layer. In addition, ANSYS was used to determine the gel flow within the gel bags for shear and pressure analyses that were done separately. Figure 190 shows a typical ANSYS result. The CWP is on the left and the gripper steel frame is on the far right. Between the pipe and the frame is the gel filled bag (green), the tension layer (blue) and the friction layer (dark brown). Note that the friction layer is distorted due to the weight of the CWP and the gel inside the gel bag has migrated downward to compensate for the distortion in the CWP. Not shown in this static representation are the stretch of the nylon bag and the elasticity of the tension layer.

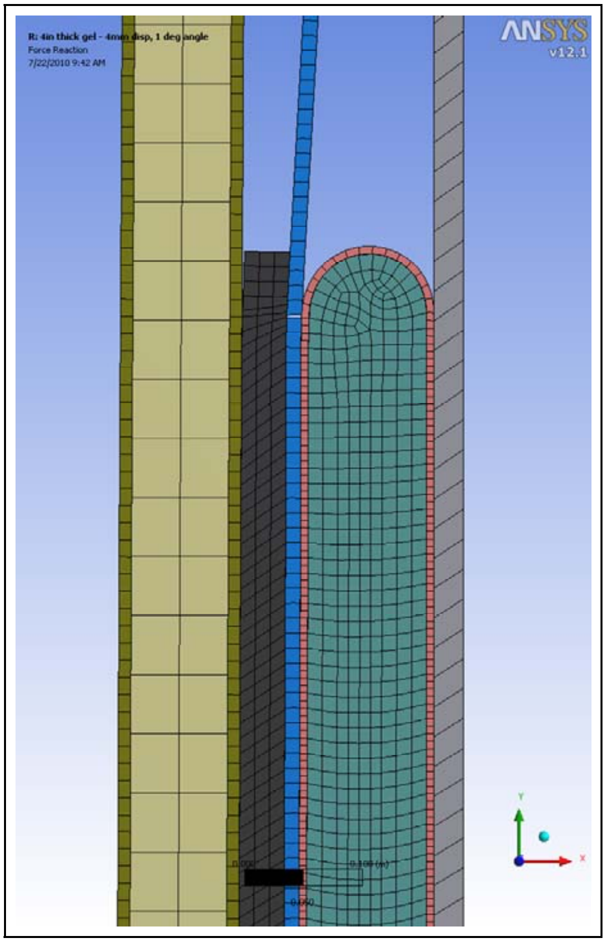


Figure 190. ANSYS Representation of CWP and Gripper Pads

6.11.5 Friction and Tension Layer

6.11.5.1 Function and Concept

The primary requirements for the friction layer are:

a. Contact the CWP uniformly and provide a high friction surface.

b. Hold the entire weight of the CWP. Since the pad behind the friction layer provides normal pressure but no shear, all the frictional force between the pipe and the friction layer ends up as tension at the top of the friction layer. This requires a reliable termination of the tension layer at the top that takes a high tension.

c. Withstand slight abrasion if the pipe slips over the surface.

d. Reasonably flexible to flow over bumps and irregularities in the CWP.

e. Operate in marine environment (seawater spray) without degradation for a one year lifetime.

The concept is:

a. A rubber surface provides the high friction needed with the pipe.

b. The vertical tension is carried by embedded Kevlar or steel tension members. These tension members take the entire vertical tensile load and provide high vertical stiffness, very low elongation. Kevlar is most likely preferred insert.

c. The vertical shear between the tension members and the rubber is low: nominally 12.5 psi, maximum 30 psi.

d. The tension members are terminated at top and bottom in an attachment that supports full tensile capability of the tension layer. The tension members may be wrapped about a horizontal bar and secured to themselves with the whole termination coated in rubber. The design is changeable relative to the termination.

6.11.5.2 Friction and Tension Layer Analysis

Makai used an Excel spreadsheet to optimize the dimensions and characteristics of the friction and tension layers that are in direct contact with and supporting the cold water pipe. Figure 191 illustrates these components contacting the CWP both before and after taking the CWP weight. Each illustration shows the cold water pipe wall in contact with a thick rubber friction layer which is attached to a tension layer, a reinforced portion of this rubber sheet. In operation, the weight of the cold water pipe is transferred through the friction layer in shear to the reinforcement members in the tension layer.

Figure 191 illustrates how these components behave as the weight of the cold water pipe is carried by these gripper pads. As the gripper assumes the vertical load, the CWP drops relative to the tension layer and the friction layer distorts due to shear. This carries the shear load from the cold water pipe to the tension layer. At the same time there is a redistribution of tensions both in the cold water pipe and in the tension layer which affects their length. The tension layer picks up a load and thus stretches while the cold water pipe either sheds its tension or increases in tension (depending upon whether it is a lower or upper gripper) and thus both the tension layer and the cold water pipe lengths are changing.

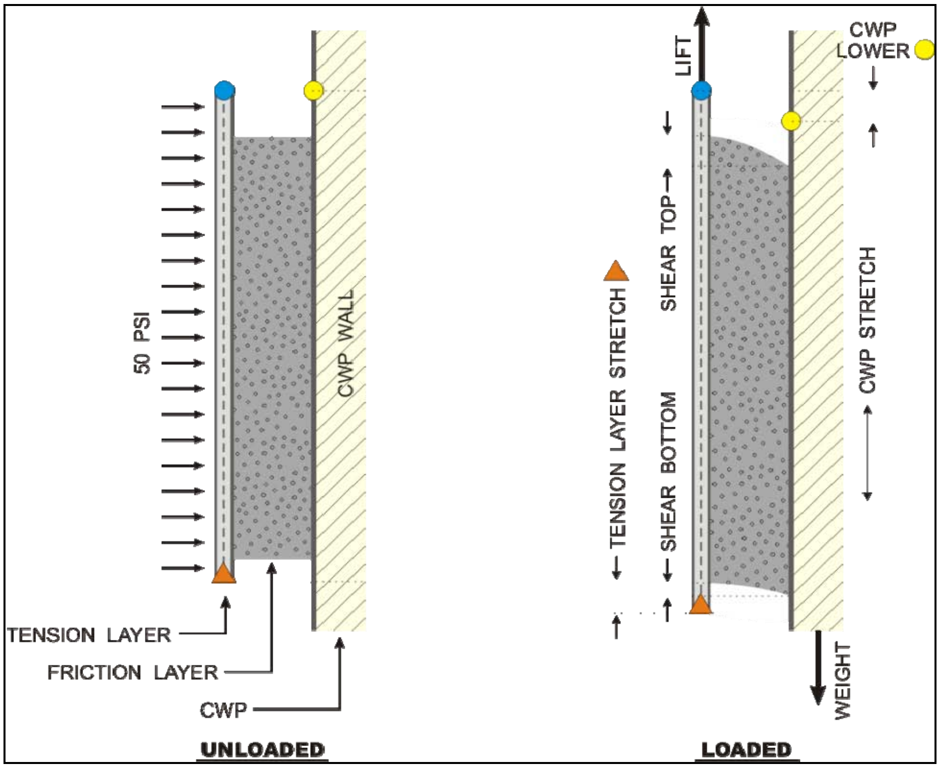


Figure 191. Gripper Pad and CWP Load Distortion

The friction layer is attached to the tension layer and is in direct contact with the cold water pipe. It can be severely distorted as it carries the load of the cold water pipe and the level of distortion is different at the top and bottom of the friction layer as illustrated in Figure 191. Note that as the gripper picks up the load of the cold water pipe, the cold water pipe drops slightly relative to the tension layer. This puts the friction layer in shear and thus transfers load to the tension layer. The tension layer elongates and this causes the shear distortion at the bottom of the friction layer to be smaller than at the top. Therefore there is a gradient in friction or shear between the gripper and the CWP from the top of the gripper to the bottom.

The factors governing the performance and frictional shear distribution of this system are:

- Tensions layer elasticity
- Friction layer thickness
- Friction layer shear modulus
- Cold water pipe elasticity

The upper gripper and bottom grippers are different relative to this pad and CWP relationship.

- The lower gripper always grabs onto a CWP that is fully tensioned. As it takes the load from the upper gripper, the pipe actually shrinks within the pad area.
- The upper gripper, however, is always attaching onto a non-tensioned CWP; as it picks up the load the pipe within the gripper stretches slightly.

- In addition, the lower gripper is hanging from a set of hydraulic rams that allow the gripper to gimbal or follow the pipe as the CWP twists due to current and platform motions. The upper gripper, however, is fixed relative to the platform and as the CWP twists, the pads on opposite sides of the gripper will see slight pipe movement and a shift in shear loads. On one side of the gripper the pipe wall will move down relative to the gripper pads and on the opposite side the pipe wall will move upward.

In the analysis that follows, both upper and lower grippers are individually analyzed. All the analysis is performed with the full weight of the 1,000 meter long CWP.

6.11.5.2.1 4 meter Lower Gripper Pad Analysis

Table 36 shows the dimensions and characteristics of the lower gripper pads. Total weight of the pipe is 807,000 lbs with a circumference of 521 inches results in a loading of 1,550 lbs per inch of circumference. The elasticity of the tension layer is characterized relative to the elasticity of the cold water pipe. In this particular case, the elasticity of the tension layer is 6.23 times that of the cold water pipe. This results in a 0.2 percent strain in the tension layer at the full load of 1,550 lbs per inch of circumference. The friction layer is 1 inch thick and has a coefficient of friction of 0.6 on the cold water pipe wall. At a normal load of 50 psi the maximum shear is thus 30 psi and the shear displacement of this 1 inch thick rubber is 0.375 inches at the maximum load. Once it reaches that displacement the rubber begins to slip on the CWP. The overall length of the gripper is 125 inches and our analysis breaks this up into multiple elements each 1.74 inches long.

The analysis also checked the natural frequency of the cold water pipe hanging within the gripper. Because of the elasticity in the tension layer and within the gripper friction layer, the overall pipe moves up and down slightly within the gripper. It is a classic mass-spring system. In this particular example, with the tension and friction layers described as above, the natural period of the full pipe is 0.16 seconds. This is a very short period and well outside the natural motions of the OTEC platform.

Figure 192 shows the shear distribution and loads in the tension layer and cold water pipe for the above example. The total load in the tension layer starts out at 1,550 lbs per inch and drops to zero lbs per inch from the top to the bottom of the gripper. Conversely the tension in the CWP goes from zero lbs per inch at the top of the gripper to the full load of 1,550 lbs per inch at the bottom of the gripper. The green curve shows the shear between the cold water pipe and the friction pad in lbs per square inch. Note that there is not a uniform shear between the top and bottom of the gripper. At the top the shear is approximately 18psi and near the bottom it is slightly less than 10psi. The following graph, Figure 193, illustrates the reason for this non-uniformity.

Table 36. 4m Lower Gripper Tension and Friction Layer Loads, Characteristics

4m Bottom Tension Layer Loads:			
CWP			
CWP Load	806,884	lbs	
Circumference	521	in	
wt/inch	1549	lbs/inch	
EA	2.5E+09	lbs	
k	4.8E+06	lbs/in/in	for 1" circumference
E	4.18E+06	psi	
Tension Layer			
Elasticity	6.23	multiplier of CWP	
k	7.75E+05	lbs/in/in	for 1" circumference
	0.200%	Strain at full load	
	1.00%	Strain at breaking	
	5.0	Estimated Safety Factor	
Friction Layer			
Rubber t	1	inch	
Rubber G	80	psi/in/in	80
Mu	0.6		
Normal Load	50	psi	
Max Shear	30	psi	
Max Disp:	0.375	inch	before slipping
Gripper Length			
Length	125	inch	
Increment	1.74	inch	
Nat Period, sec:	0.16		

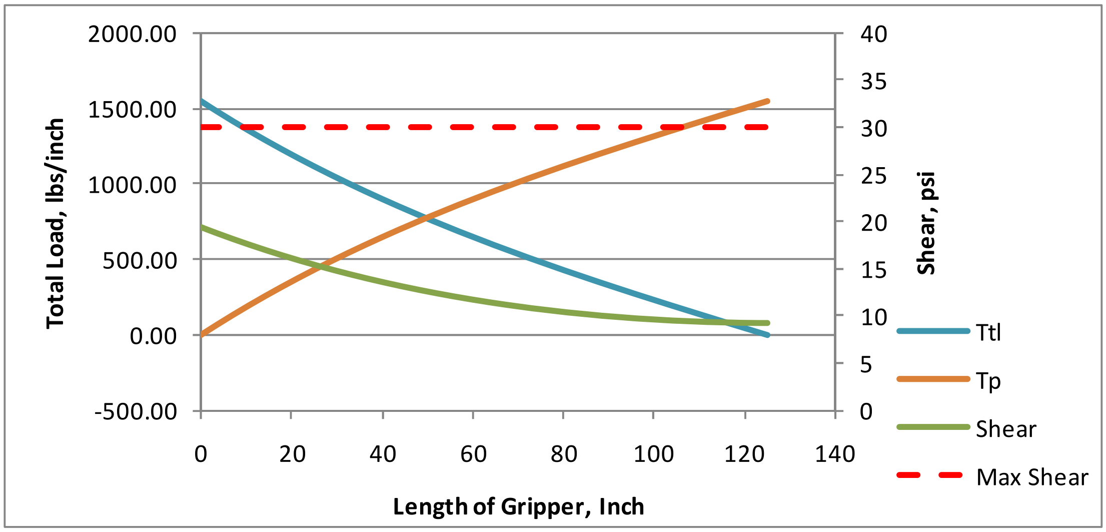


Figure 192. Tension in CWP, Total Load and Shear of Gripper Pads

Figure 193 shows the vertical deflection or stretch in both the cold water pipe and the tension layer. Because this is the bottom gripper, it attaches to a fully tensioned pipe. As it take the load off the upper gripper, the tension in the pipe between the grippers drops and the length of the pipe within the lower gripper shrinks. As a result the red line in this curve shows that the CWP settles within the gripper nearly 0.25 inch at the top of the gripper and somewhat less than that further down within the gripper. Conversely, the tension layer stretches considerably. At the top the tension layer does not move relative to the gripper but near the bottom it is stretched nearly 0.1 inch. The difference between these two curves is the relative displacement that is carried as shear within the friction layer so the green line curve in Figure 192 above is directly proportional to the difference between these two displacement curves for the cold water pipe and tension layer deflections.

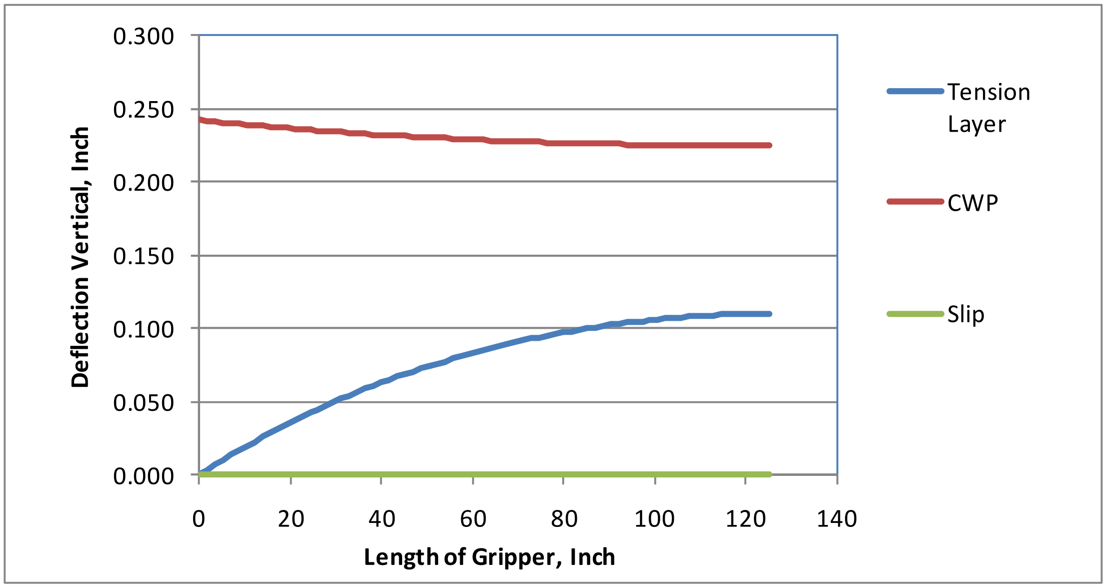


Figure 193. Relative Movement of Tension Layer and CWP over Length of Gripper Pad

This analysis was used to select the friction layer thickness and the tension layer elasticity that provides an adequate performance for the overall gripper. Figure 194 illustrates the frictional shear distribution within a gripper pad for various friction layer thicknesses. The 1 inch value is the nominal selected value was a compromise between keeping the shear distribution relatively flat and not being excessively thick. Note the difference between the curves for 1 inch thick and 2.25 inches thick are not significant.

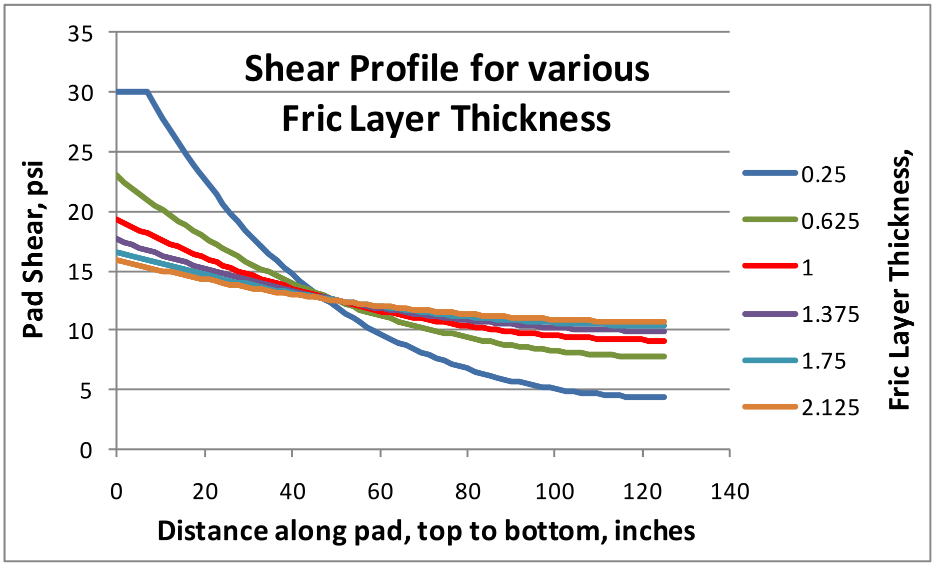


Figure 194. Frictional Shear Profile for Various Friction Layer Thicknesses

In addition, sensitivity analysis was performed on the tension layer elasticity and this is shown in Figure 195. Elasticity is characterized as the total strain in the tension layer at the maximum working load. The Red Line is the nominal design value with a 0.2 percent strain which is typical of a Kevlar fabric. Steel fabrics could achieve a .05 percent strain. Note that materials considerably more elastic than Kevlar result in very severe shear variations which would be unacceptable for the gripper design.

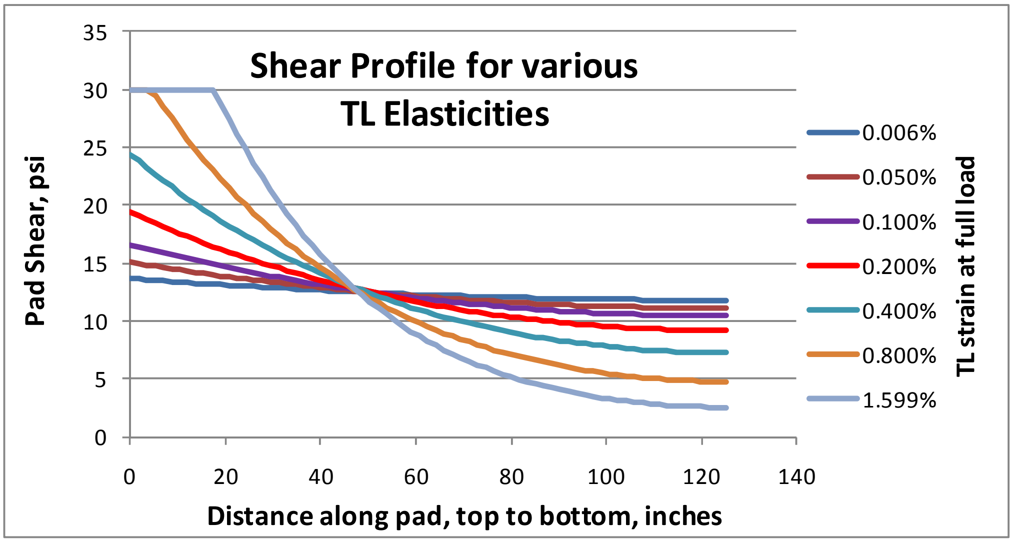


Figure 195. Frictional Shear Profile for Varying TL Elasticity (Stretch Under Full Load)

There is a relationship between tension layer elasticity and friction layer thickness and this is illustrated in Figure 196. Every point along the Blue Line results in a frictional shear profile identical to the baseline shear profile shown on the previous charts. Therefore a very stiff tension layer with a thin friction layer thickness would have the same performance in terms of frictional shear profile as a more elastic tension layer with a much thicker friction layer. The baseline design is shown on this curve. Moving to the left, the tension layer would need to be much stiffer and that could only be achieved by using steel tension members. Conversely, by moving to the right the rubber thickness becomes very thick and the overall pad would also become quite stiff in bending.

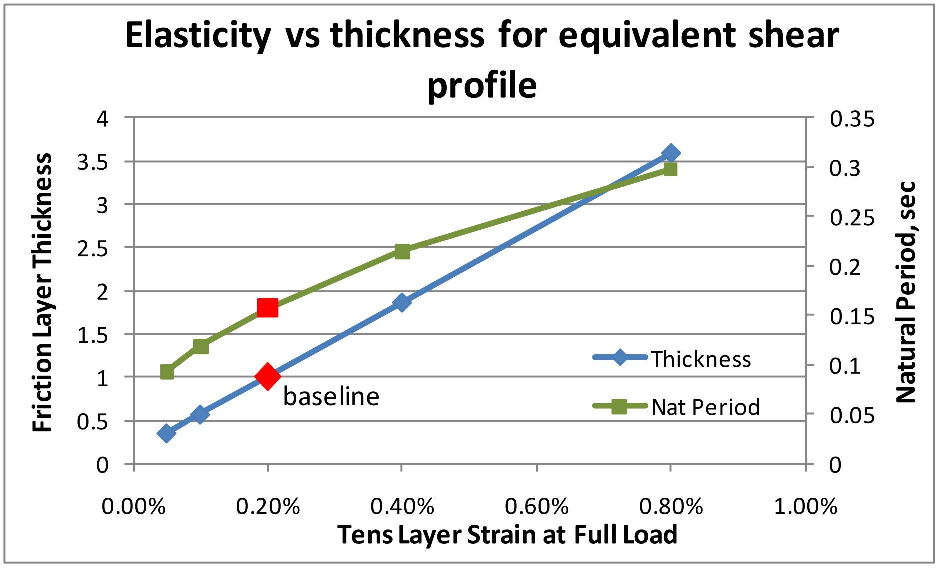


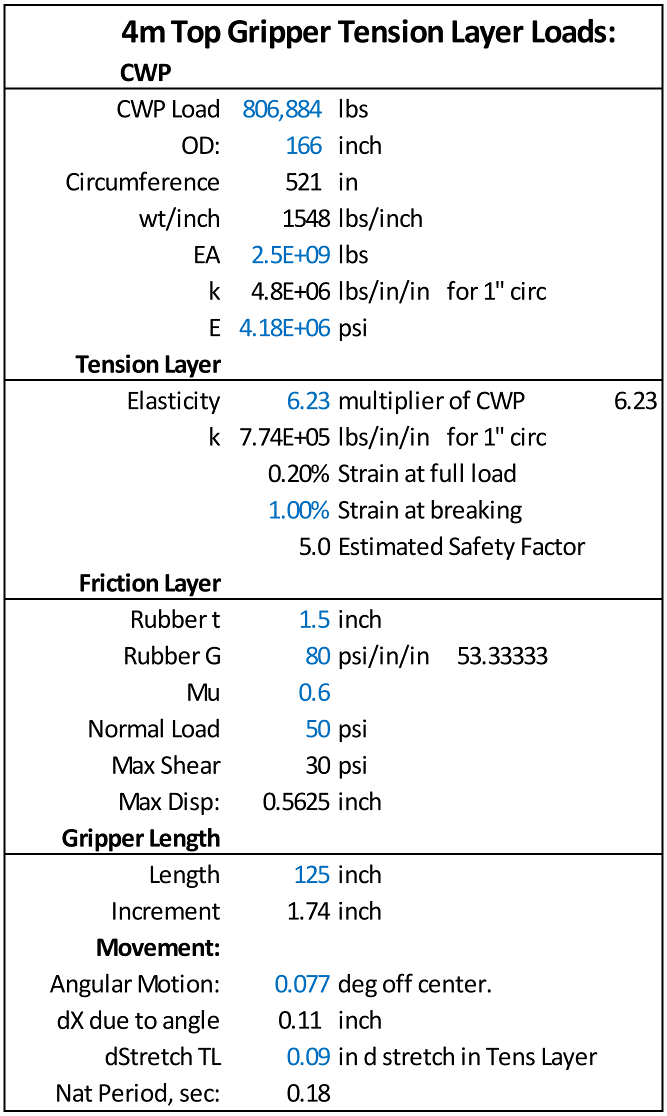
Figure 196. Elasticity vs. Friction Layer Thickness and CWP/Gripper Natural Periods

6.11.5.2.2 4 meter Upper Gripper Pad Analysis

The same analysis was performed on the upper gripper pads. The upper gripper is different because the pipe can rotate slightly within a gripper and the upper gripper always grabs onto a pipe that is not tensioned in advanced.

Table 37 shows the characteristics of the tension layers and friction layers in the upper gripper. The cold water pipe characteristics and the tension layer characteristics are identical to that in the lower gripper. The only difference for the upper gripper is that the friction layer is 1.5 inches thick as opposed to 1 inch thick on the lower gripper. In addition, with the upper gripper there is the possibility of having the pipe move slightly within the gripper. The pipe can move during storm conditions 0.077 degrees off of vertical. This results in the wall of the CWP moving upward 0.11 inch on one side of the gripper and 0.11 inch downward on the opposite side. This results in differential pad load sharing between these opposite pads.

Table 37. 4m Upper Gripper Tension Layer and Friction Layer Loads and Characteristics



4m Top Gripper Tension Layer Loads:				
CWP				
CWP Load	806,884	lbs		
OD:	166	inch		
Circumference	521	in		
wt/inch	1548	lbs/inch		
EA	2.5E+09	lbs		
k	4.8E+06	lbs/in/in	for 1" circ	
E	4.18E+06	psi		
Tension Layer				
Elasticity	6.23	multiplier of CWP		6.23
k	7.74E+05	lbs/in/in	for 1" circ	
	0.20%	Strain at full load		
	1.00%	Strain at breaking		
	5.0	Estimated Safety Factor		
Friction Layer				
Rubber t	1.5	inch		
Rubber G	80	psi/in/in	53.33333	
Mu	0.6			
Normal Load	50	psi		
Max Shear	30	psi		
Max Disp:	0.5625	inch		
Gripper Length				
Length	125	inch		
Increment	1.74	inch		
Movement:				
Angular Motion:	0.077	deg off center.		
dX due to angle	0.11	inch		
dStretch TL	0.09	in d stretch in Tens Layer		
Nat Period, sec:	0.18			

Figure 197 illustrates the deflection in both the cold water pipe and the tension layer for the upper gripper. This graph is very similar to that of the lower gripper except that the slope of the cold water pipe deflection is opposite.

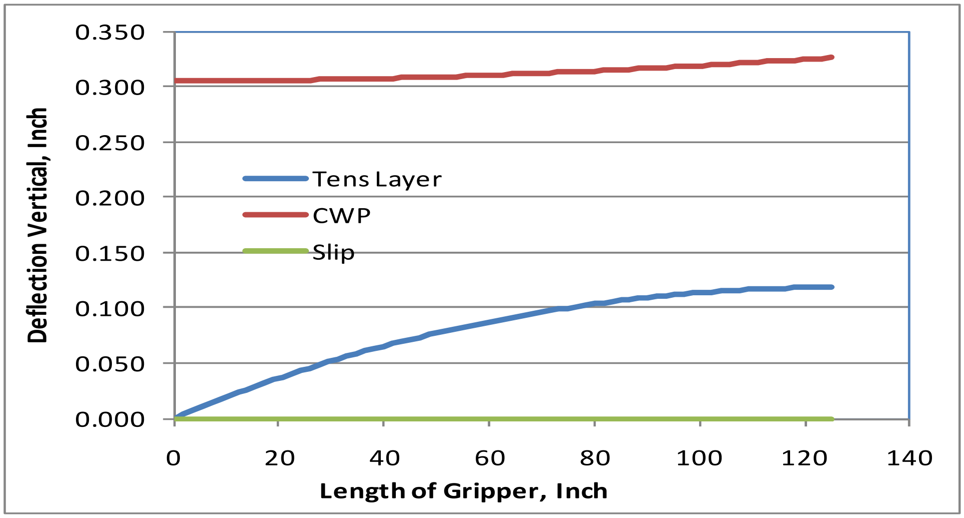


Figure 197. Upper Gripper CWP and TL Relative Movement

Figure 198 shows the frictional shear distribution for the upper gripper. There are three shear distribution curves. The middle curve is the nominal value and the upper and lower curves are the extreme values when the pipe is moving within the gripper. When one pad on one side of the gripper has a shear distribution equal to the maximum shear curve the pad on the opposite side of the gripper has a shear distribution equal to the minimal shear distribution.

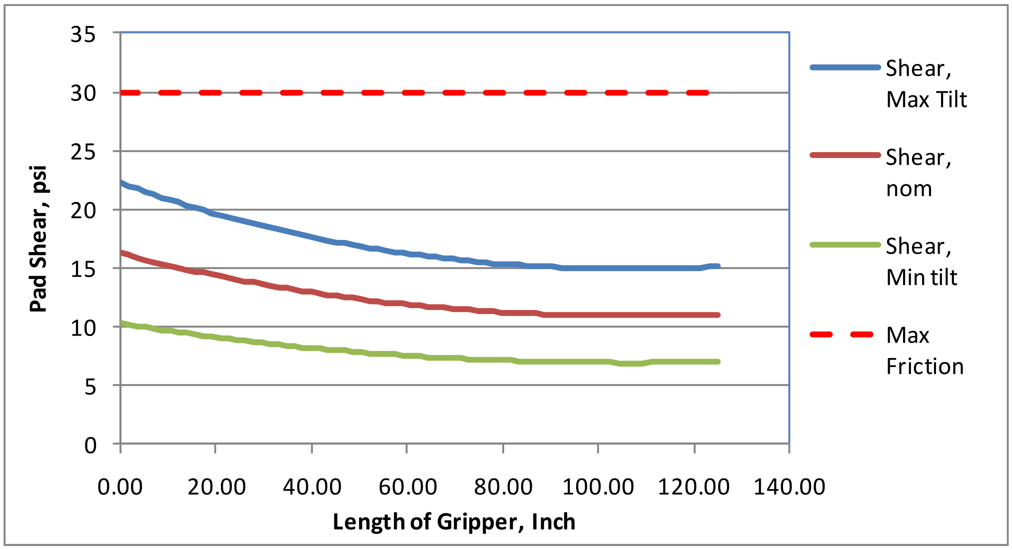


Figure 198. Lower Gripper Shear Distribution Variation

Figure 199 shows the tension distribution in the tension layer for the nominal loading conditions and for the maximum and minimum loading conditions occurring when the pipe is twisting within the gripper. Thus the maximum tension in the tension layer oscillates between 1,000 and 2,100 lbs per inch. We should note that this is an extreme condition which is unlikely to occur in practice. The loading conditions applied are survival conditions under which the operators would most likely have both grippers clamped on the CWP. However, the gripper could perform under these conditions.

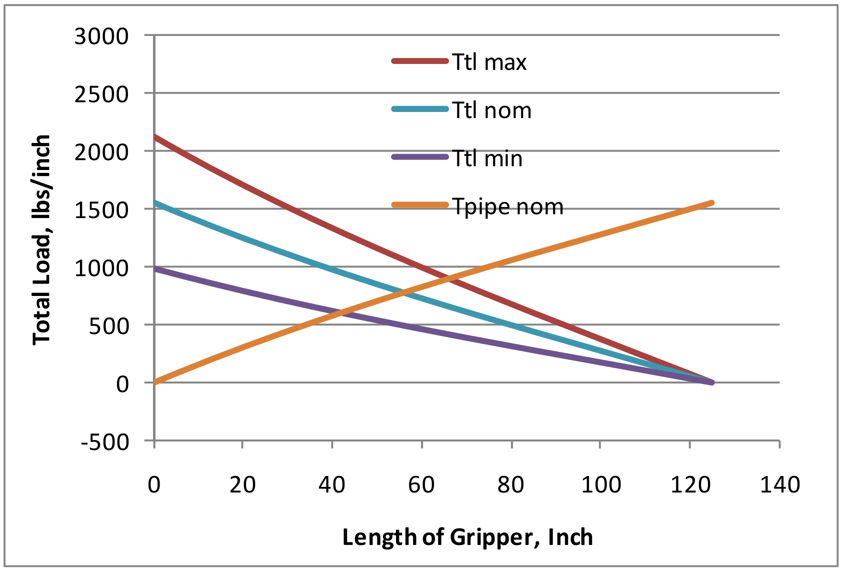


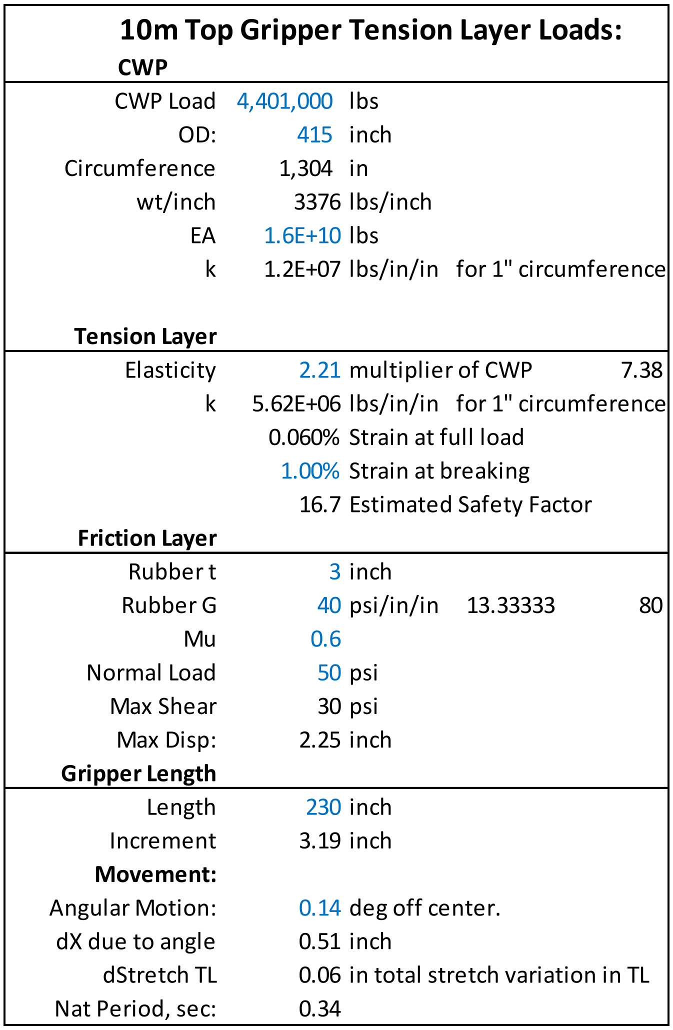
Figure 199. Tension in Tension Layer, CWP Oscillates within Gripper

6.11.5.2.3 10 meter CWP

Makai also performed an analysis optimizing the 10m gripper pad's tension layer and friction layer characteristics. This analysis was done in parallel with the final design of the 4m gripper.

The upper gripper and characteristics are shown in Table 38 below. The total cold water pipe load is 4.4 million lbs and with a circumference of 415 inches this results in a weight per inch of circumference of nearly 3,400 lbs per inch. The tension layer needs to be very stiff in order to minimize the peak shear load of between the friction layer and the cold water pipe. In this case the tension layer has an elasticity of 0.1 percent at full load. This is equivalent to a Kevlar reinforced fabric with a safety factor between 9 and 10. The friction layer is a two inch thick natural rubber with the same properties as the rubber used in the four meter design. With these two characteristics, the distribution of the frictional shear between the cold water pipe and the friction layer is shown in the graph in Table 38 below. The maximum shear is approximately 18 psi and the minimum shear is about 13 psi.

Table 38. 10m Gripper Pad Loading Key Characteristics



10m Top Gripper Tension Layer Loads:				
CWP				
CWP Load	4,401,000	lbs		
OD:	415	inch		
Circumference	1,304	in		
wt/inch	3376	lbs/inch		
EA	1.6E+10	lbs		
k	1.2E+07	lbs/in/in	for 1" circumference	
Tension Layer				
Elasticity	2.21	multiplier of CWP		7.38
k	5.62E+06	lbs/in/in	for 1" circumference	
	0.060%	Strain at full load		
	1.00%	Strain at breaking		
	16.7	Estimated Safety Factor		
Friction Layer				
Rubber t	3	inch		
Rubber G	40	psi/in/in	13.33333	80
Mu	0.6			
Normal Load	50	psi		
Max Shear	30	psi		
Max Disp:	2.25	inch		
Gripper Length				
Length	230	inch		
Increment	3.19	inch		
Movement:				
Angular Motion:	0.14	deg off center.		
dX due to angle	0.51	inch		
dStretch TL	0.06	in total stretch variation in TL		
Nat Period, sec:	0.34			

Because of the elasticity of the tension layer and the friction pad and the very large mass of the cold water pipe, there is a natural oscillation for this system. Natural period is 0.22 seconds with the full weight of the cold water pipe, and with a natural period less than 0.22 seconds when the pipe is not fully fabricated. This is conservatively higher frequency than the natural frequency of the platform or waves and is therefore not an issue.

The upper gripper has an additional set of criteria in that it must accommodate a pipe that is rotating within the gripper due to current loads on the CWP and motions of the platform. The table below shows the characteristics of the cold water pipe, tension layers and the friction layers as well as the anticipated movement of the CWP within this gripper. This CWP is anticipated to move as much as 0.14 degrees off center with a net result that the pipe relative to the gripper pad moves up and down slightly over half an inch. This causes an oscillation in shear at the extreme opposite pads in line with this oscillation and these are shown in Figure 200. The nominal shear distribution shows that the shear between top and bottom of the gripper pad is fairly flat and nearly 15 psi when adding the oscillatory movement of the pipe within the gripper the shear loads go up and down about this nominal value that is shown in Figure 200. This relatively flat distribution and well behaved performance even with a oscillating CWP has only been achieved by having a very thick friction layer (3 inches) with a rubber that has half the shear modulus as the rubber used for the 4m CWP and by having a tension layer that is considerably stiffer than used in the 4m CWP. This may be a difficult or expensive design to achieve for the 10m CWP. A solution to this issue is to simply allow the upper gripper to gimbal approximately 0.5 degree in either direction and then the upper gripper would behave very much like the lower gripper and could be designed with thinner pads and less elastic rubber. This is an economic tradeoff that should be done at the time of the 10m gripper design.

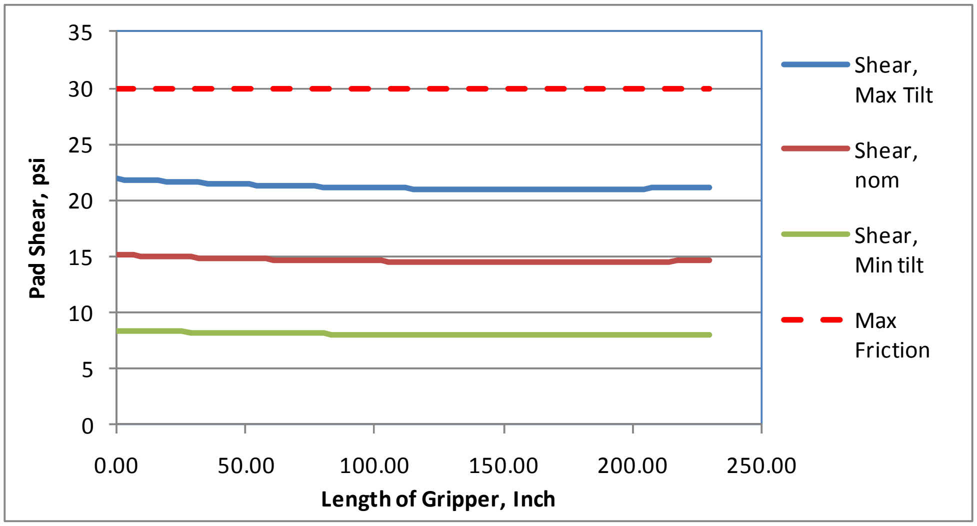


Figure 200. Shear Distribution, 10m Upper Gripper Pads, Extreme Pad Characteristics

6.11.5.3 Reinforcement

As shown above, the elasticity of the tension layer is a critical variable. Table 39 lists the tension layer reinforcement candidates and Figure 201 depicts fabric elasticity testing. Various tension layer reinforcement materials have been evaluated. Kevlar was an initial first choice and was selected for the 1/20th scale model test (see section 6.15). However, subsequent tests of actual fabric and bonding tests with the Stockton Natural Rubber all resulted in unsatisfactory elasticity or bonding strength. Use of high strength steel wires is the final design concept for both the 4m and 10m grippers. As a balance between allowable elasticity and desired ultimate safety factor, steel is a desirable candidate as both criteria are met at nearly the same quantity of steel wire. This design includes a performance specification of the tension layer specifying the allowable elasticity and loads.

Termination of the rubber layer is through a conventional bead (similar to those on tires) with the wire wrapped around the bead. The fabrication of this large reinforced rubber product is part engineering and part art form with each manufacturer approaching the fabrication differently. As a result, we have approached this design as a performance specification. Loads and tests have been specified. The specifications are in the appendix.

Table 39. Tension Layer Reinforcement Candidates

						Limiting Condition				
Material	Tensile Modulus	Tensile Strength	Elongation at Breakin	Density	Cost,	Limited by which constraint	Tensile stress at limiting condition	Area required at limiting condtion*	Tensile strain at limiting condition	SF at limiting condition
	10^6*psi	10^3*psi	%	oz/in^3	$/oz		psi	in^2	%	unitless
DuPont Technical Guide										
Kevlar 29	10.20	424	3.6	0.83	4.74	Strain	47,111	0.074	0.46	20.8
Kevlar 49	16.30	435	2.4	0.83	4.74	Strain	48,333	0.046	0.30	13.3
S-Glass	12.40	665	5.4	1.44	1.7	Strain	73,889	0.060	0.60	26.8
E-Glass	10.50	500	4.8	1.49	0.75	Strain	55,556	0.071	0.53	23.8
Steel Wire	29.00	285	2	4.5	0.18	SF	31,667	0.047	0.11	9.0
Nylon-66	0.80	143	18.3	0.66		Strain	15,889	0.938	1.99	89.4
Polyester	2.00	168	14.5	0.8		Strain	18,667	0.375	0.93	42.0
HS Polyethylene	17.00	375	3.5	0.56		Strain	41,667	0.044	0.25	11.0
High-Tenacity Carbon	32.00	450	1.4	1.04	2.71	SF	50,000	0.030	0.16	9.0
Hexcel Product Specification										
Carbon Fiber Hexcel AS4	33.00	647	1.8	0.578	3.54	Strain	71,889	0.023	0.22	9.8
Carbon Fiber Hexcel IM10	44.00	1010	2.1	0.578	3.54	Strain	112,222	0.017	0.26	11.5

Figure 201. Testing Elasticity of Kevlar Fabric

6.11.5.4 Friction and Tension Layer Characteristics

The key characteristics for the tension layer are:

a. Height: 18.5 feet with 16.5 feet in contact with the CWP, 1-2 feet top and bottom attachment length.

b. Width: 3.5 feet

c. Curvature: pre-formed about an 83 inch radius.

d. Thickness: as necessary: 1 inch (lower gripper) and 1.5 inch (upper gripper) pure rubber layer plus a reinforced layer with thickness as needed to obtain stiffness and strength given below.

e. Normal pressure: 50 psi

f. Average rubber shear over full surface: 12.5 psi. Max shear 30 psi.

g. Vertical tension: Linearly varies from 200 lbs/inch to 2500 lbs/inch max.

h. Vertical tension at yield: 9x nominal load safety factor min – 14,000 lbs/inch minimum.

i. Horizontal tension: 500 lbs/inch nominal; 2x safety factor = 1000 lbs/inch.

j. Vertical elasticity: Very stiff: <=0.2% strain at 1550 lbs/inch load.

k. Rubber compound: Makai has tested a natural rubber with the characteristics shown in Table 40. The rubber compound must have a high coefficient of friction on the FRP pipe. Any final compound needs to be tested by Makai prior to its final selection.

Table 40. Rubber Friction Layer Characteristics

TEST	TEST NAME	TYPICAL RESULTS
ASTM D-412	**Tensile Strength**	**3400 psi**
ASTM D-412	**Elongation**	**580%**
ASTM D-412	**300% modulus**	**1375psi**
Durometer		**63+/-5 Shore A Scale**

6.11.6 Pressure Distribution Layer

6.11.6.1 Function and Concept

The gel bag key requirements are:

a. Transfers the squeezing force from the steel clamp to the back of the friction layer. The force is distributed over the surface of the pipe as an even pressure.

b. Withstand operational abrasion between the steel pad and the friction layer.

c. The skin keeps the gel constrained such that the radial stiffness of the overall pad is extremely high.

d. Operate in a marine environment (seawater spray) without degradation – lifetime one year.

e. Does not distort unacceptably when disengaged (bag is operating in air, above the water). No pot belly.

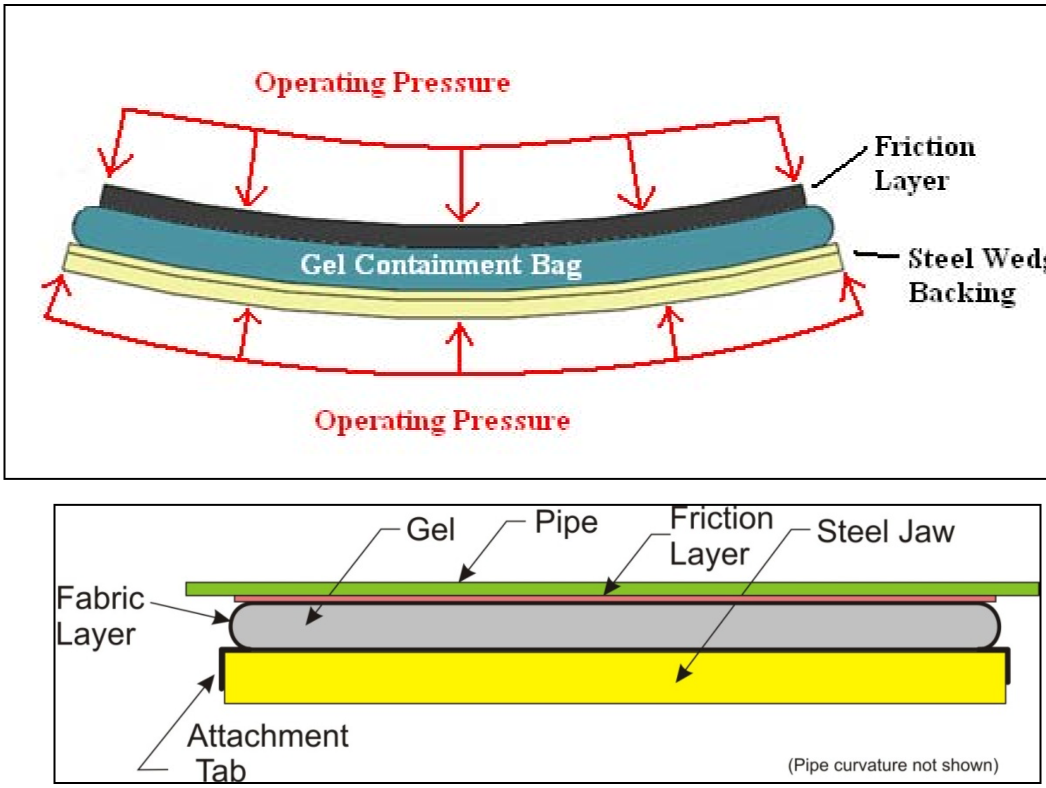


Figure 202. Gel Bag Concepts

The gel bag concept is shown in Figure 202. The key features are :

a. The bag contains a very low shear strength urethane that flows around pipe irregularities and pipe distortion.

b. The outer layer is a nylon or other fabric that:

  (1) prevents the gel from being extruded from the gap between the steel plate and the pipe,

  (2) adheres to the gel and supports the gel when the bag and pad are retracted from the pipe,

  (3) provides an attachment tab on all sides for connecting the pad to the steel wedge.

6.11.6.2 Gel Selection, Pressure Distribution

Early n the design process it was realized that a properly functioning gel bag must conform to the shape of the CWP including surface bumps and ratio distortion due to pressure. Also the gel bag must transmit the clamping pressure to the CWP and hold its shape when the gripper disengages from the CWP. A water filled bag, for instance, would behave beautifully when engaged on the CWP but all the water would run to the bottom of the bag when the gripper disengages. Therefore having a very low shear strength when engaged on the pipe and thus transmitting pressure equally is a desired characteristic but also having enough shear strength to support its own weight when disengaged is also required. A large number of concepts were considered and tested. These include:

a. Sand filled bags (sand actually carries a shear load when packed but not when loose)

b. Very soft rubber

c. Low strength urethane

d. Water with thickeners

e. A combination of thickeners and micro spheres to reduce weight and thus lower shear load when disengaged

f. Compartmentalized bag that limits water flow when disengaged.

The concept of the bag filler moving to the bottom of the bag when disengaged was given the nickname "Pot Belly". Therefore finding a bag filler or bag construction that has an even pressure distribution when engaged and does not Pot Belly when disengaged was the design challenge.

Most materials did not do well on the pressure distribution when engaged. Wide ranges of thickening agents combined with microspheres were tried. We tried mixtures that were much like the lightweight spackle that is common in hardware stores today. This is a microsphere plus thickener mixture that has a low shear strength but will move readily once disturbed. Semi-solid materials such as gels were initially discounted because the early FEA analysis of the CWP indicated that there were very large distortions of the CWP under pressure. Once the problems with the ANSYS analysis were found, the distortion was considerably smaller and more viscous gels became more practical. With the ANSYS correction, the focus concentrated on finding an appropriately soft urethane gel.

Figure 203 shows some of the soft urethane samples that were fabricated and then tested for shear strength. Small uniform cylinders were placed under a vertical load and the bulge in the cylinder was measured. By modeling the experiment in ANSYS, we could calibrate the shear strength values used in ANSYS to the experimental results. Matching the ANSYS model with the experimental results is illustrated in Figure 204. Soft urethanes can be mixed as a part A plus part B plus a plasticizer. The shear strength characteristics vary dramatically dependent upon the ratio between A: B: plasticizer. Typical experimental results are illustrated and plotted in Figure 205.

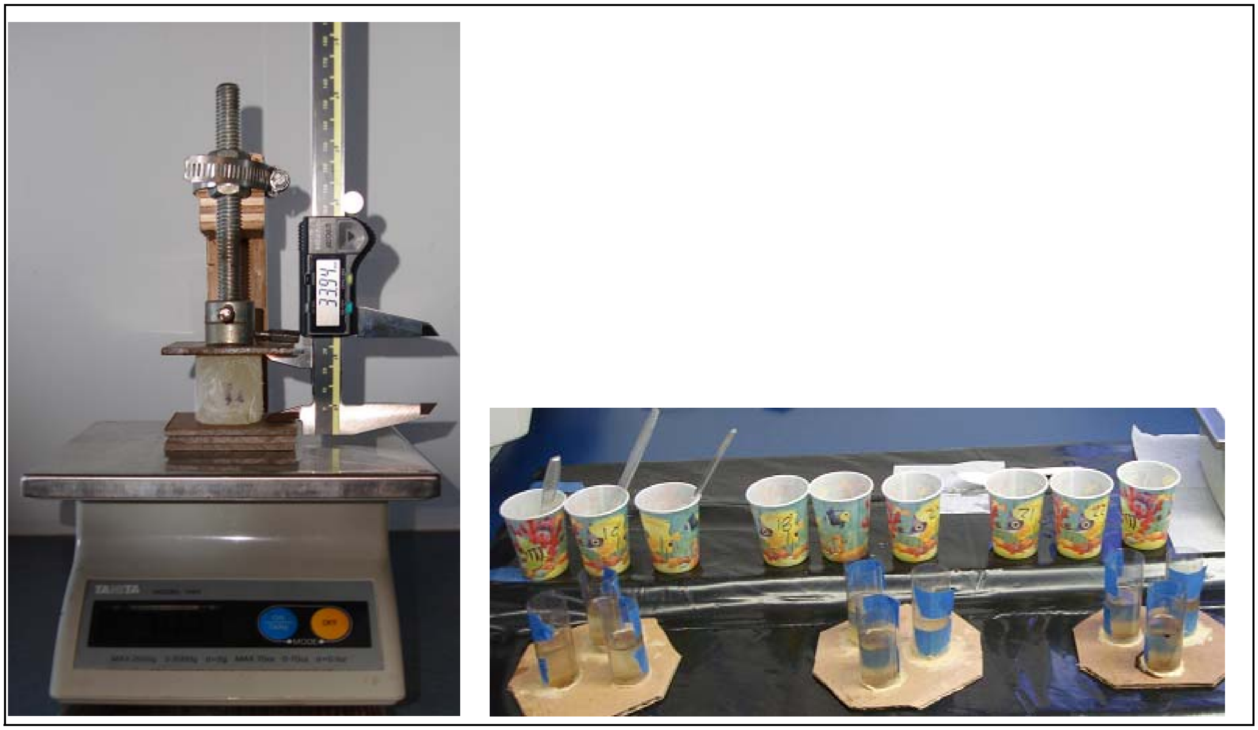


Figure 203. Mixing and Testing Various Urethane Compounds for Shear Strength

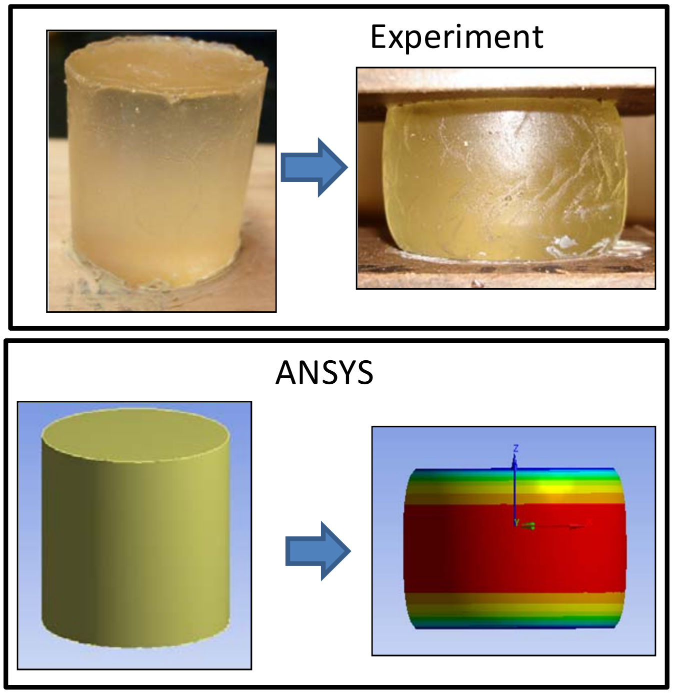


Figure 204. Matching Experimental Results with ANSYS Modeling

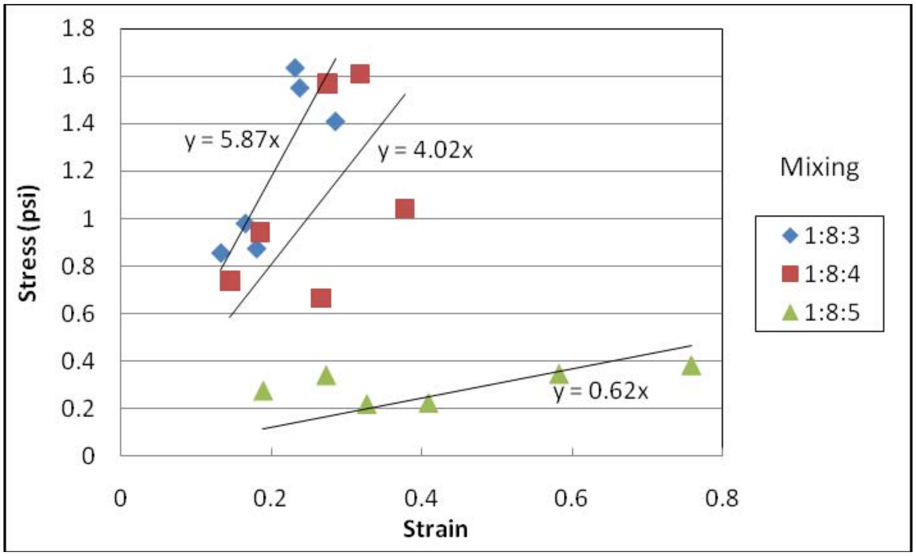
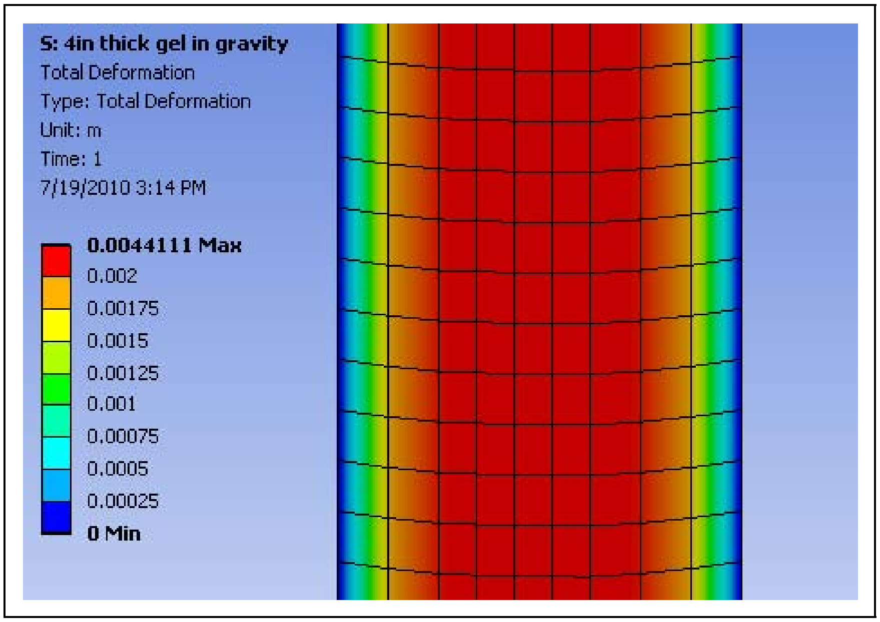


Figure 205. Typical Property Variations as a Function of Urethane Component Ratios

The success of any particular gel is dependent upon how it performs in a gel bag when engaged (even pressure distribution) and when disengaged (no Pot Belly). The tendency to Pot Belly was modeled in ANSYS by simply hanging the gel under its own weight between two nylon walls of the bag. The result for the final gel selected is show in Figure 206. There is minimal movement of the gel and thus no Pot Belly.



S: 4in thick gel in gravity
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
7/19/2010 3:14 PM

Figure 206. Maximum Flow of the Selected Gel Hanging Under Its Own Weight

To determine the pressure distribution when the gripper is engaged, the ANSYS analysis of the engaged pads that was previously discussed and illustrated in Figure 194 was used. This analysis used a water filled bag to show the level of movement and shear that would occur in a bag. By knowing the shear angles of the material along the walls of the bag, the dimensions of the bag and the shear characteristics of the gel, it is possible to compute the necessary pressure distribution within the gel bag to support the level of shear shown in ANSYS. The result is shown in Figure 207. The blue curve shows the pressure distribution when the gripper is first engaged but without a pipe load. The variation is due to the distortion of the CWP. A major distortion is near the center of the bag and therefore gel is squeezed from the two ends toward the center. Therefore the pressure at the top and bottom of the guide pad is higher than at the center. The second curve shows the additional distortion in the bag once the CWP load is carried by the gripper. In this case the tension layer additionally squeezes the top of the bag and further increases the gel pressure.

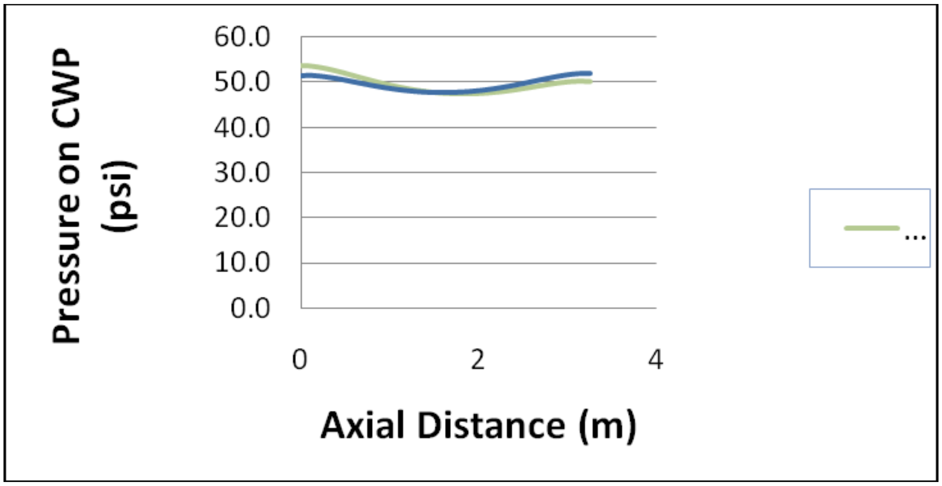


Figure 207. Pressure Distribution in the Gel in the 4m Gripper

6.11.6.3 Gel Bag Characteristics

Key gel bag characteristics are:

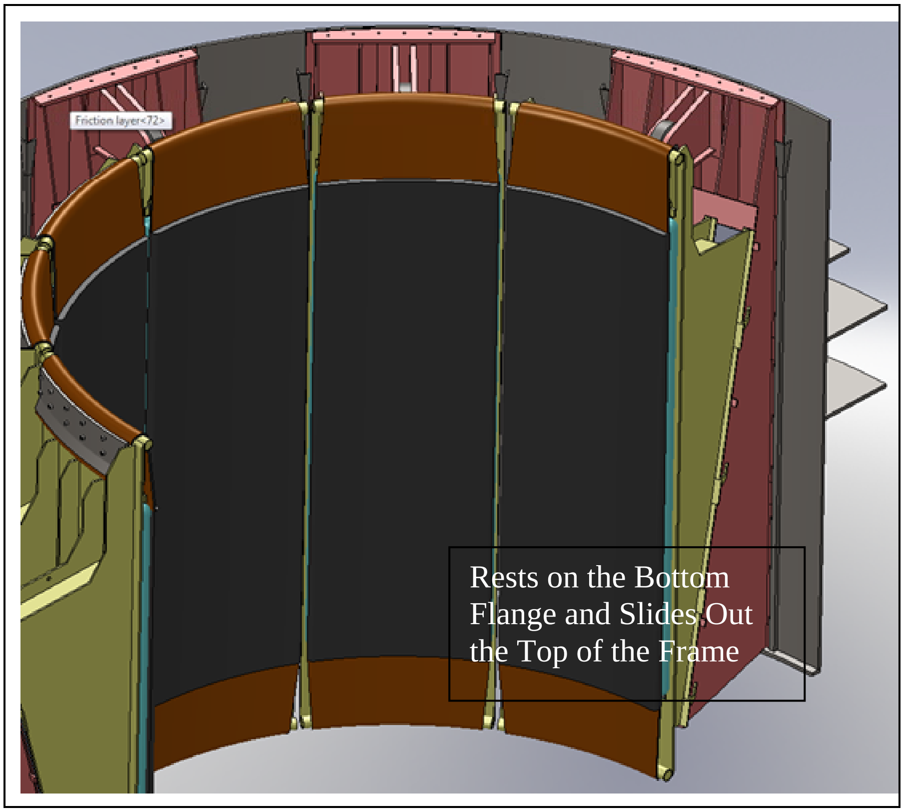
a. Height: 16.5 feet
b. Width: 3.5 feet
c. Thickness: 2 inch to 4 inch
d. Max working pressure: 50 psi
e. Weight: 700 to 1300 lbs depending upon thickness (sg=~1)
f. Vertical tension: support its own weight.
g. Fabric tension: max 100 lbs/inch working; 400 lbs/inch design minimum.
h. Fabric elasticity: nylon is satisfactory.
i. Gel Compound: polyurethane with plasticizer; OOO Shore Durometer softness range ~ 30 to 50

6.11.7 Wedges

The two wedges have been introduced in Section 6.11.1. These are further defined in the drawings in the appendix. These wedges are hydraulically driven and move the gripper pads radially in and out.

6.11.7.1 Wedge Configuration

The upper and lower wedges are identical although they attach to the gripper frames differently. Both slide into slots on the wall of the gripper frames although they are removed from the bottom of the upper gripper and from the top of the lower gripper. This arrangement allows replacement at sea for repairs and easy removal for the final lowering of the CWP. The upper wedge assembly hangs from a bolted flange connection at the top of the upper gripper. The lower gripper wedge assembly simply sits on a bottom flange, no bolts are needed. See Figure 208 and Figure 209.



Rests on the Bottom Flange and Slides Out the Top of the Frame

Figure 208. Lower Wedge Assembly

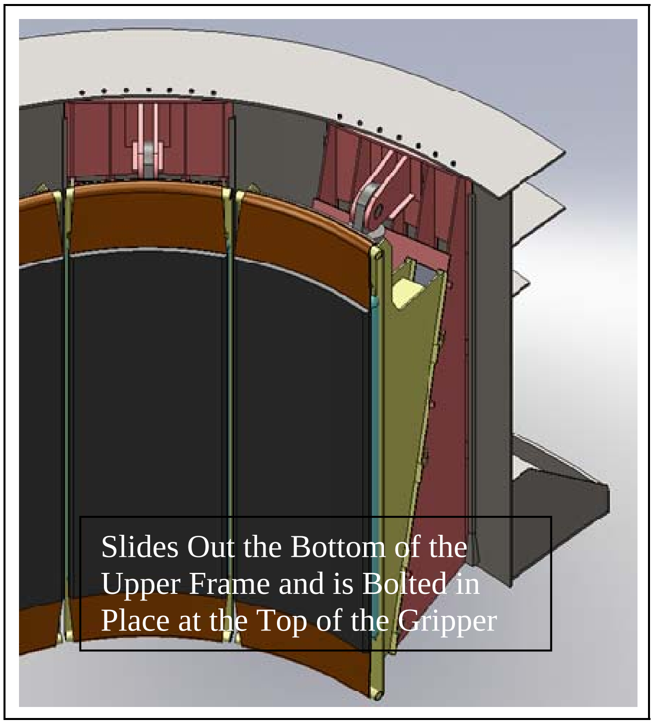


Figure 209. Upper Wedge Assembly

6.11.7.2 Wedge Friction

There is a bearing layer applied between the two wedges to minimize friction. A 3/8 inch sheet of UHMW polyethylene is between the two wedges. This coefficient of friction is less than 0.2.

6.11.7.3 Wedge Structure

The structure was analyzed in ANSYS with loading determined by the maximum loads defined in the dynamic coupled CWP and platform analysis described in Section 6.5.

The structure is fabricated of ASTM A36 mild (low carbon) steel. Ultimate strength is 58,000 psi and yield is 36,000 psi. Maximum stress was kept below 18,000 psi for a minimum safety factor of 2.0 on yield. Fatigue analysis was not performed since the functioning lifetime of these structures is only a few months during pipe fabrication. The ANSYS results are shown in Figure 210. The detailed structural report is in the appendix.

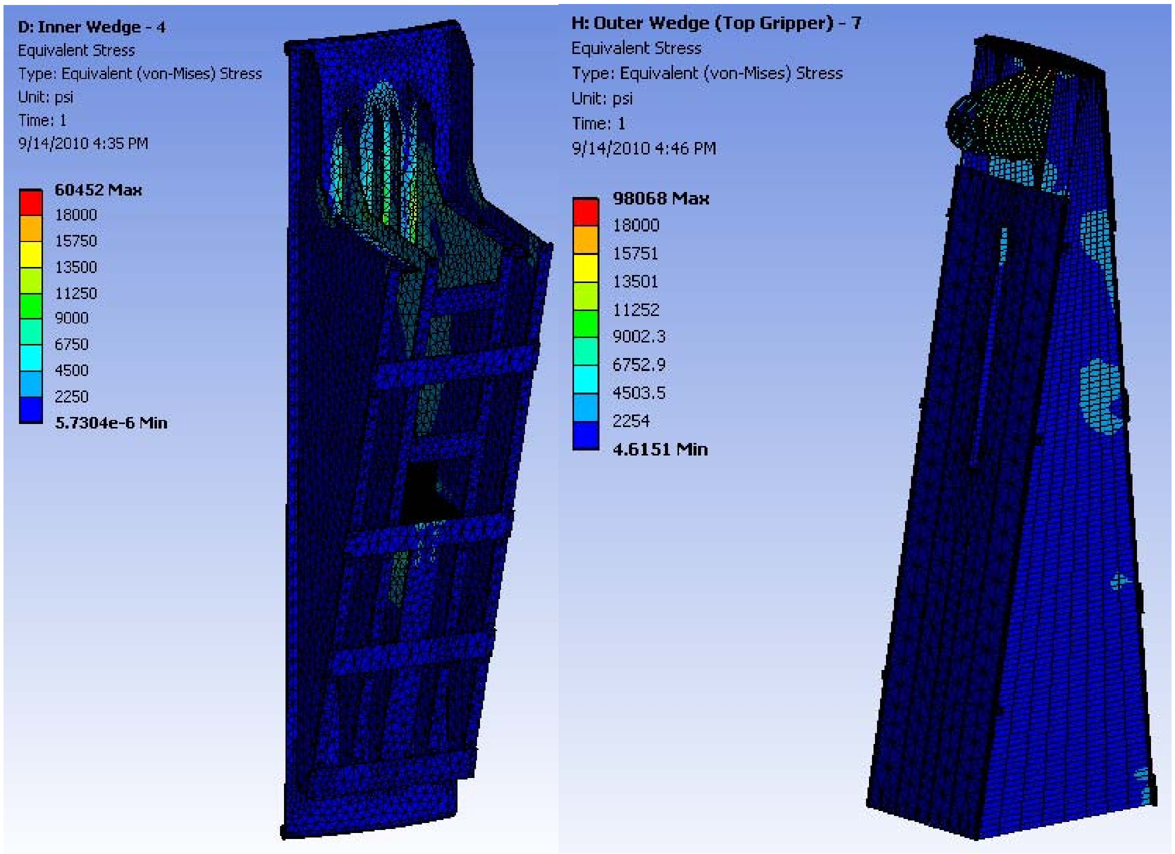


Figure 210. ANSYS Analysis of the Wedge Structure

All gripper and guide components, including the wedges, were calculated to have acceptable fatigue life by means of the following steps:

a. FE analysis was done using ANSYS to verify that the maximum Von Mises Equivalent stress is less than18,000 psi.

b. The cycles to failure was found to be ~100,000 for an alternating stress of 18,000 psi using the S-N curve shown in Figure 211. The fatigue data was taken from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1. Note that the assumption of an 18,000 psi alternating stress is very conservative as 18,000 psi is the maximum possible stress at any location and the loads during operation will not be fully cyclic.

c. The number of anticipated loading cycles near the same magnitude as the maximum load was found to be 30 events per hour. This was based on the time history data provided by the platform/CWP dynamic analysis for 500m of CWP during a 10 yr swell shown in Figure 212.

d. 100,000 cycles to failure divided by 30 cycles per hour gives an expected lifetime of 3,333 hours (~ 134 days) during 10 yr swell conditions. Since 10 yr swell conditions only last for less than 1 day, the safety factor for fatigue will be greater than 134 for all gripper and guide components.

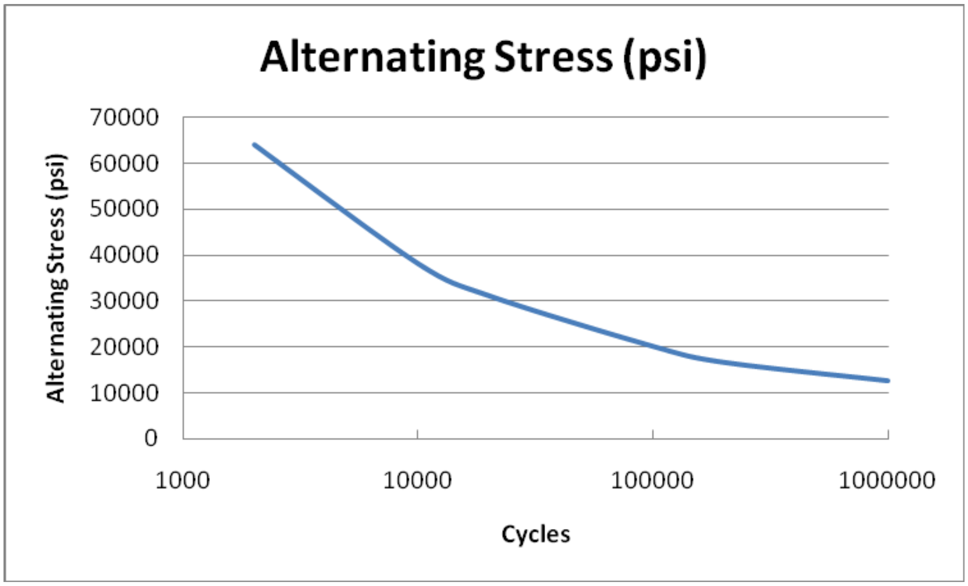


Figure 211. ASTM A36 Mild (low carbon) Steel S-N curve.

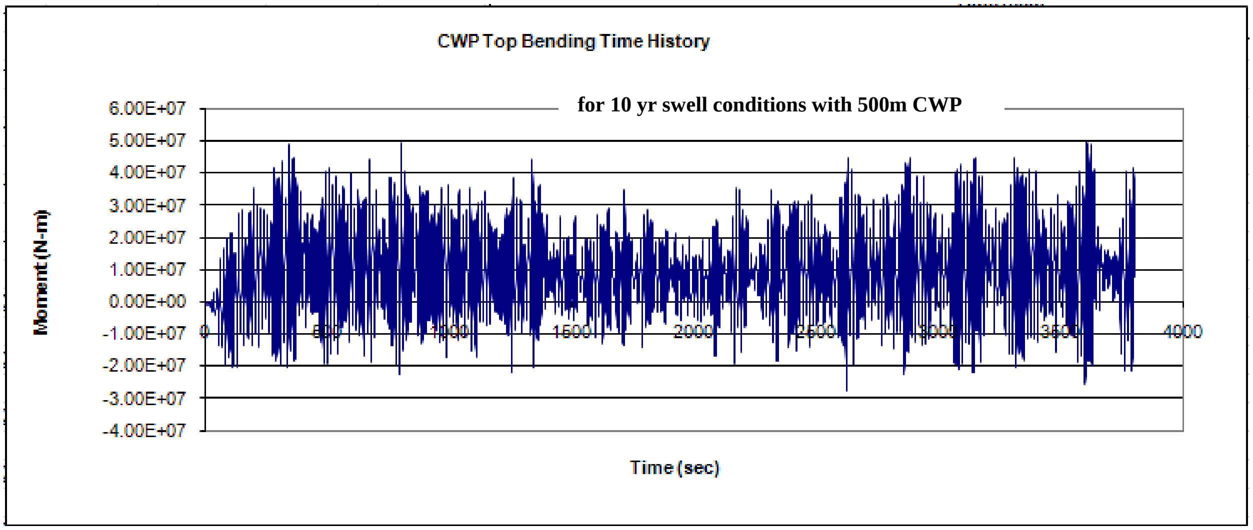


Figure 212. CWP Bending Moment Time History

6.11.7.4 Pipe Centering

The upper Gripper is rigidly attached to the lower deck of the platform. Unlike the lower Gripper, it can resist lateral loads. Therefore, it is the uppermost “guide” for centering and positioning the CWP within the pipe fabrication apparatus. This gripper acts somewhat like a 12-jaw chuck. Since each of the 12 jaws can be adjusted slightly relative to the other, the pipe position is adjustable.

The wedges are driven by hydraulic rams that are individually controlled with proportional valves and with position feedback on each ram. Thus the neutral position of each wedge can be programmed into the system PLC and all subsequent wedge movement can be relative to that neutral position. At start-up, the wedge and CWP positions will need to be accurately surveyed in order to set these relative neutral positions.

As the upper gripper engages and disengages the CWP, the pipe will move laterally. If there are large moments or shear in the CWP, and the upper griper is disengaged while the lower gripper is lowering the CWP, the pipe will no longer be centered in the upper Gripper structure. As the upper gripper re-engages the pipe, the wedges need to re-center the CWP. This can be done since each wedge is on an independent motion control. All the wedges will be driven inward at an equal speed and synchronized about the center of the gripper. Thus, if the pipe is off center, the wedges on one side will engage the pipe first and move it toward the center.

6.11.8 Gripper Structure

The Upper and Lower gripper structure is functionally described in Section 6.11.1. It is further defined in the drawings in the appendix. The grippers are functionally rigid cylinders supporting a set of 12 individual wedge and pad assemblies. The upper gripper sits on the lower deck of the platform at fixed points and the lower griper hangs below the upper gripper by 6 hydraulic rams.

The structure was analyzed in ANSYS with loading determined by the maximum loads defined in the dynamic coupled CWP and platform analysis described in Section 6.5.

The structure is fabricated of ASTM A36 mild (low carbon) steel. Ultimate strength is 58,000 psi and yield is 36,000 psi. Maximum stress was kept below 18,000 psi for a minimum safety factor of 2.0 on yield. Fatigue analysis was not performed since the functioning lifetime of these structures is only a few months during pipe fabrication. Typical ANSYS results are shown in Figure 213. The detailed structural report is in the appendix; this report provides the loading conditions and the results for each condition.

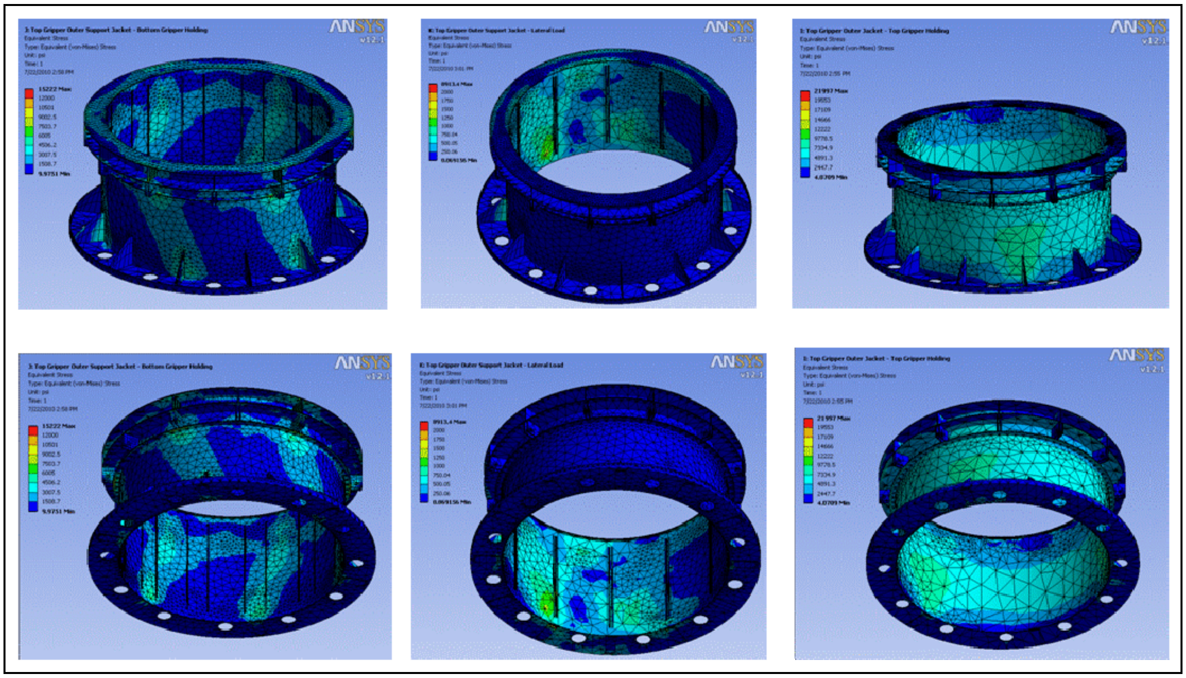


Figure 213. Typical Results of ANSYS Structural Analysis of Gripper Structure

primary purpose for the 1/20th scale testing.

6.11.8.1 Control Requirements

In satisfying the gripper requirements presented in Section 6.2; control is critical for the following:

a. Reliably support the CWP weight during all stages of fabrication.
   1. The final CWP length is 3280ft (1000m)

b. Reliably hold the CWP in shear currents, wave loads, and bending moments due to platform motion.
   1. Support CWP fabrication operations in 90% swell and wave conditions
   2. Accurately control the vertical placement of the CWP

c. Fabricate incrementally in ~11m segments
   1. Raise or lower and adjust pipe position accurately
   2. Hold, raise and lower the CWP from any point along its length

d. Eliminate damage the CWP
   1. Do not crush or collapse the CWP.
   2. Contact CWP at a uniform pressure; nominal 50 psi or below

e. Accommodate contingencies
   1. Be reversible

6.11.8.2 Sequencing

The control operates the wedges and the lifting rams. The most critical portion of the gripper control is the hand-off of the CWP load from one gripper to another and the engaging and disengaging of the grippers onto the pipe.

Figure 214 illustrates the engagement and disengagement of the lower gripper. The wedges are driven by the wedge ram. To have the wedge pad move radially inward and outward (and not up and down as it squeezes on the pipe), both the lifting rams and the wedge rams are moved together. The control system has feedback from every ram and can synchronize the movement of any ram combinations. Similarly, Figure 215 shows the engagement and disengagement of the upper gripper. Note that this operation involves the vertical movement of the CWP since the lower griper is supporting the load during this operation.

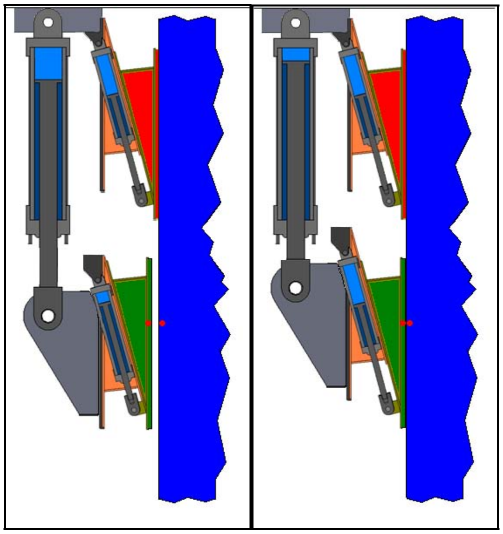
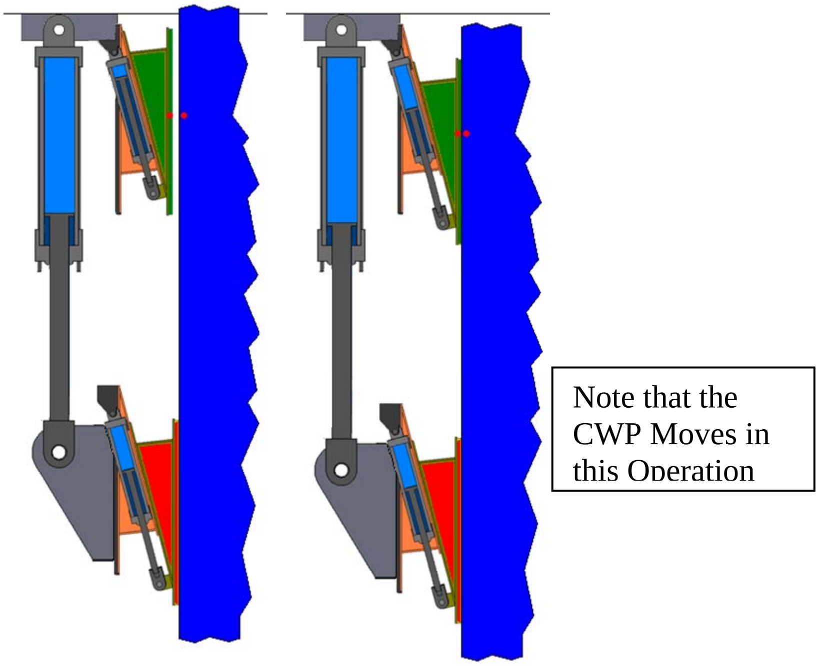


Figure 214. Engagement and Disengagement of the Lower Gripper



Note that the CWP Moves in this Operation

Figure 215. Engagement and Disengagement of the Upper Gripper

The sequence shown above is repeated many times during the pipe fabrication process. It takes 180 5.5m strokes to lower a 1000m long CWP. The hand-over cycle is illustrated in Figure 216. A more detailed description of this multi-step process is provided below.

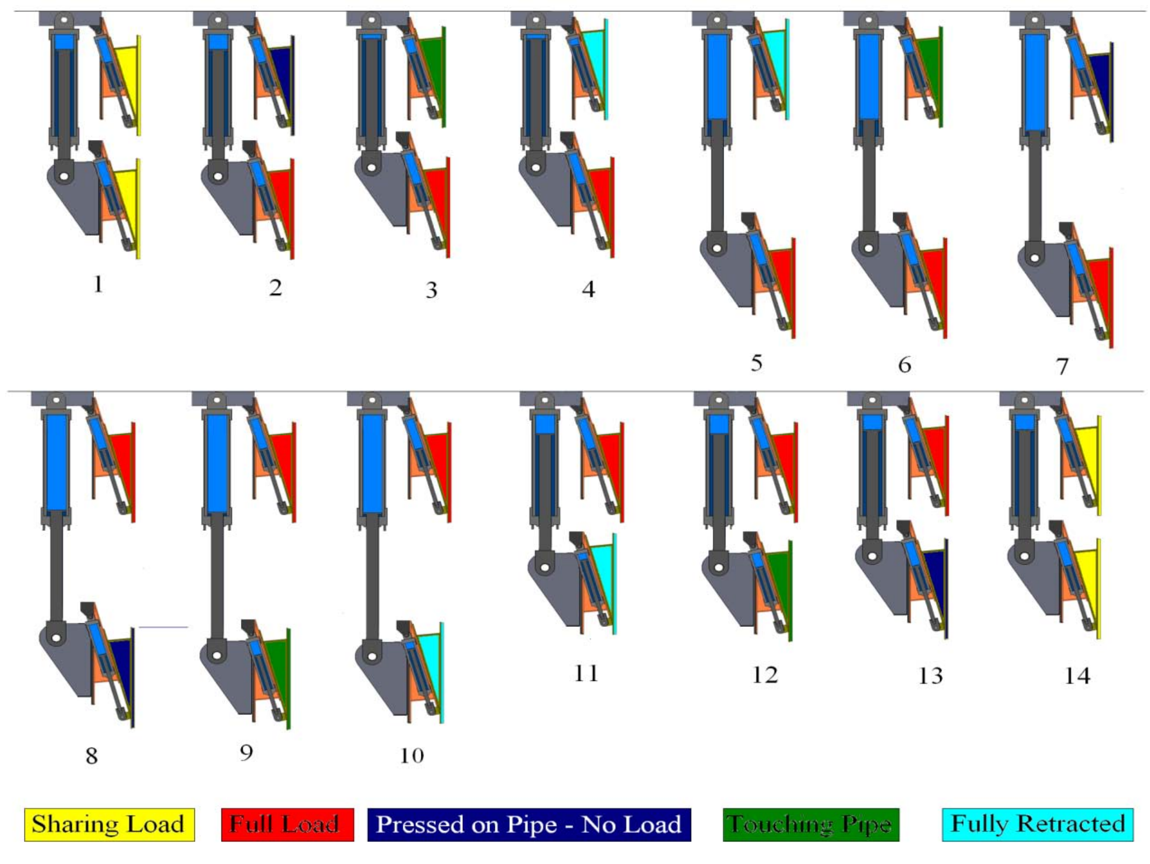


Figure 216. Hand-off Sequence between Grippers

6.11.8.3 Component and Sensor Definition and Location

Following are the component and sensor definitions and locations:

a. Components (as shown in Figure 217)
  - Upper Wedge – Inner steel wedge located on the Upper Gripper. Moves radially in toward the pipe at an angle.
  - Lower Wedge – Inner steel wedge located on the Lower Gripper. Moves radially in toward the pipe at an angle.
  - Upper Wedge Gel Bag – Bag containing soft polyurethane gel. Located on the Upper Wedge.
  - Lower Wedge Gel Bag – Bag containing soft polyurethane gel. Located on the Lower Wedge.
  - Upper Wedge Cylinder – Hydraulic cylinder that moves the inner wedge. Located on the Upper Wedge.
  - Lower Wedge Cylinder – Hydraulic cylinder that moves the inner wedge. Located on the Lower Wedge.
  - Lifting Cylinders – Hydraulic cylinders that raise or lower the Lower Gripper.

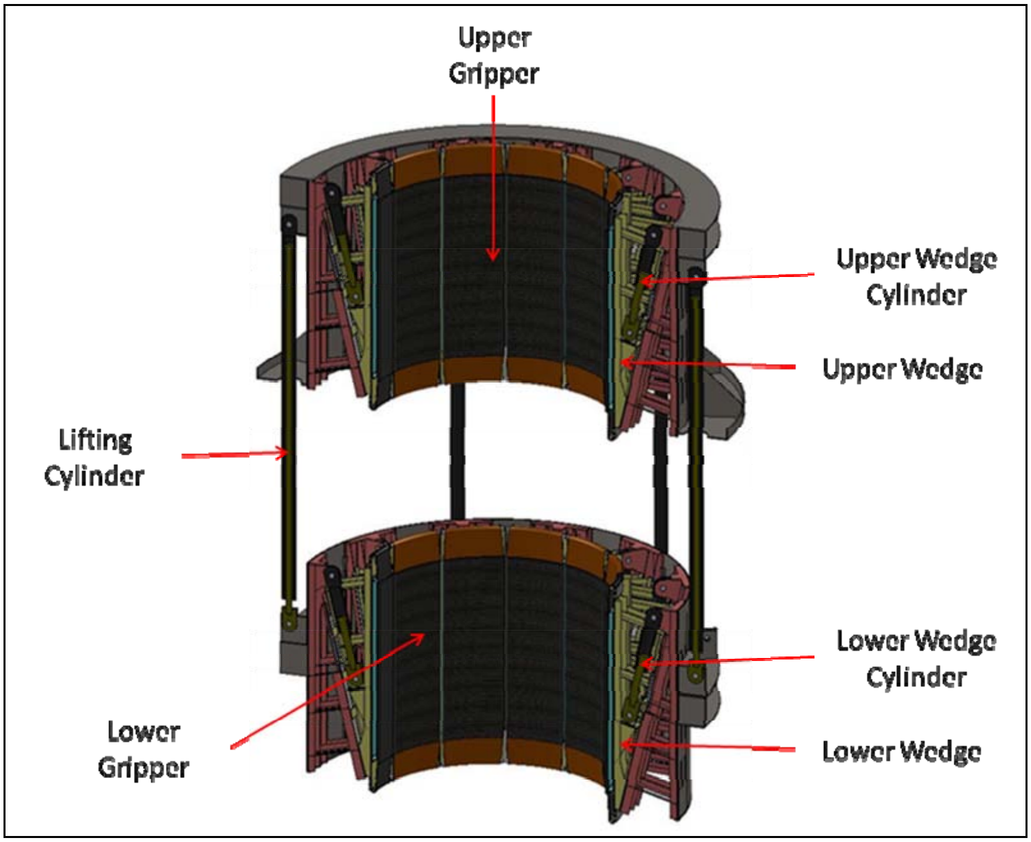


Figure 217. Components

b. Sensors (as shown in Figure 218)

- Upper Wedge Gel Pressure Sensors – Sensors measuring the pressure in the Upper Wedge Gel Bag.
- Lower Wedge Gel Pressure Sensors – Sensors measuring the pressure in the Upper Wedge Gel Bag.
- Upper Wedge Strain Sensors – Sensors measuring the strain in the tension layer connection in the Upper Wedge.
- Lower Wedge Strain Sensors – Sensors measuring the strain in the tension layer connection in the Lower Wedge.
- Lifting Cylinder Position Sensors – Internal position transducers in the Lifting Cylinders
- Upper Wedge Cylinder Position Sensors – Internal position transducers in the Upper Wedge Cylinders
- Lower Wedge Cylinder Position Sensors – Internal position transducers in the Lower Wedge Cylinders
- Lifting Cylinder Pressure Sensors – Pressure transducers in the Lifting Cylinders
- Upper Wedge Cylinder Pressure Sensors – Pressure transducers in the Upper Wedge Cylinders
- Lower Wedge Cylinder Pressure Sensors – Pressure transducers in the Lower Wedge Cylinders

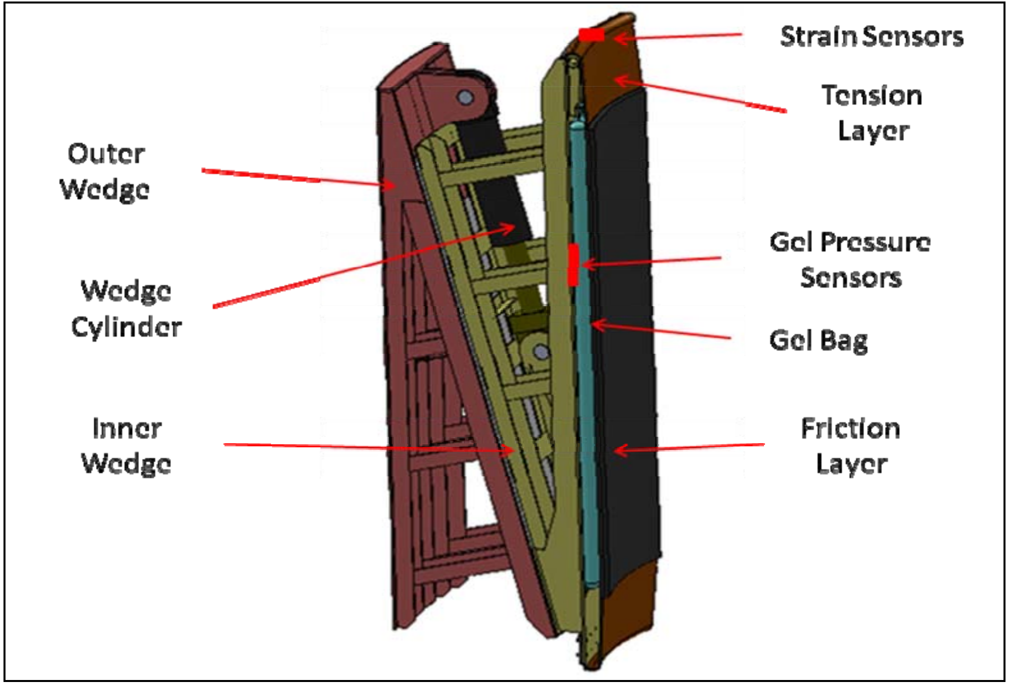


Figure 218. Sensor Locations

6.11.8.4 Basic Control

Each hydraulic ram is individually controlled with a servo proportional valve and position feedback from a built-in position sensor in the ram. Thus, any ram can be very accurately positioned at any position and can be moved at any desired velocity. Importantly for this system; rams can be moved in parallel with a high level of control. Figure 219 illustrates the relationship between all the rams and the PLC.

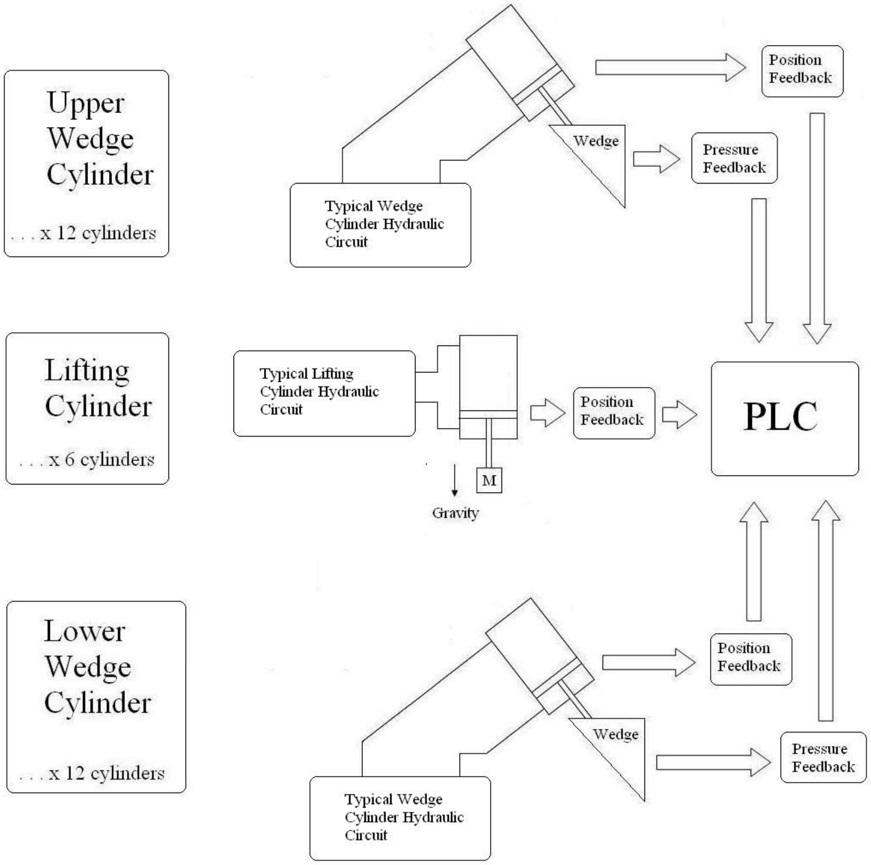


Figure 219. Hydraulic Schematic for the Gripper System

6.11.8.5 Hydraulics

The hydraulic system has been developed for the 4m gripper system and a reduced version of that system has been built and operated for the 1/20th scale model tests (See section 6.15).

There is a common hydraulic power supply operating at 5000 psi. The hydraulic fluid is either Lubritherm by Lubecorp Manufacturing Inc. or PowerFlo by Tapco. Both are water soluble, environmentally friendly, and can be easily washed off the gripper pads to maintain gripper friction.

There are two hydraulic circuits: one for the lifting cylinders and one for the wedge cylinders. The characteristics of these two cylinder types are shown in Table 41. Both operate at a nominal 4650 psi. There are six lifting cylinders and 24 wedge cylinders; 12 on each gripper.

Table 41. Lifting and Wedge Cylinder Characteristics

	Unit	**Lifting Cylinders**	**Wedge Cylinders**
# of Cylinders	-	6 total	12 per gripper, 24 total
Bore Diameter	in	7.9	7.9
Rod Diameter	in	4.3	5.5
Stroke Length	in	236.2	7.9
Working Pressure	psi	4641	4641
Max Force Needed	lbs	1.09E+05	1.70E+05
Max Force Available	lbs	1.58E+05	2.26E+05
Load Factor	-	1.4	1.3

Figure 220 is the schematic for the lifting cylinders. This schematic has the following features:

- Three cylinders are shown in this diagram. There are a total of 6 cylinders attached to the lower gripper that are used for raising and lowering the CWP.
- Each cylinder has a differential pressure sensor between the two ports. This is the most critical pressure in the control circuit. This pressure is used to determine the CWP load on the lower gripper. When the pressure corresponds to the total weight, the full load of the CWP is being carried by the lower gripper. The absence of a CWP load verifies that the upper gripper is supporting the CWP.
- Each cylinder has a gun-drilled rod to house an internal, magnetostrictive position sensor to provide accurate position feedback
- There are two operational modes for these cylinders. (1) No CWP mode which is used for lowering and raising the lower gripper when it is not attached to the CWP and (2) Gimbal mode when the lower gripper is engaged on the CWP.
- In No CWP Mode, the six cylinders are all individually controlled by the directional proportional valves VD-1 through VD-6.
- In No CWP Mode, the weight of the lower gripper is offset by the six counter balance valves VF-1 through VF-6. This valve prevents the lowering of the lower gripper when the hydraulic system fails.
- In Gimbal Mode, All the cylinders are operated from a common manifold such that the pressure is balanced on all cylinders and the gripper (which is clamped onto the pipe when in Gimbal Mode) can easily tilt and follow any tilting in the CWP due to dynamics. Hydraulic fluid can easily flow from one cylinder to another to balance pressures. The pressure sensors will all read identical values in Gimbal Mode.
- In Gimbal Mode, the six cylinders are all controlled together through a single directional proportional valve, VC-1.

- In Gimbal Mode, a counter balance valve, VE-1, offsets the total weight of the fully fabricated (1000m long) CWP. This valve prevents the CWP from lowering if hydraulic power fails.
- The two-position solenoid actuated directional valves VG-1 through VG-6 and valves VH-1 through VH-6 are used for switching between No CWP Mode and Gimbal Mode. The normal, unpowered position of all these valves is in the Gimbal Mode.

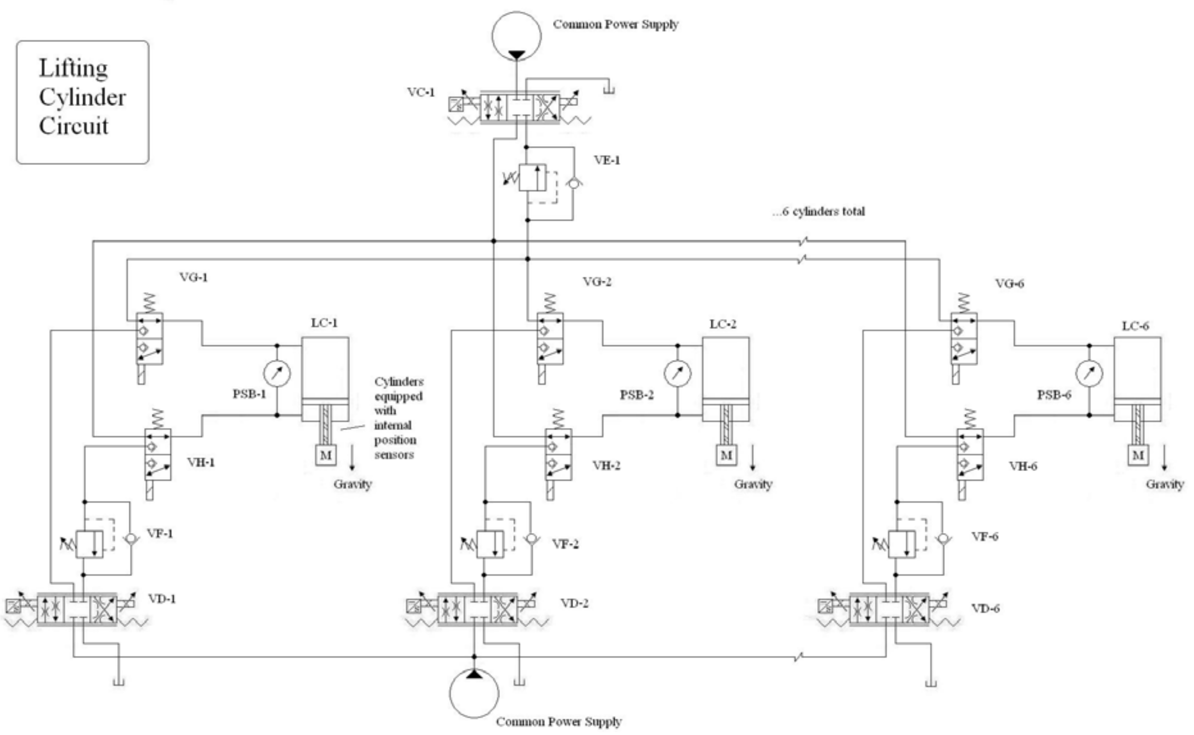


Figure 220. Hydraulic Schematic for the Lifting Cylinders

Figure 221 is the schematic for the wedge cylinders. This schematic has the following features:

- One cylinder is shown in the diagram. There are 24 such cylinders, 12 on each gripper.
- Each cylinder has a differential pressure sensor between the two ports. This pressure is used to determine the driving force for setting and unsetting the wedges, checking the centering of the CWP within the gripper, and detecting whether there are any changes in the CWP or the Gripper pads during operations.
- Each cylinder has a gun-drilled rod to house an internal, magnetostrictive position sensor to provide accurate position feedback
- The position of each wedge is controlled via the PLC using the directional proportional valves VA-1 through VA-24 and feedback from the magnetostrictive position sensors.
- When the wedges are set against the CWP, VB-1 valve is closed. This solenoid actuated valve prevents the wedge from retracting and is normally closed.

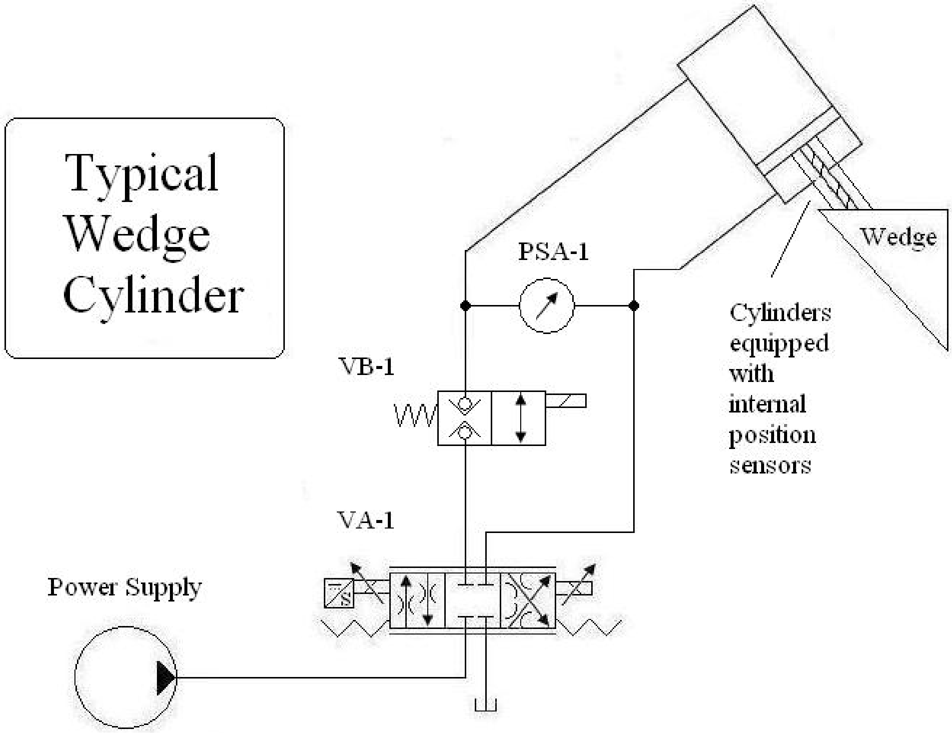


Figure 221. Hydraulic Schematic for the Wedge Cylinders.

For these hydraulic circuits, the following have been selected:

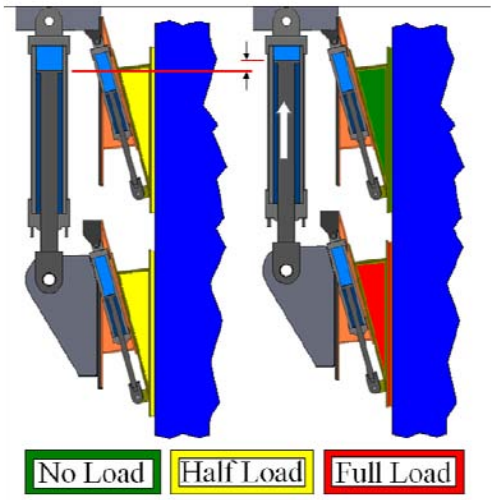
- VA – Direct operated, four-way, three-position, proportional directional flow control valve. Parker Series D1FP or equivalent.
- VB – Direct acting, two-way, two-position, solenoid operated directional poppet valve. Sun Series DTDA-XHN or equivalent.
- VC – Direct operated, four-way, three-position, proportional directional flow control valve. Parker Series D1FP or equivalent.
- VD – Direct operated, four-way, three-position, proportional directional flow control valve. Parker Series D1FP or equivalent.
- VE – Counterbalance valve. Sun Series CBAB or equivalent.
- VF – Counterbalance valve. Sun Series CBAB or equivalent.
- VG – Direct acting, three-way, two-position, solenoid operated directional valve. Sun Series DWDA or equivalent.
- VH – Direct acting, three-way, two-position, solenoid operated directional valve. Sun Series DWDA or equivalent.
- Large bore Hydrowa cylinders made by Eaton Hydraulics
- Spherical rod ends used for both wedge and lifting cylinders

- Gun-drilled cylinders will house internal, magnetostrictive position sensors to provide position feedback
- Operating time full length of lowering cylinder: 2 minutes fastest moving pipe, 1 minute without pipe.
- Operating time full length of wedge cylinder: one minute while engaging.
- Acceleration of lowering cylinders when engaged on CWP: < 0.05g

6.11.8.6 Gripper Lowering Steps and Control Logic

The following steps describe the 13 steps needed to move through one complete gripper cycle. For each step, the following describe the Action required in the step, the feedback provided, and the logic required within the PLC. The starting point is that both grippers have been holding the pipe equally (sharing the load); the lifting cylinders are in the Gimbal Mode; a CWP section has been completed; and the CWP is ready to be lowered. Reference is made to cylinders, valves and sensors in the hydraulic schematics Figure 220 and Figure 221.

1. Unload Upper Wedges

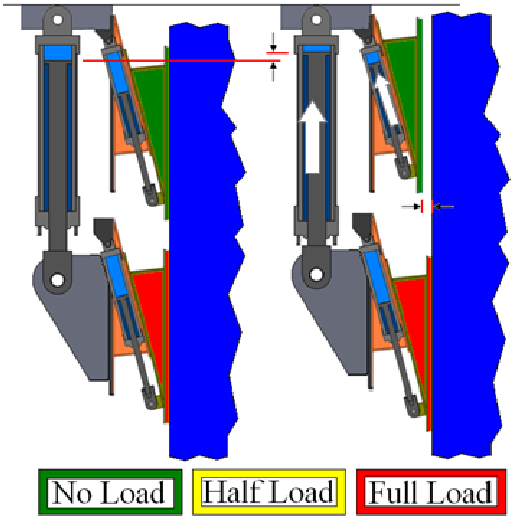


⇧

- Action:
  - Retract Lifting Cylinders to transfer the CWP load entirely to the lower Gripper
- Feedback:
  - Primary: Lifting Cylinder Pressure Sensors – PSB1-PSB6.
  - Secondary: movement of lifting cylinders.
  - Visual confirmation and inspection of lower gripper: all wedges equally engaged.
- Control Logic:
  - Control of VE-1 with feedback from PSB-1 through PSB-6. Raise CWP very short distance until weight carried by the lower gripper – measured by average of PSB-1 through PSB-6 – equals the weight of the CWP plus the weight of the lower gripper. Pressure sensors are redundant and all in parallel. Discard any incorrect values.

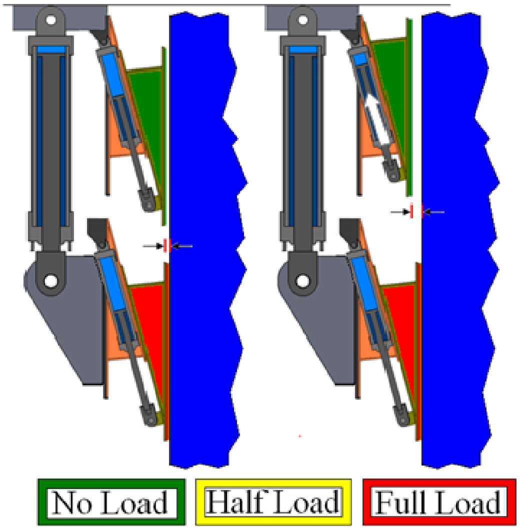
  - Weight of the CWP of prior cycle measure in Step 4. Know weight added with each fabrication increment by prior cycle measurements. Therefore, fairly accurate pressure can be computed for the weight of the CWP plus the weight of the lower gripper assembly.
  - Record distance cylinders have retracted – compare to prior values as check.

2. Disengage Upper Wedge Cylinders



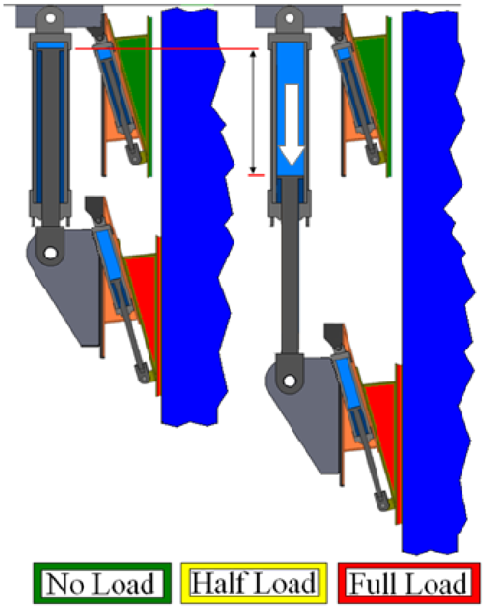
- Action:
  - Retract Lifting Cylinders
  - Retract Upper Wedge Cylinders
  - Upper wedge pads move radially outward from pipe & pressure drops.
- Feedback:
  - Lifting & Upper Wedge Cylinder Position.
  - Upper Wedge Gel Pressure.
  - Visual confirmation that the wedges are just touching the CWP
- Control Logic:
  - Open the VB valves by energizing them on all the upper gripper wedge cylinders.
  - Raise the CWP by retracting the lifting cylinders at a slow but fixed speed.
  - Monitor motion of the lifting cylinders.
  - Retract wedge cylinders in upper gripper at fixed ratio to movement of the lifting cylinders. All wedge cylinders retracted in parallel: pads move radially from the CWP.
  - Monitor the gel pad pressures (12 sensors). When pressures drop to less than 2 psi, stop retracting the lifting cylinders.
  - Log distance traveled each cylinder and compare to prior values as a check.

3. Retract Upper Wedge Cylinders



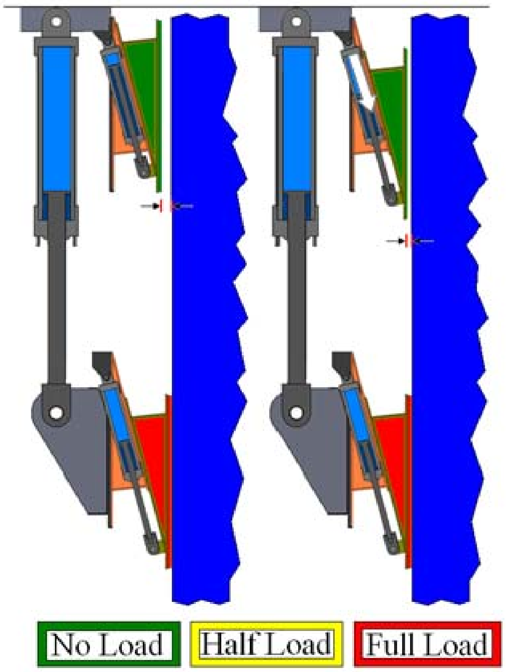
- Action:
  - Retract Upper Wedge Cylinders to build clearance between the CWP and the upper wedge pads
- Feedback:
  - Upper Wedge Cylinder Position Sensors.
  - Visual confirmation that all wedges retracted.
- Control Logic:
  - Move all upper wedge cylinders in parallel; they are no longer in contact with the CWP. You are building clearance between the pads and the CWP.
  - Feedback is the position sensor on each wedge cylinder.
  - Each cylinder has a home location based on a prior survey of all the pads such that each wedge has moved a fixed distance from a perfectly centered and circular pipeline. Due to construction tolerances, each cylinder has a different home position. Retract the cylinders in parallel to this home location.
  - Close the VB valves by de-energizing them on all the upper gripper wedge cylinders.

4. Lowering Pipe



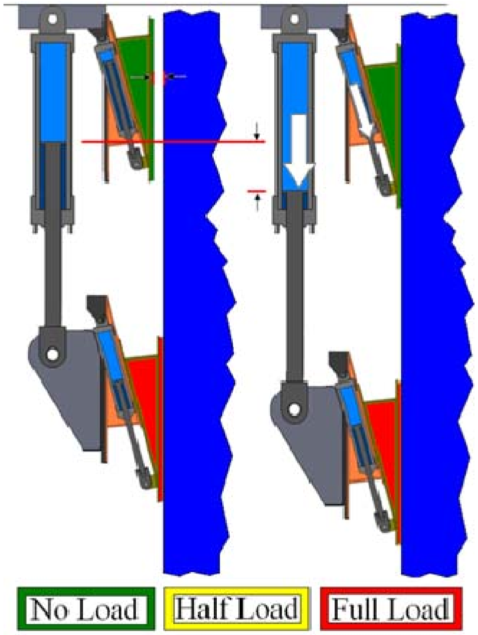
- Action:
  - Extend Lifting Cylinders to lower the CWP
- Feedback:
  - Lifting Cylinder Position Sensors
  - Lifting Cylinder Pressure Sensors
  - Manual check of pipe movement above deck
  - Manually confirm upper gripper free of CWP
- Control Logic:
  - Keep acceleration low at <0.05g
  - Accelerate slowly to uniform speed.
  - Move downward slowly, 2 minutes minimum time to lower. Use feedback from average of all 6 cylinder position sensors.
  - Confirm that the same load is being carried by the Lower Gripper for the entire stroke.
  - Log the weight of the CWP – it is free of the upper gripper and the measurement is accurate.
  - Decelerate slowly to stop 10” short of the end of the lifting cylinders – or just 4” above desired stop position for the fabrication process above deck – whichever comes first.

5. Extending Upper Wedge Cylinders



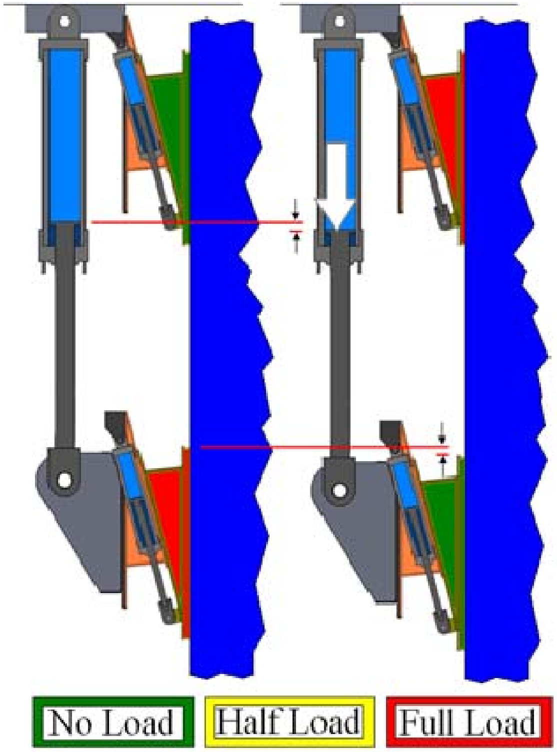
- Action:
  - Extend Upper Wedge Cylinders to almost or just contact the CWP
- Feedback:
  - Upper Wedge Cylinder Position Sensors.
  - Upper Wedge Gel Pressure Sensors.
  - Visual check upper wedges extended
- Control Logic:
  - Open the VB valves by energizing them on all the upper gripper wedge cylinders.
  - Extend all 12 upper gripper wedge cylinders identically and in parallel, stopping just short of contacting the CWP.
  - If any wedge pad pressure starts to rise – the CWP has been contacted on that side – stop the extension of all upper wedge cylinders.
  - All wedges should have moved equal amount from their home positions.
  - Log distances and compare to prior cycles for check.

6. Engaging Upper Wedge Cylinders



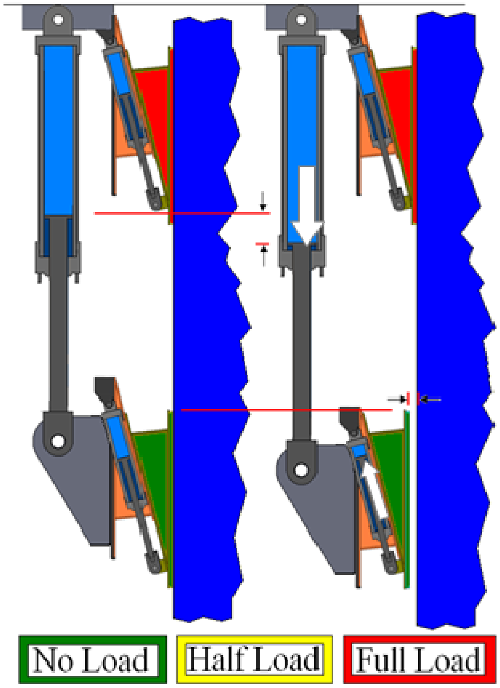
- Action:
  - Extend Upper Wedge Cylinders
  - Extend Lifting Cylinders
  - Upper pads squeeze on the pipeline by moving radially inward.
- Feedback:
  - Lifting & Upper Wedge Cylinder Position Sensors – Verifies that these two sets of cylinders are moving according to a fixed ratio.
  - Upper Wedge Gel Pressure Sensors.
- Control Logic:
  - Lower the CWP by extending the lifting cylinders at a slow but fixed speed.
  - Monitor motion of the lifting cylinders.
  - Extend wedge cylinders in upper gripper at fixed ratio to movement of the lifting cylinders. All wedge cylinders extended equally and in parallel: pads move radially toward the CWP.
  - Monitor the gel pad pressures (12 sensors). When pressures reach an average 50 psi, stop the cylinder extension.
  - Confirm that all pad sensors are nearly at 50 psi and pressure distribution from one pad to the next around the gripper is uniformly varying if not constant.
  - Close the VB valves by de-energizing them on all the upper gripper wedge cylinders.
  - Log distance traveled each cylinder and compare to prior values as a check.

7. Unload Lower Wedges



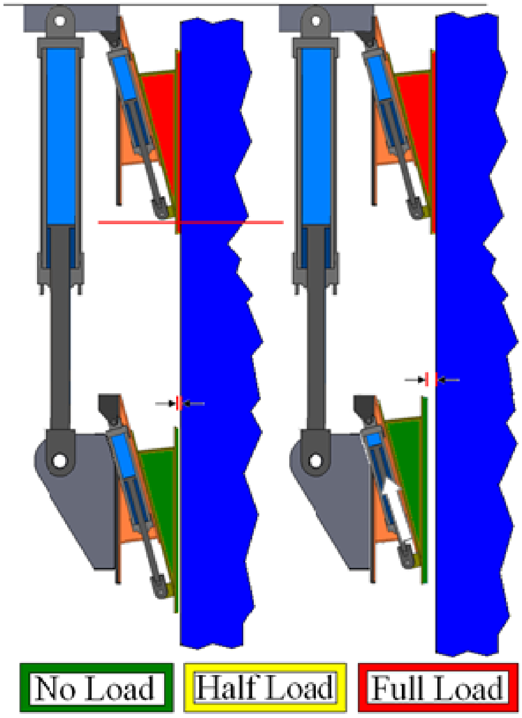
- Action:
  - Extend Lifting Cylinders to transfer the CWP load entirely to the upper Gripper
- Feedback:
  - Primary: Lifting Cylinder Pressure Sensors – PSB1-PSB6.
  - Secondary: movement of lifting cylinders.
  - Visual confirmation and inspection of upper gripper: all wedges equally engaged.
- Control Logic:
  - Control of VE-1 with feedback from PSB-1 through PSB-6. Lower CWP very short distance until weight carried by the lower gripper – measured by average of PSB-1 through PSB-6 – equals the weight of the lower gripper only. Pressure sensors are redundant and all in parallel. Discard any inconsistent values.
  - Upper gripper is holding the CWP
  - Record distance cylinders have retracted – compare to prior values as check.

8. Disengage Lower Wedge Cylinders



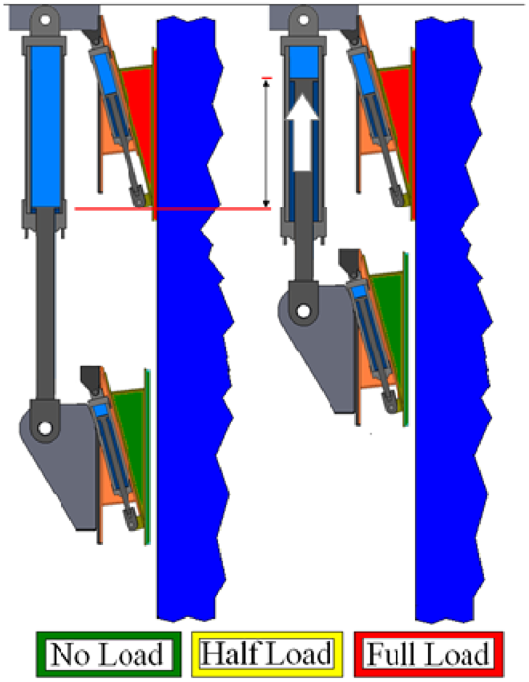
- Action:
  - Extend Lifting Cylinders
  - Retract Lower Wedge Cylinders
  - Lower wedge pads move radially outward from pipe pressure drops.
- Feedback:
  - Lifting & Upper Wedge Cylinder Position Sensors.
  - Lower Wedge Gel Pressure Sensors
  - Visual confirmation that the wedges are just touching the CWP
- Control Logic:
  - Open the VB valves by energizing them on all the lower gripper wedge cylinders.
  - Lower the CWP by extending the lifting cylinders at a slow but fixed speed.
  - Monitor motion of the lifting cylinders.
  - Retract wedge cylinders in lower gripper at fixed ratio to movement of the lifting cylinders. All wedge cylinders retracted in parallel: pads move radially from the CWP.
  - Monitor the gel pad pressures (12 sensors). When pressures drop to less than 2 psi, stop extending the lifting cylinders.
  - Switch the Lifting Cylinders from the Gimbal Mode to the No CWP Mode by energizing solenoids VG-1 through VG-6 and solenoids VH-1 through VH-6.
  - Log distance traveled each cylinder and compare to prior values as a check.

9. Retract Lower Wedge Cylinders



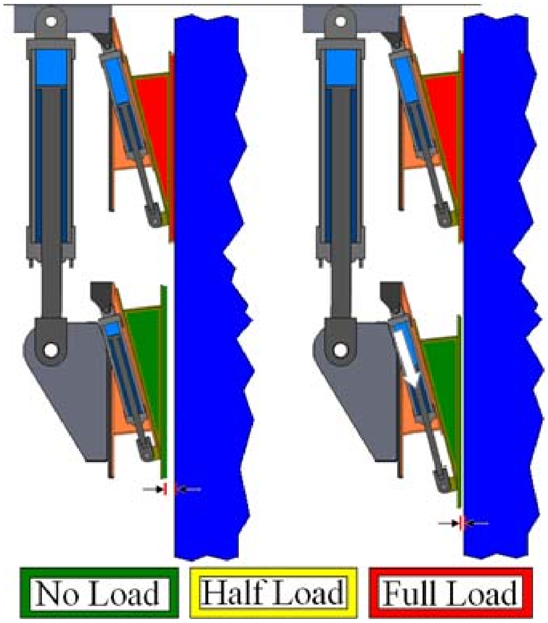
- Action:
  - Retract Lower Wedge Cylinders to build clearance between the CWP and the lower wedge pads
- Feedback:
  - Lower Wedge Cylinder Position Sensors.
  - Visual confirmation that all wedges retracted.
- Control Logic:
  - Move all lower wedge cylinders in parallel; they are no longer in contact with the CWP. You are building clearance between the pads and the CWP.
  - Feedback is the position sensor on each wedge cylinder.
  - Each cylinder has a home location based on a prior survey of all the pads such that each wedge has moved a fixed distance from a perfectly centered and circular pipeline. Due to construction tolerances, each cylinder has a different home position. Retract the cylinders in parallel to this home location.
  - Close the VB valves by de-energizing them on all the lower gripper wedge cylinders.

10. Raising Lower Gripper



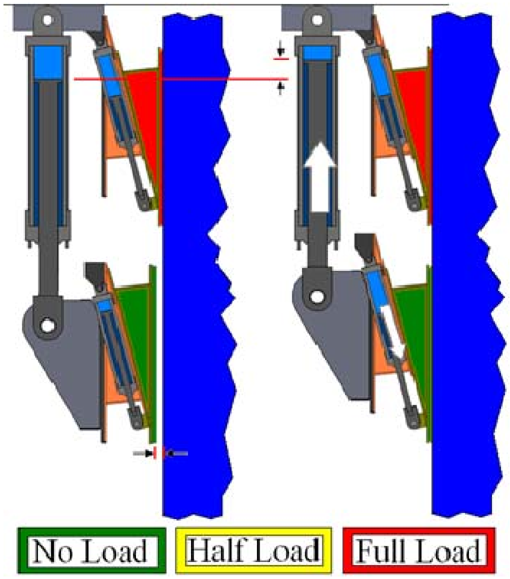
- Action:
  - Retract Lifting Cylinders to raise the lower gripper for another lowering cycle.
- Feedback:
  - Lifting Cylinder Position Sensors
  - Lifting Cylinder Pressure.
- Control Logic:
  - By operating Proportional Control Valves VF-1 through VF-6, raise the lifting cylinders all in parallel.
  - Monitor hydraulic pressures in the lifting cylinders to confirm there is no CWP drag on the lower gripper.
  - Move all the way up. Level the lower gripper by fully retracting all 6 lowering rams.
  - Lower each lifting cylinder 6”

11. Extending Lower Wedge Cylinders



- Action:
  - Extend Lower Wedge Cylinders to almost or just contact the CWP
- Feedback:
  - Lower Wedge Cylinder Position Sensors.
  - Lower Wedge Gel Pressure Sensors.
  - Visual check Lower wedges extended
- Control Logic:
  - Open the VB valves by energizing them on all the lower gripper wedge cylinders.
  - Extend all 12 Lower gripper wedge cylinders identically and in parallel.
  - Stop the extension when the average of the lower pad pressures equals 4psi.
  - All wedges should have moved an equal amount from their home positions.
  - Switch the Lifting Cylinders from the No CWP Mode to the Gimbal Mode by de-energizing solenoids VG-1 through VG-6 and solenoids VH-1 through VH-6.
  - Lower gripper is lightly engaged on the CWP and is freely moving in Gimbal Mode.
  - Log distances and compare to prior cycles for check.

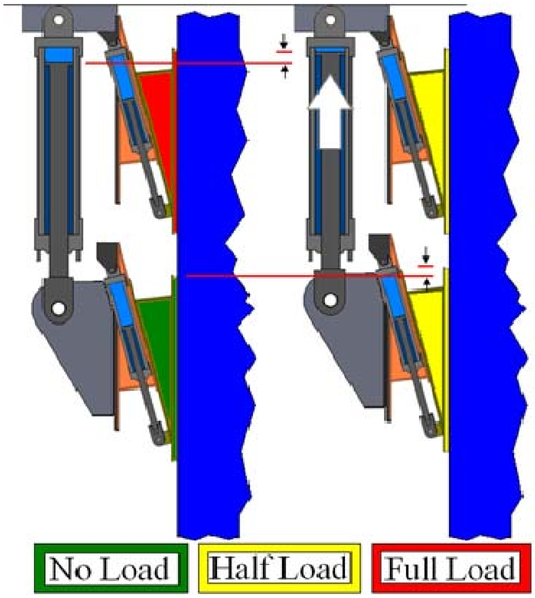
12. Engaging Lower Wedge Cylinders



- Action:
  - Extend Lower Wedge Cylinders
  - Retract Lifting Cylinders
  - Lower pads squeeze on the pipeline by moving radially inward.
- Feedback:
  - Lifting & Lower Wedge Cylinder Position Sensors – Verifies that these two sets of cylinders are moving according to a fixed ratio.
  - Lower Wedge Gel Pressure Sensors.
- Control Logic:
  - Raise the CWP slightly by retracting the lifting cylinders at a slow but fixed speed.
  - Monitor motion of the lifting cylinders.
  - Extend wedge cylinders in lower gripper at fixed ratio to movement of the lifting cylinders. All wedge cylinders extended equally and in parallel: pads move radially toward the CWP.
  - Monitor the gel pad pressures (12 sensors). When pressures reach an average 50 psi, stop the cylinder extension.
  - Confirm that all pad sensors are nearly at 50 psi and pressure distribution from one pad to the next around the gripper is uniformly varying if not constant.
  - Log distance traveled each cylinder and compare to prior values as a check.
  - Close the VB valves by de-energizing them on all the lower gripper wedge cylinders.

If the pipe is to be further lowered, then proceed to step 1 for another cycle. If the pipe is now at its position for fabricating another CWP section, proceed to step 13.

13. Load Lower Wedges



- Action:
  - Retract Lifting Cylinders to share the lifting load between the upper and lower gripper during fabrication of the next CWP section.
- Feedback:
  - Primary: Lifting Cylinder Pressure Sensors – PSB1-PSB6.
  - Secondary: movement of lifting cylinders.
  - Visual confirmation and inspection of lower and upper grippers: all wedges equally engaged.
- Control Logic:
  - Control of VE-1 with feedback from PSB-1 through PSB-6. Raise CWP very short distance until weight carried by the lower gripper – measured by average of PSB-1 through PSB-6 – equals half the weight of the CWP plus the weight of the lower gripper. Pressure sensors are redundant and all in parallel. Discard any incorrect values.
  - Record distance cylinders have retracted – compare to prior values as check.

6.12 4 m Guide Detailed Design

6.12.1 Requirements

The guides are required to support the large horizontal loads on the CWP due to shear and moments in the CWP at the base of the platform. These forces are due to currents, waves and platform motions.

The functional description of the guides has been presented in Section 6.11.2. This section will discuss the structural design, the water bags and guide layers, and testing of the guide layer.

The structure of the upper guide is shown in Figure 216 and for the lower guide in Figure 222 and Figure 223.

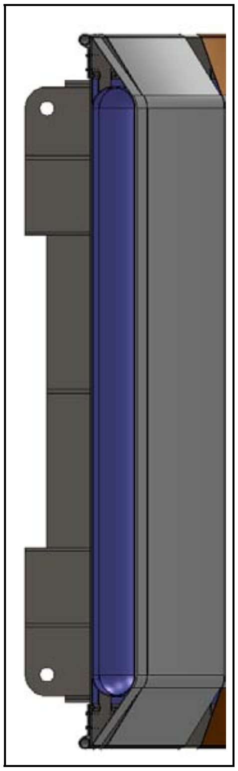


Figure 222. Upper Guide

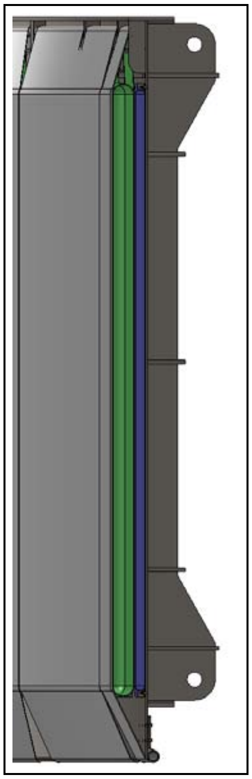


Figure 223. Lower Guide

6.12.2 Friction

The guide fits snugly on the CWP and may be pushed to one side by currents or wave motion during a CWP lowering operation. As a result, there will be a frictional load on the Guide layers similar to the loads in the tension layer of the grippers. However, this load would be only during lowering and high loads would be short duration due to oscillatory movement of the platform and CWP. It was a goal of this program to find a material that is high in abrasion resistance and low in friction for the guide layers.

Figure 224 shows the results of testing a variety of candidate materials in the friction testing apparatus. Contact pressure was 50 psi, the samples were wet with seawater, and the pipe sample was provided by the CWP development as representative of the VARTM process and CWP materials being used.

The preferred material was a high density urethane. Urethane has very high abrasion resistance – it is often used for marine buoys, fenders, and coatings on grapple lines. The urethane selected as the base material for the Guide layer is a flexible two-part chemical, applied much like epoxy, and was coated onto a Kevlar base for this evaluation.

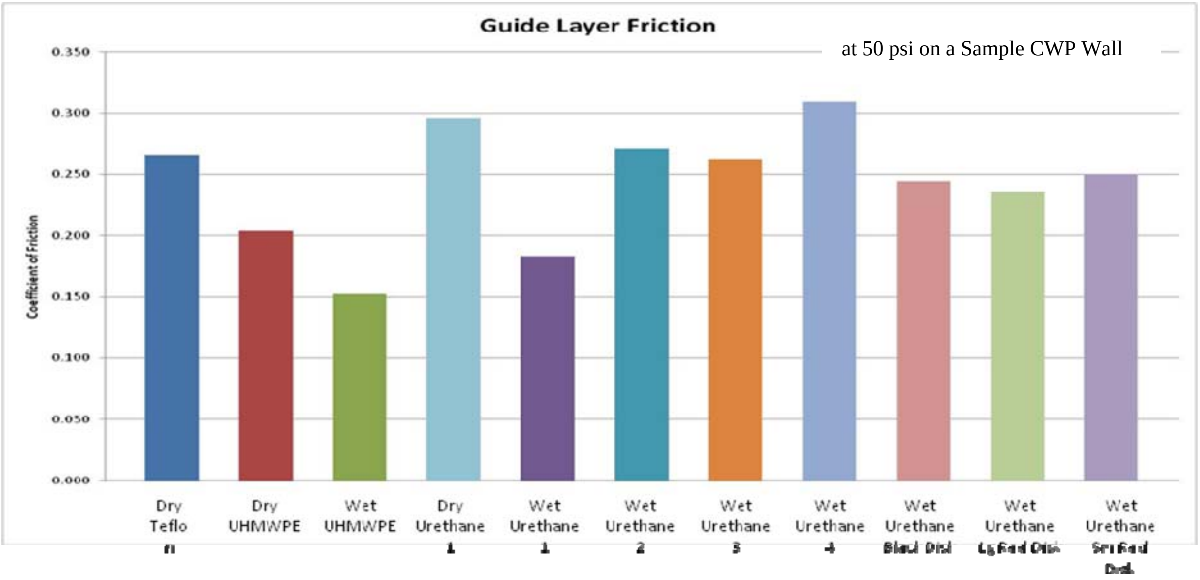


Figure 224. Guide Layer Candidate Materials Friction Coefficient

6.12.3 Pads

6.12.3.1 Guide Layer

The guide layer is supported at the top of the frame through a termination bead enclosed by a steel clamp.

<u>Guide Layer Function:</u>

a. Contact the CWP uniformly and provide a low friction surface underwater.

b. Operate in seawater without degradation – lifetime one year.

c. Withstand the abrasion as the pipe slips over the surface.

d. Withstand the tension resulting from the accumulated friction forces.

e. Reasonably flexible to flow over bumps and irregularities in the CWP.

<u>Concept:</u>

a. A urethane or polyethylene or hard rubber or other surface provides the low friction needed with the pipe. This is the base guide layer material.

b. The pipe may at times press against the guide layer at an average normal force of 50 psi.

c. As the pipe moves over the guide layer, friction will produce tension in the guide layer. This vertical tension, if not supported by the basic guide layer material, is carried by embedded Kevlar or steel tension members. These tension members take the entire vertical tensile load. Kevlar is preferred.

d. The tension members are terminated at top and bottom in an attachment that supports full tensile capability of the guide layer as shown in Figure 225. The tension members may be wrapped about a horizontal bar and secured to themselves with the whole termination coated in the guide layer material. The design is changeable relative to the termination.

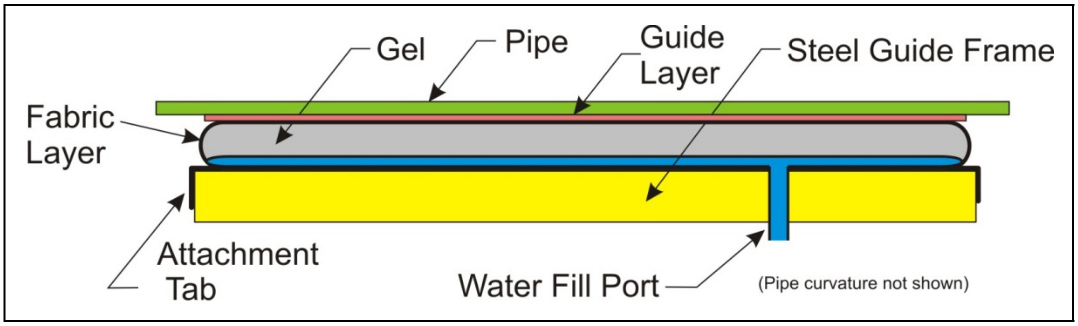


Figure 225. Guide Pad Concept

Characteristics:

a. Height: 15 feet' with 13feet in contact with the CWP, ~1 foot top and bottom attachment length.

b. Width: nominal 3.5 feet assuming 12 pads around the CWP. This could be smaller with more pads.

c. Curvature: 83 inch pipe radius.

d. Thickness: as needed for abrasion and strength - 0.5 inch anticipated.

e. Normal pressure: 2-10 psi normal, 50 psi max

f. Desired Coefficient of friction: ~< 0.2 FRP on guide underwater.

g. Vertical tension: Linearly varies from 200 lbs/inch to 1800 lbs/inch.

h. Vertical tension at yield: 3x to 5x safety factor – 5400 to 9000 lbs/inch (5x matches gripper tension layer fabric)

i. Horizontal tension: 500 lbs/inch estimate; 2x safety factor = 1000 lbs/inch.

6.12.3.2 Pressure Distribution Layer

The guides each have a pressure distribution layer called the "waterbed" bag. The guide bag is a gel and water filled bag between the rigid steel frame of the guide and a separate low friction layer pressing against the pipe. The purpose of this soft bag is to act as a waterbed and to evenly distribute the guide force over the surface of the CWP.

Guide Gel Bag Functions:

a. Transfers the high radial loads from the guide steel ring to the back of the guide layer.

b. Provides a uniform radial pressure on the CWP so there are no point loads.

c. To withstand operational abrasion between the steel plate and the guide layer.

d. To keep the gel and fluids constrained such that the radial stiffness of the overall pad is extremely high.

e. To allow the bag's thickness to be adjusted in the field.

f. To operate in a marine environment (underwater at 82 feet deep maximum) without degradation with a lifetime of one year.

Concept: See Figure 225

- a. The bag contains a very low strength urethane and water that flows around pipe irregularities and distortion.
- b. The bag contains a water-filled bladder that allows bag volume adjustment. With the water-filled bladder, the pad thickness can be adjusted and made snug on the CWP.
  - (1) The fill and volume adjustment valve is at the bottom of the bag going through the Steel Guide Frame.
  - (2) One or more manually operated vent ports are located at the top of the bag so air can be purged from the system.
- c. The bag contains a thicker gel layer that is a backup pad in case there is a water bag leak.
  - (1) This is only needed in the lower guide. In the upper guide, the pipe cannot deflect enough to contact steel directly in case of bag failure.
- d. The outer layer is a nylon or other fabric that:
  - (1) Prevents the gel/water from being extruded from the gap between the steel plate and the pipe,
  - (2) Adheres to the gel and supports the gel when the bag is handled,
  - (3) Provides an attachment tab on all sides for connecting the pad to the steel plate.
- e. The snug fit of the bags and the centering of the pipe can be achieved by:
  - (1) All bags are on a common water supply manifold. Each bag has an isolation solenoid valve. The manifold is supplied with water by a metering pump.
  - (2) Once the fabricated pipe has first exited the lower guide, pressurize all the guide bags to firmly support the pipe within the guide. Pressurize all bags at 5 psi water.
  - (3) A diver surveys the pipe and determines whether it is centered in the guide or not. Knowing the position of the CWP in the guide, the water volumes in each bag can be adjusted to properly center the CWP.
  - (4) When moving the pipe, 4 symmetrical guide bags are reduced in pressure; all bags will therefore show a drop in pressure.
  - (5) When securing the pipe position, the 4 bags are re-inflated to 5 psi ; all bags will then see that pressure due to flexibility of the CWP.

Characteristics

- a. Height: 13 feet
- b. Width: 3.5 feet nominal – could be narrower if more than 12 bags are used.
- c. Upper Guide thickness:
- d. All water: 8 inch” thick.
- e. Lower Guide thickness:
- f. Gel Thickness: 4 inch lower guide only
- g. Water adjustment thickness: 1”

h. Radius: ~86 inch radius

i. Max working pressure: 50 psi: Burst 200 psi minimum at thickness values given above.

j. Weight: 1000 lbs Gel + bag materials.

k. Vertical tension: support its own weight.

l. Fabric tension: working loads given, SF minimum of 5 on working loads:

    (1) Upper Guides: max 200 lbs/inch working for 8 inch thick upper guide bags;

    (2) Lower Guides: max 50 lbs/inch working for 2 inch thick lower guide water filled; 100 lbs/inch working for 4 inch thick lower gel-filled bag.

m. Fabric elasticity: nylon is satisfactory.

n. Gel Compound: polyurethane with plasticizer; 00 Shore softness range 1 to 5 (Modulus of Elasticity = 0.5 psi)

6.12.4 Structure

The Guide structure is functionally described in Section 6.11.2. It is further defined in the drawings in the appendix. It is basically a rigid cylindrical frame supporting 12 individual bags and glide layers. The upper portion of the upper guide has the additional requirement to support the final CWP for the lifetime of the OTEC plant.

The structure was analyzed in ANSYS with loading determined by the maximum loads defined in the dynamic coupled CWP and platform analysis described in Section 6.5.

The structure is fabricated of ASTM A36 mild (low carbon) steel. Ultimate strength is 58,000 psi and yield is 36,000 psi. Maximum stress was kept below 18,000 psi for a minimum safety factor of 2.0 on yield. Fatigue analysis was not performed since the functioning lifetime of these structures is only a few months during pipe fabrication. The ANSYS results are shown in Figure 226 and Figure 227. The detailed structural report is in the appendix.

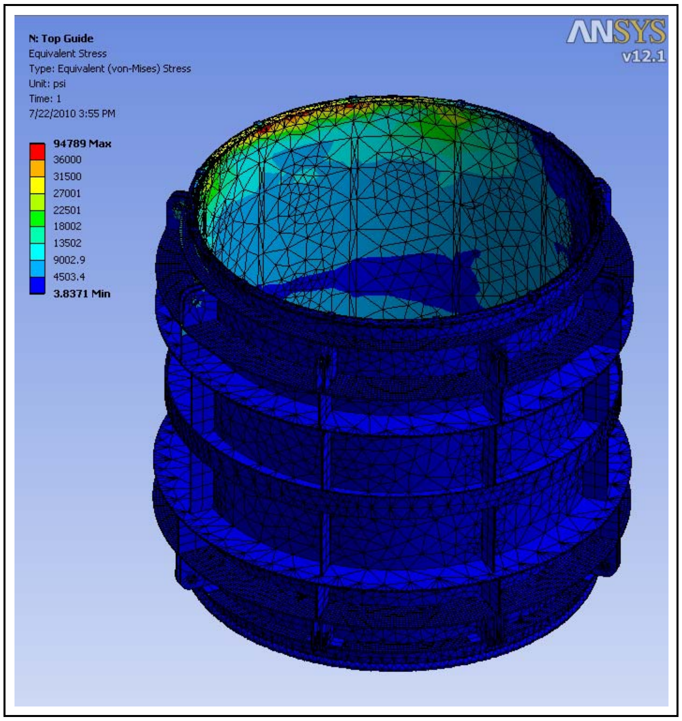


Figure 226. Structural Analysis of the Upper Guide

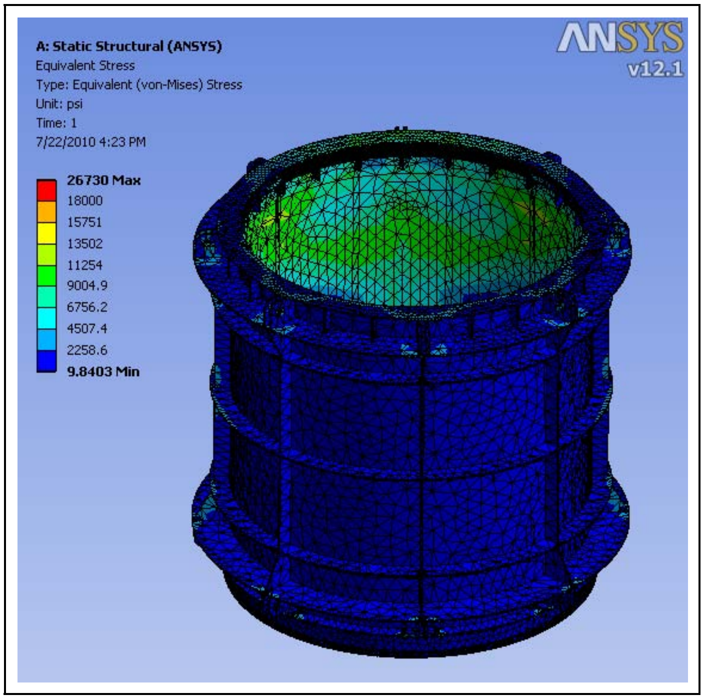


Figure 227. Structural Analysis of the Lower Guide

6.12.5 Control

Each Guide has 12 individually controlled water-filled bladders for controlling the position and removing the gap between the glide layers and the CWP. The goal of the Guides is to have zero pipe movement tolerance. By keeping the pipe centered and the bags slightly pressurized at 3 psi, any gap will be removed.

All of the 12 water filled guide bags on each of two Guides are placed on a common water supply manifold. Each bag is isolated from that manifold with a remote controlled on/off solenoid valve. A metering pump on deck can supply or remove measurable quantities of water from this manifold. Thus, by opening one valve at a time, a known amount of water can be added or removed from any one guide bag. The guide bag valves and the metering pump are controlled by the gripper/guide PLC.

Feedback on guide behavior is provided by pressure transducers measuring the water pressure in each guide pad. Knowing the amount of water in each bag and the resulting pressure, the compensating water volume can be adjusted. Once a pipe is centered in a guide the water bag volumes will remain constant. Pipe centering is accomplished during the initial pipe fabrication and during calm weather. If guide bag pressures increase during a pipe movement, then the CWP may be slightly larger and water can be removed from selected bags. If pipe movement is excessive above the deck and bag pressures are low then water can be added to the bags.

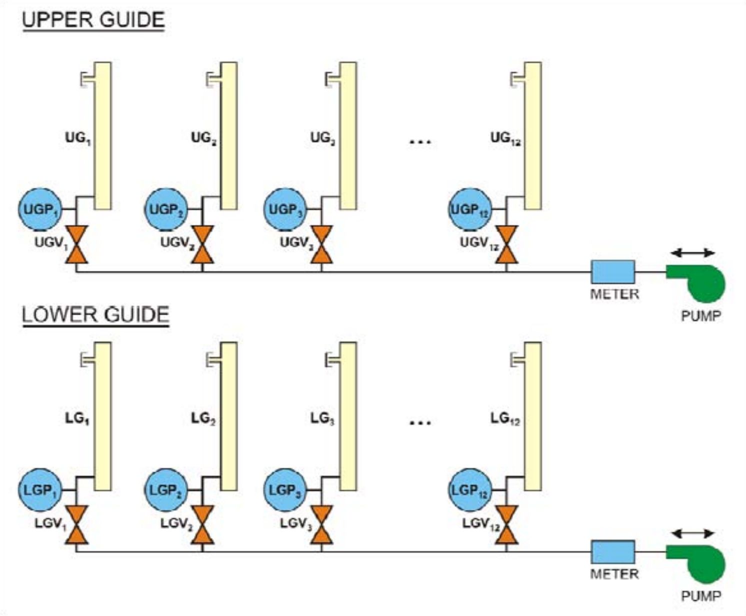


Figure 228. Hydraulic Schematic for Guide Bags:

Figure 228 is a schematic of the water supply for the guide bags. Two manifolds and two pumps supply seawater to the 12 bags in the upper and lower guides. Each bag has a separate solenoid controlled fill valve at the bottom of the bag. Each bag also has a vent port at the top of the bag that is manually (diver) operated when the bags are initially filled and purged of air. A pump provides water into the manifold and the meter can determine accurately the accumulated flow into and out of any one bag. Only one bag is adjusted at a time. Pressure transducers are located at each guide bag to monitor the bag pressure.

Control Logic is as follows:

- At start-up, center the CWP manually in the guide. Open all guide valves and equally fill and pressurize all bags to 4 psi.
- Close all valves.
- Measure the relationship between bag pressure and added water to one and to all bags. This is the basis for adjusting bag volumes for subsequent pressure adjustments during fabrication.
- If pressure drops in the guide bags or there is excessive CWP movement or pressure goes up and there is excessive drag on the CWP lowering; sequentially adjust small measured equal amounts of water to the bags. Sequence the bags by adjusting the volume in bag 1, and then clockwise adjust every 5th bag (see Table 42), after 5 cycles all bags are adjusted evenly. This sequence will keep the pipe centered in the guide.
- A PLC keeps track of water volume in each bag. Withdraw water from bags that were most recently filled. Goal is to keep water volume adjustments even among bags relative to the initial baseline value.
- If pipe movement is required, the PLC computes volume adjustments to the 12 bags to achieve the movement desired. Volume adjustments are made sequentially per Table 42 breaking large movements into multiple steps.

Table 42. Adjustment Sequence for Guide Bags

1 x	1	1	1	1
2	2	2 x	2	2
3	3	3	3	3 x
4	4 x	4	4	4
5	5	5	5 x	5
6 x	6	6	6	6
7	7	7 x	7	7
8	8	8	8	8 x
9	9 x	9	9	9
10	10	10	10 x	10
11 x	11	11	11	11
12	12	12 x	12	12

6.13 Platform Interface

Makai has issued an interface document, “Gripper/Platform Interfacing” dated 4/6/10 which is included in the Appendix. The purpose was to define platform requirements for the Gripper and to define design conditions for the Platform Group due to the presence of the Grippers and Guides. Weights, loads, dimensions, clearances, and structural stiffness have been specified. The following sections summarize the key characteristics of weights, loads, dimensions, clearances, and structural stiffness of the Gripper-Platform interface.

6.13.1 Structural

Figure 229 shows the overall location and dimensions of the Gripper and Guide Pads.

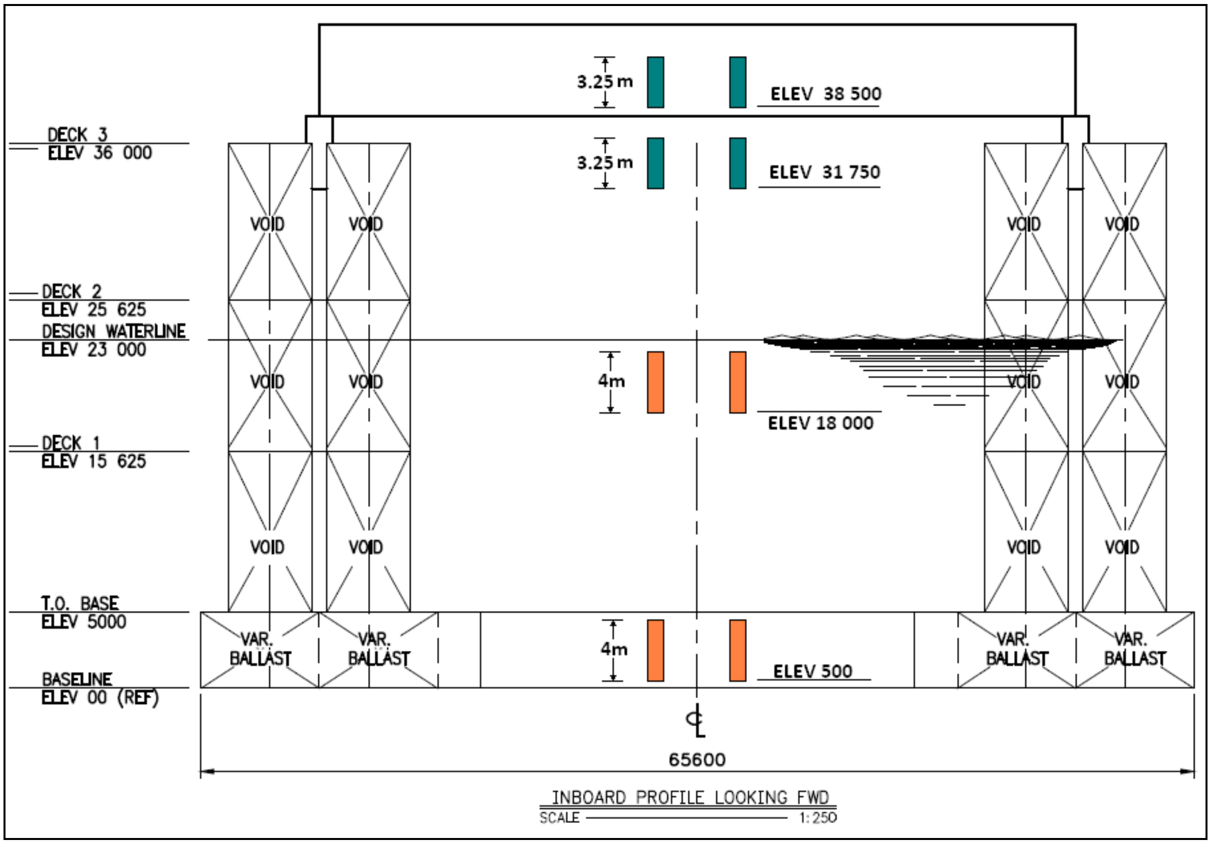


Figure 229. Gripper and Guide Dimensions

Figure 230 shows the support structure envelope for the pipe fabrication process below the main deck. The central portion of the platform will be occupied by the CWP and the CWP handling system during the fabrication of the CWP.

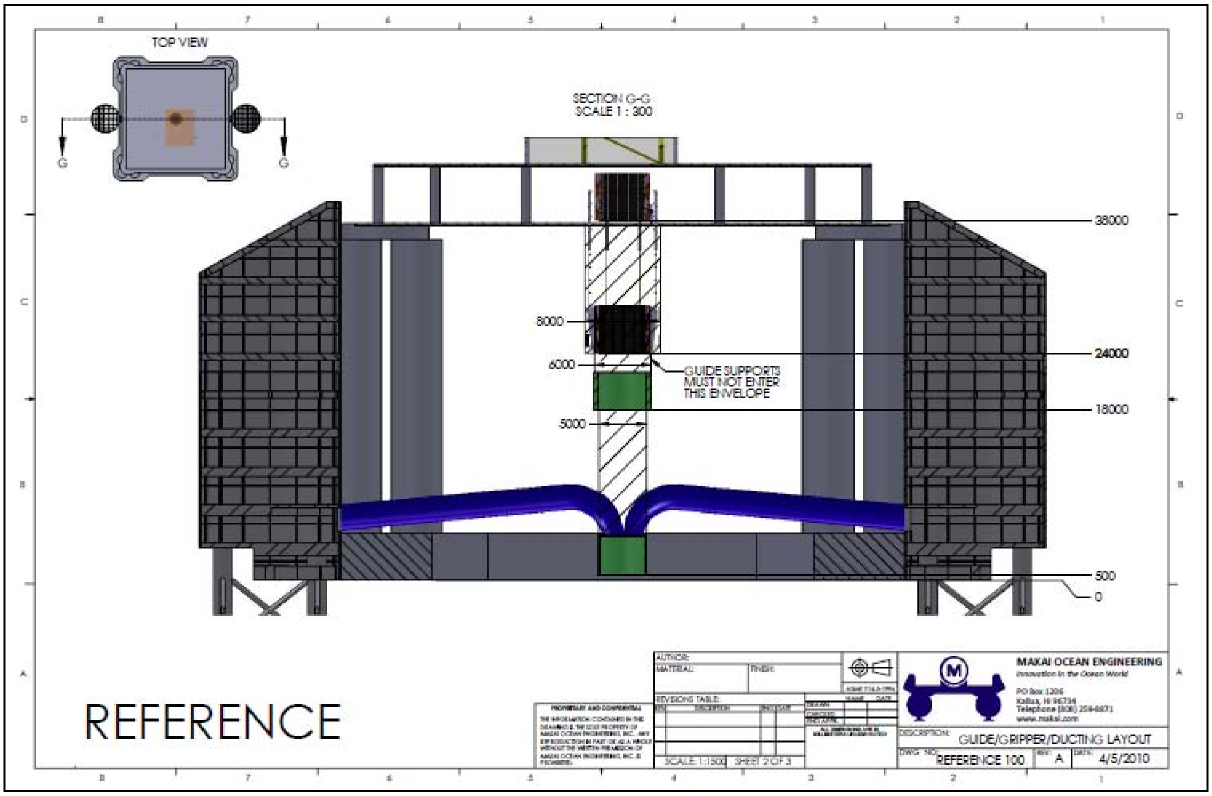


Figure 230. Support Structure Envelope

The maximum loads are shown in Table 43. The loads shown are calculated using the 10 yr swell sea states.

Table 43. Component Loading

Component	Vertical Load (KN) Static	Vertical Load (KN) Dynamic (+/-)	Lateral Load (KN) Static	Lateral Load (KN) Dynamic (+/-)
Upper Gripper	2,912	173	39	170
Lower Gripper	2,912	173	-	-
Upper Guide	291	17	566	2,413
Lower Guide	291	17	722	3,078

6.13.2 Weight

Platform-CWP Interface Weight Characteristics are shown in Table 44.

Table 44. Platform-CWP Interface Weight Characteristics

		Total, Dry Weight	Total, Wet Weight	Removed / Remain after Fabrication	Submerged	Est. Basis	Contingency	~CG Relative to Pontoon Bottom
		tons	tons	--	%		%	m
Pipe Handling Equipment	Top Griper structure	20	n/a	remain	0%	D	25%	37
	Top Gripper pads	60	n/a	Remove	0%	E	30%	37
	bottom Gripper	20	n/a	Remove	0%	D	25%	29.5-23.5
	bottom gripper pads	60	n/a	Remove	0%	E	30%	29.5-23.5
	Top guide	15	13.1	Optional	100%	D	25%	18
	Top guide pads	50	20.0	Remove	100%	E	30%	18
	Bottom Guide	36	24.0	Remain	100%	D	25%	0
	Winch/ Heave Compensator	4	n/a	Remain	0%	E	30%	+44
	Hydraulic Supply, control	2	n/a	Remove	0%	E	30%	+44
	Blower/compressor	1	n/a	Remove	0%	E	30%	+44
	Top Pipe Pressure Cap	7.5	n/a	Remove	0%	E	30%	+44 to 0
	Allowances	5	n/a	n/a	0%	F	30%	+40
CWP	Water Manifold Completion Cap	2	1.74	Remove	100%	F	30%	4
	Bottom Weight	48	41.3	Remain	finally	D	10%	+40 to -1000
	Bottom Wt handling equipment	5	n/a	Remove	0%	F	30%	n/a
	CWP fabricated	663	320	Remain	100%	D	10%	-500

Estimate Basis:

A	Manufacturer Catalog
B	Final engineering Dwg total
C	80% design Eng Dwg total
D	Preliminary Engineering Dwg total
E	Engineering Estimate
F	Guesstimate

6.13.3 Stiffness

One major requirement specified by the Gripper system is the stiffness of the platform. For the Gripper to adequately hold the CWP and to minimize the motion of the CWP above the platform, the platform must have very little deflection due to pipe bending and lateral loads. Figure 231 shows the minimum required lateral stiffness of the platform at the guides and gripper locations.

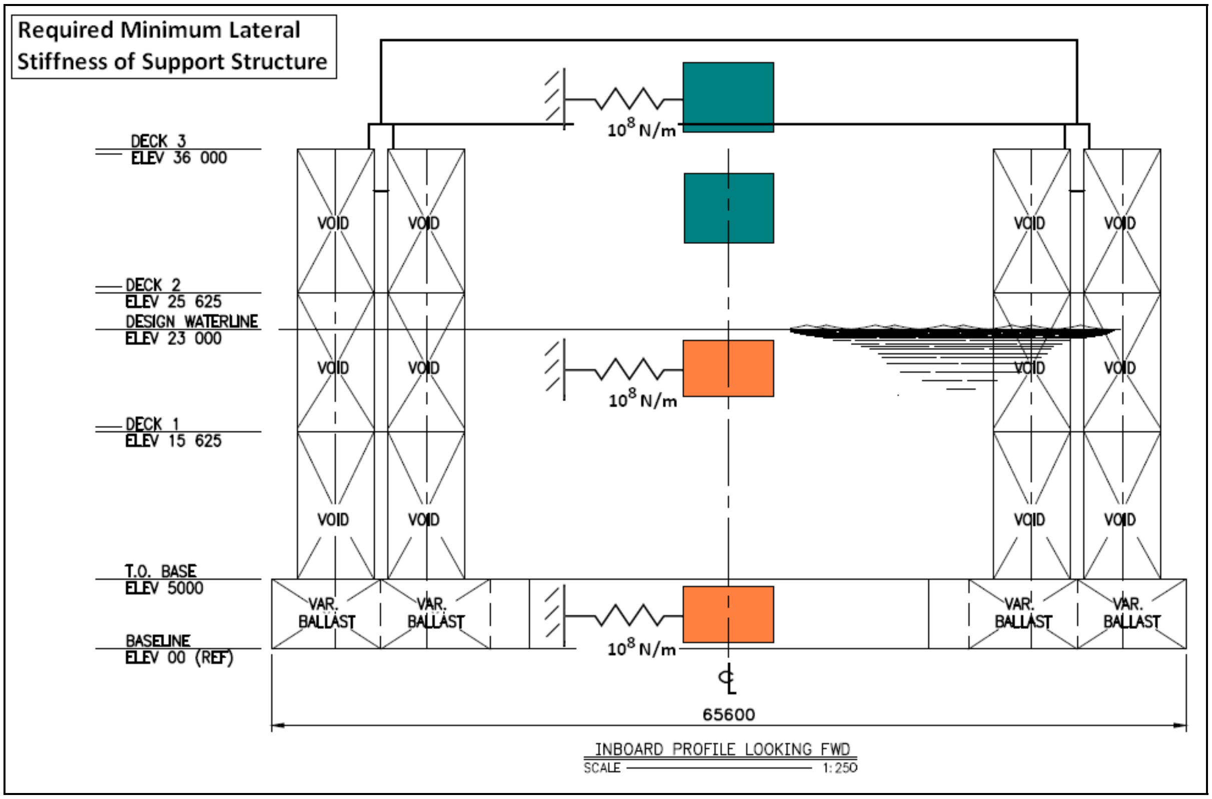


Figure 231. Required Support Structure Stiffness

6.13.4 Operational

Operational procedures affect the design of the platform. For instance, a 2m gap between the upper deck and the top of the upper gripper is designed for access and inspection of the completed CWP. Also, once the pipe is terminated, the upper flange on the CWP is lowered through the upper and lower grippers. This requires the removal of the wedge systems in both grippers. Lifting capacity and a means of lowering these structures to a vessel below or through a hole in the platform decks is needed. The operational procedures are summarized later in this document (Section 6.14).

6.13.5 Water Ducting

The water ducting was investigated in two tasks of this contract.

- The water ducting plays an integral role in the pipe fabrication process. The CWP manifold sits directly above the final in-place CWP and is in the path of the CWP during fabrication. Once the pipe has been completed, the CWP manifold must be dropped in place to complete the water connection to the two Remoras. The ability to keep this space clear during fabrication and the ability to easily complete this piping has been the focus of the CWP fabrication portion of this study.
- In the Systems Design Report, the CWP manifold analysis and design for low-resistance flow to the two Remoras is documented.

These two tasks have been coordinated; the CFD analysis performed on the manifold also included the features needed for the CWP fabrication.

Figure 232 and Figure 233show the manifold in place between the top of the CWP and the Remoras. A removable section of this manifold just above the upper guide contains three flanges: one to the CWP or the top of the bellows attached to the gimbal and two to each of the pipes going to the Remoras. This section is put in place only after the CWP construction is complete. The manifold closure piece drops in place and is lowered through the two upper grippers once their wedges have been removed which is a prior step in the final CWP lowering process.

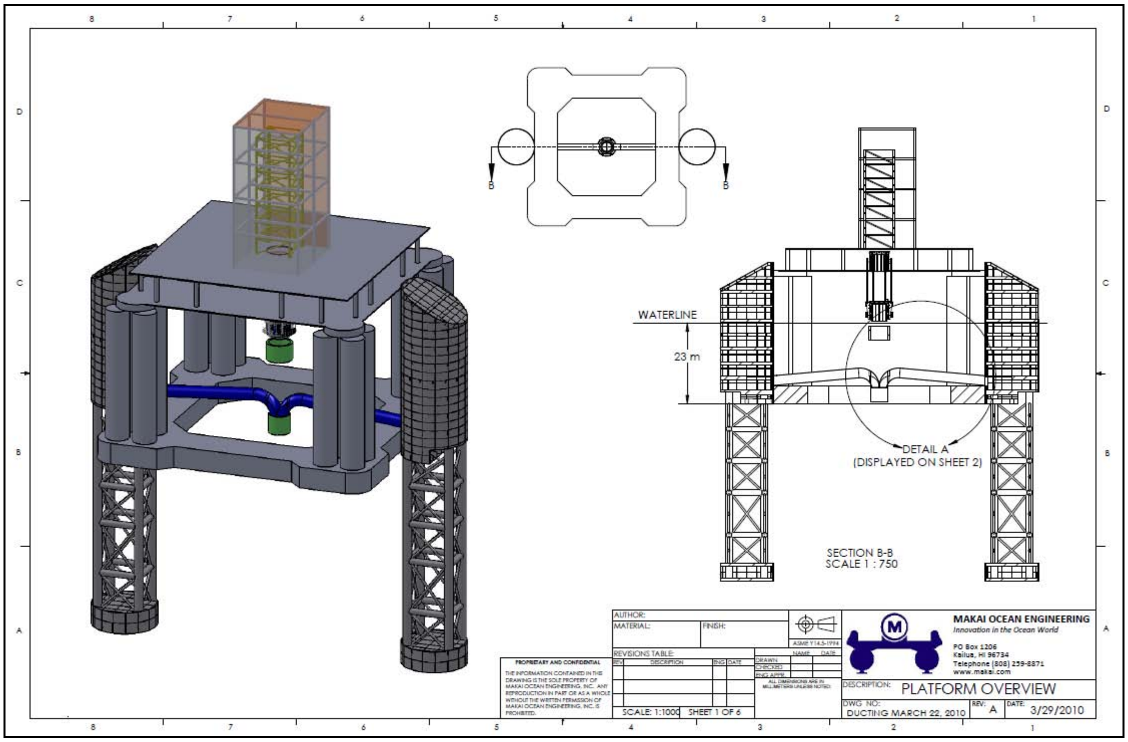


Figure 232. Cold Water Duct Layout

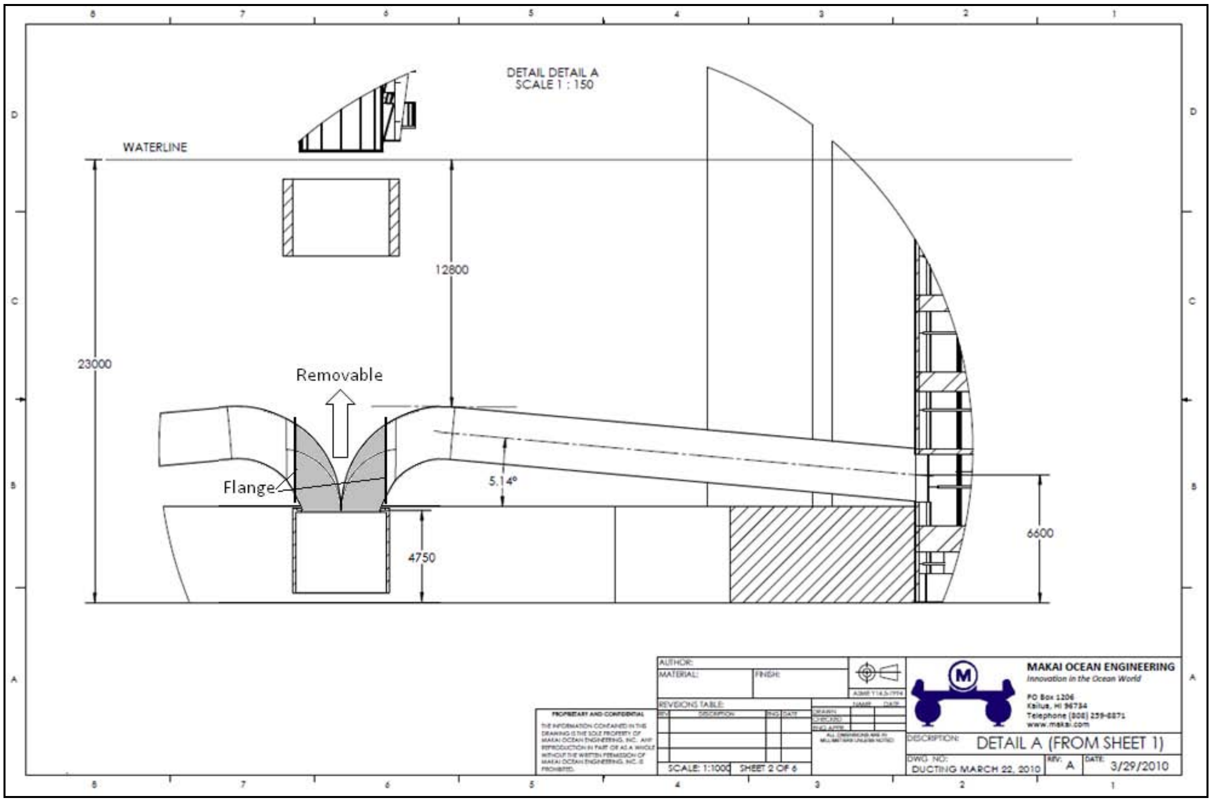


Figure 233. Cold Water Duct Elevations

6.14 Gripper Operations

6.14.1 Basic Gripper Operations

See section 6.11.8.6.

6.14.2 Basic Guide Operations

NOT COMPLETED YET - pending model results.

6.14.3 Adding Bottom Weight

The 4m CWP requires a 91,000 lb wet weight bottom clump weight to constrain the lateral movement of the intake. Several configurations of attaching this bottom weight were considered and the most promising was simply filling the voids in the extruded core with a heavier material. Table 45 shows the length of pipe needed for various fill materials varying from lead shot to basalt gravel. Iron, steel and lead shot are all candidates for achieving the 91,000 lbs within the length of one fabrication increment of 11m, or 36.1 feet.

Table 45. Bottom Weight in CWP Walls

void: 10.10 ft^3/ft
Wet Weight Needed: 91,000 lbs

fill	SG	Eff	length	Dry Wt
lead	11.378	0.66	21.1 ft	100,009 lbs
steel	7.708	0.66	32.7 ft	104,956 lbs
iron	7.083	0.66	36.1 ft	106,396 lbs
magnetite	5.048	0.66	54.4 ft	114,185 lbs
concrete	2.468	1	100.1 ft	155,642 lbs
basalt	2.949	0.67	112.0 ft	139,487 lbs

Adding the shot can be accomplished in two ways:

Concept 1

Drill holes in CWP 11m from bottom of pipe

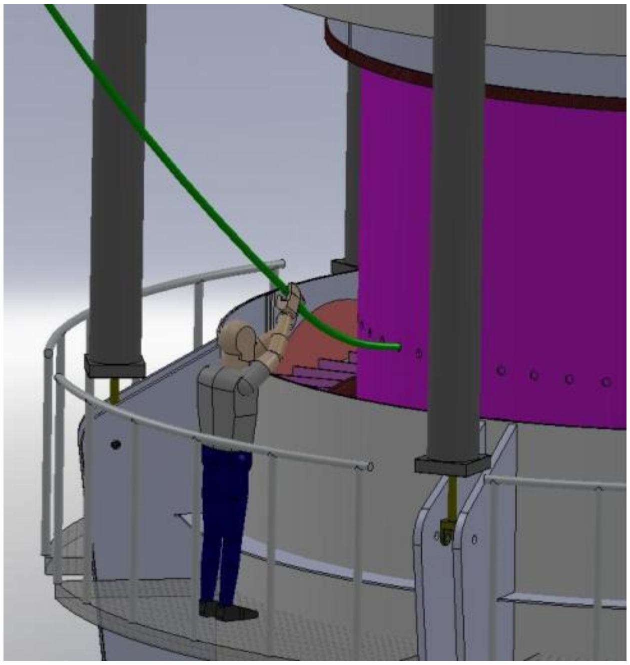
Fill with steel or iron shot from outside through hose (see figure)

Refinish cut holes with resin coat and allow holes to remain open for flooding remainder of CWP

Concept 2

Steel shot is filled in to a core segment at the top of the CWP apparatus (This is done above the vacuum chamber, before the face sheets are applied.)

The shot is filled once both grippers are holding the pipe. This means the fourth or fifth segment will be the one filled with shot.



Concept 1 has multiple penetrations in the CWP but at a location with very low strains. Concept 2 involves more complex handling of heavy weights through the fabrication process. A preferred option was not developed. The final decision can be made once the fabrication process development has been completed.

6.14.4 Final Lowering

This section describes the final lowering of the CWP once fabrication has been completed.

Figure 234 shows schematically the upper end of the cold water pipe being held in the upper gripper. The termination flange has been placed on the end of the CWP and it is ready to be lowered to its final location just above the lower pontoon at about 18m water depth. The grip-lock design, developed as a termination and discussed in Chapter 5, is shown schematically in the figure.

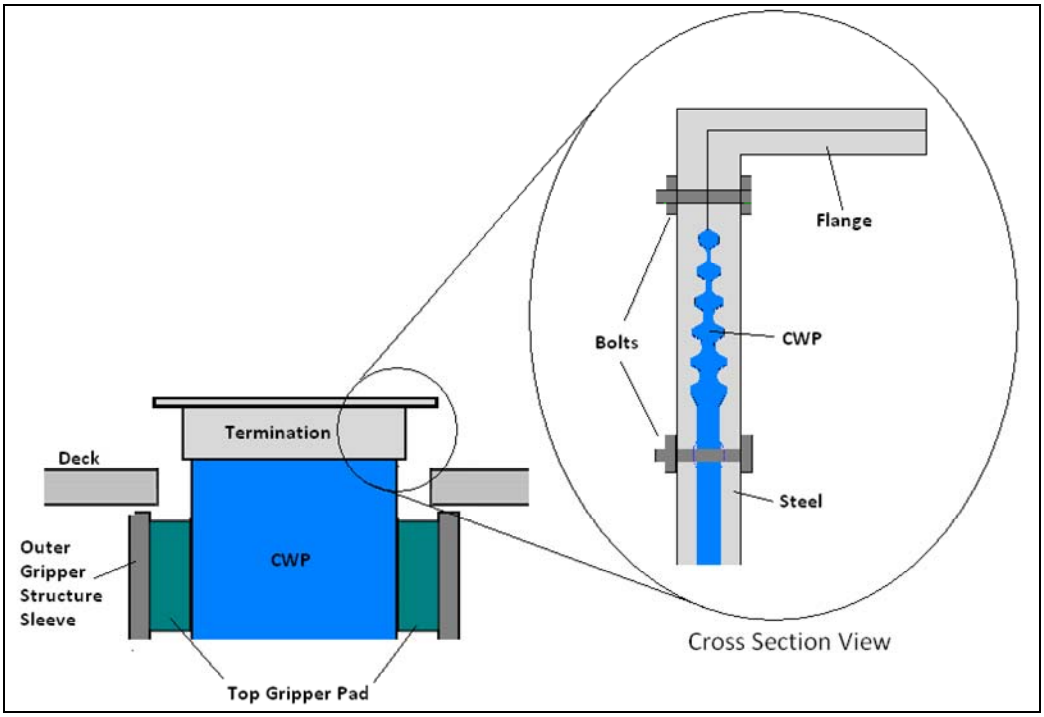


Figure 234. Schematic of Final Termination Added to Top of CWP

The means of lowering the pipe from this position is to use pressurized air to expel some of the water from the inside of the pipe and thus greatly reduce its weight such that it can be lowered from with a winch. Figure 235 shows a 40 psi fiberglass cap being moved onto the top of the CWP termination. In Figure 236 the pipe is pressurized with air at approximately 40 psi. This will de-ballast enough water to nearly support the entire weight of the CWP.

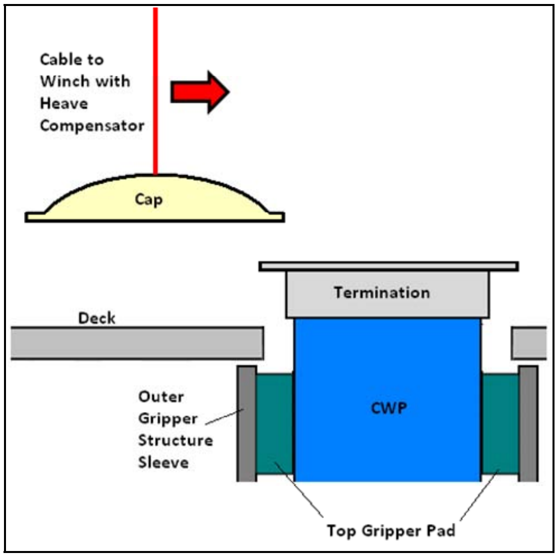


Figure 235. Capping the CWP

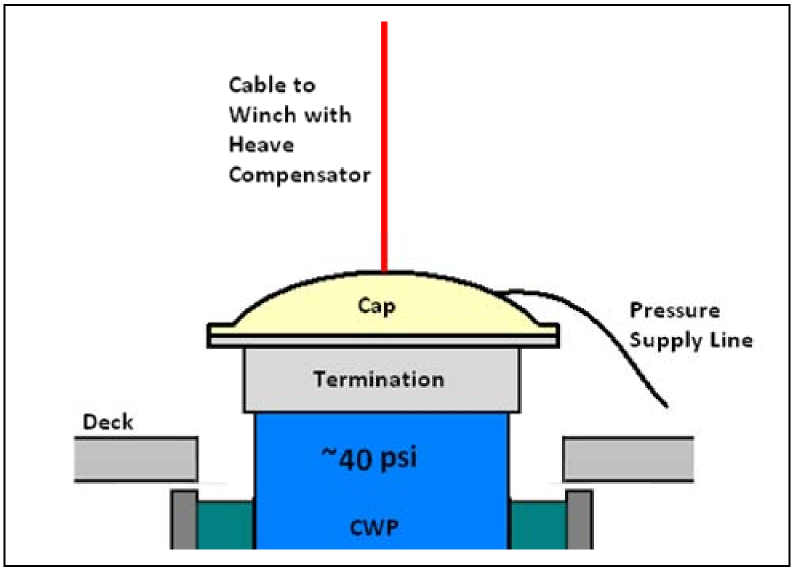


Figure 236. Pressurizing the CWP and Supporting with a Winch

In order to move the CWP lower, the wedge and pad assemblies in both the upper and lower gripper must be removed. There are twelve wedge assemblies in each gripper. The wedge assemblies in the upper gripper slide out of the gripper by dropping them downward and the wedge assemblies in the lower gripper are pulled out at the top of the gripper.

Wedge assemblies in the upper gripper are held in place by a series of bolts hanging the assembly from the upper gripper flange. The inner wedge of the gripper is first retracted entirely such that the locking dogs lock two wedges firmly together. Locked together, wedge and pad assembly can be easily handled by hanging from an eye located at the top of the wedges. If desirable, the up and down motion of the lower gripper can be used to support the upper gripper wedge assemblies as they're being lowered. Alternately, they can be removed individually with a deck winch. Once lowered, the wedge assemblies need to be swung away from the CWP and lifted up through a penetration in the lower deck or lowered to a boat below.

Similarly, the wedge and pad assemblies of the lower gripper can be lifted out the top of that gripper. As shown in Figure 237 the hydraulic rams of the lower gripper can be used to drop the frame away from the individually suspended gripper wedge assemblies. A variety of rigging configurations are possible for this operation.

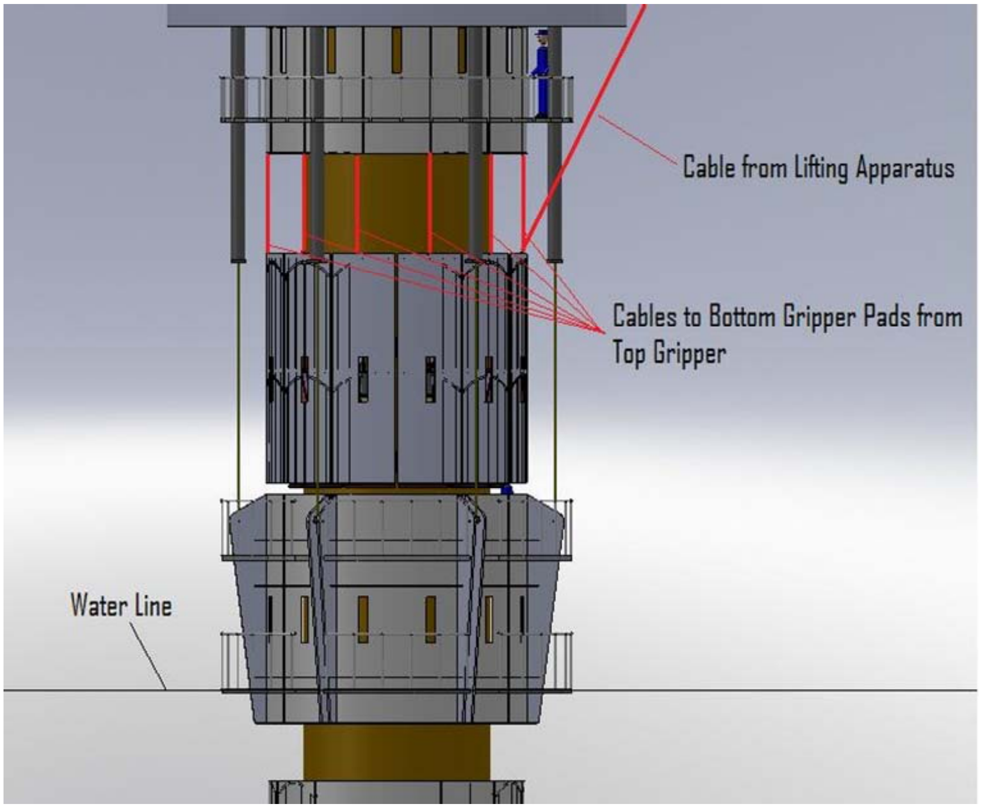


Figure 237. Remove Gripper Wedge and Pad Assemblies

While the gripper wedge and pad assemblies are being removed from the top and bottom gripper, the pipe is held in place by the two guides and is held vertically by the buoyancy of the compressed air plus an attached winch. A 30 ton winch with a compensator would be adequate for this operation in calm seas.

Figure 238 shows the CWP pipe being lowered through the gripper outer structures. The CWP is held laterally by the two guides. As the pipe is being lowered air is vented from the CWP. Figure 239 shows the air pressure requirements during this operation. Pressure vs. the elevation of the pipe termination is plotted in this figure. As the termination is moved from the upper deck at +20m to the water line, air is vented and the CWP loses a small amount of wet weight. Therefore, the required pressure drops slightly. Once the cap penetrates the surface, air will be needed to keep the volume of air bubble inside the CWP at a constant volume. It will be critical to coordinate the pipe lowering with the air pressure supply. Figure 239 shows the absolute pressure (blue line) inside the CWP as the pipe is being lowered below the surface and the constant pressure across the pipe wall (red line) during this lowering operation.

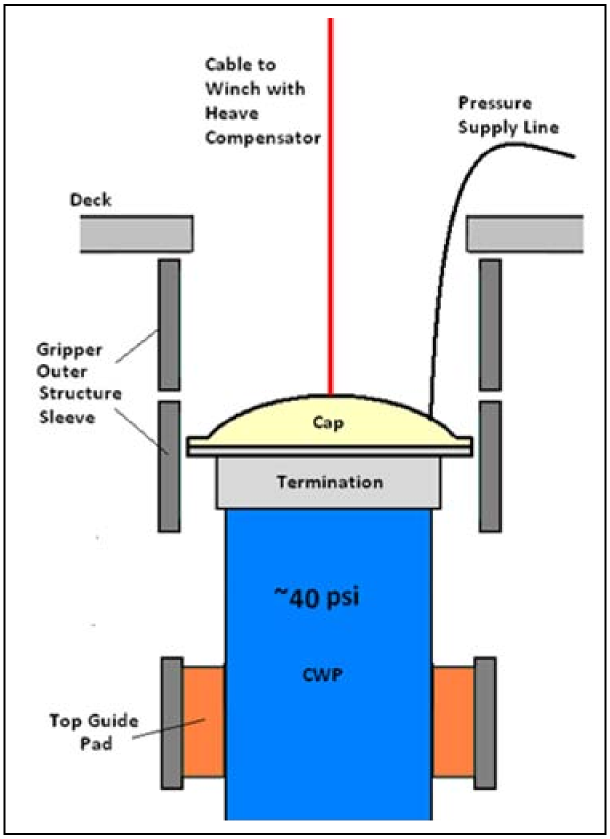


Figure 238. CWP Lowering Through Guides

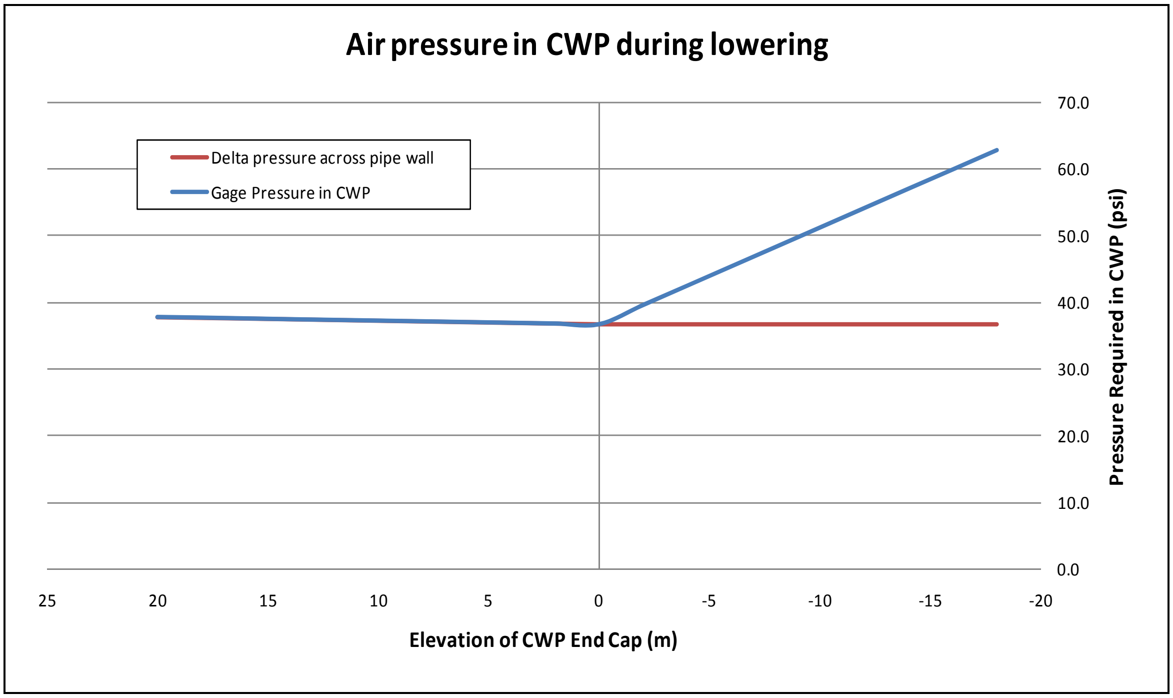


Figure 239. Pressure Regulation during Lowering

As the pipe termination approaches the upper guide, the 8 inch thick water bags in the upper guide must be evacuated. The water bags will retract and allow room for the termination to pass through. Once the upper guide pads are deflated, the pipe will only be supported laterally by only one guide. This is a critical timing issue and this step should not be started unless currents and seas are low. By using the pressure feedback from the upper guide pads, it can be determined whether deflating these bags are safe. Once these bags are deflated, the pipe should be quickly lowered to its final location at the top of the lower guide as shown in Figure 240.

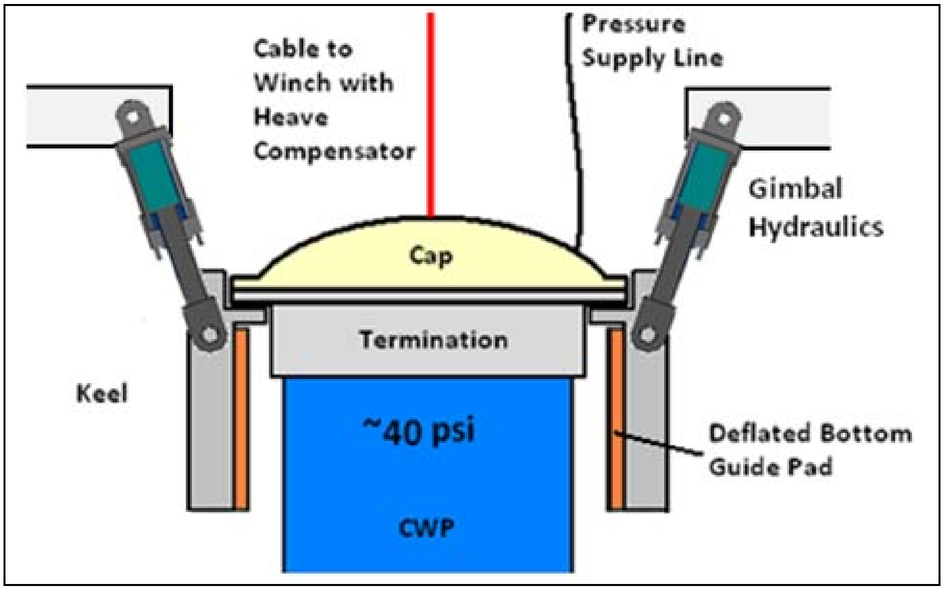


Figure 240. Setting CWP Termination on Lower Guide Flange

Figure 241 shows the removal of the pressure cap and Figure 242 shows the lowering of the bellows (if a gimbal is used) and the cold water manifold completion structure. When this is bolted in place, the cold water path from 1000m depth to the Remora(s) is complete.

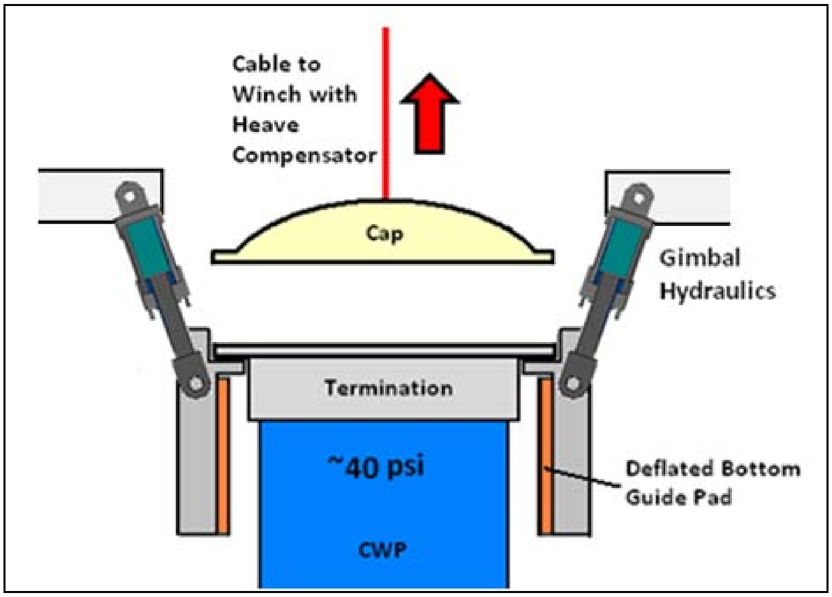


Figure 241. Cap Removal

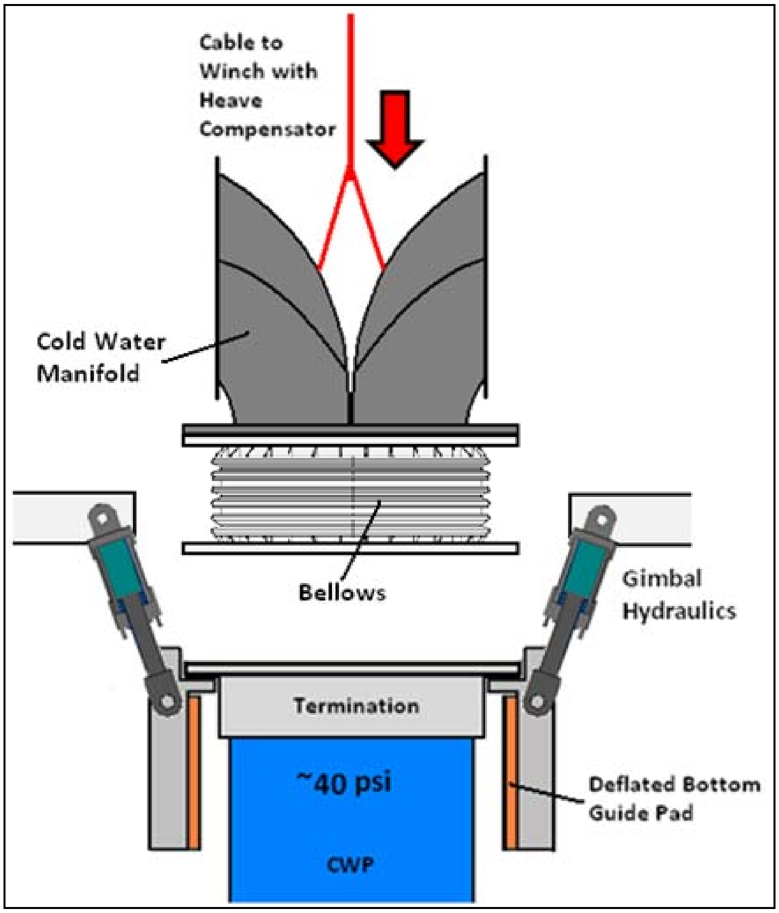


Figure 242. Completing the CWP Manifold Connection

6.15 1/20 Scale Model Test

NOTE: This apparatus is currently being assembled and tested on the Makai Research Pier. The assembly was completed on September 3rd, the apparatus has been going through shakedown and control sequencing through September 15th, and testing will commence by September 16th. Test results are not available for this report.

The more complex test is the construction and operation of a full scale model of the gripper and guides on a representative 20.5 inch FRP CWP. This is a scale model of the 10m gripper; the scale (s) is 20.5. The CWP will be a model of the 10m pipe and will have similar deflections and compression under the gripper load as the real pipe. Stresses and pressures have a scale factor of 1, forces have a scale factor of s^2, all linear dimensions and deflections have a scale of s. Total load on the gripper model will be 10,000 lbs representing the total wet weight of the 10m pipeline. This model is a fully functioning gripper being able to move the pipe up and down at varying total loads. The scale model will allow Makai to test most features of the grippers and guides.

6.15.1 Objectives

Table 46 gives the objectives of this series of tests:

Table 46. 1/20th Scale Model Test Objectives

	Objectives	Measurements needed
1	Show that top gripper is able to support full pipe weight	none
2	Show that bottom gripper is able to support full pipe weight	none
3	Show that gel pads provide uniform pressure across the length pad	pressure sensors on wedges with 3 sensors
4	Show that top gripper provides uniform pressure in each pad (all pads engage equally)	All top gripper pressure sensors
5	Show that bottom gripper provides uniform pressure in each pad (all pads engage equally)	All bottom gripper pressure sensors
6	Show that the control system is able to synch the screw jacks and the lifting hydraulics in order to engage the pipe without loading the tension layer	Strain gages
7	Show that the control algorithm ensures that the load has been transferred to the lower gripper before disengaging the upper gripper	strain gages, lifting hydraulic load, all pressure sensors
8	Show that the control algorithm ensures that the load has been transferred to the upper gripper before disengaging the lower gripper	strain gages, lifting hydraulic load, all pressure sensors
9	Show that the pressure in the guides are below 50 psi when the maximum shear and moment load are applied to the pipe	guide pressure sensors
10	Show that the weight supported by each wedge when a shear load and moment are applied to the pipe is within the accepatable limit	strain gages
11	Show that the distribution of pressure over the height of a pad when a shear and moment load are applied to the pipe is within the acceptable limit	pressure sensors on wedges with 3 sensors
12	Show that the pressure in each pad when a shear and moment load are applied to the pipe is within the acceptable limit	all pressure sensors
13	Show that the gripper can hold the pipe with a dynamic shear and moment load applied	none
14	Show that the gripper can run through a complete lowering sequence with a dyamic shear and moment load applied	none
15	Show that the movement of the pipe in the grippers is below the acceptable limit when a shear and moment are applied to the pipe	location of the pipe in the top gripper and both guides
16	Show that the apparatus can run through lowering cycles with different pipe weights	

6.15.2 Test Apparatus

The following figures illustrate the configuration and development of the Gripper Model. Figure 243 shows the Solid Works design of the test apparatus. An elevated platform was constructed on the Makai pier and cantilevered off the side. Two grippers and guides have been fabricated on this platform. An FRP pipe provided by Lockheed with the same characteristics as the actual CWP can be raised and lowered by the grippers. Variable loading was applied to the CWP by hanging concrete weights below the pipe. The load on the gripper can be varied by adjusting the number of weights attached to the pipe. Shear loads and moments can be applied to the guides and gripper pads by rocking the platform and pulling laterally on the pipe below the pier.

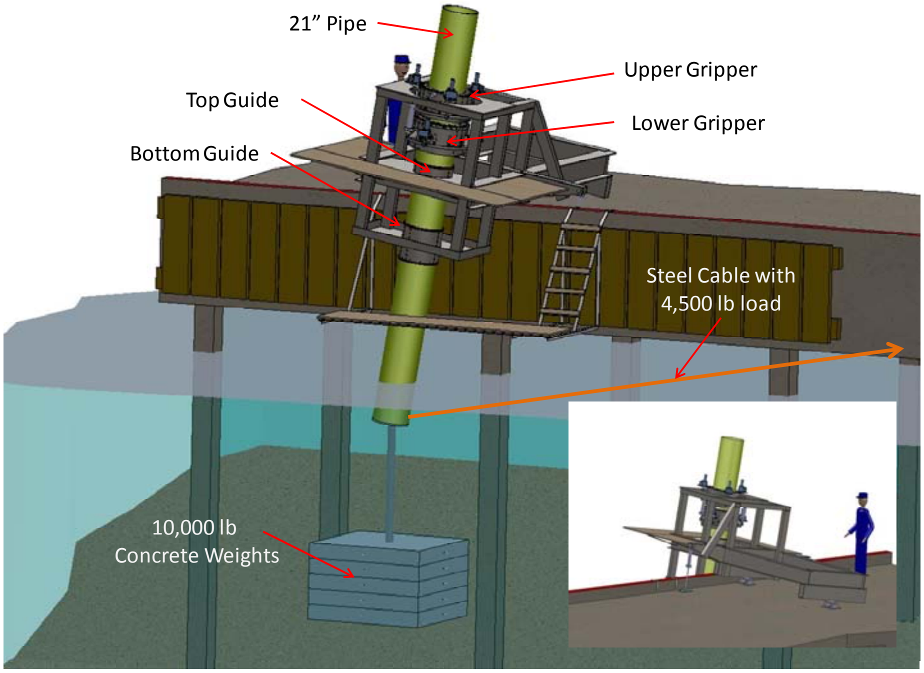


Figure 243. Gripper and Guide Test Apparatus

Figure 244 shows the test apparatus with the CWP installed. The two grippers are above the main deck. The upper guide is just below the main deck (not visible) and the lower guide is shown below.

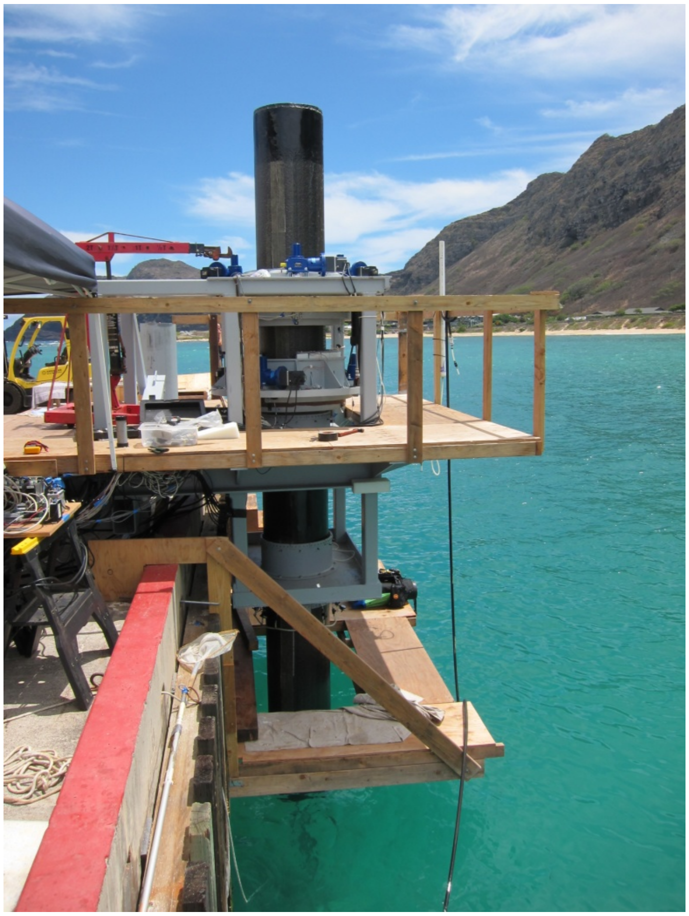


Figure 244. 1/20th scale Gripper Test Arrangement

Figure 245 shows the Solid Works detail of the upper and lower grippers. Three lifting rams are used to move the lower gripper. Figure 246 shows a similar view of the physical model.

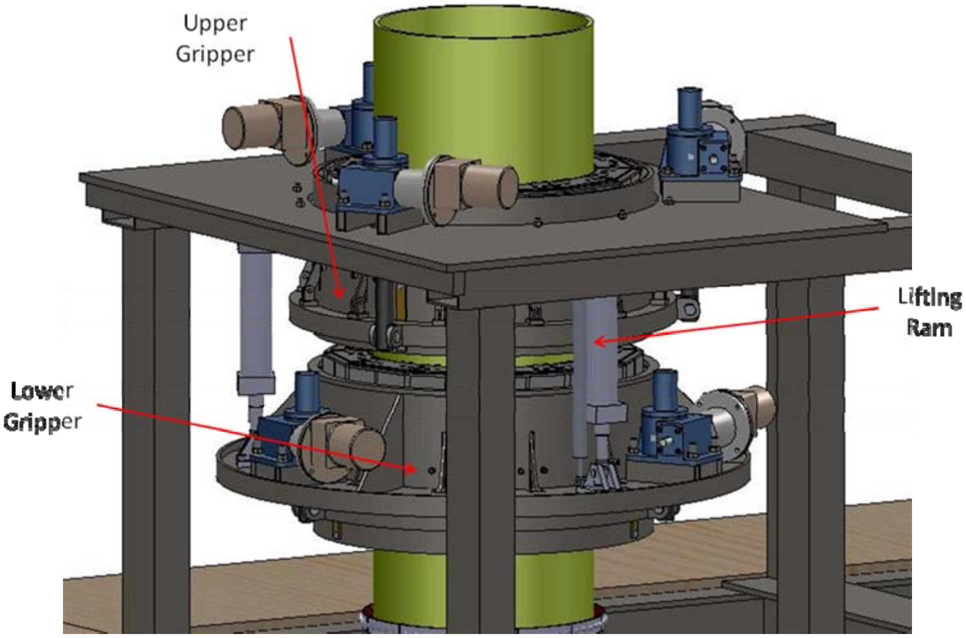


Figure 245. Upper and Lower Gripper

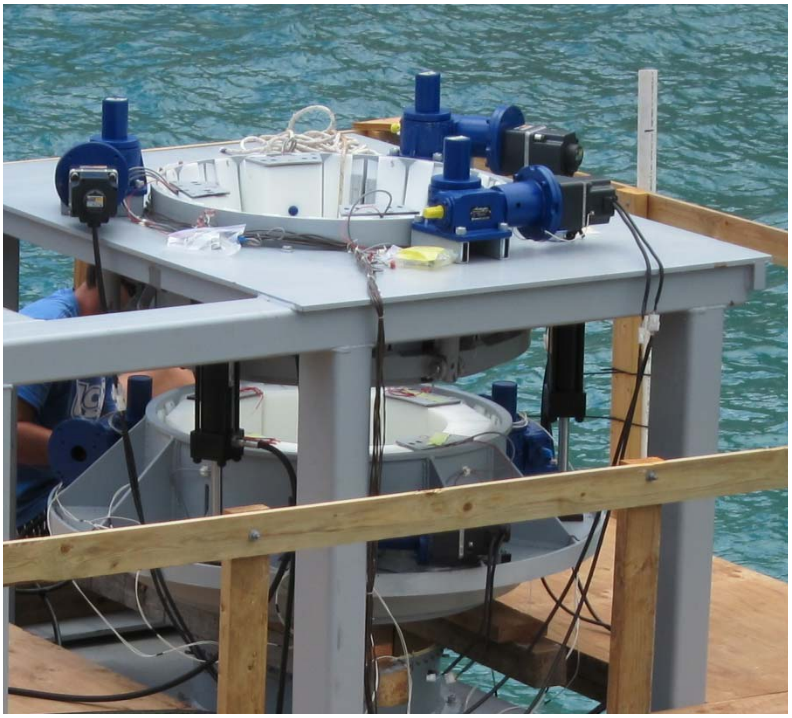


Figure 246. Upper and Lower Gripper Model

Figure 247 shows a cross section of the upper and lower grippers. The inner wedge is raised and lowered by a linkage arm attached to a circular engagement ring. This ring is driven up and down by three screw jacks that are driven by an electric stepper motor. Thus, the model works differently than the actual 4m gripper. It was not economically feasible to have all 24 wedges driven independently by hydraulic rams in this model. Since the model is not a hydraulic control model, this variation was acceptable.

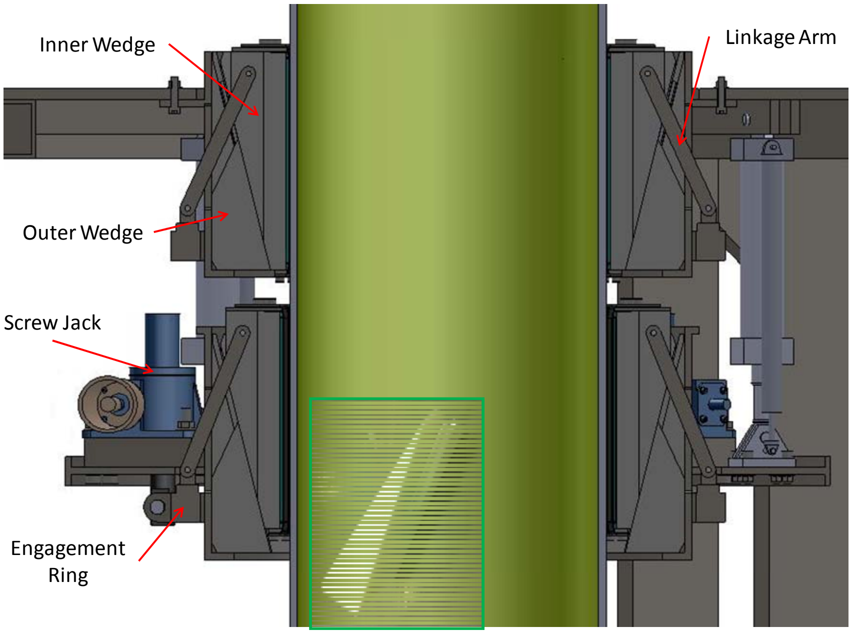


Figure 247. Gripper Wedges, Gripper Cross-section

Figure 248shows the lower gripper partly assembled. The outer polyethylene wedges have been installed. In Figure 249, some outer wedges have been attached with the alignment apparatus between the wedges. Figure 249 shows the upper gripper installed on the apparatus with all wedges installed (but the tension layers have not yet been installed). It is possible to see the pressure transducers in selected inner wedges. Four wedges also have strain gages in the upper steel plate from which the tension layer hangs – thus the vertical load can be measured in these wedges.

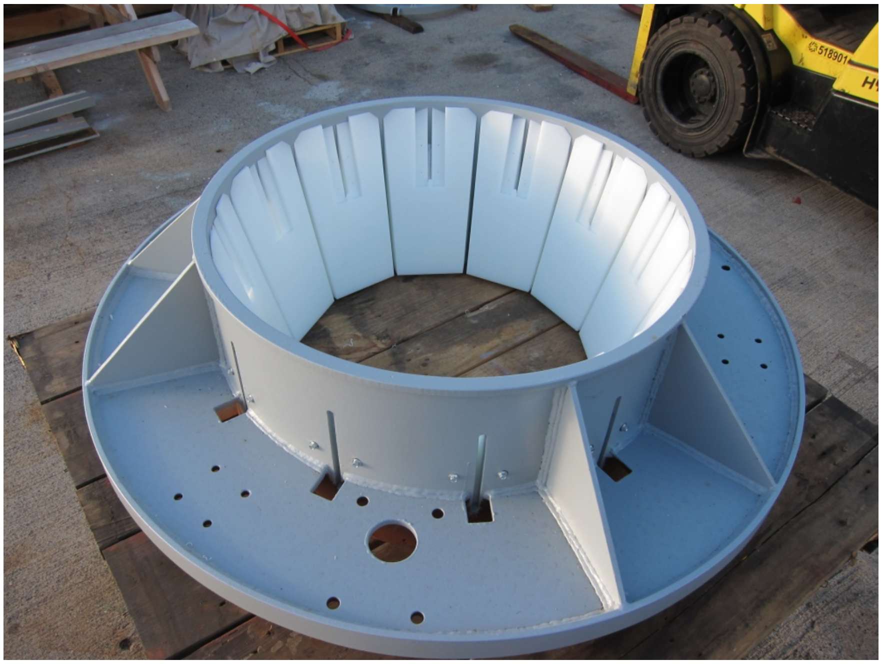


Figure 248. Lower Gripper Being Assembled

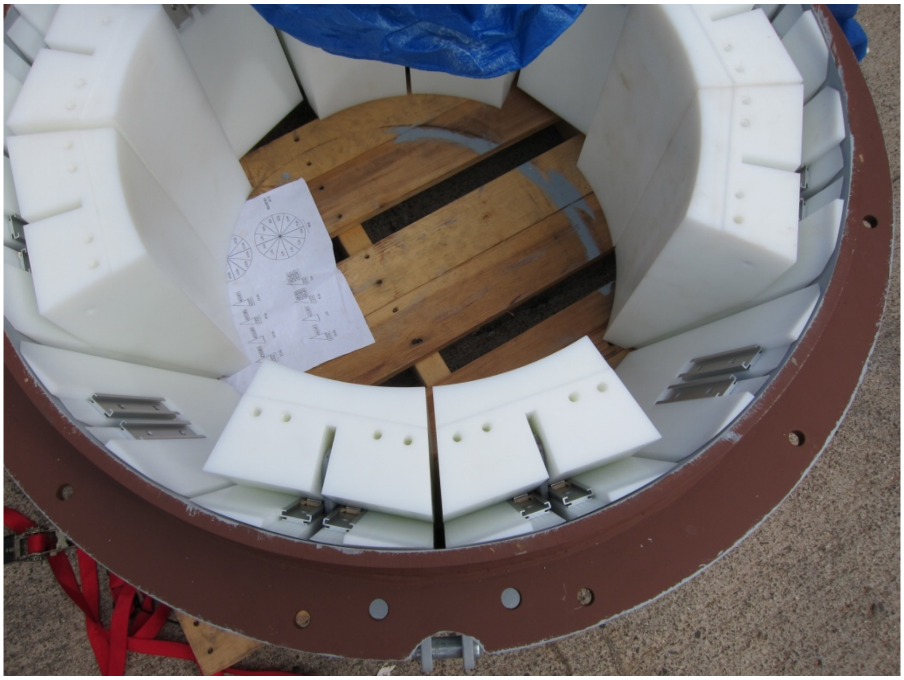


Figure 249. Inner Wedge Assembly, Wedge Guides.

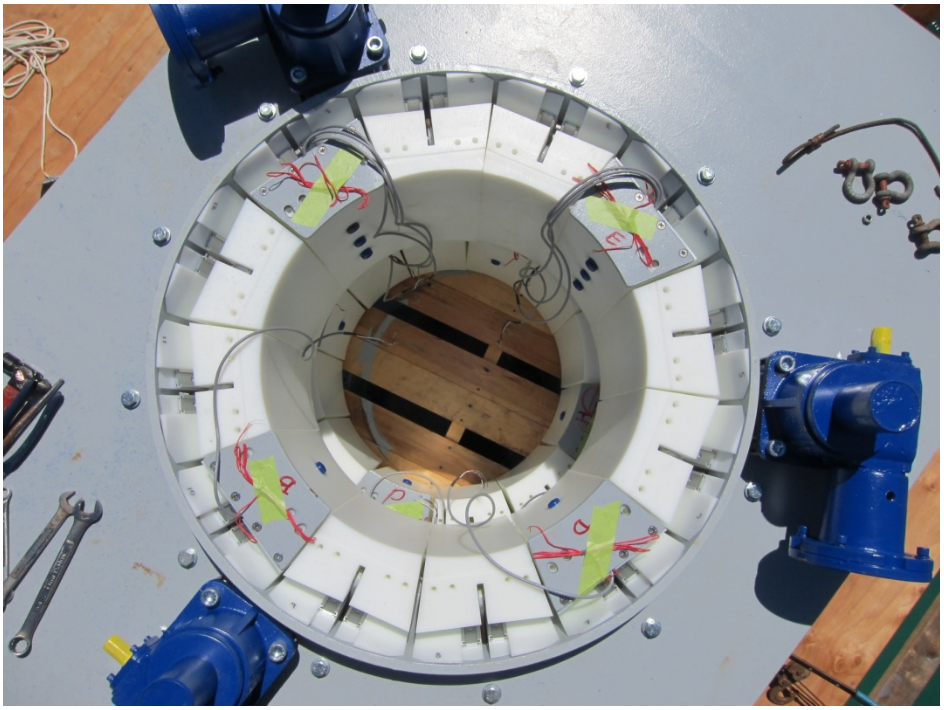


Figure 250. Inner Wedges with Pressure Sensors and Strain Gages

Procuring and fabricating the tension and friction layers for the model proved to be a significant challenge. All attempts by the rubber supplier to imbed Kevlar fabric in the selected natural rubber failed primarily because Stockton rubber had not done this before. Kevlar is commonly use in rubber tires, so the technology exists. Because time was short, Makai built the tension layers. These consisted of two layers of Kevlar fabric that were adhesively bonded. These were molder and tensioned in the wedges to achieve the proper shape as shown in Figure 251. The 0.25 inch Stockton rubber was then adhesively bonded to the inner surface of the Kevlar. After experimenting with a wide variety of adhesives, a common “Super Goop” from the hardware store displayed nearly indestructible yet flexible adhesion in Kevlar to Kevlar and Kevlar to natural rubber. A wedge with a gel bag and tension layer is shown in Figure 252.

Figure 251. Fabricating Tension and Friction Layers

Figure 252. Wedge with Gel Pad, Tension and Friction Layers.

One other fabrication challenge has been the Gel bags for the gripper wedges. The same gel developed for the 4m gripper has been used in the model and place in fine nylon bags. After pressurizing the pipe for 72 hours with the lower gripper at 50 psi, some of the gel escaped through the seam stitch holes as shown in Figure 253. A revised bag was developed with a more impervious nylon fabric and sealant tape over the longitudinal stitches and no stitches at the end seams – the ends were simply folded over and taped down. These gel bags have worked satisfactory.

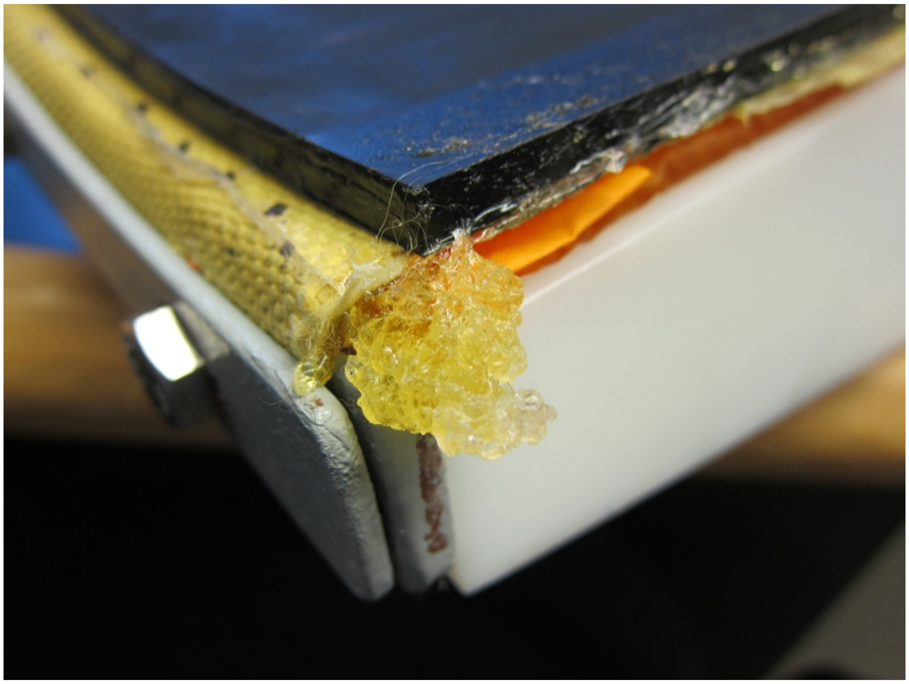


Figure 253. Gel Leakage from Gel Pad

The inner wedges of both the upper and lower grippers are driven by a step motor connected to a jack screw. The motor and gear box are shown in Figure 254and Figure 255. The connection to the engagement ring and the subsequent linkage to the inner wedges are shown in Figure 256.

Figure 254. Motor and Jack Screw

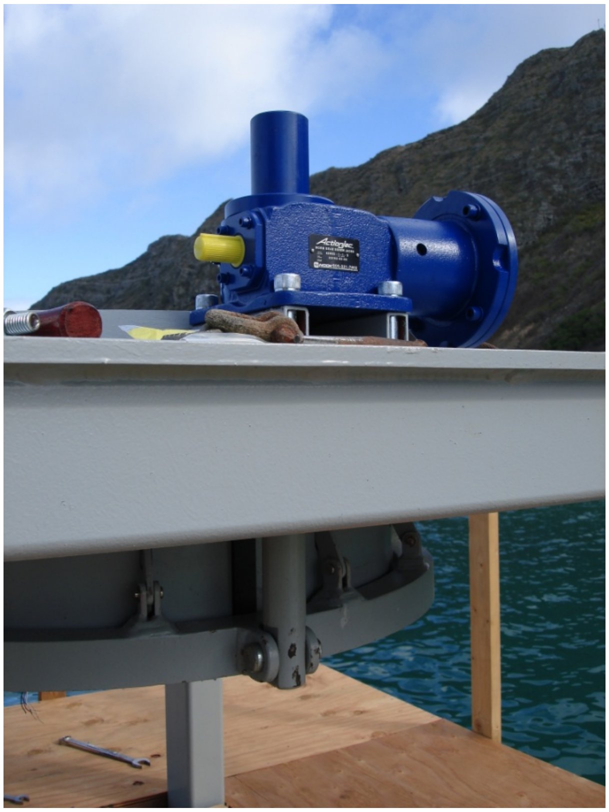


Figure 255. Jack Screw Driving Upper Gripper Engagement Ring.

Figure 256. Engagement Ring with Jack Screw Drive Pin

Figure 257 shows the lower gripper assembly. This assembly is lowered with three hydraulic rams. The arrangement is shown in Figure 258.

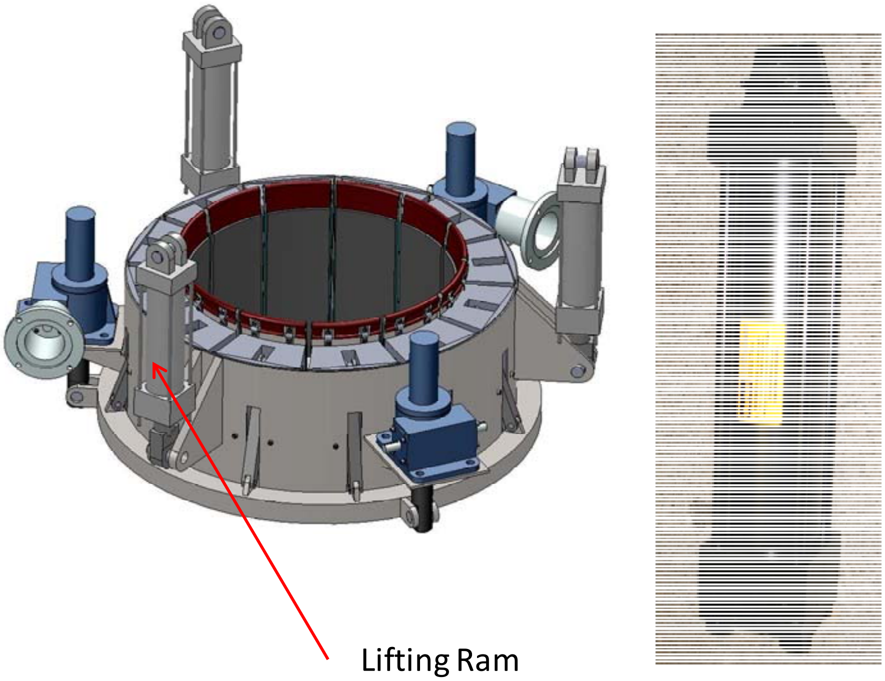


Figure 257. Lower Gripper Assembly

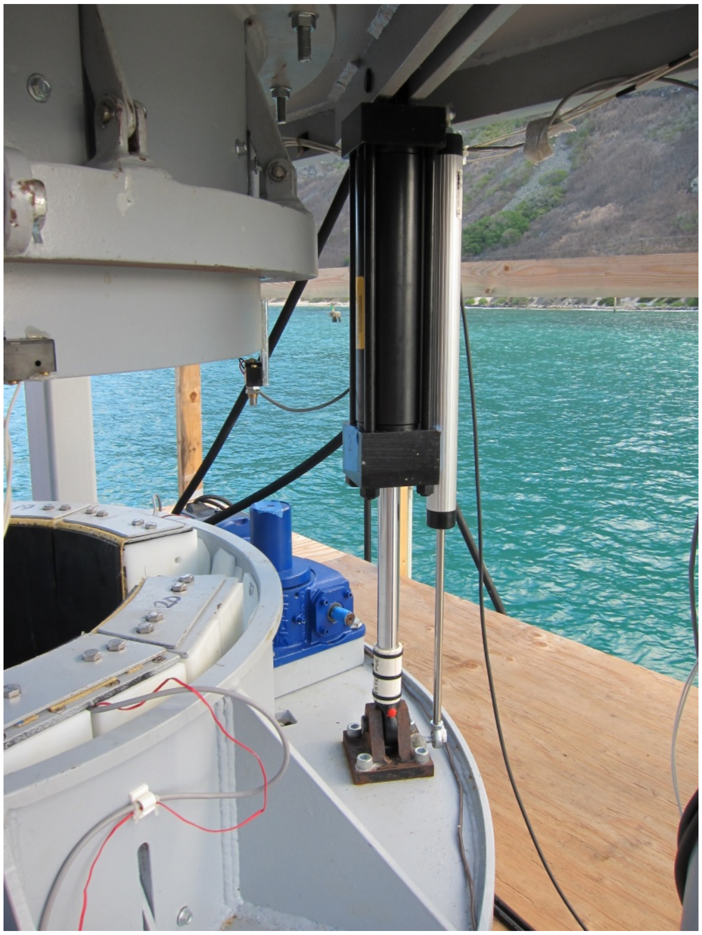


Figure 258. Lifting Ram for the Lower Gripper.

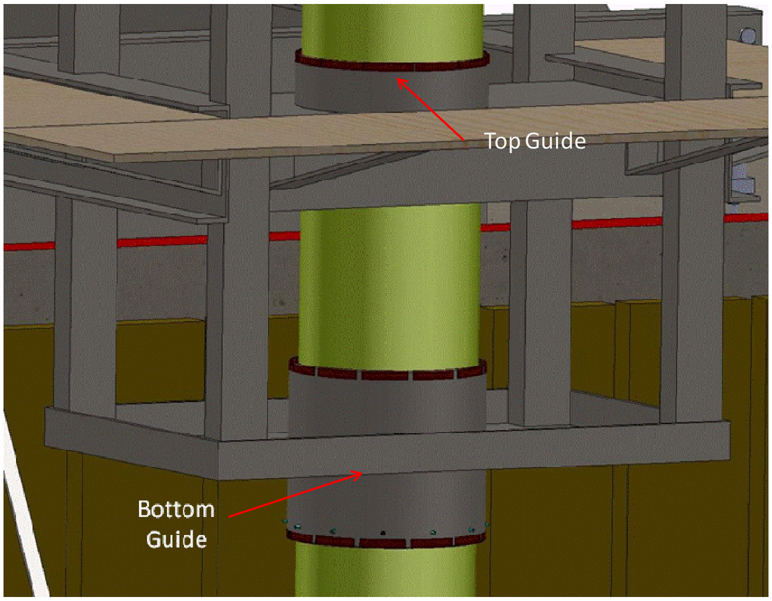


Figure 259. Model Guides

The location of the upper and lower guides is shown in Figure 260. The guide bags are water filled rubber bladders contained in a Dacron bag. Each bladder is connected to a common manifold as shown in Figure 261 . Each can be individually adjusted for pressure. There are pressure gages on twelve of the guide bags to monitor loads during pipe operations.

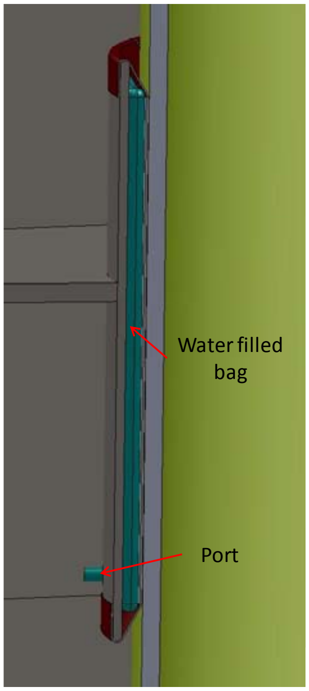


Figure 260. Guide Pads

Figure 261. Upper Guide Ring with Water Manifold Attachment

A termination has been added to Lockheed's CWP model as shown in Figure 262. This termination provides a connection to the 10,000 lbs bottom weights and for lateral attachment when the pipe is being tested with high moments. Figure 263shows the pipe being lowered into the water and Figure 264shows the pipe being pulled into the test apparatus from below. Figure 265 shows the three concrete weights at the bottom of the harbor under the test apparatus.

Figure 262. Termination Added to Lower End of CWP

Figure 263. Lowering CWP into the water

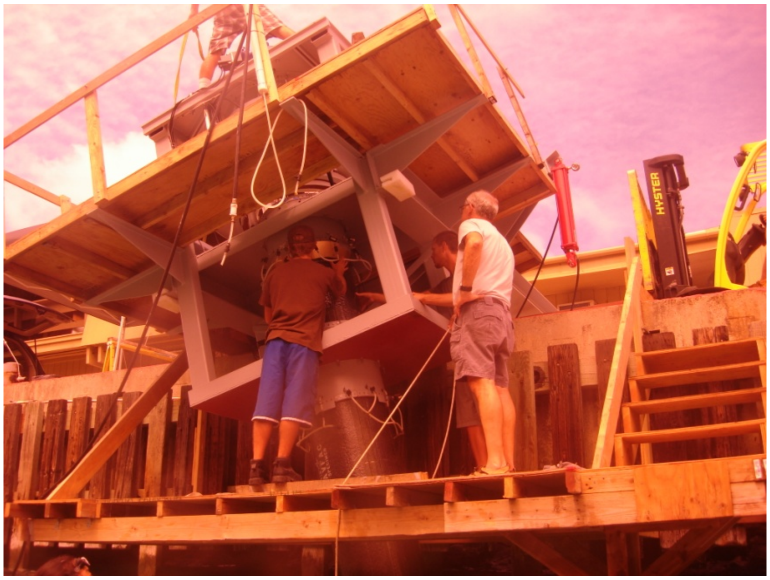


Figure 264. Pulling CWP into the Gripper from Below

Figure 265. 10,000 lbs Wet Weight on Bottom below Test Apparatus

6.15.3 Design of the Model

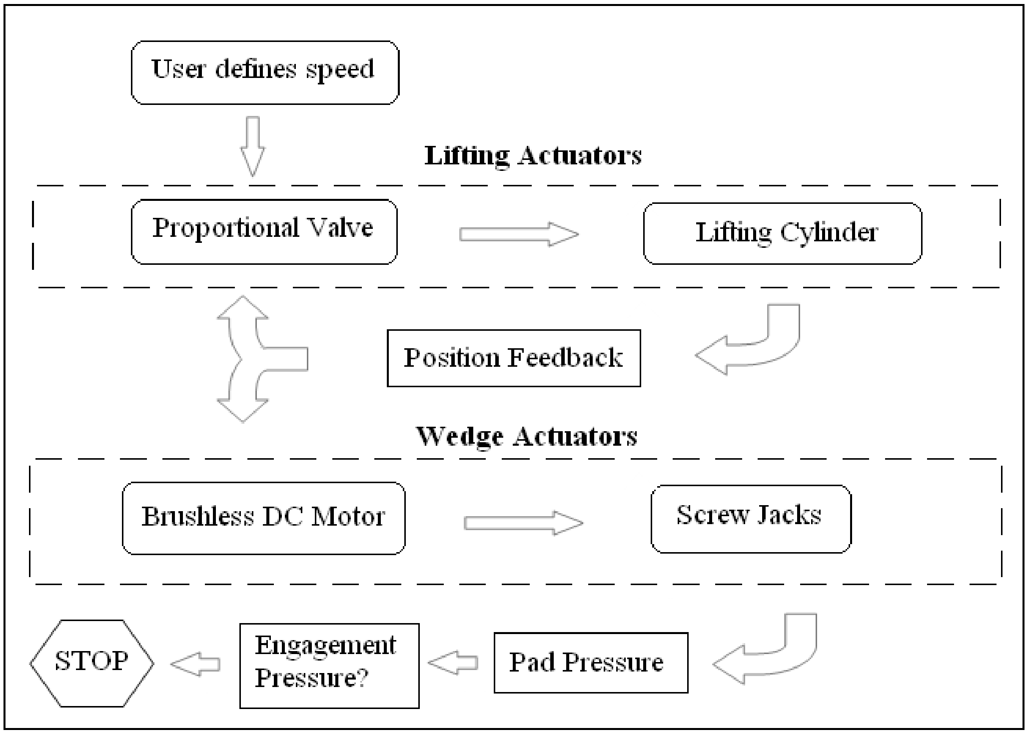


Figure 266. Gripper Control Feedback

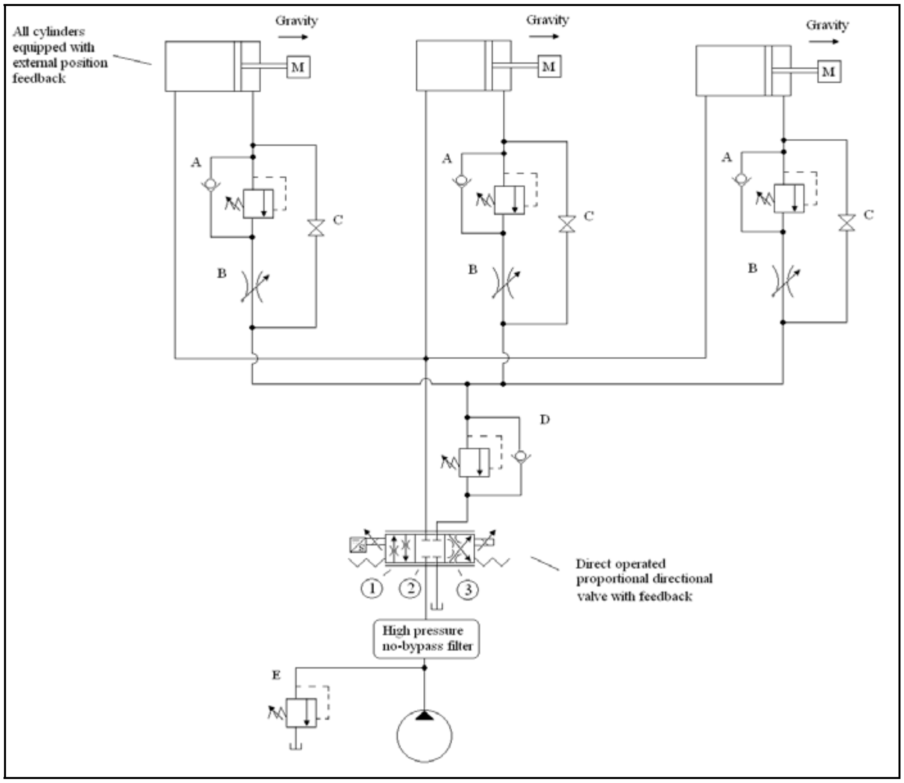
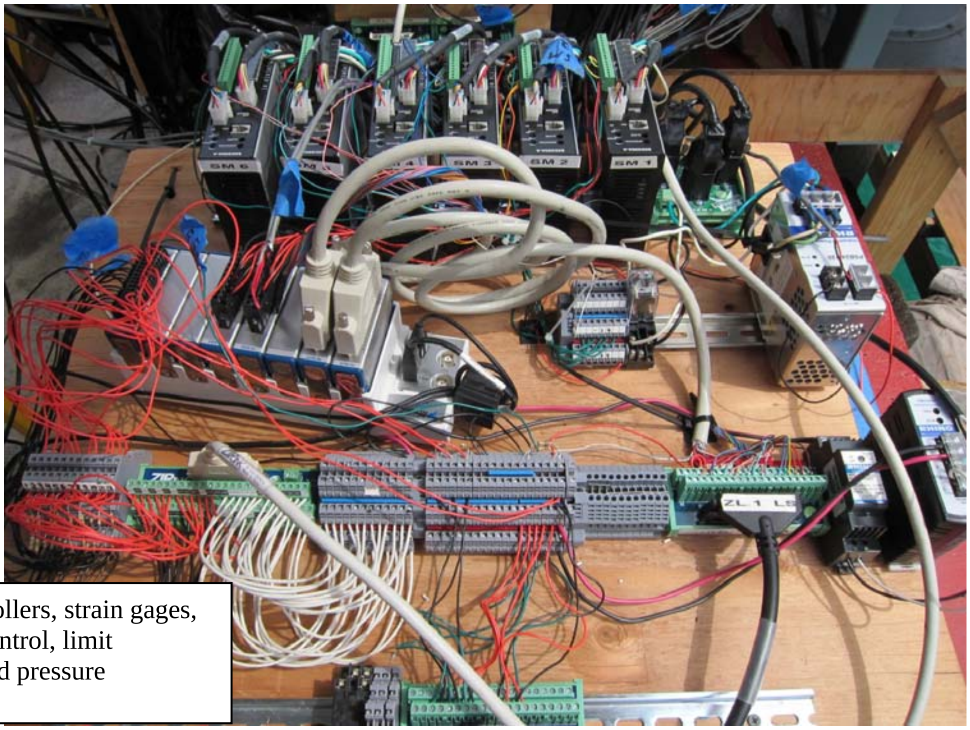


Figure 267. Lowering Ram Control



motor controllers, strain gages, hydraulic control, limit switches, and pressure transducers

Figure 268. Electronic Wiring

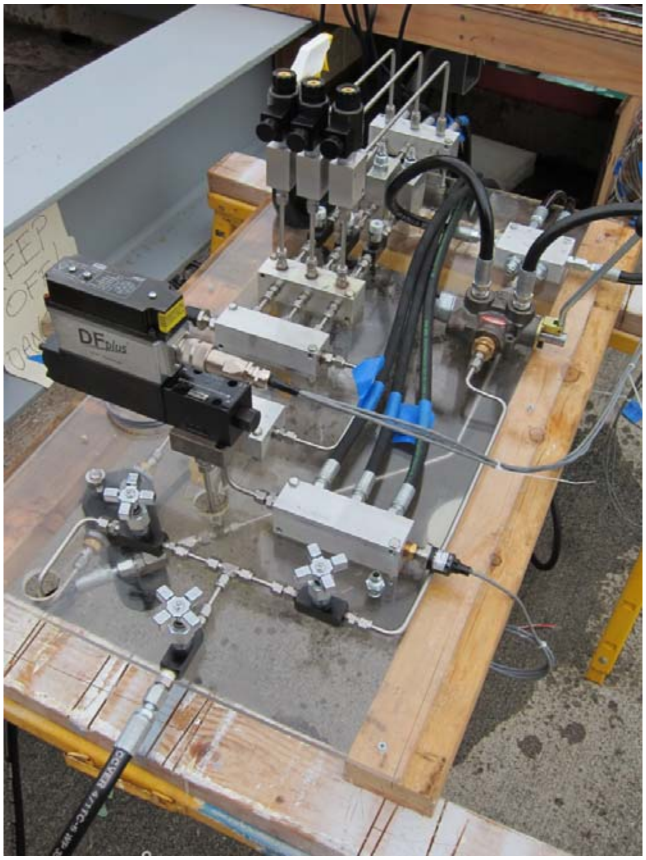


Figure 269. Hydraulic Valves and Controllers

The gripper and Guides Control Panel is shown in Figure 270. The gripper control system was written in National Instrument's Labview. This software is ideal for this type of control system in many ways. For example, the simple 'drag and drop' controls and indicators provide a quick method of displaying the data needed during operation. Also, these controls and indicators can easily be added or removed during a given test if more information is needed. Data can be saved to file for later analysis or simply discarded. Finally, the data acquisition hardware, firmware and software were all provided by National Instruments which adds the element of reliability and minimized the long setup times observed in typical control systems.

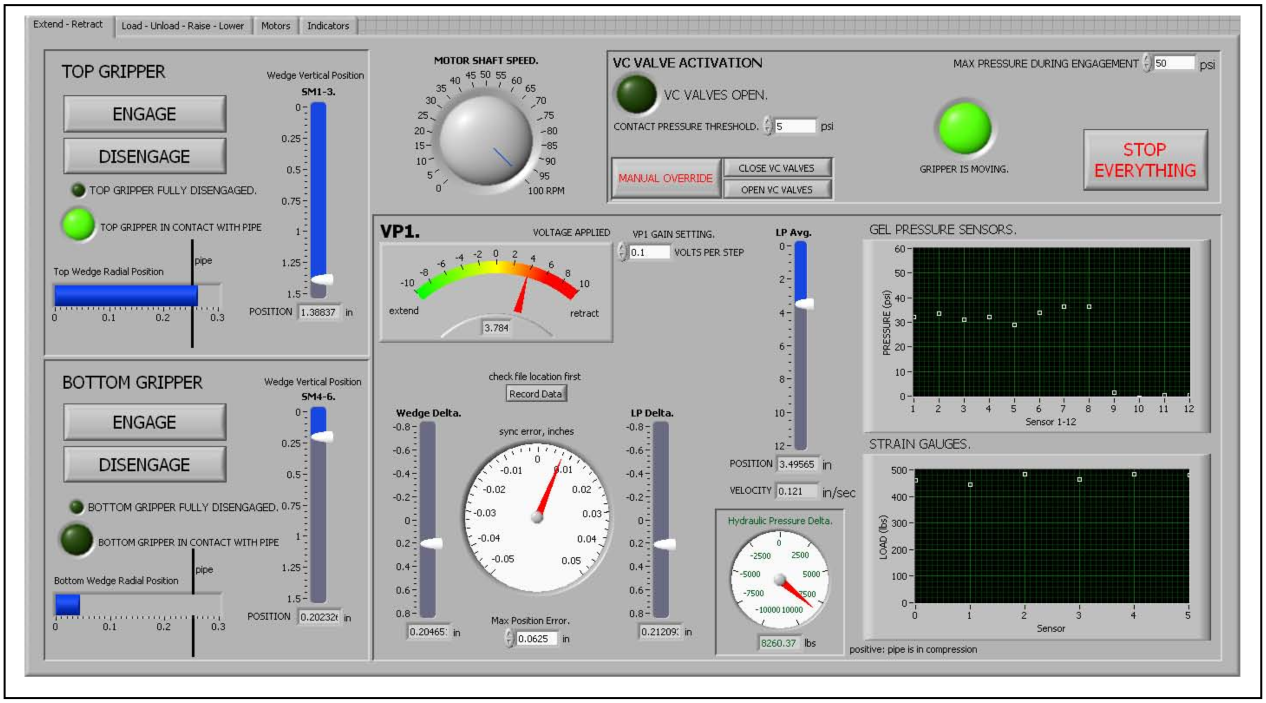


Figure 270. Control Panel for the Operation of the Gripper and Guides

The foundation of the software is a high speed data capture loop. In this loop, all the data from the sensors are read, converted into standard units, and sent out for display or further conversion. The pressure on the pipe, the load on the wedges, and the position of the hydraulic cylinders are examples of information the user will always need to know during operation, and the data is directly displayed on the front panel. Other information requires user input to display the correct data. For example, whether or not the gripper is in contact with the pipe depends on the user-specified 'contact pressure threshold'. In this case the software scans the pressure sensors, determines the maximum, and lights up the indicator if the maximum is greater than the threshold. The software also waits for commands from the user, such as 'Engage Top Gripper'. If this command is sent, the control system will enter a second loop where, depending on the user-specified speed, it will activate the motors and hydraulics to move along a specific linear path of position versus time. During this step, it is critical that the wedges and hydraulic cylinders move synchronously. Using data from the motor encoders and hydraulic linear potentiometers, the system calculates the error and makes adjustments to the hydraulic control valve, VP1, to minimize the error during engagement. Finally, the control software searches for failures during every loop. Some examples include stopping all motors or all hydraulics when a limit switch is tripped, stopping engagement if a pressure or load is too high, and activating the gimbal mode when the gripper is in contact with the pipe.

6.15.4 Testing

Testing was underway at the time this report was prepared. Therefore reporting on the testing, results and conclusions were not available in time to be included in this report. These sections will be made available in a update when testing is completed.

Table 47. Test Procedures Planned for the 1/20th Scale Model Gripper

Test #	Description	Objectives Satisfied
1	Squeeze fiberglass pipe at 50 psi with lower gripper - No added weight	3,4
2	Engage the upper gripper while the lower gripper is holding the pipe - No weight added	3,5
3	Run through a complete lowering sequence - No added weight	6
4	Lift 3000 lbs with bottom gripper	None
5	Lift 6000 lbs with bottom gripper	None
6	Lift 9000 lbs with bottom gripper (done to center weights)	2
7	Run through a complete lowering sequence holding 3000 lbs	6,7,8
8	Tilt platform while holding 3000 lbs with both grippers	15
9	Run through a complete lowering sequence holding 3000 lbs with platfrom tilted	16
10	Run through a complete lowering sequence holding 6000 lbs	16
11	Tilt platform while holding 6000 lbs with both grippers	15
12	Run through a complete lowering sequence holding 6000 lbs with platfrom tilted	16
13	Run through a complete lowering sequence holding 9000 lbs	1,2
14	Tilt platform while holding 9000 lbs with both grippers	
15	Run through a complete lowering sequence holding 9000 lbs with platfrom tilted	1,2
16	Run through a complete lowering sequence holding 3000 lbs with dynamic shear and moment loads	13, 14, 15
17	Run through a complete lowering sequence holding 6000 lbs with dynamic shear and moment loads	13, 14, 15
18	Run through a complete lowering sequence holding 9000 lbs with dynamic shear and moment loads	13, 14, 15
19	Apply maximum shear and moment loads (using cables attached to pier) while holding 3000 lbs with both grippers	9, 10, 11, 12, 15
20	Apply maximum shear and moment loads (using cables attached to pier) while holding 6000 lbs with both grippers	9, 10, 11, 12, 15
21	Apply maximum shear and moment loads (using cables attached to pier) while holding 9000 lbs with both grippers	9, 10, 11, 12, 15

DETAILS TO BE PROVIDED LATER

6.15.5 Results

Testing was underway at the time this report was prepared. Therefore reporting on the testing, results and conclusions were not available in time to be included in this report. These sections will be made available in a update when testing is completed

6.15.6 Conclusions

Testing was underway at the time this report was prepared. Therefore reporting on the testing, results and conclusions were not available in time to be included in this report. These sections will be made available in a update when testing is completed

6.16 Cold Water Pipe Pad Test

A key concern and a focus of analysis has been the external pressure capacity of the CWP. The CWP pressure limits dictate the size of the Grippers and Guides and determine whether this method of CWP handling is practical. The CWP has gone through changes as the program has adjusted the external pressure capacity. This test was designed to address these pressure concerns.

6.16.1 Purpose of the Test

This test is designed to test the external pressure capacity of version 1 CWP under uniform external loads, under conditions with gaps between the pressure bags (as with the small gaps between gripper pads) and with surface irregularities.

The Tests will externally load a sector of the 4m, Version 1, CWP. By ANSYS analysis, this pipe should fail at 70 psi. This pipe is not the current version 5 which should fail at 140 psi. Version 1 core materials have been fabricated by Lockheed under a separate contract and are available; core planks for Version 5 pipe are not available. For calibrating and validating the ANSYS analysis and the CWP design, the Version 1 pipe is adequate.

6.16.2 Test Apparatus

The following is an illustration of a static test that is designed to test the CWP/gripper interaction that is of most concern to the team today. The CWP under high pressure fails as the internal ribs buckle under compression. Half the external compressive load is carried by the outer facesheet, half by the inner facesheet and the ribs transfer the compression between the two layers. Lockheed has analyzed the pipe and predicted a failure point. This is a critical design safety factor for the CWP design and this test is designed to confirm the FEA model and demonstrate the external loading capability on the CWP.

In this test, a section of the existing CWP is mounted between two triangular pivot supports as shown in Figure 271. These supports can only provide circumferential compressive loads on the face sheets as the pivot evenly loads both face sheets. An inflatable bag, as shown in Figure 272, is used to provide a uniform external load on the CWP section (which is approximately 30 inches wide). The pivot on the right side includes rollers so the CWP section can compress and shrink simulating the compression of the full CWP (the 10m pipe will shrink over 8 cm on the diameter).

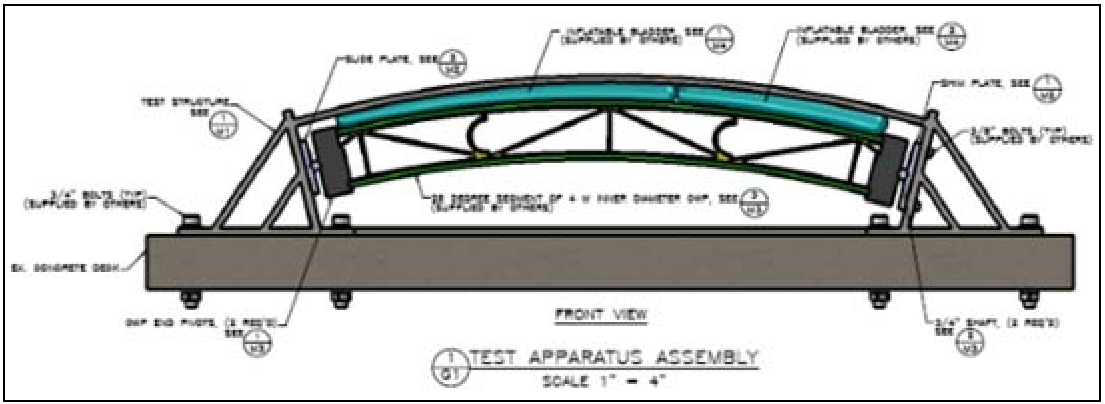


Figure 271. Profile of the CWP Pad Test

Figure 272. Pressure Bags

The higher platform interface loads on the CWP occur at the CWP guides. Pressures exceeding 50 psi may occur in the 10m CWP. FEA of the current 4m CWP (version 1) predicts a failure at 70psi in the core struts. A 4m CWP version 5 has been redesigned for 70 psi operation (>140 psi failure).

6.16.3 Test Samples

6.16.4 Test Plans

Three pipe sectors will be tested:

a. The first section will be loaded uniformly with no surface abnormalities and no gaps between the pressure bags. Pressure will be increased slowly observing the buckling of components. The test apparatus can pressurize the CWP to as high as 150 psi. Failure is expected at about 70 psi with buckling in the core ribs.

b. If the pipe sector fails as expected in test 1, the next test will be to determine if there is a significantly lower failure mode if there is a representative gap between the pressure bags (as there will be with the gripper).

c. If the pipe sector fails prematurely in the first test, and depending upon the failure mode and consultation with the CWP designer, it may be desirable to stiffen the core planks by adding polyurethane foam to the core interior. This approach would be used if the foam core option appears to be a viable design solution to the premature failure.

A fourth test will be conducted with a pressure point introduced on the surface of the CWP by adding a bump placed specifically to enhance failure.

6.16.5 Test Results

Testing was underway at the time this report was prepared. Therefore reporting on the testing, results and conclusions were not available in time to be included in this report. These sections will be made available in a update when testing is completed.

6.17 4 meter Gripper and Guide Drawings

Appendix 6.17-1 contains the drawings for the grippers and guides. The following drawings are included in this appendix:

G - GENERAL
S - STRUCTURAL
M - MISCELLANEOUS

G1	TITLE SHEET, DRAWING INDEX
G2	GENERAL COMPONENT ARRANGEMENT, ABBREVIATIONS, GENERAL NOTES
S1	TOP/BOTTOM GRIPPER ASSEMBLY - COMPONENT CALLOUTS
S2	TOP GUIDE ASSEMBLY - COMPONENT CALLOUTS
S3	BOTTOM GUIDE ASSEMBLY - COMPONENT CALLOUTS
S4	TOP GRIPPER OUTER FRAME
S5	BOTTOM GRIPPER OUTER FRAME
S6	INNER WEDGE ASSEMBLY
S7	NNER WEDGE ASSEMBLY (CONT.)
S8	OUTER WEDGE ASSEMBLY
S9	WEDGE ALIGNMENT TRACK AND SLIDER
S10	GRIPPER GEL BAG CLAMPS
S11	GRIPPER FRICTION LAYER CLAMPS
S12	TOP GUIDE OUTER FRAME
S13	TOP GUIDE SLIDE LAYER CLAMP AND WATERBED CLAMP
S14	BOTTOM GUIDE OUTER FRAME
S15	BOTTOM GUIDE SLIDE LAYER CLAMPS, WATERBED CLAMPS, AND GEL BAG CLAMPS
M1	SLIDE SHEET, WEDGE ALIGMENT TRACK BUSHING
M2	GRIPPER GEL BAG
M3	GRIPPER FRICTION LAYER
M4	TOP GUIDE WATERBED
M5	TOP GUIDE SLIDE LAYER
M6	BOTTOM GUIDE GEL BAG
M7	BOTTOM GUIDE WATERBED
M8	BOTTOM GUIDE SLIDE LAYER

6.18 4 meter Gripper and Guide Specifications

TO BE PROVIDED LATER

6.19 Gripper and Guide Conclusions

6.19.1 Conclusions

- 10m Conceptual Design has been completed:
  - Trades lead to friction external CWP support, hydraulic movement, very stiff waterbed pads & separate guides.
  - Natural Rubber selected & tested with adequate coefficient of friction wet, dry and w/hydraulic oil. SF>2.
  - The 10m concept has been the basis for the 4m G/G design
  - Gripper design can be similar to the 4m design but the upper gripper may need to gimbal ~0.5 deg to minimize cost of pads.
- CWP/Platform dynamic coupling
  - Strains adequate for fabrication period. 10m needs re-evaluation with final platform.
  - Guide pressure can be kept at 50 psi by placing and sizing guides properly.
  - CWP external pressure can be adjusted at moderate CWP cost impact; current version has a safe working pressures of 70 psi.
  - Movement of the CWP within the fabrication structure is adequate based on static and dynamic modeling results. This can be achieved only with very stiff guide pads and structure.
- 4m Design meets all design goals:
  - Reliable CWP handling: self locking, no power to hold, SF >2 when moving and SF > 4 when holding.
  - Safely grips CWP: uniform pipe pressure, handles pipe distortion and irregularities
  - Adequately restricts CWP movement within the fabrication apparatus. Pipe movement is acceptable
  - Dynamic Guide pressures @ 50 psi
- Design interfaced with 10MW platform
- “Waterbed” Pad concept important for reliable holding and even pressure distribution; this is best achieved with low strength polyurethane gel in heavy nylon bags.
- ANSYS structural analysis complete, stresses have been kept below 18,000 psi.
- Operation of the gripper is best achieved with 30 individually controlled rams each with a proportional valves and length feedback.

- The process of transferring the CWP load from one gripper to the other has positive feedback that the receiving gripper is holding the CWP weight prior to release by the transferring gripper.
- Operation of the guides requires water filling the bags to keep a snug lateral hold on the CWP.
- Final lowering of the CWP upper termination to its mating flange above the upper guide can be achieved by relieving the CWP weight by capping and blowing the interior (41 psi) and lowering the CWP with a winch. The gripper and upper guide pads can be retracted to pass the upper termination.
- All gripper operations are reversible.
- Individual wedges and pads can be removed for repair during CWP fabrication and for re-use after fabrication.

MORE TO COME WITH TESTING RESULTS…

6.19.2 Remaining Risks and Mitigation Plans

While the design of the grippers and guides for the 4m CWP is nearly complete, there are a few tasks that remain prior to implementing this concept. It is recommended that:

- Actual rubber frictional characteristics may vary from those tested in this program. A particular rubber (supplier and type) has been selected. It is common practice to reverse engineer rubber compounds and these may be proposed by the fabricator. Whatever rubber is used, samples must be tested for coefficient of friction on the most current version of the CWP external wall prior to building the gripper. The shear modulus of the rubber should be measured at the same time.
- The elasticity of the tension layer must be measured at 1550 lbs per inch. Based on the elasticity measured and the rubber properties, the thickness of the final friction layer should be confirmed per the analysis procedure given in this report.
- The terminations of the tension layer should be tested prior to fabricating the final tension/friction layers.
- The ability to vacuum seal to a moving CWP needs to be tested to verify the allowable movement.
- Allowable movement criteria may change if the CWP fabrication tower is lowered or the fabrication process is changed.
- The gripper and guides should be built and tested prior to use at sea building a real CWP. This can be done in conjunction with a CWP fabrication test.
- A model basin test of the coupled platform/CWP should be performed. This would validate the dynamic models used to predict CWP loads and strains.
- This design is more advanced than those of the platform or CWP fabrication. There are no immediate plans to build the gripper and guides. Prior to construction, the design should be reviewed taking into account any progress and changes made on platform and CWP design.

- OTHERS PENDING…

7. APPARATUS PLATFORM INTERFACE

The Cold Water Pipe Fabrication Environmental Enclosure (CWP-FEE) is intended to facilitate the complete construction of the CWP by providing a safe and secure area for the people, equipment and materials required for the fabrication process. The CWP-FEE is intended to be erected on the platform and then decommissioned after service and before start-up operations. The CWP-FEE primary purpose is to provide an environmentally controlled area for the CWP fabrication process. Part of the CWP-FEE requirements includes the capability of providing a staging area for the CWP bulk materials including, fabric rolls, resin distribution media, resin and resin transfer equipment. In addition the CWP-FEE supports assembly requirements for pultruded planks which are pre-assembled prior to entering the mold chamber. At the completion of the CWP construction the pipe will be moved to a hang-off site at the keel of the platform. This procedure will involve attaching a metal termination flange onto the CWP and then fixing a structural cap onto the pipe with associated attachment point for lifting operations. The termination attachment procedure requires that the CWP Apparatus and the CWP-FEE be moved to facilitate an expedient process. The movement of these structures will be accomplished using conventional rig skidding equipment.

7.1 Design Basis and Requirements

The CWP-FEE facilitates the CWP manufacturing by providing a safe, secure, and environmentally controlled area for the people, equipment and materials required for the fabrication process.

FRP composite manufacturing requires a controlled environment.

- Nominal temperature range of 20°-22 °C/68°-72°F
- Humidity between 60-65% should be maintained.
- For the Vinyl Ester Resin a suggested storage temperature is below 27°C/80°F with no direct sunlight exposure.

The CWP-FEE will be erected on the OTEC platform dockside in Hawaii, moved aside following completion of the CWP, and then decommissioned after service and before start-up operations.

The CWP-FEE also supports storage and assembly requirements for the staged bulk materials, resin and resin transfer equipment as well as the pultruded core plank handling system & the fabric roll handling system. Other supporting and derived requirements that contribute to the overall design are as follows:

- **Environmental Control**: The bulk materials for CWP fabrication require a controlled environment to ensure maximum mechanical properties. Typical requirements for fabric used in composite manufacturing are:
  - temperature range of 20°-22 °C/68°-72°F
  - relative humidity between 60 -65%
  - Vinyl Ester Resin storage temperature is below 27°C/80°F and no direct sunlight exposure.

- **Staged Materials**: At the manufacturing deck level the floor layout shall be able to accommodate one full 12 hour shift of bulk materials, which is one complete 39 ft step in the process.
- **Material Handling Requirements**: at the manufacturing deck level must accommodate two main items.
  - Roll Handling Requirements: must lift fabric rolls from storage pallet or carriage delivery system and place onto inner & outer roll guides.
    - Weight of rolls = 1800 lb
    - Roll Diameter = 30 inches
    - Roll Length = two lengths for inner & outer rolls at 88 inches and 92 inches
  - Plank Handling Requirements:
    - Move planks from staging area to assembly area.
    - Lift approximately 312 lbs
    - Handle 39 foot lengths
    - Orient planks vertically for assembly.
    - Insert planks in circular tooling assembly around central column 28 each.
- **HVAC System:** The HVAC system shall be able to provide safe working temperatures to manufacturing personnel while following applicable guidelines and standards. The system shall also maintain the internal CWP-FEE environment within predetermined guidelines of the bulk material suppliers. These guidelines shall describe the optimum safe working environment for materials including temperature range and humidity levels.
- **Air Handling:** The air handling system shall be capable of providing safe and breathable air for manufacturing personnel following safety guidelines as required by applicable codes and standards.
- **Exhaust Air Requirements:** The CWP manufacturing process will have associated gases that will need to be exhausted after each molded section is finished. The Air Handling system shall be able to provide adequate exhausting of the enclosed areas as required by applicable codes and standards including safety and fire and hazardous materials.
- **Fire & Safety:** All equipment and materials shall comply with applicable fire and safety regulations as per the designated area classifications.
- **Utility Interface Requirements**: The CWP Fabrication system requires access to standard utilities for the successful manufacturing process of the CWP, including electrical supply, hydraulic supply.

The interface between the complete Cold Water Pipe Fabrication system and the sub-system components is illustrated in Figure 273. There are three primary components that comprise the Fabrication system. First is the CWP-Apparatus a self supported structure that is fixed to the platform and holds the vacuum mold tooling and associated hardware for CWP manufacturing. Second Is the CWP-FEE which is also self supported structure and provides support to the CWP manufacturing process by controlling the environment for the bulk materials used for fabrication as well as providing a staging area for materials. Material handling systems for the pultruded core planks and the fabric rolls are also located in this area. Third is the pipe handling and gripping system which moves pipe through the CWP-Fabrication Apparatus.

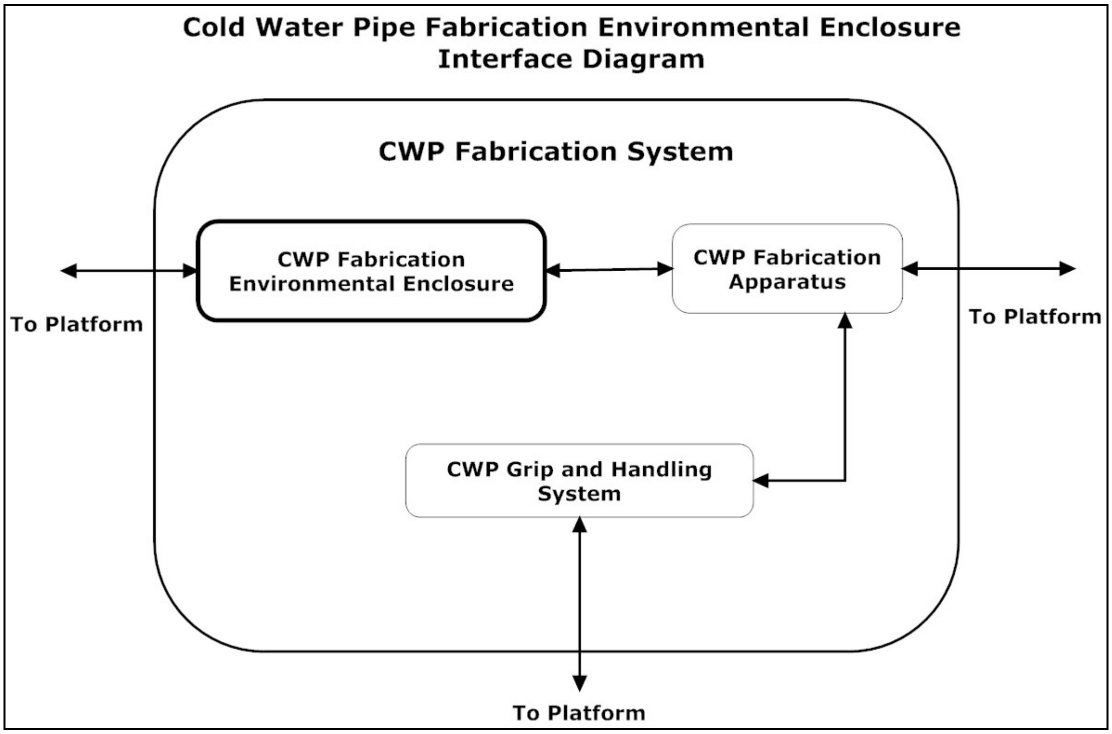
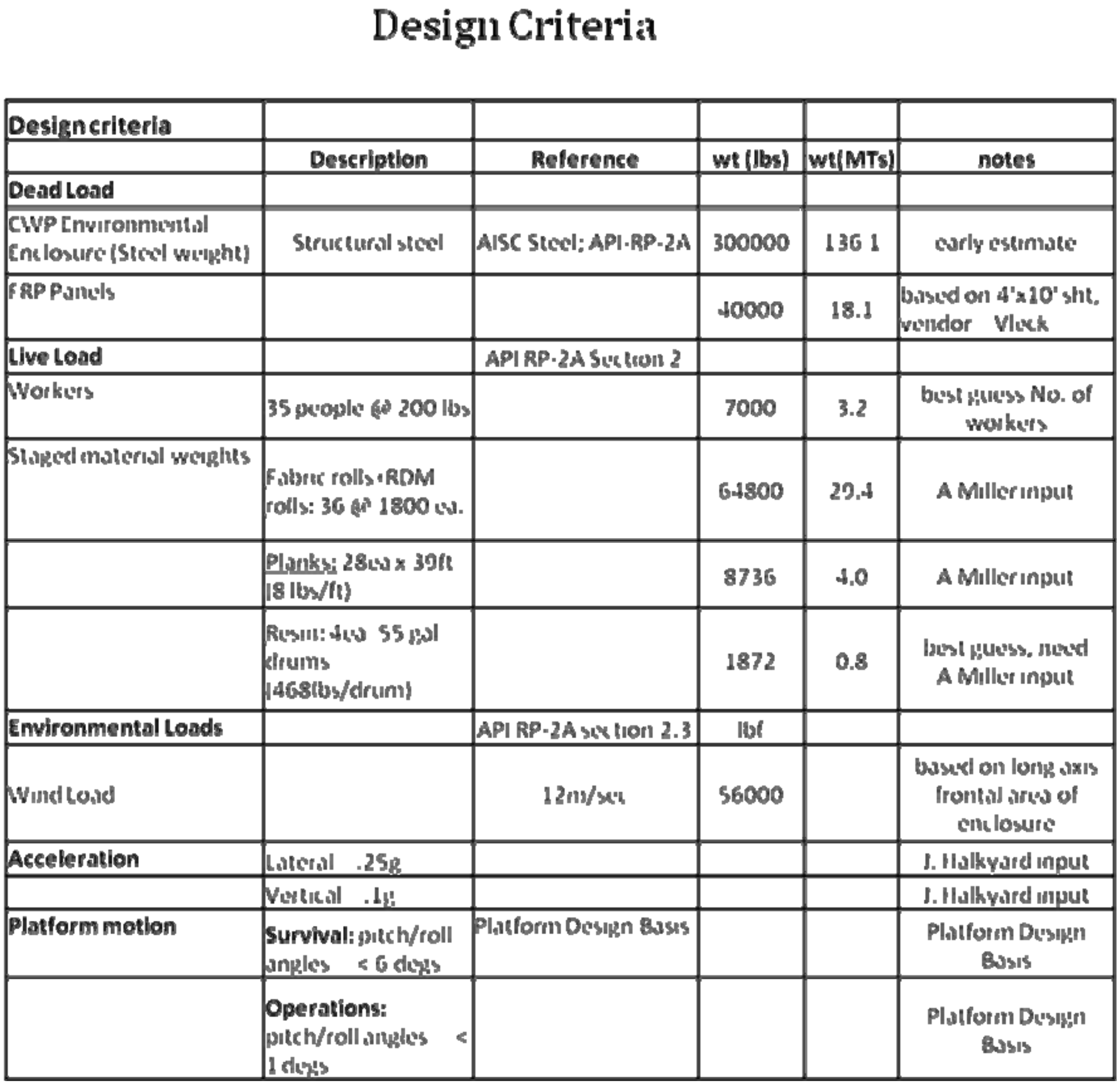


Figure 273. Cold Water Pipe Fabrication System Interface Diagram

7.2 Models and Analysis

The design criteria shown in Table 48 were used for the structural analysis of the enclosure and included oil & gas industry standard guidelines from the American Petroleum Industry Recommended Practice -2A (API RP-2A). Estimated live loads and dead loads were used for structural calculations as well as finite element analysis. The analysis results showed that no special conditions exist and the basic structural concept falls within industry standard practices.

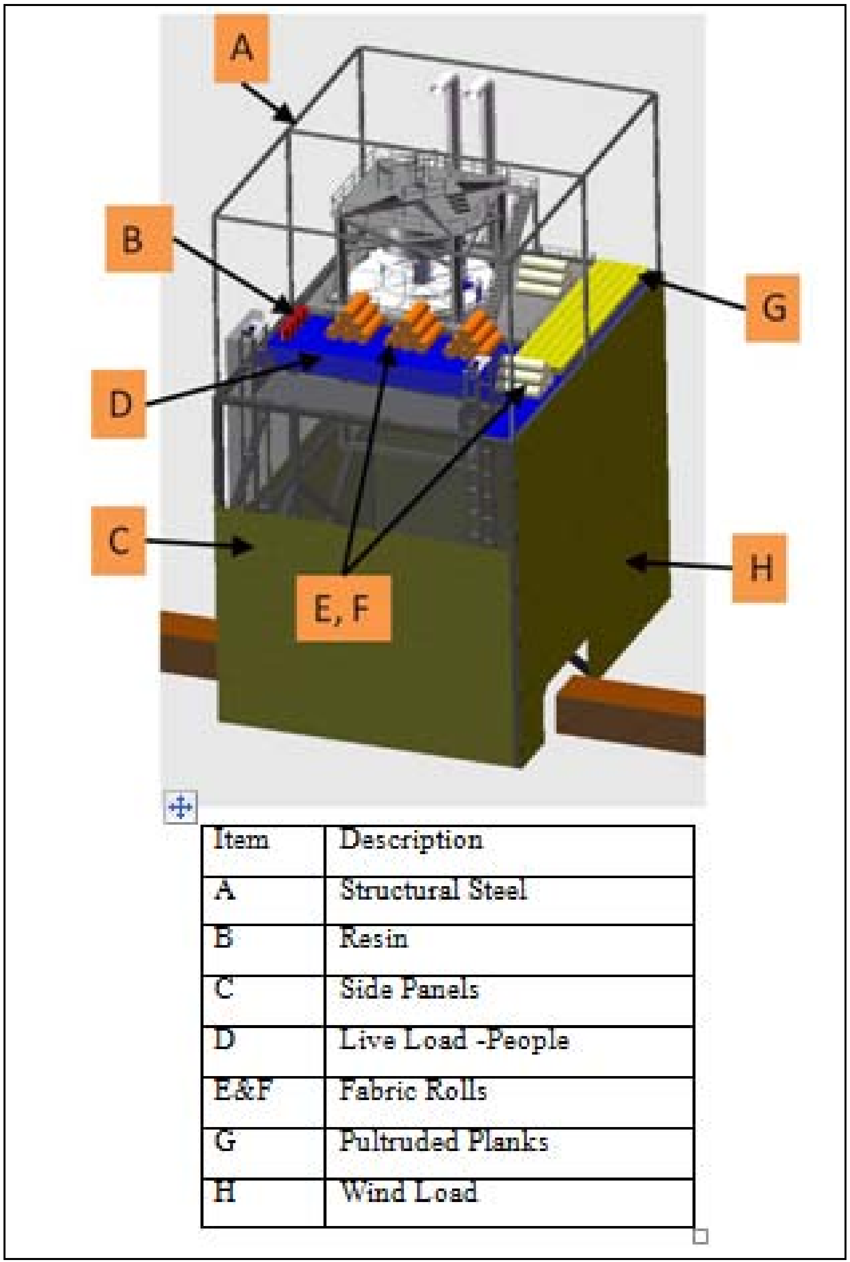
Table 48. Design Criteria



Design Criteria

Design criteria					
	Description	**Reference**	**wt (lbs)**	**wt(MTs)**	**notes**
Dead Load					
CWP Environmental Enclosure (Steel weight)	Structural steel	AISC Steel; API-RP-2A	300000	136.1	early estimate
FRP Panels			40000	18.1	based on 4'x10' sht, vendor Vleck
Live Load		API RP-2A Section 2			
Workers	35 people @ 200 lbs		7000	3.2	best guess No. of workers
Staged material weights	Fabric rolls+RDM rolls: 36 @ 1800 ea.		64800	29.4	A Miller input
	Planks: 28ea x 39ft (8 lbs/ft)		8736	4.0	A Miller input
	Resin: 4ea 55 gal drums (468lbs/drum)		1872	0.8	best guess, need A Miller input
Environmental Loads		API RP-2A section 2.3	lbf		
Wind Load		12m/sec	56000		based on long axis frontal area of enclosure
Acceleration	Lateral .25g				J. Halkyard input
	Vertical .1g				J. Halkyard input
Platform motion	**Survival:** pitch/roll angles < 6 degs	Platform Design Basis			Platform Design Basis
	Operations: pitch/roll angles < 1 degs				Platform Design Basis

The illustration of Figure 274 shows an assumed graphical layout and locations for live and dead loads for the preliminary analysis. The loads include the fabricators, workers and materials such as fabric rolls, pultruded planks and resin distribution media plus other associated materials. Loads also include calculated wind force (REF: API-RP 2A) and estimated side paneling.



Item	Description
A	Structural Steel
B	Resin
C	Side Panels
D	Live Load -People
E&F	Fabric Rolls
G	Pultruded Planks
H	Wind Load

Figure 274. Assumed Loads

The loading conditions for the Finite Element model depicted on the structural frame in Figure 275 are taken from the design criteria. This structural analysis is for the structural steel associated with the CWP-FEE. For this first iteration the following assumptions are applicable:

- The CWP-FEE is fabricated from structural steel beams.
- Beams are 16” x 16” square tube.
- Material is ASTM A36 carbon steel.
- Worst case loads are applied simultaneously for a conservative result.
- All connections and intersections between beams are assumed as rigid.

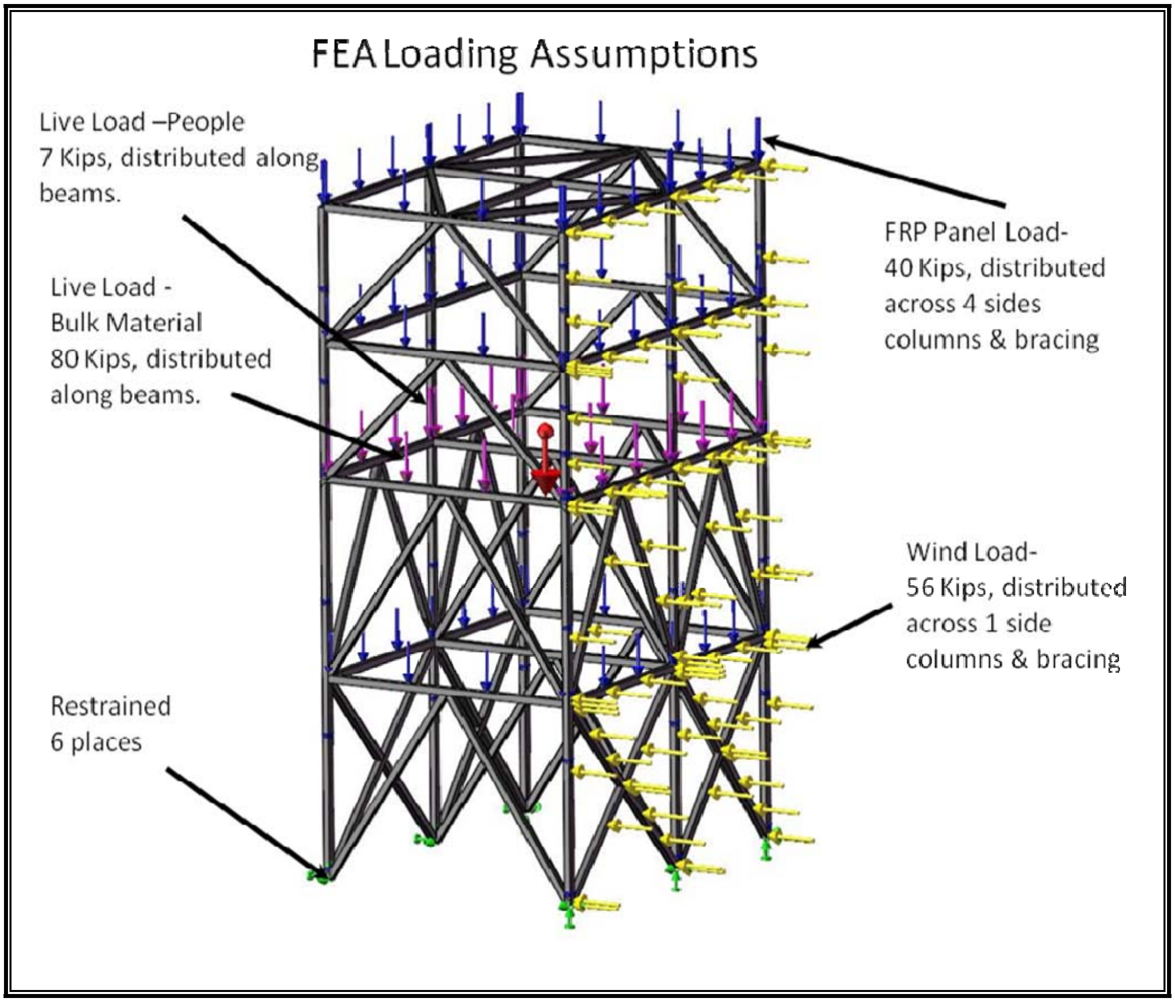


Figure 275. Load Distribution Assumptions

Figure 276 shows stress results for the given loading conditions. High stress areas were located near unsupported sections that were near the production level. Additional bracing or structural design iteration will address these areas in the Detailed Design phase of the project. The conclusion obtained from preliminary design analysis is that the proposed structure for the CWP-Fabrication Environmental Enclosure is well within industry standards for structural steel buildings and offshore topsides structures. Further refinement will take place when a contractor is selected and detailed design iteration begins to converge on the most cost effective solution.

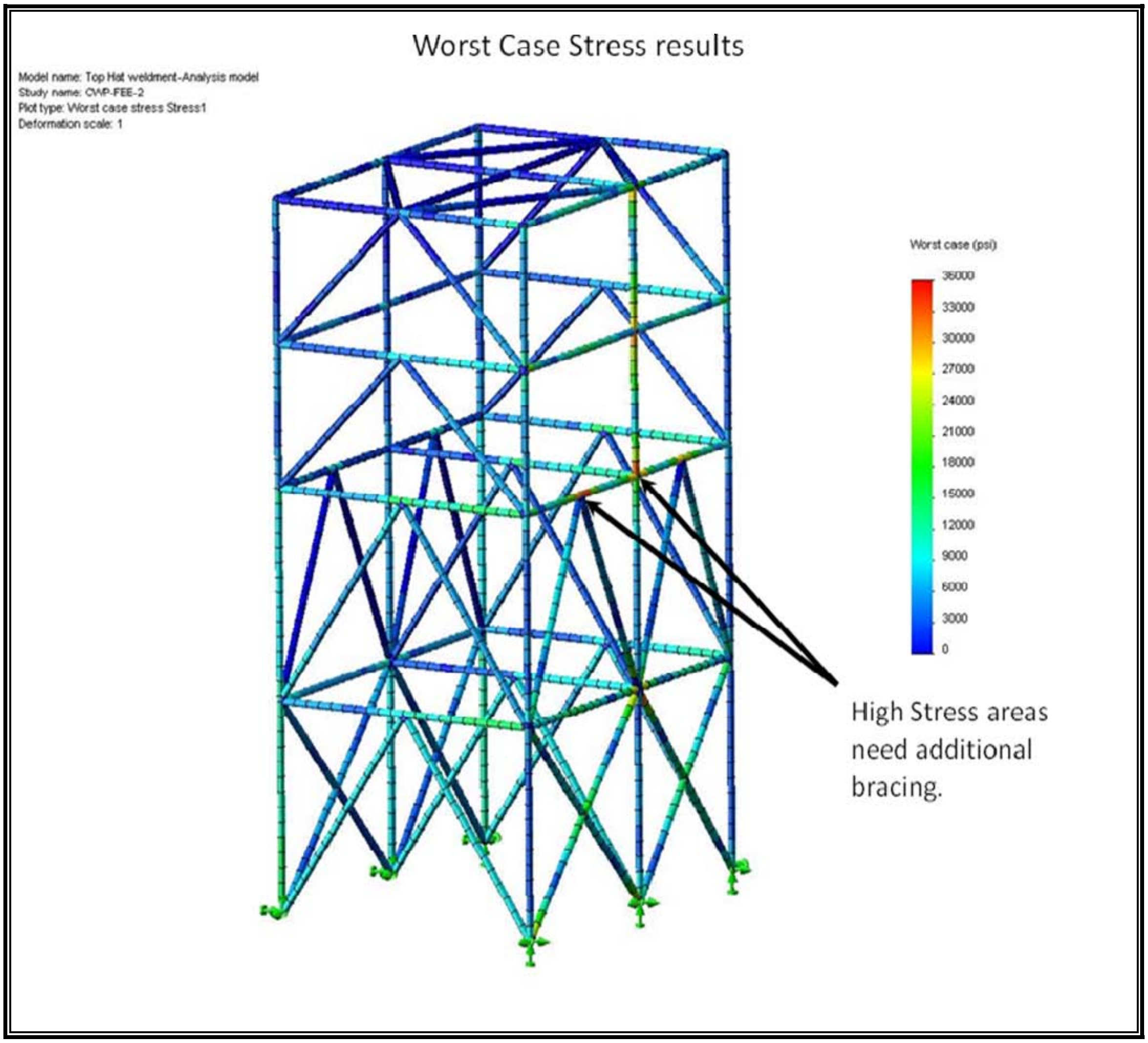


Figure 276. Stress Results (Worst Case)

Preliminary hand calculations were conducted to provide a benchmark for the Finite Element Analysis development and provide validation for results. The most conservative analysis numbers from the FEA runs are within an acceptable margin when compared with the calculated numbers, which provides a good validation of results. The calculation package used was MathCad. The applicable codes included API-RP-2A and AISC for Steel Construction.

Structural Material Properties:

Material: A36 Carbon steel

Density: $\rho_s := .28 \frac{lb}{in^3}$ $\rho_s = 483.84 \frac{lb}{ft^3}$ Yield strength $F_y := 36000 psi$

Modulus of Elasticity $E := 29000000 psi$

Factors of safety:

For stresses: $FS_y := 1.$ (Based on yield strength of material)

For buckling: $FS_b := 2.$ (based on critical load for columns)

Loads:

Accelerations:

$A_{lat} := .25 g$ (Lateral load due to vessel motion)

$A_{vert} := 1.1 g$ (total upward acceleration due to vessel motion)

Dead/Live loads:

Enclosure panels: $W_{ep} := 40 \frac{kip}{g}$ (Static weight of enclosure panels, vertical and down)

CWP raw supplies: $W_{sup} := 64.8 \frac{kip}{g}$ (static weight of rolls, planks, vertical down)

Resin + other: $W_r := 1.84 \frac{kip}{g}$ (Static weight of resin + other, vertical and down)

People working: $W_p := 7 \frac{kip}{g}$ (Dynamic weight of people, vertical down)

Enclosure panels

vertical $Fv_{ep} := W_{ep} \cdot A_{ver}$ $Fv_{ep} = 44000\,lbf$

Assume negligible lateral component at deck level

Raw supplies:

Vertical $Fv_{sup} := W_{sup} \cdot A_{ver}$ $Fv_{sup} = 71280\,lbf$

Horizontal: $Fl_{sup} := W_{sup} \cdot A_{lat}$ $Fl_{sup} = 16200\,lbf$

Resin:

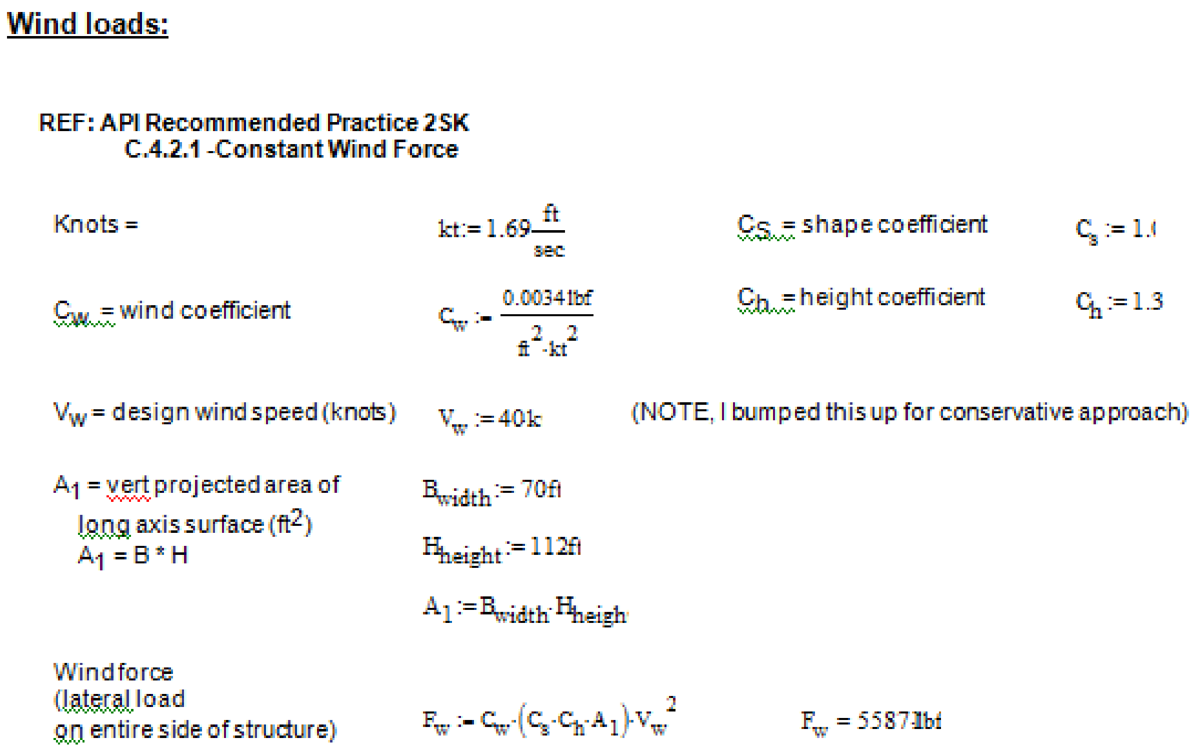
Vertical $Fv_r := W_r \cdot A_{ver}$ $Fv_r = 2024\,lbf$

Horizontal: $Fl_r := W_r \cdot A_{lat}$ $Fl_r = 460\,lbf$

People:

Vertical $Fv_p := W_p \cdot A_{ver}$ $Fv_p = 7700\,lbf$

Horizontal: $Fl_p := W_p \cdot A_{lat}$ $Fl_p = 1750\,lbf$



Wind loads:

REF: API Recommended Practice 2SK
C.4.2.1 -Constant Wind Force

Knots = $kt := 1.69\frac{ft}{sec}$

C_S = shape coefficient $C_s := 1.($

C_W = wind coefficient $C_w := \frac{0.0034\,lbf}{ft^2 \cdot kt^2}$

C_h = height coefficient $C_h := 1.3$

V_W = design wind speed (knots) $V_w := 40k$ (NOTE, I bumped this up for conservative approach)

A_1 = vert projected area of long axis surface (ft^2)
$A_1 = B * H$

$B_{width} := 70ft$

$H_{height} := 112ft$

$A_1 := B_{width} \cdot H_{heigh}$

Wind force (lateral load on entire side of structure)

$F_w := C_w \cdot (C_s \cdot C_h \cdot A_1) \cdot V_w^2$

$F_w = 55871lbf$

Properties for Structural Tube/Pipe used for columns

16 x 16 square tube properties from AISC

Cross sectional area: $A_{c1} := 37.4 \cdot in^2$

Section modulus: $s_{c1} := 182 \cdot in^3$

Moment of Inertia: $I_{c1} := 1450 \cdot in^4$

Radius of gyration: $r_{c1} := 6.23 \cdot in$

Calculate weight of columns and cross braces:

Width of frame section: $W_f := 30 \cdot ft$

Depth frame section: $D_f := 70 \cdot ft$

Height of cross braces/levels: $H_{cb} := 36 \cdot ft$ (changed column levels to reflect load patterr)

Length of cross braces: $L_{cb} := 43 \cdot ft$

Number of levels: $n_l := 2$ There are 2 levels to the main work area

Number of cross braces per level: $ncb_l := 8$

Total number of cross braces: $n_{cb} := ncb_l \cdot n_l$ $n_{cb} = 16$

Total length of cross braces: $Ltot_{cb} := L_{cb} \cdot n_{cb}$ $Ltot_{cb} = 688 ft$

Length of columns: $L_c := 72 \cdot ft$ (changed column ht to reflect A.Miller input)

Number of columns: $n_c := 6$

Total length of columns: $Ltot_c := n_c \cdot L_c$ $Ltot_c = 432 ft$

Total length of laterals: $Ltot_{lt} := 2 \cdot (W_f + D_f) \cdot (n_l - 1)$

$Ltot_{lt} = 240 ft$

Cross sectional areas:

Columns: $A_{c1} = 0.26 ft^2$

Cross braces: $A_{cb} := A_{c1}$

Laterals: $A_{lt} := A_{c1}$ Verify w/ FEA

Allowable stress AISC 5-42

Effective length $K1 := L_c$ slenderness ratio $C_c := \sqrt{\frac{2 \cdot \pi^2 \cdot E}{F_y}}$

Allowable stress $F_a := \frac{\left[1 - \frac{\left(\frac{K1}{r_{c1}}\right)^2}{2 \cdot C_c^2}\right] \cdot F_y}{\frac{5}{3} + 3 \frac{\left(\frac{K1}{r_{c1}}\right)}{8 \cdot C_c} - \frac{\left(\frac{K1}{r_{c1}}\right)^3}{8 \cdot C_c^3}}$ $F_a = 7 \cdot \text{ksi}$

Calculate compressive stress in columns:

Max compressive load per column: $Fmax_c = 1.41 \times 10^5 \, \text{lbf}$

Area of column: $A_{c1} = 37.4 \, \text{in}^2$

Compressive stress per column: $Sc_c := \frac{Fmax_c}{A_{c1}}$ $Sc_c = 3.77 \, \text{ksi}$

Margin of safety:

(Note: AISC equation for allowable stress has built in factor of safety) $MS_{sc} := \frac{F_a}{Sc_c} - 1$ $MS_{sc} = 0.973$

7.3 Design Trades

The major design trades revolved around three key issues:

a. Bulk Material storage & logistics for handling the materials
b. Moving the structure out of the way at the end of CWP fabrication so that the termination flange can be attached and the CWP can be lowered to its final hang-off location.
c. Removal of the structure at the end of CWP fabrication

Bulk Material Storage & Logistics: There is approximately 746 MT's worth of bulk materials that need to be transported to the offshore platform. A breakout and summary of bulk materials required to fabricate the 1000 meter CWP is shown in Table 49. Approximately forty three shipping containers are required for delivering bulk materials to the platform as shown in Table 49. The goal for fabrication is to run 12 hour shifts on a 24/7 basis with one shift producing a single 39 foot section of completed pipe. For 1000 meters or approximately 3300 feet of pipe this results in 84 pipe sections. For pipe fabrication operations running 24/7 the optimal time for completion would be 42 days. Initial trade studies looked at the feasibility of storing all materials on the platform during cold water pipe construction. This option was determined to be not optimal due to deck space limitations and the actual volume of materials being considered. The final decision was the shipping containers will be delivered to the offshore platform by an appropriate vessel of opportunity and loaded onto the platform by using the existing platform crane.

Table 49. Bulk Material Logistics/Quantities

Material	Containers Required	Notes
Pultruded Planks	26	2380 total planks required 92 planks per container.
Resin	7	Container QTY requirement is driven by weight not size
Fabric Rolls	9	The roles weigh 1800 lbs each, there are 138 Inner and 138 Outer rolls required for fabrication. The weight of rolls drives container QTY requirement not size of rolls
Resin Media	1	Resin distribution media used on both ID & OD of pipe.
	43 total	

The requirement to control the environmental conditions for all bulk materials drives the requirement to build an enclosure for manufacturing and drives the requirement for the ability to dock shipping containers to the enclosure. Potential weather conditions for the Hawaii site and deck space constraints necessitate adequate storage of bulk materials equal to seven days worth of operations. The seven day material supply was determined to be adequate to keep pipe construction going given the potential for adverse weather, and considering deck space limits and fabrication schedule. For bulk material resupply approximately six trips offloading seven containers is required. The average weight per container is about 17.3 MT's which is due to material dimensions that limit the quantity that can be transported or the bulk material weights that also limit the quantity that can be transported. The onboard platform cranes are rated at 45 MT's capacity so there is plenty of safety margin in regards to container handling.

Standard 40 foot shipping container dimensions are shown in Figure 277 and capacity/payloads are shown in Table 50. These standard dimensions and payloads drive the logistics for getting materials to the platform and also how much material is stored on the platform.

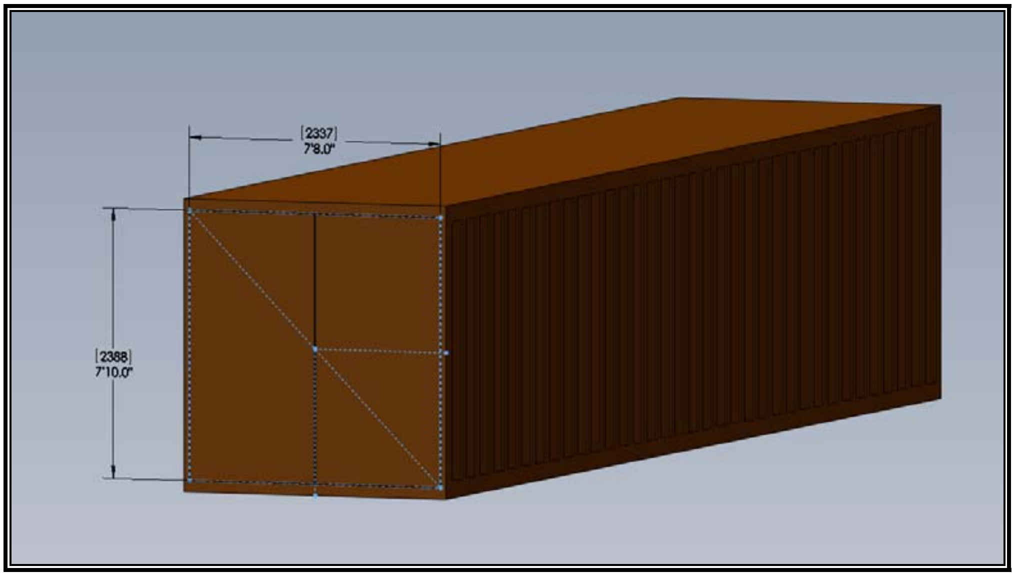


Figure 277. Shipping Container Dimensions

Table 50. Shipping Container Weight & Payload

Standard 40 foot Shipping Container 7'10"H X 7'8"W X 39'5L	Rating = max gross (Kgs)	TARE = container wt (Kgs)	Payload wt = (Rating-Tare) (Kgs)	Allowable payload wt total (MTs)
	30,480	4,000	26,480	26.5

The drawing in Figure 278 below is a plan view of the proposed platform top deck showing the footprint for the CWP-FEE toward the center (dotted line) and lay down areas for the shipping containers. Shipping containers located on the platform will be docked to the CWP-FEE and sealed and secured to ensure that the materials will be environmentally controlled and protected from exposure to the ambient weather conditions. Materials will be moved from the containers to the fabrication level by a freight elevator. The materials staged on the fabrication level will be sufficient for one complete processing of one pipe section.

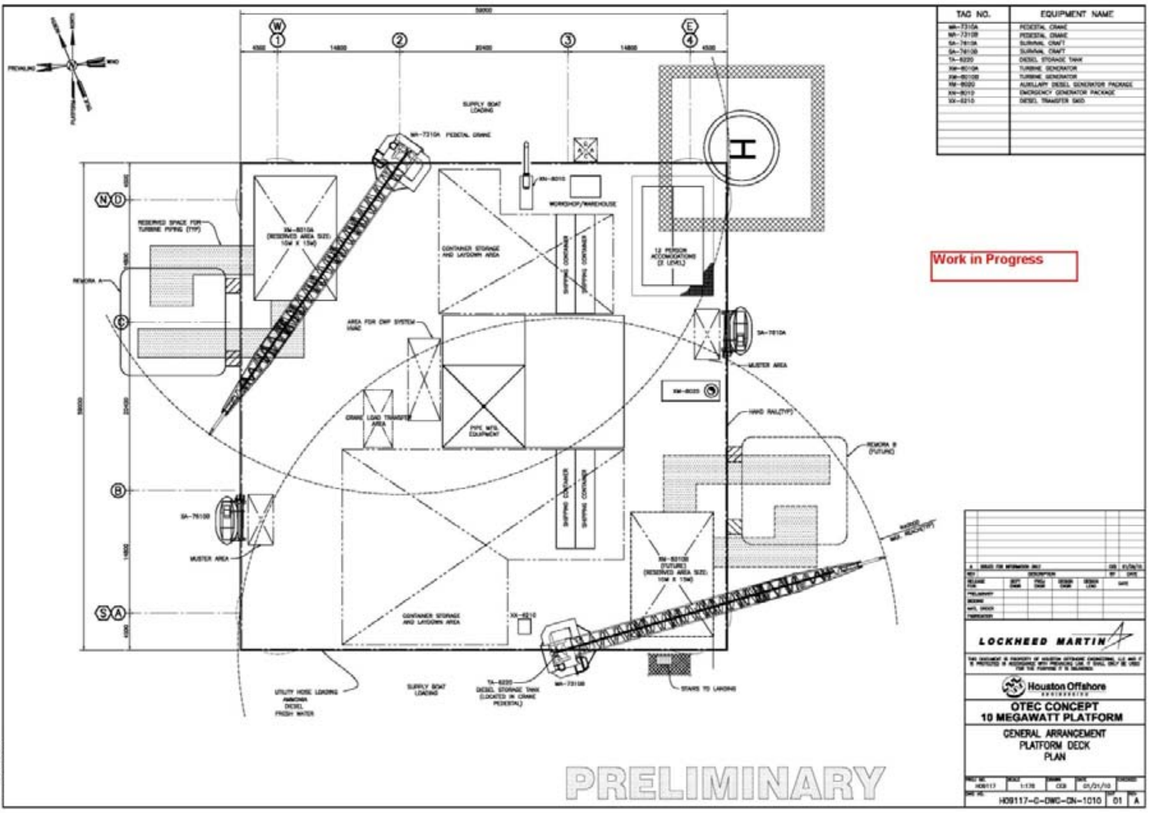


Figure 278. Plan View of Platform Top Deck

Shipping containers located on the platform will be docked to the CWP-FEE and sealed and secured to ensure that the materials will be environmentally controlled and protected from exposure to the ambient weather conditions. Materials will be moved from the containers to the fabrication level by a freight elevator. The materials staged on the fabrication level will be sufficient for one complete processing of one pipe section.

The spreadsheet in Table 51 below outlines the bulk materials required to maintain seven days worth of fabrication operations onboard the platform. It was determined that weather conditions necessitate an adequate amount of bulk materials will need to be onboard the platform to ensure seven days of operations. Operations run 24/7 with two 12 hour shifts, the goal is to completely fabricate one 39 foot section every shift. For the approximately 42 required fabrication days there will need to be approximately 6 deliveries to the platform. These are optimized numbers that will be revisited as more information is gathered during CWP fabrication test runs. The lay down deck area driven by these quantities requires at least eight containers worth of bulk materials

This 39 foot predefined length for pultruded planks dictates the production level floor area required for staged materials. Adequate floor space must provide for fabric rolls, pultruded planks, and resin distribution media.

Table 51. Onboard Bulk Material Required Quantities

Face sheet	**QTY of rolls for entire CWP**	**Rolls/ring**	**# of change outs**	**# of rolls per container**	**Fabrication steps per ring replenishment**		**containers for 7 days**
Inner	138	12	11.5	32	7.3		1.0
Outer	138	12	11.5	32	7.3		1.0
RDM							1
Inner	22	6	3.7	84	22.9		
Outer	22	6	3.7	84	22.9		
Pultruded planks				# of planks per container	qty/ring	qty for 14 shifts	
				92	28	392	4.3
Total Containers required							7.3
Lay Down Area needed							*room for 8 containers required lay down area*
Resin	total gallons	No. of steps	gal/step	gal/tank	tanks req'd	tanks/step	tanks for 7 days
	44,332	84	527.8	550	80.6	1	14

Bulk materials are loaded from transport barges onto the offshore platform by the platform cranes. The materials are stored in shipping containers which are docked to the CWP Environmental Enclosure. Materials are moved from the shipping containers by fork lift to the freight elevator which transports them to the production level. The section cut-away in Figure 279 depicts the bulk material transport sequence from shipping container on the platform top deck (1), then into the freight elevator by fork lift (2), then materials ride up the elevator to the production level (3) and finally the materials move from elevator to staging areas on the production level (4).

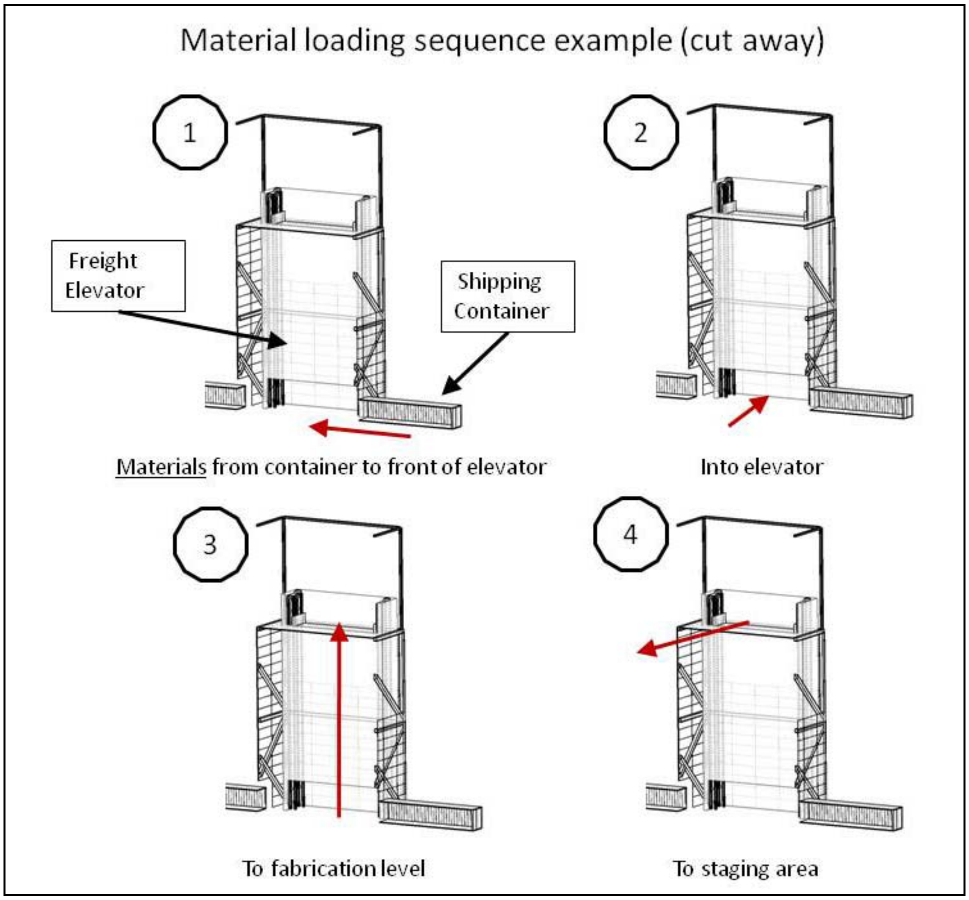


Figure 279. Freight Elevator Load Sequence

At any given time there are seven containers onboard the platform with four containers docked to the Enclosure and the remaining three staged in the lay down areas. As the bulk material is consumed during fabrication operations the platform cranes will be utilized to move the staged containers into the docked position(s) for material replenishment.

The production level has storage available for one complete section of pipe this includes Inner & Outer fabric rolls, resin distribution media and pultruded planks. Materials move from the staged areas on the production level and into the CWP Fabrication Apparatus which has the mold vacuum chamber and associated tooling. Fabric rolls are loaded into the roll holders and the tooling is lowered into the mold vacuum and secured. The pultruded planks are moved from the staging area and into the assembly area above the mold vacuum and then assembled into core rings. The rings are lowered into the chamber by extending the entire CWP with the gripper cylinders which also pulls the fabric into the mold region for the next section. Once the section is lowered the vacuum seal rings are activated and sealed, both top and bottom of the section. The section of pipe is infused with resin and then allowed to cure.

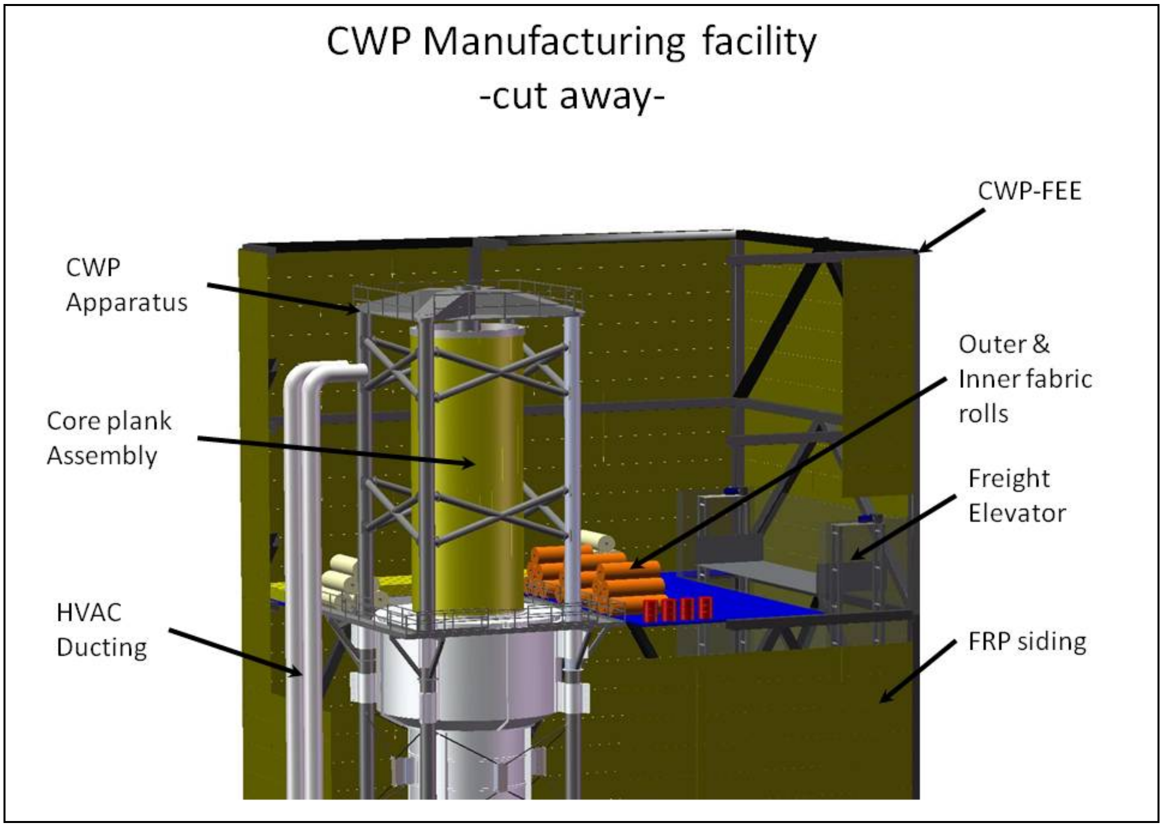


Figure 280. Cutaway View -CWP Production Level

At the end of the cure sequence the chamber is opened and fumes are exhausted at which point another sequence begins. The manufacturing flow chart shown in Figure 281 depicts the sequence of events. The materials required to complete a 39 foot section include: 28 each Pultruded planks; 18 each outer rolls with resin distribution media; 18 each inner rolls with resin distribution media, the associated resin and cure media are proposed to be pumped from the top deck level to the production level during fabrication. There are 138 Inner & 138 Outer fabric rolls required for the pipe construction. There is enough material on the fabric rolls to run approximately 24 pipe sections before a change out is required.

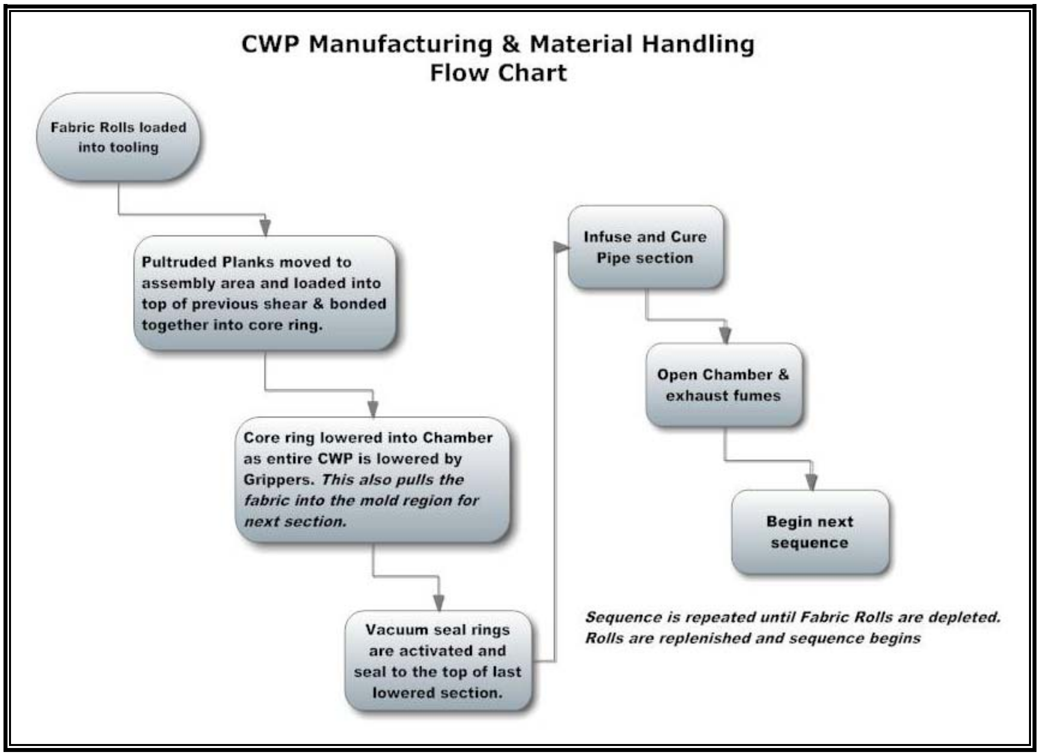


Figure 281. Manufacturing Flow Chart

<u>Moving the Structure for CWP termination & hang-off</u>: The final process of attaching a metal flange adaptor to the CWP completes the CWP fabrication. The adaptor will be the physical interface and attachment point to the platform. This termination connection takes place before the CWP is lowered to the hang-off site. This flange termination process resulted in a trade study looking at the options for moving the CWP Fabrication Apparatus and CWP Environmental Enclosure out of the way to allow attachment of the end flange piece and positioning of the lowering mechanism. Figure 282 below shows a depiction of the CWP-Fabrication Enclosure surrounding the CWP Apparatus on the platform.

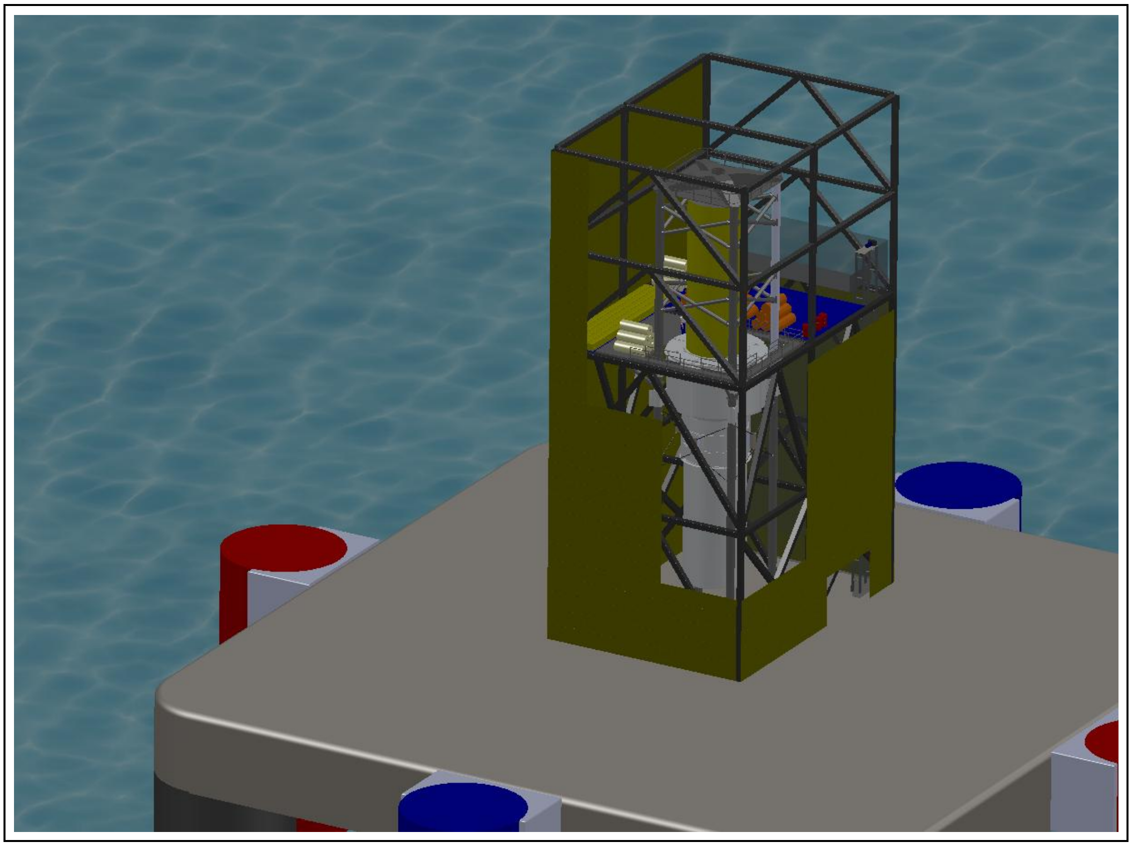


Figure 282. CWP-FEE on the Semi Submersible Platform

Two Options were investigated and evaluated for clearing the area for termination and hang-off operations. Both options rely on standard offshore skidding system technology used primarily for moving large topside equipment around offshore platforms as shown in Figure 283. The two options included skidding both the CWP Fabrication Apparatus and the CWP-FEE at the same time versus taking a side section off of the CWP-FEE and then skidding only the CWP-Apparatus. Figure 284 shows the Pros & Cons that were considered when looking at the two concepts. The two concepts for moving the structures are shown below in Figure 285 and Figure 286.

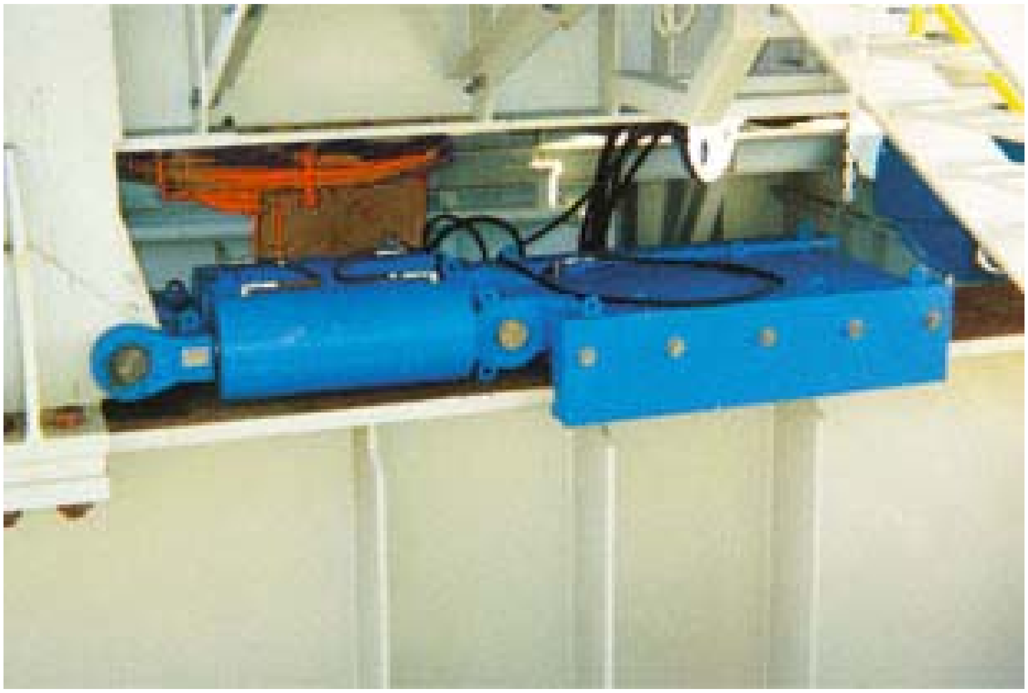
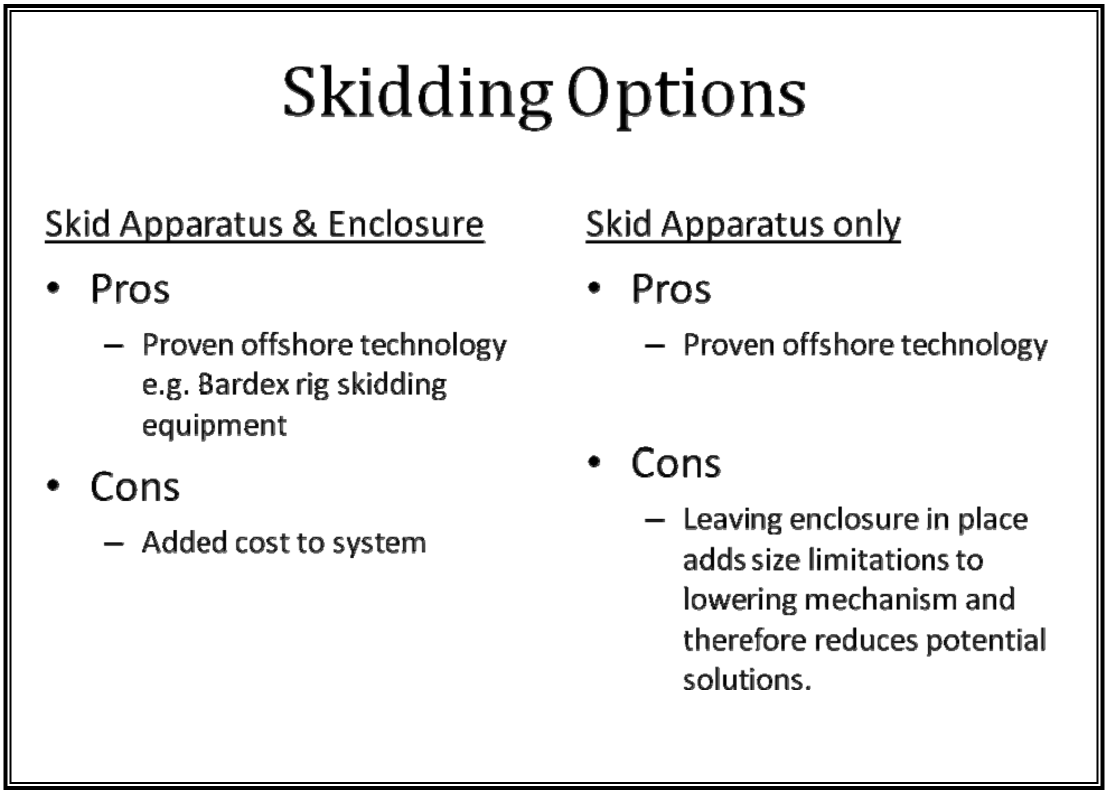


Figure 283. Rig Skidding Equipment from Bardex Corp



Skidding Options

Skid Apparatus & Enclosure

- Pros
  - Proven offshore technology e.g. Bardex rig skidding equipment
- Cons
  - Added cost to system

Skid Apparatus only

- Pros
  - Proven offshore technology
- Cons
  - Leaving enclosure in place adds size limitations to lowering mechanism and therefore reduces potential solutions.

Figure 284. Skidding Options Pro vs. Con

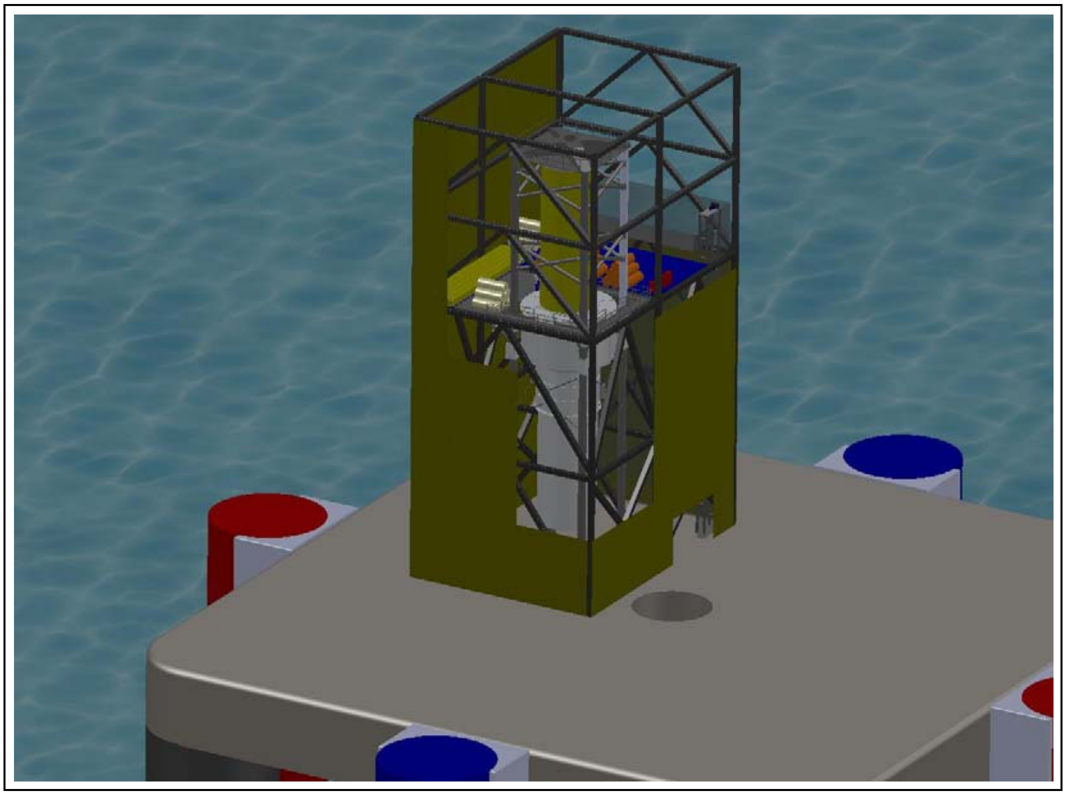


Figure 285. Skid Both Structures Clear of Center

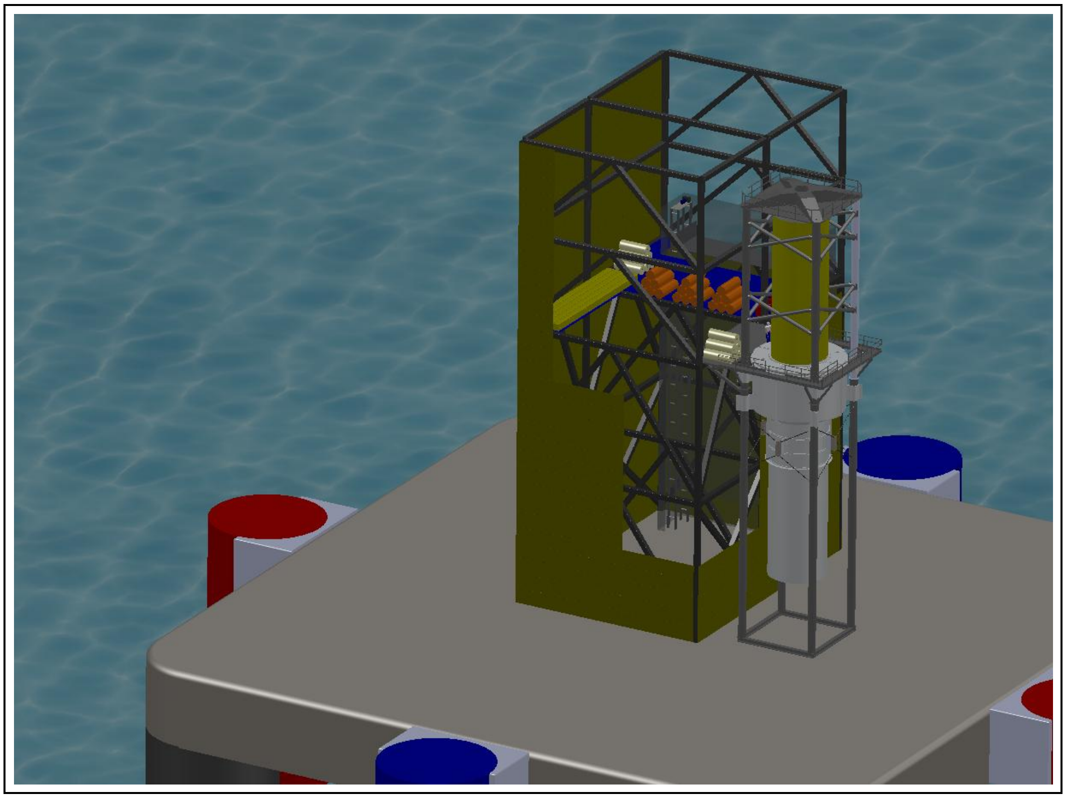
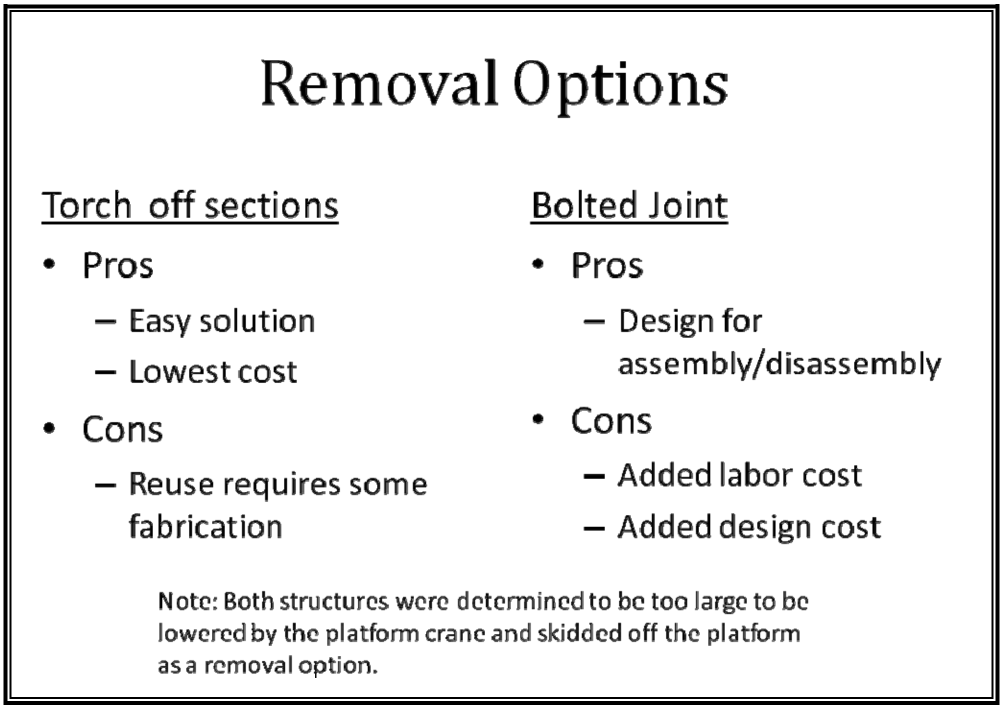


Figure 286. Skid CWP-Apparatus Clear of Center

Concept -1: This concept illustrates skidding both structures clear of the center section using conventional offshore technology rig skidding equipment. After the central section where the CWP is located is clear of structures then the start of termination attachment operations can take place. This includes the positioning of a lowering mechanism for final placement of the CWP at the lower hang-off site. This option was determined to be the most expedient in regards to time and also allowed more options to be explored for the CWP lowering mechanism. As illustrated in Concept 2 and Figure 286, moving only the CWP-Apparatus puts a size constraint on designing or specifying a lowering mechanism because it would need to be placed into the CWP-FEE after the Apparatus was skidded clear.

Concept -2: This concept moves the CWP Apparatus away from the enclosure and allows for the flange end piece attachment process to be carried out from inside the enclosed area. The concept requires positioning the lowering mechanism inside the enclosure. This option was eliminated early due to the logistics involved with additional time for removing a wall or large section of the Enclosure in order to skid the Apparatus clear as well as positioning a lowering mechanism such as winch system.

Removing Structure at end of CWP Fabrication Operations: As described above at the completion of the CWP construction the pipe will be moved to a hang-off site at the keel of the platform, this procedure will involve terminating a metal flange onto the CWP and then fixing a structural cap onto the flange with associated attachment point for lifting operations. The transition to termination of the metal flange onto the CWP marks the end of pipe fabrication process and the beginning of the removal of the CWP-Apparatus and the CWP-FEE structures. Two options were investigated for removal, the first was torch cutting the structure into sections that could be handled by the platform crane and the second was using a bolted joint connection with sections sized for removal by the platform crane. Some of the investigated Pros and Cons associated with each option are summarized in Figure 287. More detailed explanations of the two options investigated are illustrated in the following pages.



Removal Options

Torch off sections

- Pros
  - Easy solution
  - Lowest cost
- Cons
  - Reuse requires some fabrication

Bolted Joint

- Pros
  - Design for assembly/disassembly
- Cons
  - Added labor cost
  - Added design cost

Note: Both structures were determined to be too large to be lowered by the platform crane and skidded off the platform as a removal option.

Figure 287. Removal Options

<u>Option 1:</u> Figure 288 illustrates the option for torch cut sections sized so that they could be manipulated by the platform crane. This was determined to be the most cost effective option but reuse of the structure could be jeopardized without a detailed and elaborate cut plan. The optimal weight for each section was determined to be 20MT or under, which would allow the platform crane to easily handle them.

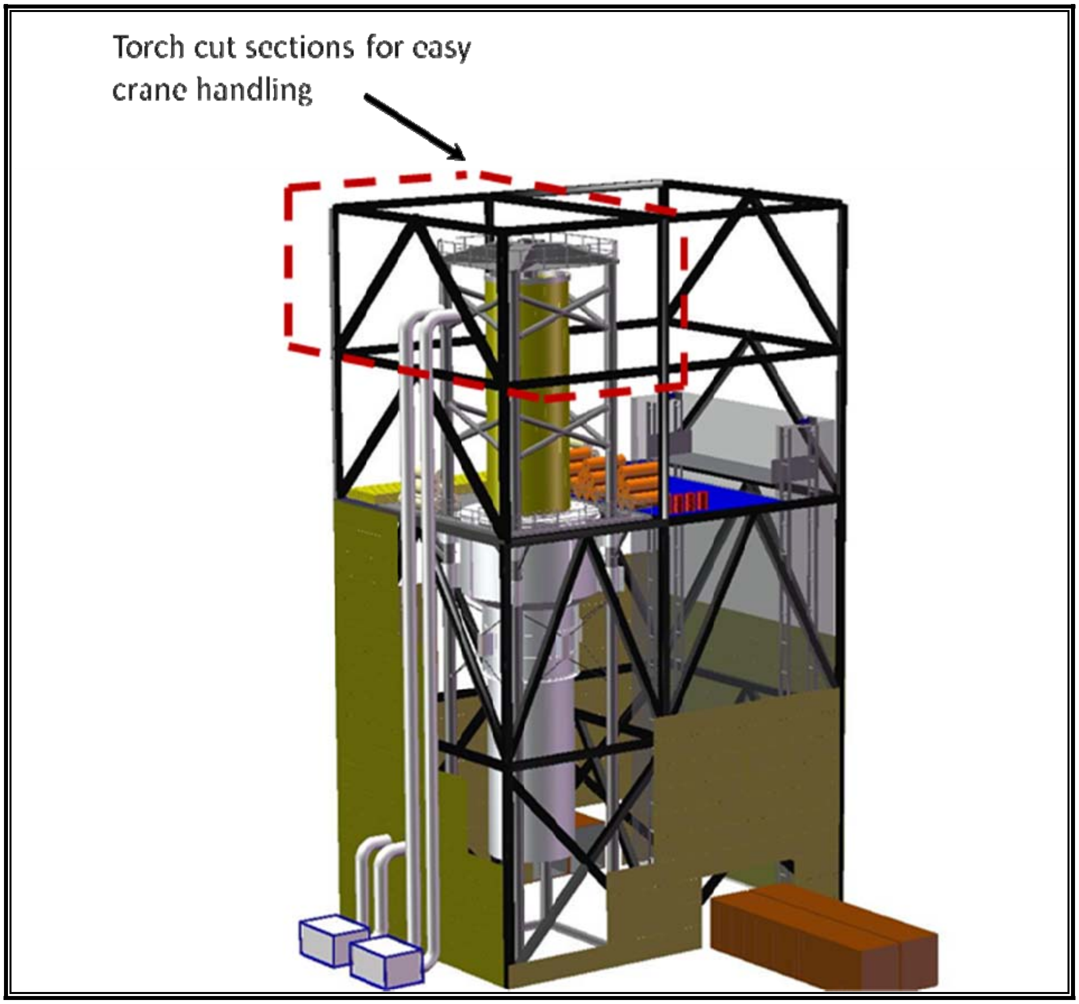


Figure 288. Torch Cut Sections

<u>Option 2:</u> Figure 289 shows a bolted joint connection. This illustration depicts the option for removal of the structure by unbolting sections, with sections sized for manipulation by the existing platform crane. This option was determined to be the most prudent choice due to industry experience with self erecting rigs where the erection and subsequent disassembly of offshore structures has been reduced to standard practice. Also the requirement for reuse of the structure lends itself more readily to the bolted joint design.

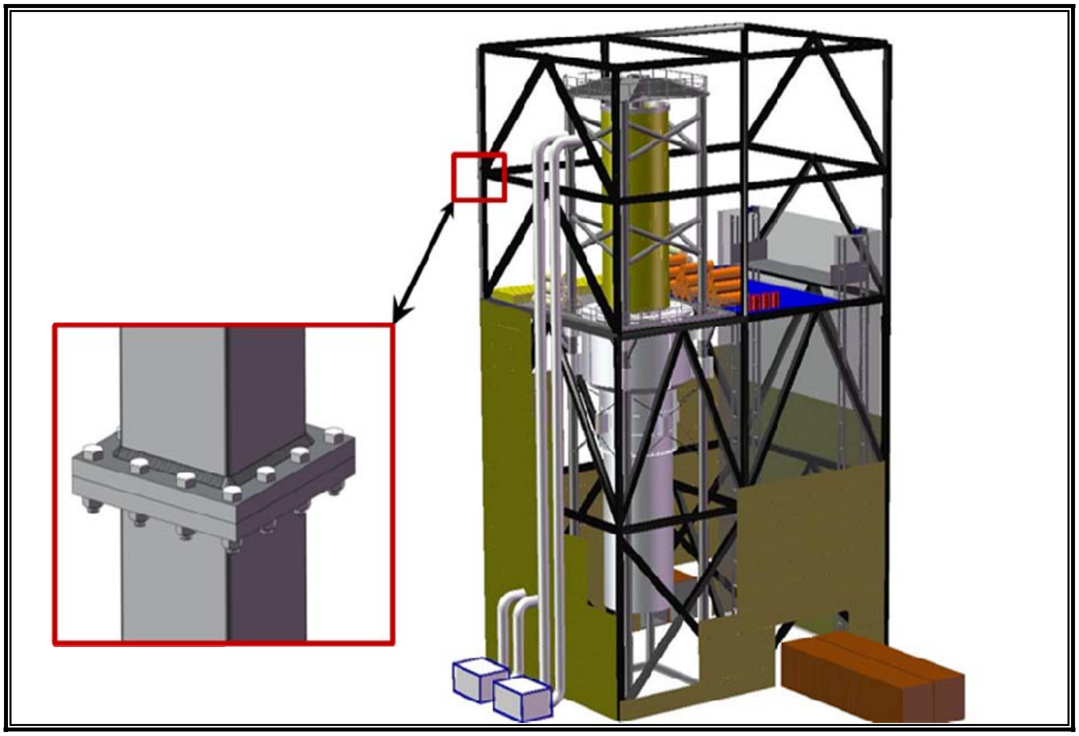
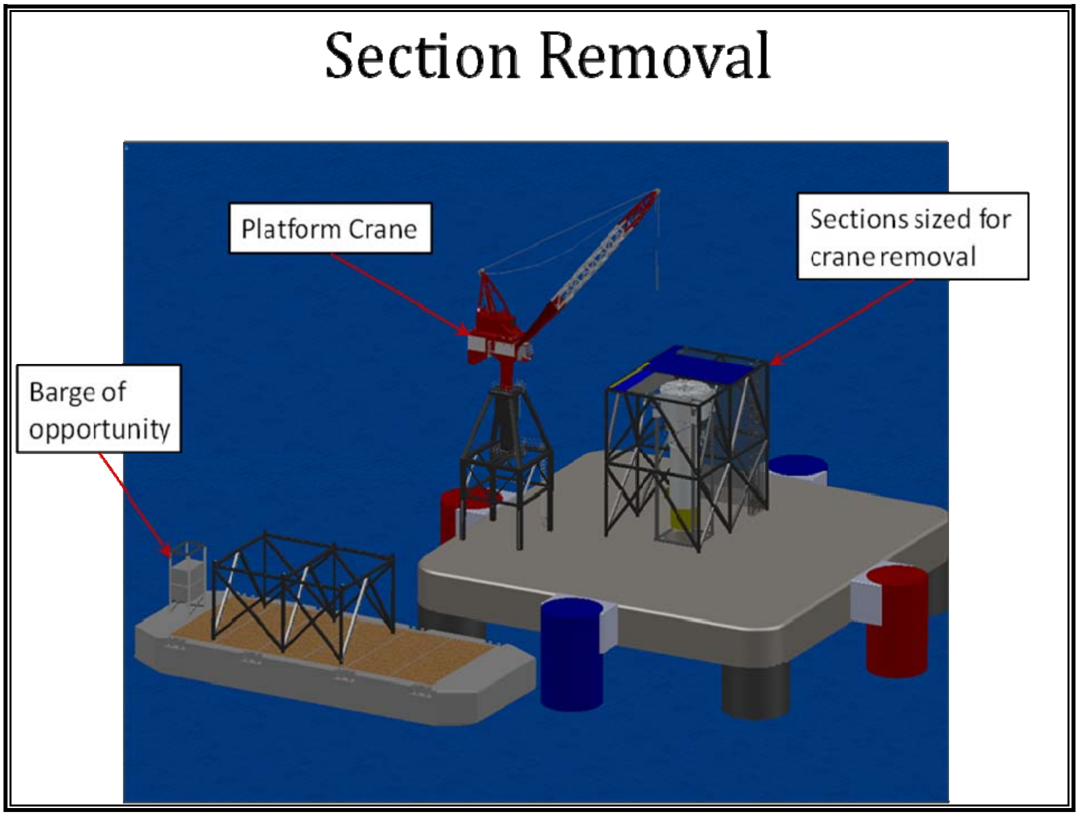


Figure 289. Bolted Sections

The illustration below, Figure 290 portrays the preferred method for removal of sections which are sized to be handled by an onboard crane. The bolted joint sections would be designed for easy removal for offloading to a standby barge for transport to a predetermined storage location. The flow chart in Figure 291 shows an assumed sequence for disconnecting utilities and associated operations for removing and loading sections.



Section Removal

Figure 290. Section Removal

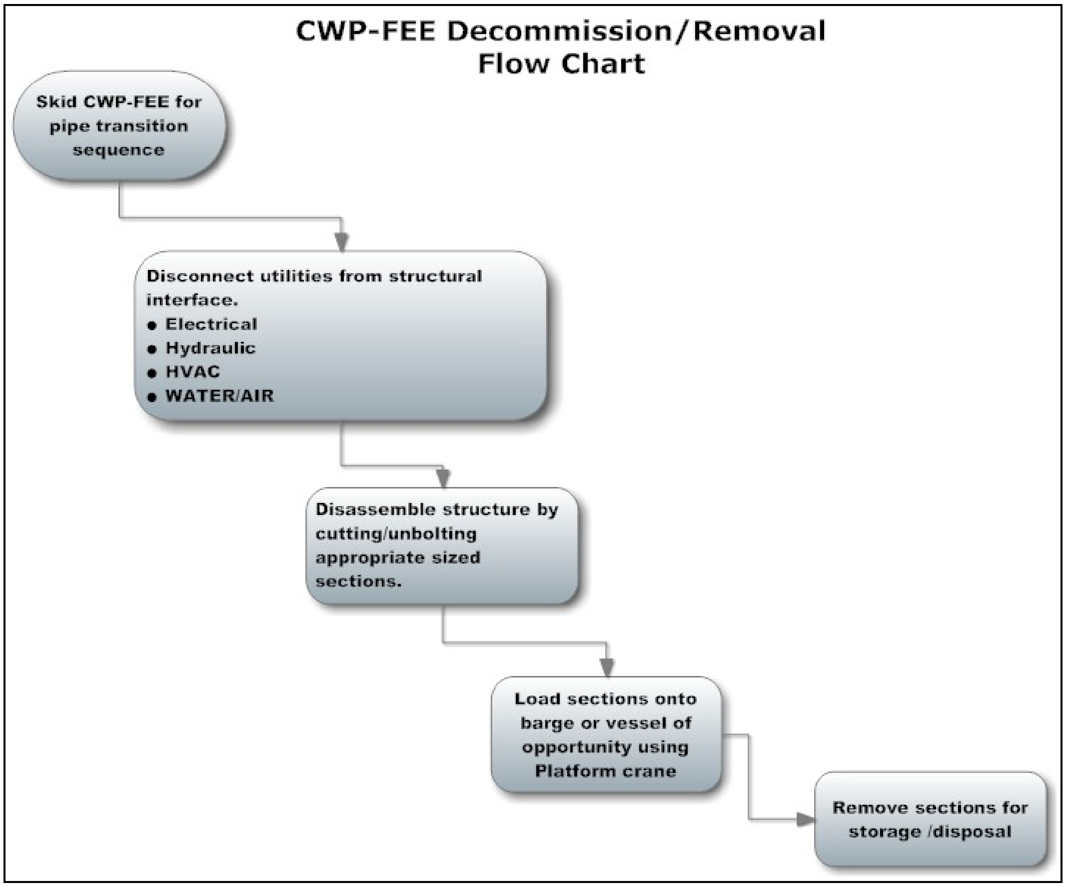


Figure 291. CWP-FEE Decommission

7.4 Trades Summary

Bulk Material storage: The trade looking at bulk material storage on the platform versus scheduled deliveries to the platform resulted in selecting scheduled deliveries. The platform deck space was deemed too valuable and the logistics for handling 43 containers onboard was too complicated to pursue storing all the material onboard.

Moving the Structure: The trade for moving or skidding both structures versus just the CWP-Apparatus resulted in the decision to move both structures. Moving only one structure didn’t result in any time saving or other cost saving that was evident. In addition removing a large section of the CWP-FEE in order to move only the Apparatus added time to the operation and complexity to the design.

Removing the Structure: The trade looking at removing the structure at the end of CWP fabrication operations examined using a bolted joint design versus cutting the structure into sections resulted in selecting the bolted joint design. The bolted joint lends itself to potential reuse in the future which was a requirement for the project and any potential cost savings with cutting the structure were deemed too small to drive that option any further.

7.5 System Removal

The illustration below, Figure 292, portrays the preferred method for removal of sections which are sized to be handled by an onboard crane. The bolted joint sections would be designed for easy removal for offloading to a standby barge for transport to a predetermined storage location. The flow chart in Figure 293 shows an assumed sequence for disconnecting utilities and associated operations for removing and loading sections.

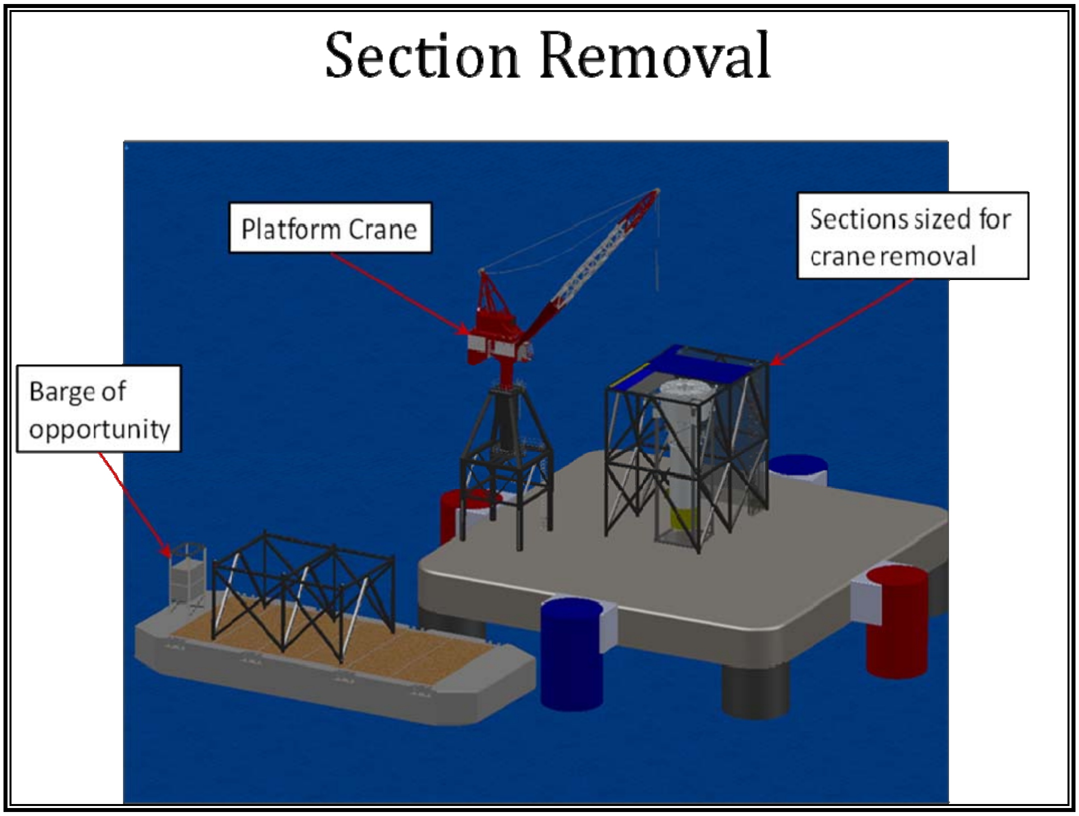


Figure 292. Section Removal

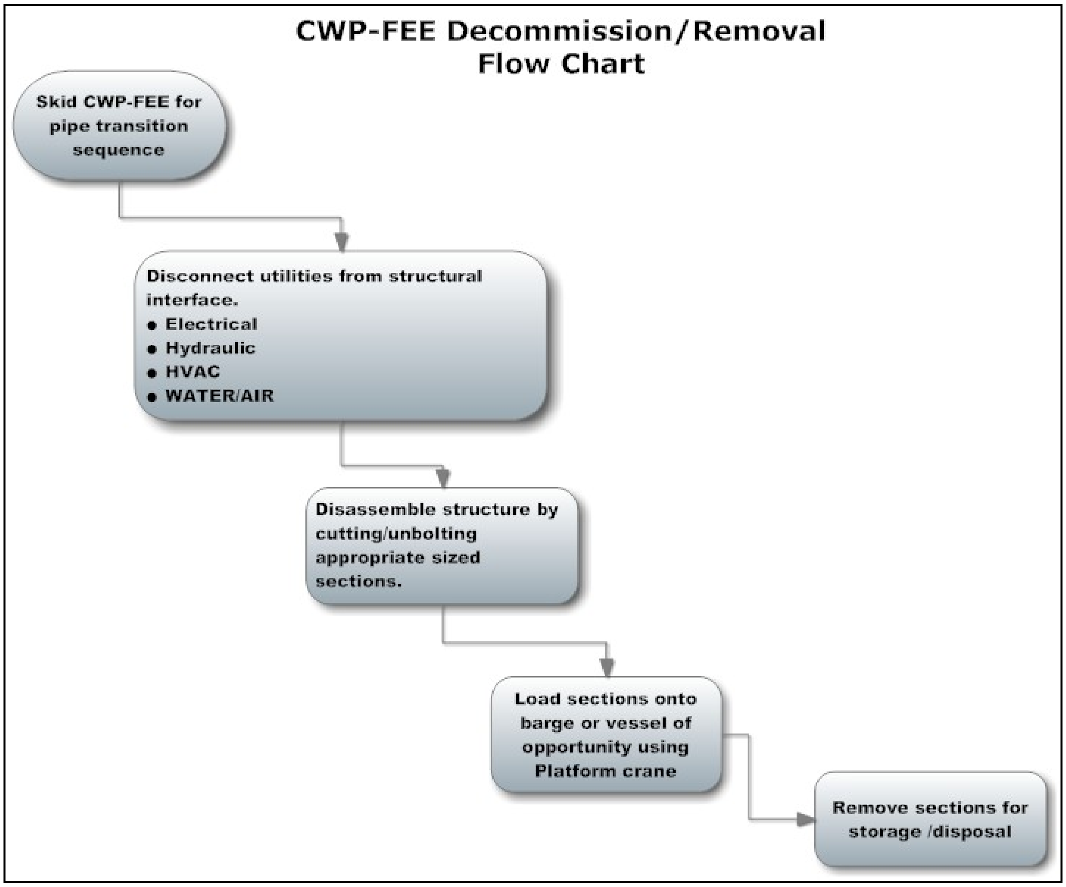


Figure 293. CWP-FEE Decommission

7.6 Remaining Risks and Mitigation Plans

The CWP-FEE sole purpose is to support the construction of the CWP. Before any further consideration of system design in regards to the CWP-FEE takes place the CWP-Fabrication Apparatus design for the pilot plant needs to begin and advance to the point where most of the interface elements and sub-system elements are well understood.

With regard to CWP-FEE sub-systems, the material handling systems for the fabric rolls and the pultruded planks have unique attributes that make the solution challenging. These unique attributes are a combination of basic material geometry and the handling requirement for each material.

Fabric Rolls: The Inner and Outer core fabric rolls are approximately 30 inches in diameter and between 88 and 92 inches long respectively and weigh about 1800 lbs. The size and weight are not extreme or unique but the requirement to precisely place the rolls into the guide tooling requires lifting and extending and potential turning all in a coordinated sequence. Initial research into existing handling systems found an OEM manufacturer that had systems that were close in practice but would require engineering to accommodate the unique requirements for the CWP fabrication system.

Pultruded Planks: The size and shape of the pultruded core planks are unusual enough that they don’t lend themselves to Commercial Off The Shelf (COTS) material handling systems. While not heavy, at approximately 312 lbs, the length of 39 feet combined with the width of approximately 20 inches requires a unique handling solution. The other challenging part of this handling solution is the requirement to align the planks vertically at some point in time prior to assembly. If this occurs before storage then placing them in storage vertically is the challenge. If this occurs after storage and the planks are horizontal then turning them 90 degrees to the upright orientation is the challenge.

In addition the 39 foot pultruded planks are a design and cost drivers for moving material by freight elevator. The length doesn't fit standard sizing and requires non recurring engineering by a vendor to accommodate the unusual size. A potential mitigation is to use 15 or 20 foot planks that fit into existing freight elevator standard sizes. Another potential solution is to use a standard knuckle boom crane with an open shaft to move material to the production level. There is a potential safety risk associated with moving material in an open shaft and the number of moves may increase due to lift capacity and rigging configuration.

7.7 Remaining Tasks

The remaining tasks related to moving to a build phase for the CWP-FEE system revolves around four areas listed below.

- HAVAC CONTRACTOR
- CWP APPARATUS AND ENCLOSURE
- CWP-FEE DETAILED DESIGN
- MATERIAL HANDLING SYSTEMS

<u>HVAC Contractor:</u> The selection of a HVAC vendor familiar with the offshore segment is essential to help develop a HVAC specification for the facility. The contractor Alscott was involved with delivering a ROM estimate for the HVAC & Air Handling for the system and they have expressed the desire to work on a HVAC specification that would detail the requirements and allow for a more accurate cost estimate to be developed. The next step for this element is to proceed with a detailed HVAC specification that can be used to design the system.

<u>CWP Apparatus & Enclosure:</u> The driver for further development of the CWP-FEE is the design for the CWP-Apparatus itself. Further development of the Apparatus design should include a close and considered look at the interfaces to the CWP-FEE. Future work should jointly integrate the CWP-Apparatus, CWP-FEE and the material handling systems for optimized results.

<u>CWP-FEE Detailed Design</u>: Refinement of the concept design into detailed structural design and fabrication drawings is the next step for the Environmental Enclosure. This includes working closely with the contractor to establish the constraints for design such as the platform crane as well as requirements for dismantling the structure at the end of CWP fabrication.

<u>Material Handling Systems:</u> A collaborative design team needs to be formed that includes material handling system OEM/vendors working collaboratively with the CWP Apparatus design team and the CWP-FEE design team. At this stage in the program the bulk material handling systems need front end engineering design.

8. SUMMARY

Lockheed Martin supported by Makai Ocean Engineering, John Halkyard & Associates, and Sound & Sea Technology completed development and prototype testing of the interface between the Cold Water Pipe and the platform.

This effort is a key milestone leading to eventual OTEC commercialization, and ultimately the ability to purchase OTEC generated electricity from privately developed OTEC facilities. This work was performed for the Naval Facilities Command Engineering Support Center, Port Hueneme under contract N62583-09-C-0083 initiated on 21 August 2009. This report provides the results of the critical component task.

It should be clear from this report that designing an OTEC system requires the skill of multiple disciplines. Every member of the Lockheed Team brings offshore, energy, and engineering expertise to further OTEC commercialization. The Lockheed Martin team worked in an Integrated Product Team environment where members had individual responsibilities and contributed in many cases to multiple teams. Lockheed was responsible for CWP termination and contract conduct. Makai Ocean Engineering was responsible for the gripper and guide development. Sound & Sea Technology developed the CWP Fabrication Apparatus environmental enclosure. John Halkyard & Associates provided platform and metocean support to each effort. This study is the result of significant efforts on all parties.

Several approaches were considered for the CWP termination. Based on analysis of requirements, a trap-lock approach was chosen for this application. Multiple methods of handling the CWP during the fabrication phase were considered. The use of “grippers” to hold the pipe circumferentially was determined to be the best approach. Two sets of grippers were designed. A stationary set provided the ability to hold the pipe while the next section was fabrication. A moving gripper set provided the ability to lower the pipe in preparation for the next fabrication step. Guides were developed to limit the motion of the pipe during fabrication. Finally, the whole CWP fabrication apparatus required isolation from weather effects to optimally conduct the VARTM process.

Based on the efforts conducted under this contract, it was determined the interface approaches are technically feasible and can provide a solution for commercial OTEC plant design.

APPENDICES:

Appendices are included in a separate document.

Appendix

END NOTES

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[i] See, e.g. Random Vibrations: Theory and Practice by Paul H. Wirsching, Thomas L Paez, and Keith Ortiz, Dover Publications, 2006

[ii] John Halkyard & Associates, “Metocean Design Conditions for a Moored OTEC Pilot Power Plant (Barbers Point)”, Technical Note 2009-124, December 9, 2009

[iii] Edward K. Noda, “Current Data from the Kahe Point, Oahu and Keahole Point, Hawaii OTEC Benchmark Sites June 1980 – June 1981”, Technical Report No. 49, University of Hawaii Look Lab-81-2, Sept. 1981

[iv] Houston Offshore Engineering, “OTEC Cold Water Pipe Analysis - CWP Termination Fatigue Analysis, 4th January, 2009

[v] Horton Wison Deepwater, “Cold Water Pipe Strain Comparisons – ABAQUS vs. CHARM3D”, Technical Note TN-HWD09-008-01, April 15, 2010

[vi] Houston Offshore Engineering, “OTEC Coupled Analysis Benchmark - HARP vs. FLEXCOM”, April 15, 2010

[vii] Houston Offshore Engineering, “100MW OTEC Hydrodynamic Panel Model Sensitivity Study Report”, May 26, 2010

[viii] John Halkyard & Associates, “Preliminary Analysis of OTEC Concepts, Technical Note TN-JHA-2008-102, Author: Krish Thiagarajan & John Halkyard, Aug. 29, 2008

[ix] Fatigue Design Handbook, AE-10, (1988), Society of Automotive Engineers, Warrendale, PA

[x] John Halkyard & Associates, “Design Basis for a Moored OTEC Pilot Power Plant (Barbers Point)”, Version 4E, June 28, 2010

[xi] Houston Offshore Engineering, “OTEC CWP ANALYSIS - Top Termination Study for 4 m and 10 m Cold Water Pipe – Strength and Fatigue Report”, 25th June 2010

[xii] Houston Offshore Engineering, “OTEC CWP ANALYSIS - Top Termination Study for 4 m and 10 m Cold Water Pipe – Strength and Fatigue Report”, 25th June 2010

[xiii] Personal communication, Alan Miller

[xiv] Makai Ocean Engineering, “Gripper/Platform Interfacing”, Rev. 1, 6 Apr 2010, by Nick Reese

NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report Appendices

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
Naval Facilities Engineering Service Center (NFESC)
1100 23rd Avenue
Port Hueneme, CA 93043-4370
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Prepared by:

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Revision Status

Revision	Date	Summary of Changes
Rev –	18 August 2010	Preliminary Draft Release
Rev A	21 September 2010	Final Release

Technology Development Report (CDRL A002) Appendices

Appendix	Title
A	Acronym List
5-1	Houston Offshore Engineering “OTEC FRP Pipe Design – Results for Various CWP Bottom Clump Weights and CWP Top Connections”
5-2	Houston Offshore Engineering “OTEC Cold Water Pipe Analysis – CWP Termination Fatigue Analysis”
5-3	Houston Offshore Engineering “OTEC Coupled Analysis Benchmark – HARP vs. FLEXCOM”
5-4	Horton Wison Deepwater “Cold Water Pipe Strain Comparisons – ABAQUS vs. CHARM3D”
5-5	Houston Offshore Engineering “100MW OTEC Hydrodynamic Panel Model Sensitivity Study Report”
5-6	John Halkyard & Associates “OTEC Platform Data for Benchmarking of Pipe – Platform Analysis, TN-HWD09-008-01”
5-7	Houston Offshore Engineering “OTEC Termination Study”
5-8	Houston Offshore Engineering “OTEC CWP Analysis – Top Termination Study for 4 M and 10 M Cold Water Pipe – Strength and Fatigue Report”
6-1	Makai Engineering “Preliminary Gripper Analysis Sizing, Arrangement & Performance”
6-2	Makai Engineering “Gripper/Platform Interfacing”
6-3	Makai Engineering “NOTES: LMCO NAVFAC Pilot Plat Program, CWP-Platform Interface Meeting: 3-4 March 2010”
6-4	Makai Engineering “Gripper Hydraulic System Steps”
6-5	Makai Engineering Drawing Set Gripper and Guide”
6-6	Makai Engineering “OTEC Current Data”
6-7	Makai Engineering “Specifications: 4m Gripper and Guides”

NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report

Appendix A

Acronym List

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
Naval Facilities Engineering Service Center (NFESC)
1100 23rd Avenue
Port Hueneme, CA 93043-4370
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Distribution Statement A: Approved for public release; distribution is unlimited.

Acronym	Definition
3d	Three-dimensional
ABS	American Bureau of Shipping
AC	Alternating Current
AFB	Air Force Base
AFFF	Aqueous Film Forming Foam
AHV	Anchor Handling Vessel
AIS	Air Insulated Switchgear
AIS	Air Insulated Switchgear
AL	Aluminum
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society Of Mechanical Engineers
ASTM	American Standard of Testing Materials
ATE	Automated Test Equipment
ATP	adenosine 5'-triphosphate
BA	Biological Assessment
BCS	Ballast Control System
BHP	Brake Horsepower
BS	Breaking Strength
BULL	Bulletin
C&CC	Command and Control Center
C&CS	Command and Control System
CA	California
CAA	Clean Air Act
CB	Center of Buoyancy
CD	Consistency Determination
CDRL	Contract Data Requirements List
CEROS	Center of Excellence in Ocean Systems
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CG	Center of Gravity
CIA	Cultural Impact Analysis
CNO	Chief of Naval Operations
COE	Corps of Engineers
CONOPS	Concept of operations
COTS	Commercial Off The Shelf
CPT	Cone Penetration Testing
CTD	Conductivity, Temperature, Depth
CW	Cold Water
CWA	Clean Water Act
CWB	Clean Water Branch
CWP	Cold Water Pipe
CZM	Coastal Zone Management

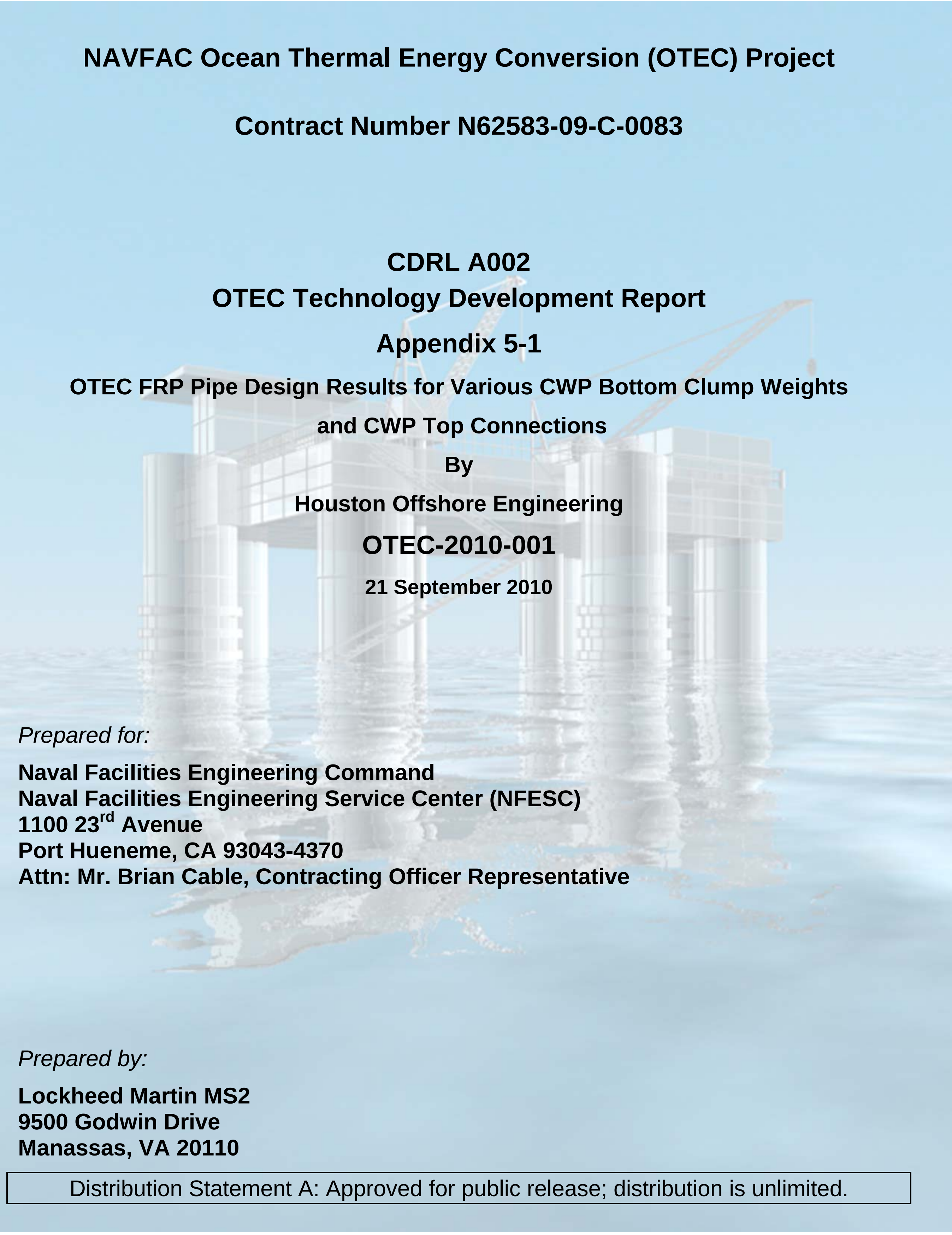
Acronym	**Definition**
CZMA	Coastal Zone Management Act
DAR	Division of Aquatic Resources
DC	Direct Current
DOE	Department of Energy
DOORS	Dynamic Object Oriented Requirements System
DP	Dynamic Positioning
DVT	Design Verification Test
EA	Environmental Assessment
EEIPS	Extra Extra Improved Plow Steel
EFDC	Environmental Fluid Dynamics Code
EIPS	Extra Improved Plow Steel
EIS	Environmental Impact Statement
EMC	Electro-magnetic Conductance
EMF	Electromagnetic Frequency
EMI	Electro-magnetic Interference
EMP	Electro-Magnetic Pulse
EMS	Environmental Management System
EPA	Environmental Protection Agency
EQT	Environmental Qualification Tests
ESA	Endangered Species Act
ESD	Electro Static Discharge
FAT	Factory Acceptance Tests
FCS	Facility Control System
FE	Finite Element
FEA	Finite Element Analysis
FEED	Front End Engineering Design
FGS	Fire and Gas Detection System
FMECA	Failure Modes Effects And Criticality Analysis
FONSI	Finding of No Significant Impact
FPI	Floating Production Installations
FQT	Formal Qualification Test
FRP	Fiberglass Reinforced Plastic
FSW	Friction Stir Welding
FWS	Fresh Water System
FY	Fiscal Year
GA	General Arrangement
GALV	Galvanized
GE	General Electric
GFI	Government Furnished Information
GIS	Gas Insulated Switchgear
GPS	Global Positioning System
HARP	HARmonic Phase loads analysis software
HDD	Horizontal Directional Drilling

Acronym	Definition
HECO	Hawaiian Electric Company
HI	Hawaii
HMI	Human Machine Interface
HOE	Houston Offshore Engineering
HOS	Hornbeck Offshore Services
HOTS	Hawaii Ocean Timeseries
HP	Horse Power
HPLC	High Performance Liquid Chromatography
Hs	Significant Wave Height
HVAC	Heating Ventilation and Air Conditioning
HWD	Horton Wison Deepwater
HX	Heat Exchanger
I&C	Instrumentation and Control
ICEA	Insulated Cable Engineers Association
ICSS	Integrated Control and Safety System
ID	Identifier
ID	Inner Diameter
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical & Electronics Engineers
II&C	Integrated Instrumentation and Control
IMMS	Integrated Marine Monitoring System
IMMS	Integrated Marine Monitoring System
IMO	International Maritime Organization
INCO	Integration and Checkout/Test
INCOSE	International Council of Systems Engineering
INU	Inertial Navigation Unit
IPT	Integrated Product Team
IR&D	Independent Research and Development
IRP	Integrated Resource Planning
ISO	International Standard Organization
ISO	International Standards Organization
IWRC	Independent Wire Rope Core
Ixx	Mass moment of inertia about the x axis
Iyy	Mass moment of inertia about the y axis
Izz	Mass moment of inertia about the z axis
JBPHH	Joint Base Pearl Harbor – Hickam
ksi	kilo-pound per square inch
kV	kilo Volts
kVAR	kilovolt-ampere reactive
KW	Kilowatt
kxx	Gyradius about the x axis
kyy	Gyradius about the y axis
kyy	Gyradius about the z axis

Acronym	**Definition**
LAMP	Large Amplitude Motions Program
LBTF	Land Based Test Facility
LBTS	Land Based Test Site
LCD	Longitudinal Center of Buoyancy
LCG	Longitudinal Center of Gravity
LCP	Local Control Panels
LDS	Loads
LDSX	Load x axis
LDSY	Load y axis
LDSZ	Load z axis
LLC	Limited Liability Company
LM	Lockheed Martin
LO	Lower
LS	Landing Site
MARPOL	International Convention for the Prevention of Pollution From Ships
MASA	Mobilization and Staging Area
MATLAB	Matrix Laboratory
MBL	Mean Breaking Load
MCBH	Marine Corps Base Hawaii
MCC	Master Control Center
MCDA	Multi-Criteria Decision Analysis
MCF	Multi-Column Floater
MCP	Master Control Panel
MD	Maryland
MGD	Million Gallons per Day
MIL	Military
MK	Mark
MMPA	Marine Mammal Protection Act
MMS	Minerals Management Service
MODU	Mobile Offshore Drilling Unit
MOTEM	Makai OTEC Thermodynamic and Economic Model
MS2	Mission Systems & Sensors
mt	Metric tonne
MTP	Master Test Plan
MV	Medium Voltage
MVA	Mega Volt Ampere
MW	Megawatt
MWe	Megawatts, electric
NAVFAC	Naval Facilities Engineering Command
NE	North East
NELHA	Natural Energy Lab of Hawaii Authority
NEMA	National Electrical Manufacturer's Association
NEPA	National Environmental Policy Act

Acronym	Definition
NFESC	Naval Facilities Engineering Service Center
NFPA	National Fire Protection Association
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollution Discharge and Elimination
NPSH	Net Positive Suction Head
NSFDG	Naval Support Facility Diego Garcia
NW	North West
OCCL	Office of Coastal & Conservation Lands
OCEES	Ocean Engineering and Energy Systems
OD	Outer Diameter
ONR	Office of Naval Research
OPNAVINST	Office of the Chief of Naval Operations Instruction
OSHA	Occupational Safety and Health Act
OTEC	Ocean Thermal Energy Conversion
OTECA	OTEC Act of 1980
P&ID	Piping and Instrumentation Diagram
PANAX	Panama Canal
PCS	Process Control System
PDMS	Piping Design Management System
PEAMMP	Proponent’s Environmental Assessment, Management and Monitoring Plan
PF	Power Factor
PFM	Policy File Memorandum
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
PMRF	Pacific Missile Range Facility
POL	Petroleum, Oil and Lubricants
PSD	Process Shutdown
PSI	Pacific Shipyard, Inc. in Oahu, Hawaii
PSV	Pressure Safety Valves
PVC	Polyvinyl Chloride
RAO	Response Amplitude Operators
RCRA	Resource Conservation and Recovery Act
RFP	Request For Proposal
ROD	Record of Decision
ROV	Remotely Operated Vehicle
RP	Recommended Practice
RPM	Revolutions Per Minute
SBIR	Small Business Innovation Research
SCADA	Supervisory Control and Data Acquisition
SE	System Engineering
SECNAVINST	Secretary of the Navy Instruction
SEI&T	System Engineering, Integration and Test

Acronym	**Definition**
SEIPT	System Engineering Integrated Product Team
SI	International System of Units
SI	System Integration
SIP	System Integration Plan
SME	Subject Matter Expert
SOT	System Operational/Operability Test
STEP-R	Strategic Environmental Planning Roadmap
SVR	Steel Vessels
SW	Sea Water
SWBS	Ship Work Breakdown Schedule
SWRO	Sea Water Reverse Osmosis
TBD	To Be Determined
TBR	To Be Reviewed
TCG	Transverse Center of Gravity
TEAAC	Totally Enclosed Air to Air Cooled
TLC	Total Lifecycle Cost
TLI	Tank Level Indicators
TLR	Top Level Requirements
TN	Technical Note
Tp	Peak Wave Period
UN	United Nations
UP	Upper
UPS	Uninterruptable Power Supply
US	United States
USACE	US Army Corps of Engineers
USCG	United States Coast Guard
USFWS	United States Fish & Wildlife Service
USGS	United States Geological Survey
UV	Ultra Violet
V L-L	Voltage Line-to-Line
VA	Virginia
VAC	Volts Alternating Current
VCG	Vertical Center of Gravity
VDC	Volts Direct Current
WAMIT	Wave Analysis Massachusetts Institute of Technology,
WBS	Work Breakdown Structure
WF	Working Fluid
WL	Water Line
WSD	Working Stress Design
WW	Warm Water
XLPE	Cross-linked Polyethylene



NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report
Appendix 5-1
OTEC FRP Pipe Design Results for Various CWP Bottom Clump Weights and CWP Top Connections

By

Houston Offshore Engineering

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
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OTEC FRP Pipe Design

3 December, 2009

Results for Various CWP Bottom Clump Weights and
CWP Top Connections

HOE-OTEC-3	A	3 December 2009	Issue for information	NVK		
Doc. No.	**Rev.**	**Date**	**Description**	**By**	**Appr.**	**Client**

Houston Offshore
ENGINEERING

1 SUMMARY

The report presents the results of a Cold Water Pipe(CWP) attached to a semisubmersible platform. The CWP is attached to the platform by a rigid and pinned connection at the platform keel. Riser analysis program Flexcom3D is used for the study. The environmental conditions considered are 100 yr cyclone and maximum current for CWP design cases. The study considers the effect of various clumped weights at the bottom of the CWP. For each design environment and each type of topside connection we consider 3 cases, no clumped weight attached to the CWP, 200 t and 400 t attached to the bottom of the CWP.

2 DESIGN DATA

2.1 CWP properties

Summary Dynamic and Gripper Values

Property					
Inside Diameter	394	in		10.01	m
Outside Diameter	415.148			10.545	m
Length below transition	39400	in		1,000.8	m
Cross sectional area, solid:	2945.75	in ^2		1.90048	m^2
Void inside core, cross sectional area	10493.87	in^2		6.77	m^2
% wall that is void	78%			78%	
Density of composite, average	0.06710	lbm/in^3		1857	kg/m^3
Mass (excludes internal water)	197.7	lbm/in		3,529.9	kg/m
CWP (no bottom weight) Total Mass (excludes internal water)	7,787,922	lbm		3,532,542	kg
Mass including internal water in walls only	586.3	lbm/in		10,469	kg/m
Mass including internal water -walls and interior	4514.9	lbm/in		80,627	kg/m
Dry Weight CWP (no bottom weight)	197.7	lb/in		34,616	N/m
Total Dry Weight (no bottom weight)	7,787,922	lbs		34,642	kN
Total Dry Weight (no bottom weight)	7,787,922	lbs		3,533	tonnes
Wet weight (no bottom weight)	88.58	lb/in		1.582	tonnes/m
Total wet Weight (no bottom weight)	3,490,071	lbs		1,583	tonnes
Total wet Weight inc bottom weight	3,490,071	lbs		1,583	tonnes
EA	1.30E+10	lbs		57,826,881	kN
EI	2.64E+14	lb-in^2		757,631,070	kN-m^2
Cm	2			2	
Cd	1			1	

Table 1 :**10m CWP Properties**

2.2 Environment Conditions

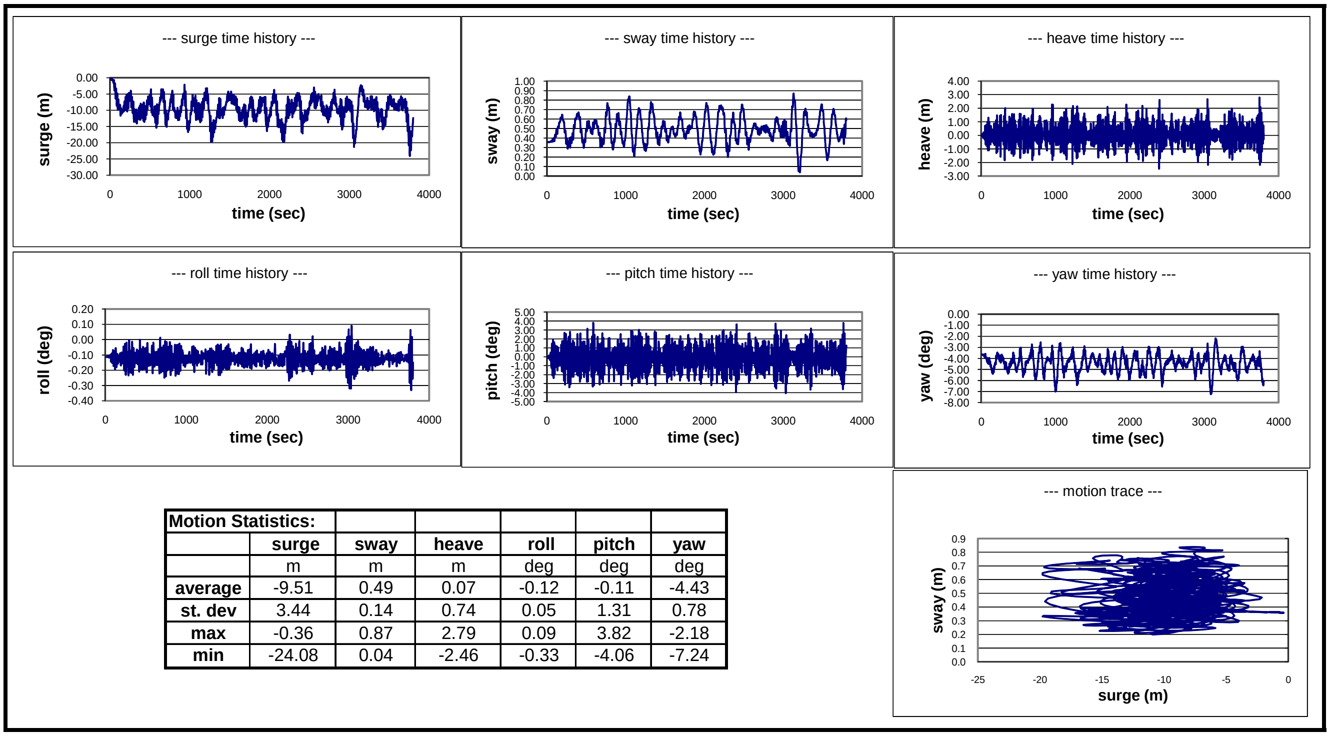
	100 Year Cyclone	**Max Current for CWP Design**	10-yr Sea	10-yr Swell	90% Sea	90% Swell	Fatigue Cases
			(Kahe Hindcast)	(Kahe Hindcast)	(Kahe)	(Kahe)	2 sigma current
			2 sigma current	2 sigma current	4 sigma current	4 sigma current	
Termination (100MW)	**X**	**X**					X
CWP Fab Operational (100 MW)					X	X	
CWP Fab Standby Survival (100 MW)		**X**	X	X			
Termination (10MW)	**X**	**X**					X
CWP Fab Operational (10 MW)							
CWP Fab Standby Survival (10 MW)							
Case ID	**100YrWave**	**Max Current**	10yrSeaKahe	10yrSwell Kahe	90%Sea (1yr)	90% Swell	
Hs, m	**10.2**	**1.5**	4.4	4	2.7	1.5	
Tp, sec	**12**	**14**	8.3	16	5.3	14	
Spectrum, Jonswap gamma	**2**	**6**	1	6	1	6	
Uw, m/sec (1-hr ave)	**34.9**	**8**	15.7	14.3	7.5	8	
Uc, m/sec @ surface	**1.4**	**0.875**	0.478	0.478	0.724	0.724	0.478
Uc, m/sec @ 50m	**1**	**0.774**	0.473	0.473	0.717	0.717	0.473
Uc, m/sec @ 100 m	**0.691**	**0.715**	0.327	0.327	0.493	0.493	0.327
Uc, m/sec @ 150 m	**0.691**	**0.701**	0.327	0.327	0.485	0.485	0.327
Uc, m/sec @ 350 m	**0.431**	**0.334**	0.204	0.204	0.302	0.302	0.204
Uc, m/sec @ 800 m	**0.385**	**0.330**	0.182	0.182	0.276	0.276	0.182
Uc, m/sec @ 1000 m	**0.323**	**0.291**	0.153	0.153	0.230	0.230	0.153

Table 2: **Proposed Design Environments for CWP Design**

3 MOTIONS OF SEMISUBMERSIBLE

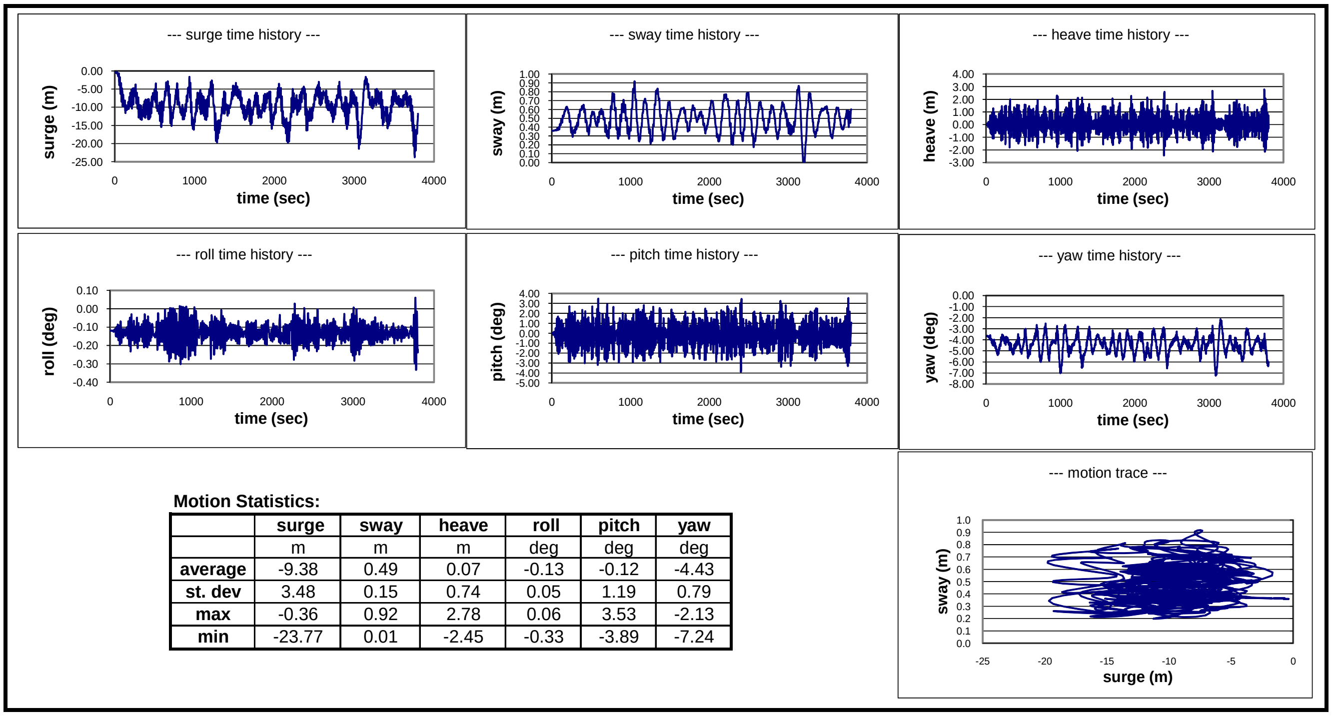
The motions of the Semi were generated using the program HARP. Both the 100 year cyclone case and maximum current for CWP design were considered.

3.1 100 year cyclone case



Motion Statistics:						
	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-9.51	0.49	0.07	-0.12	-0.11	-4.43
st. dev	3.44	0.14	0.74	0.05	1.31	0.78
max	-0.36	0.87	2.79	0.09	3.82	-2.18
min	-24.08	0.04	-2.46	-0.33	-4.06	-7.24

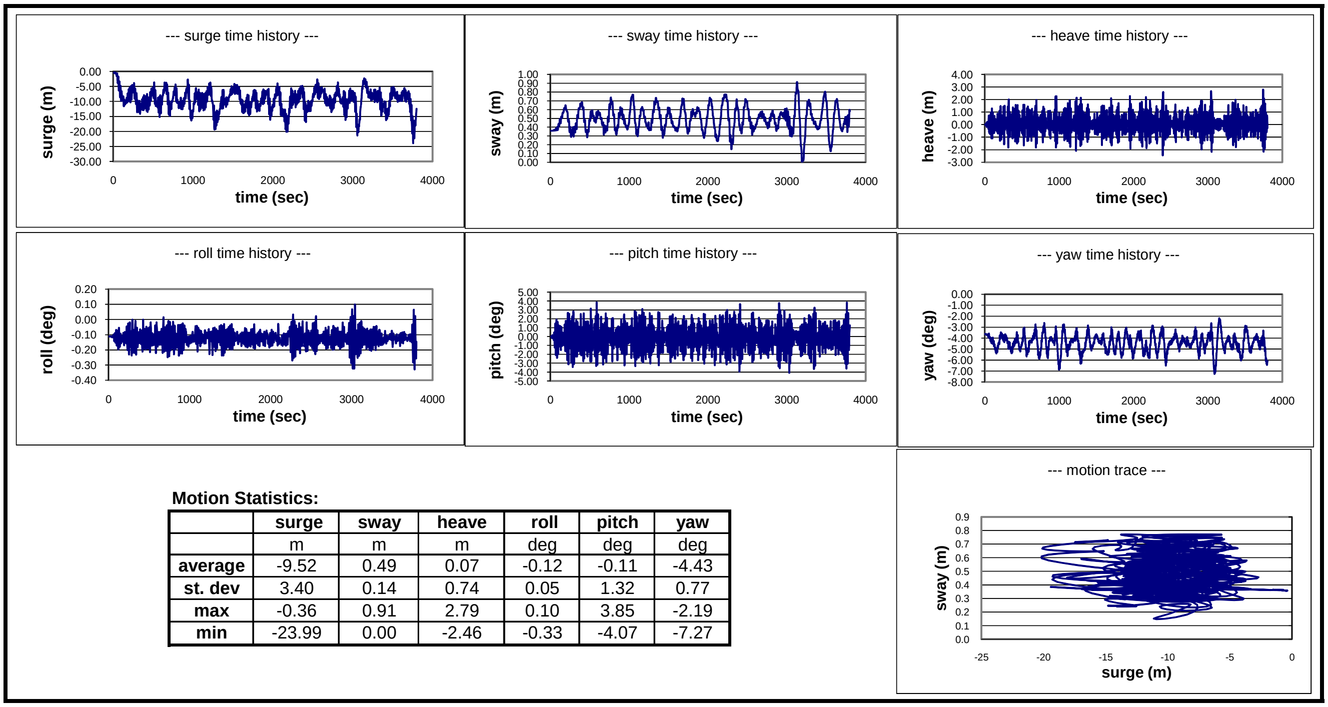
Figure 1: Semi Motions with CWP Rigid Connected at Keel and no Clumped Weight Attached



Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-9.38	0.49	0.07	-0.13	-0.12	-4.43
st. dev	3.48	0.15	0.74	0.05	1.19	0.79
max	-0.36	0.92	2.78	0.06	3.53	-2.13
min	-23.77	0.01	-2.45	-0.33	-3.89	-7.24

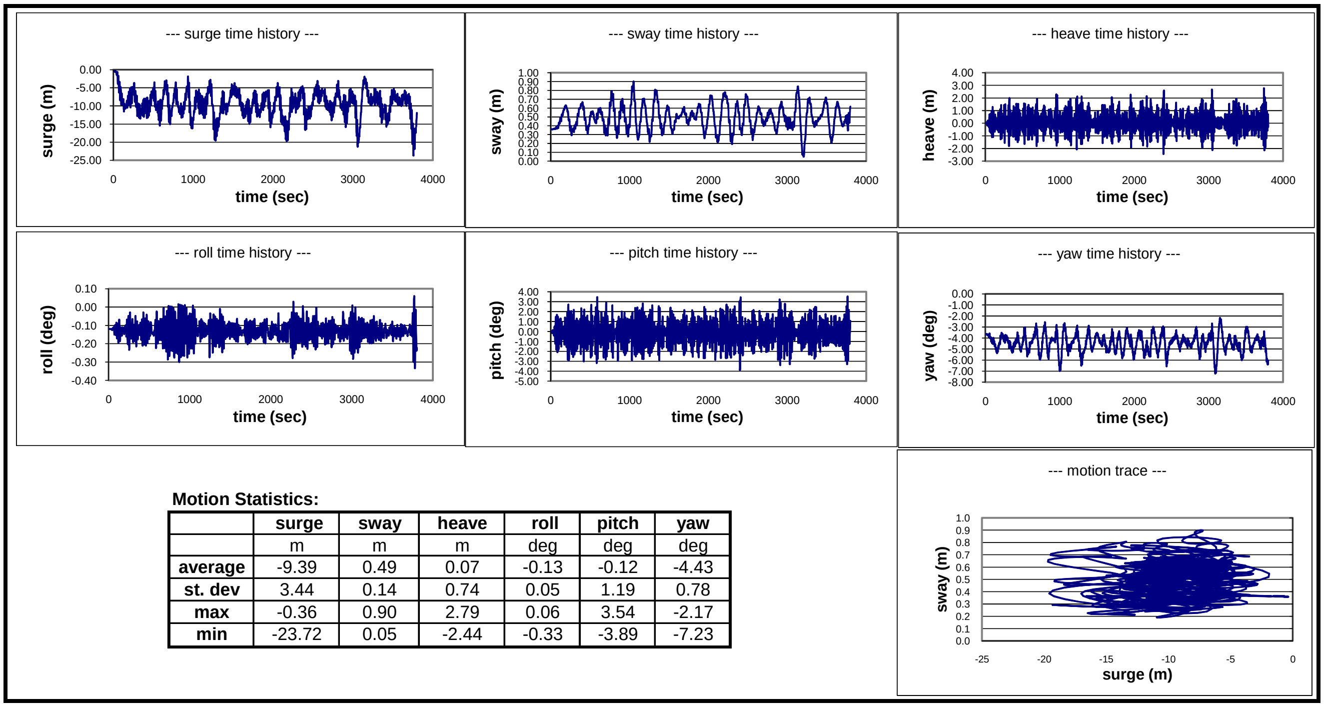
Figure 2: Semi motions with CWP Pin Connected at Keel and no Clumped Weight Attached



Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-9.52	0.49	0.07	-0.12	-0.11	-4.43
st. dev	3.40	0.14	0.74	0.05	1.32	0.77
max	-0.36	0.91	2.79	0.10	3.85	-2.19
min	-23.99	0.00	-2.46	-0.33	-4.07	-7.27

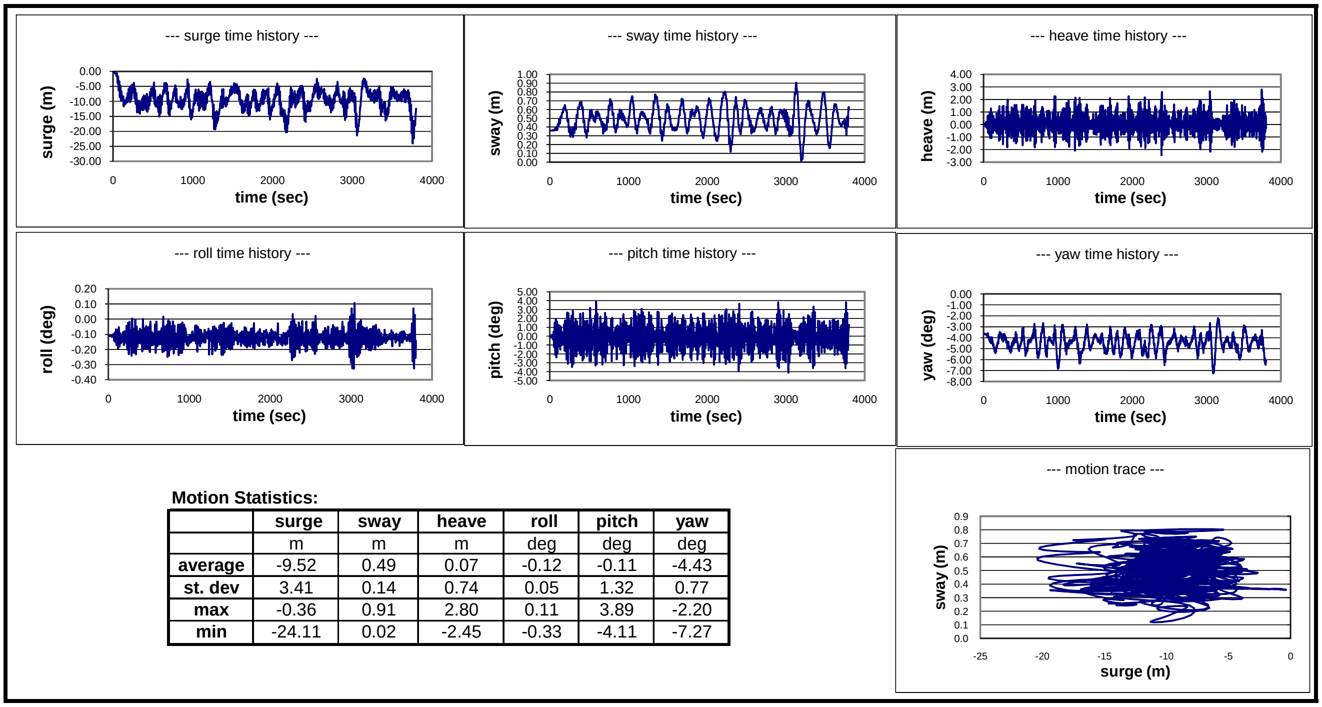
Figure 3: Semi motions with CWP Rigid Connected at Keel and 200 t Clumped Weight Attached



Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-9.39	0.49	0.07	-0.13	-0.12	-4.43
st. dev	3.44	0.14	0.74	0.05	1.19	0.78
max	-0.36	0.90	2.79	0.06	3.54	-2.17
min	-23.72	0.05	-2.44	-0.33	-3.89	-7.23

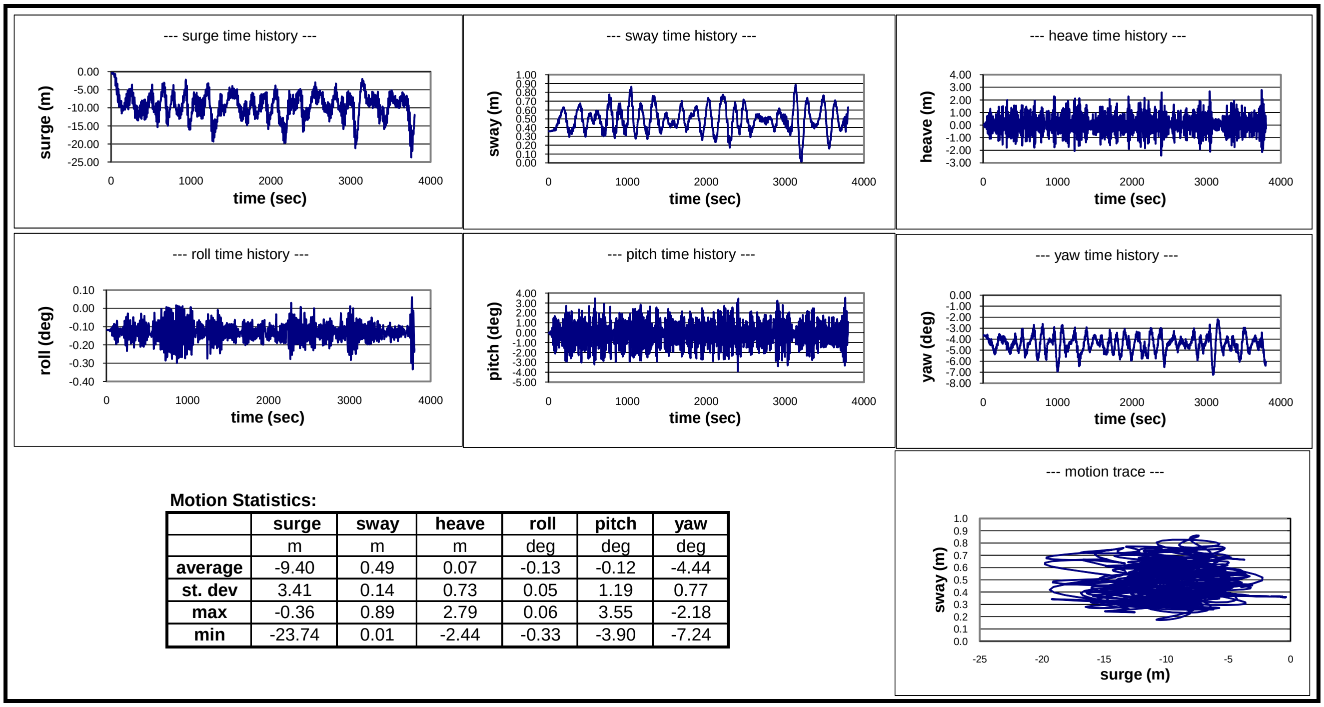
Figure 4: Semi motions with CWP Pin Connected at Keel and 200 t Clumped Weight Attached



Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-9.52	0.49	0.07	-0.12	-0.11	-4.43
st. dev	3.41	0.14	0.74	0.05	1.32	0.77
max	-0.36	0.91	2.80	0.11	3.89	-2.20
min	-24.11	0.02	-2.45	-0.33	-4.11	-7.27

Figure 5: Semi motions with CWP Rigid Connected at Keel and 400 t Clumped Weight Attached

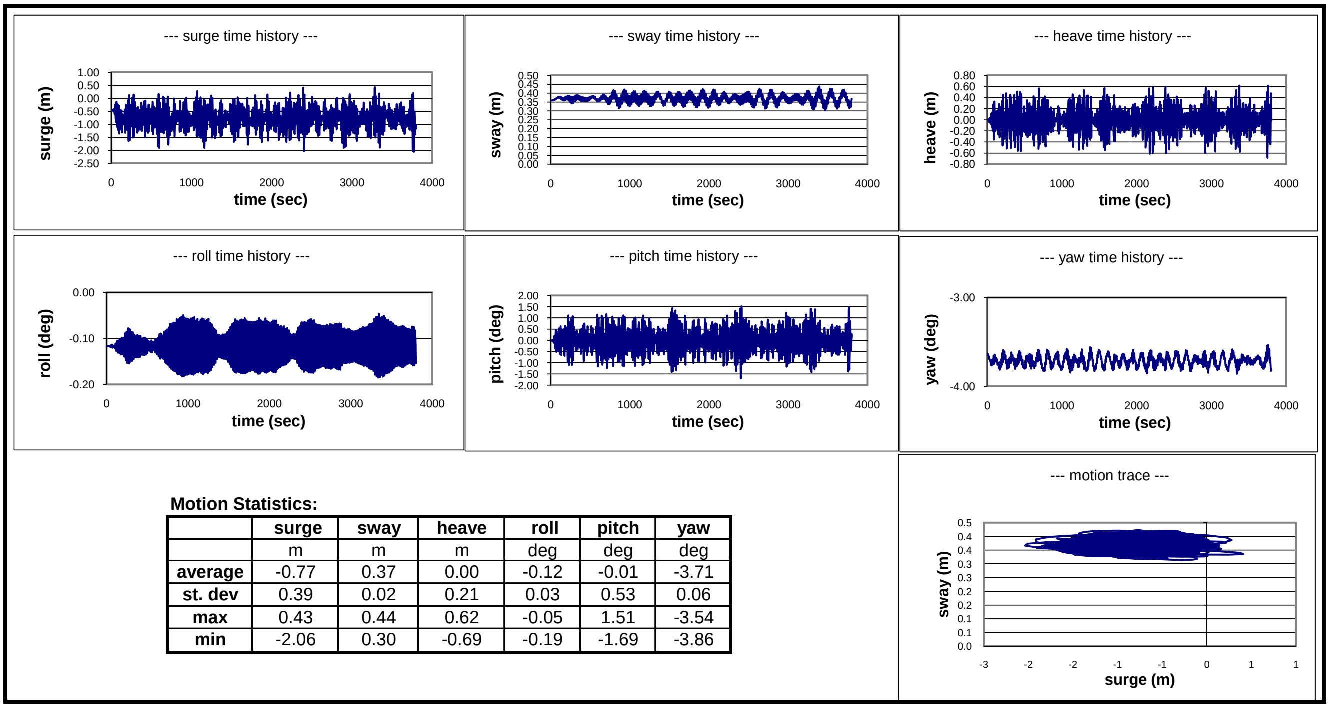


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-9.40	0.49	0.07	-0.13	-0.12	-4.44
st. dev	3.41	0.14	0.73	0.05	1.19	0.77
max	-0.36	0.89	2.79	0.06	3.55	-2.18
min	-23.74	0.01	-2.44	-0.33	-3.90	-7.24

Figure 6: Semi motions with CWP Pin Connected at keel and 400 t Clumped Weight Attached

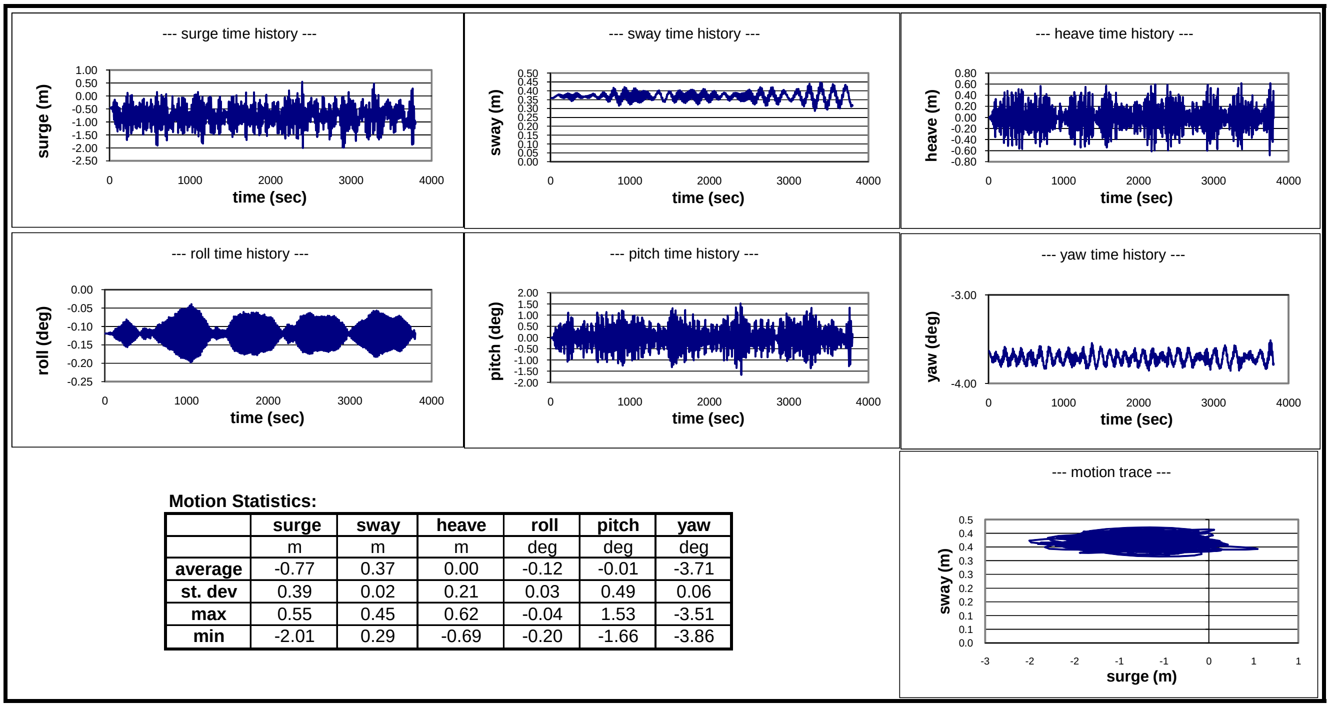
3.2 Maximum Current for CWP Design case



Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-0.77	0.37	0.00	-0.12	-0.01	-3.71
st. dev	0.39	0.02	0.21	0.03	0.53	0.06
max	0.43	0.44	0.62	-0.05	1.51	-3.54
min	-2.06	0.30	-0.69	-0.19	-1.69	-3.86

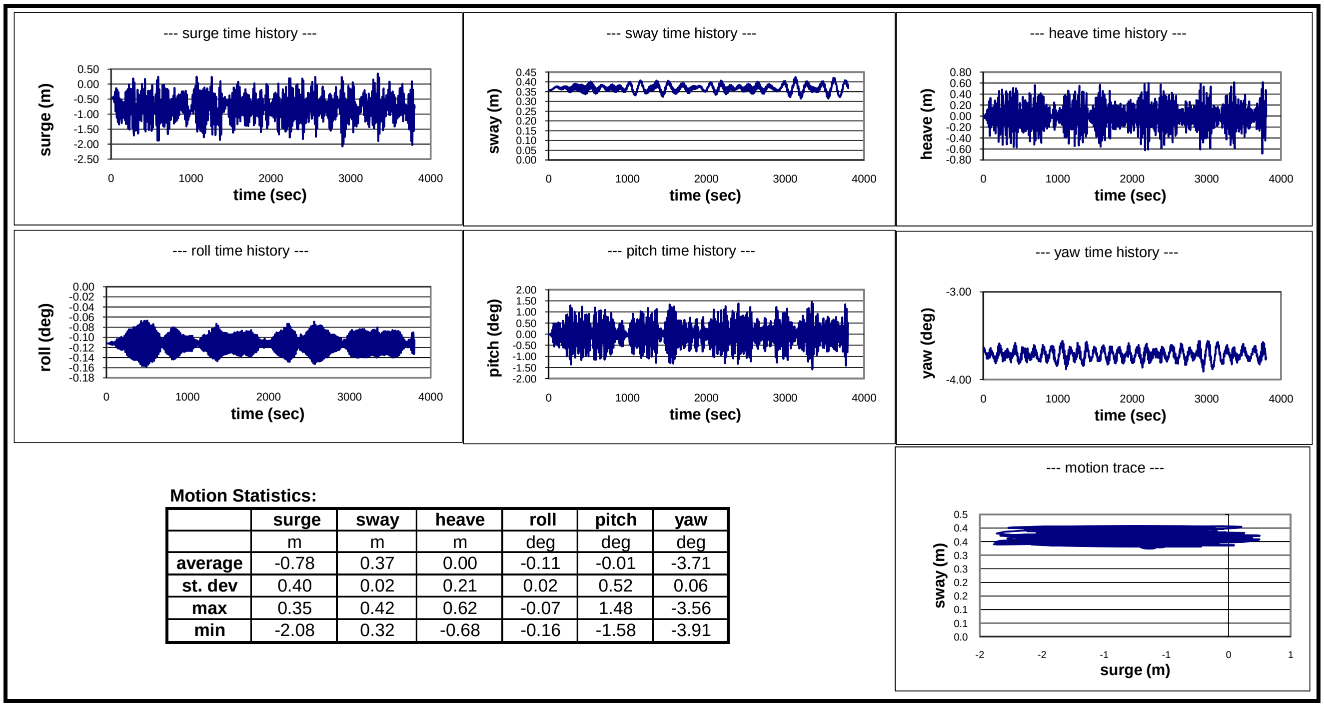
Figure 7: Semi motions with CWP Rigid Connected at keel and no Clumped Weight Attached



Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-0.77	0.37	0.00	-0.12	-0.01	-3.71
st. dev	0.39	0.02	0.21	0.03	0.49	0.06
max	0.55	0.45	0.62	-0.04	1.53	-3.51
min	-2.01	0.29	-0.69	-0.20	-1.66	-3.86

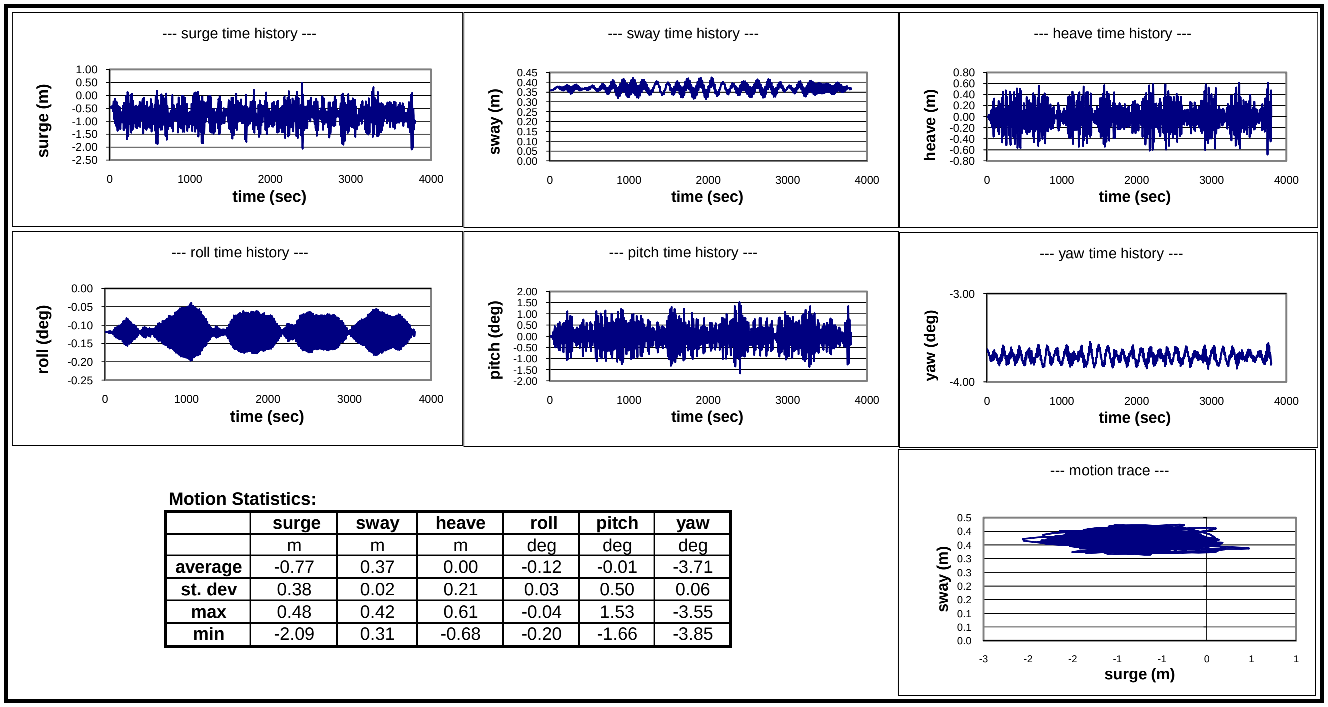
Figure 8: Semi motions with CWP Pin Connected at keel and no Clumped Weight Attached



Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-0.78	0.37	0.00	-0.11	-0.01	-3.71
st. dev	0.40	0.02	0.21	0.02	0.52	0.06
max	0.35	0.42	0.62	-0.07	1.48	-3.56
min	-2.08	0.32	-0.68	-0.16	-1.58	-3.91

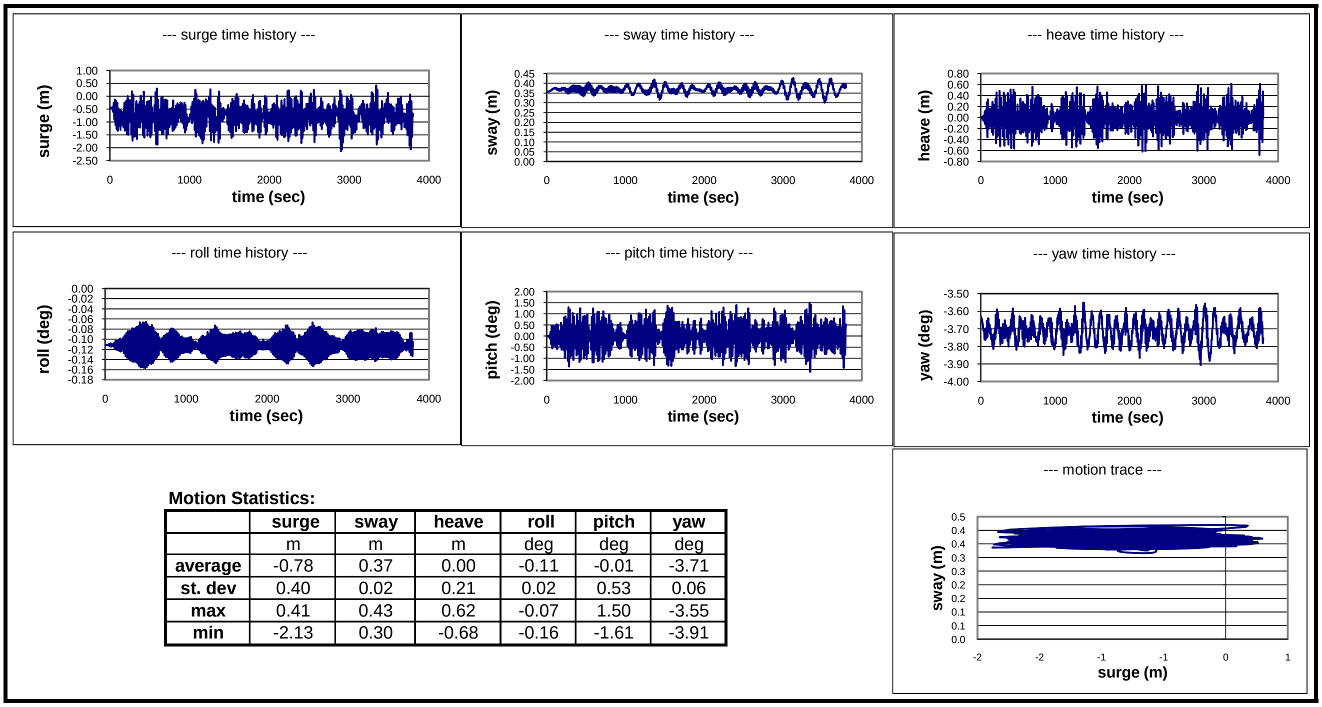
Figure 9: Semi motions with CWP Rigid Connected at keel and 200 t Clumped Weight Attached



Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-0.77	0.37	0.00	-0.12	-0.01	-3.71
st. dev	0.38	0.02	0.21	0.03	0.50	0.06
max	0.48	0.42	0.61	-0.04	1.53	-3.55
min	-2.09	0.31	-0.68	-0.20	-1.66	-3.85

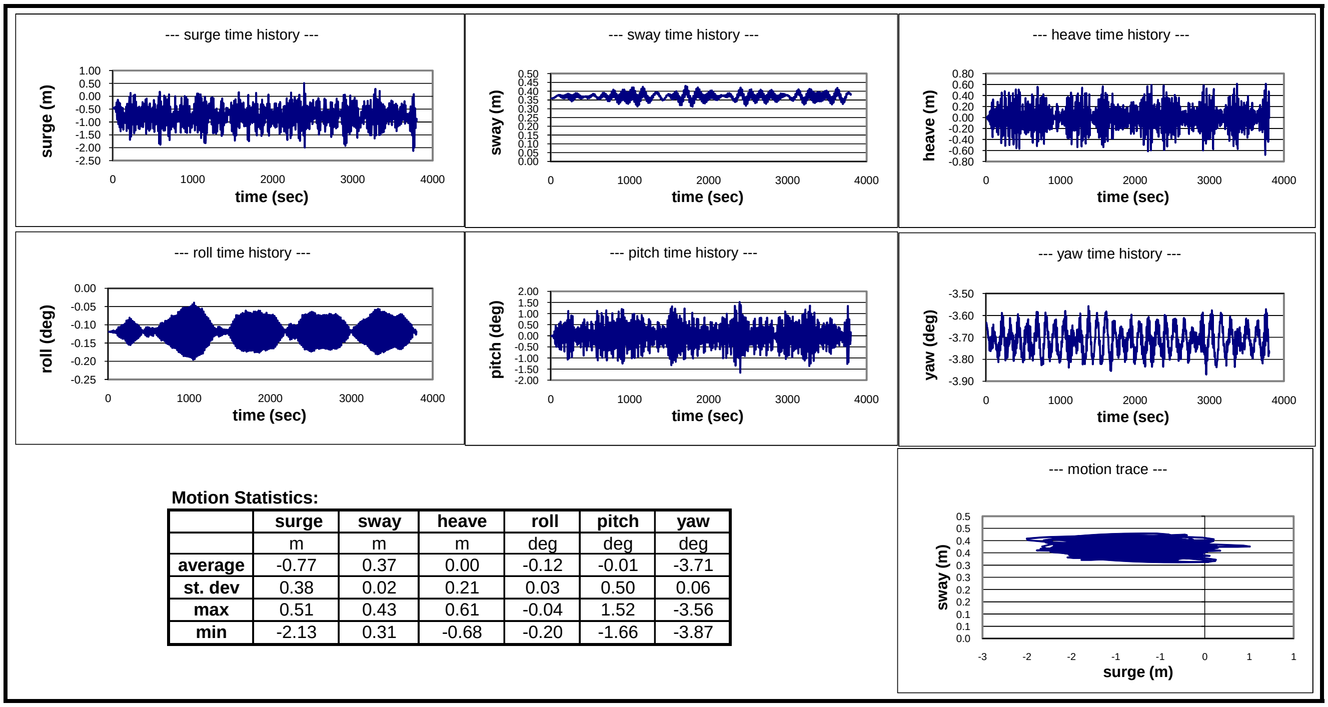
Figure 10: Semi motions with CWP Pin Connected at keel and 200 t Clumped Weight Attached



Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-0.78	0.37	0.00	-0.11	-0.01	-3.71
st. dev	0.40	0.02	0.21	0.02	0.53	0.06
max	0.41	0.43	0.62	-0.07	1.50	-3.55
min	-2.13	0.30	-0.68	-0.16	-1.61	-3.91

Figure 11: Semi motions with CWP Rigid Connected at keel and 400 t Clumped Weight Attached



Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-0.77	0.37	0.00	-0.12	-0.01	-3.71
st. dev	0.38	0.02	0.21	0.03	0.50	0.06
max	0.51	0.43	0.61	-0.04	1.52	-3.56
min	-2.13	0.31	-0.68	-0.20	-1.66	-3.87

Figure 12: Semi motions with CWP Pin Connected at keel and 400 t Clumped Weight Attached

4 RESULTS

Table 3 and 4 summarized the most interesting values from the results. The CWP motion envelope, bending moment envelope, bending strain envelope, mean bending strain, standard deviation of bending strain and effective tension envelope for each case are shown in the following figures.

		100 year cyclone					
		CWP **rigid connected** to Semi			CWP **pin connected** to Semi		
	Units	No clumped weight	200 t clumped weight attached	400 t clumped weight attached	No clumped weight	200 t clumped weight attached	400 t clumped weight attached
CWP Max Bottom Offset	m	86.95	73.48	65.22	92.88	76.84	67.15
Max Bending Moment	N-m	1.37E+09	1.31E+09	1.27E+09	3.77E+08	3.82E+08	3.92E+08
Location of Maximum Bending (Location from keel)	m	0	0	0	797.1	798	796
Max Bending Strain		0.0095	0.009	0.0088	0.00273	0.00266	0.00262
Max Effective Tension at CWP Top	t	2.77E+03	2.57E+03	2.24E+03	2.75E+03	2.43E+03	2.12E+03
CWP Top Connection angle of rotation	deg	-	-	-	8.16	7.32	6.93

Table 3: Results for 100 yr Cyclone Case

		Max Current for CWP Design					
		CWP **rigid connected** to Semi			CWP **pin connected** to Semi		
	Units	No clumped weight	200 t clumped weight attached	400 t clumped weight attached	No clumped weight	200 t clumped weight attached	400 t clumped weight attached
CWP Max Bottom Offset	m	34.65	26.22	22.2	42.8	34.2	28.82
Max Bending Moment	N-m	6.22E+08	5.60E+08	5.60E+08	1.22E+08	1.15E+08	1.08E+08
Location of Maximum Bending (Location from keel)	m	0	0	0	137.6	135.9	124.7
Max Bending Strain		0.0043	0.0039	0.0039	0.00085	0.0008	0.00075
Max Effective Tension at CWP Top	t	2.03E+03	1.82E+03	1.61E+03	2.02E+03	1.81E+03	1.61E+03
CWP Top Connection angle of rotation	deg	-	-	-	4.25	3.87	3.64

Table 4: Results for Maximum Current for CWP Design Case

4.1 100 year cyclone (Rigid Connected to keel)

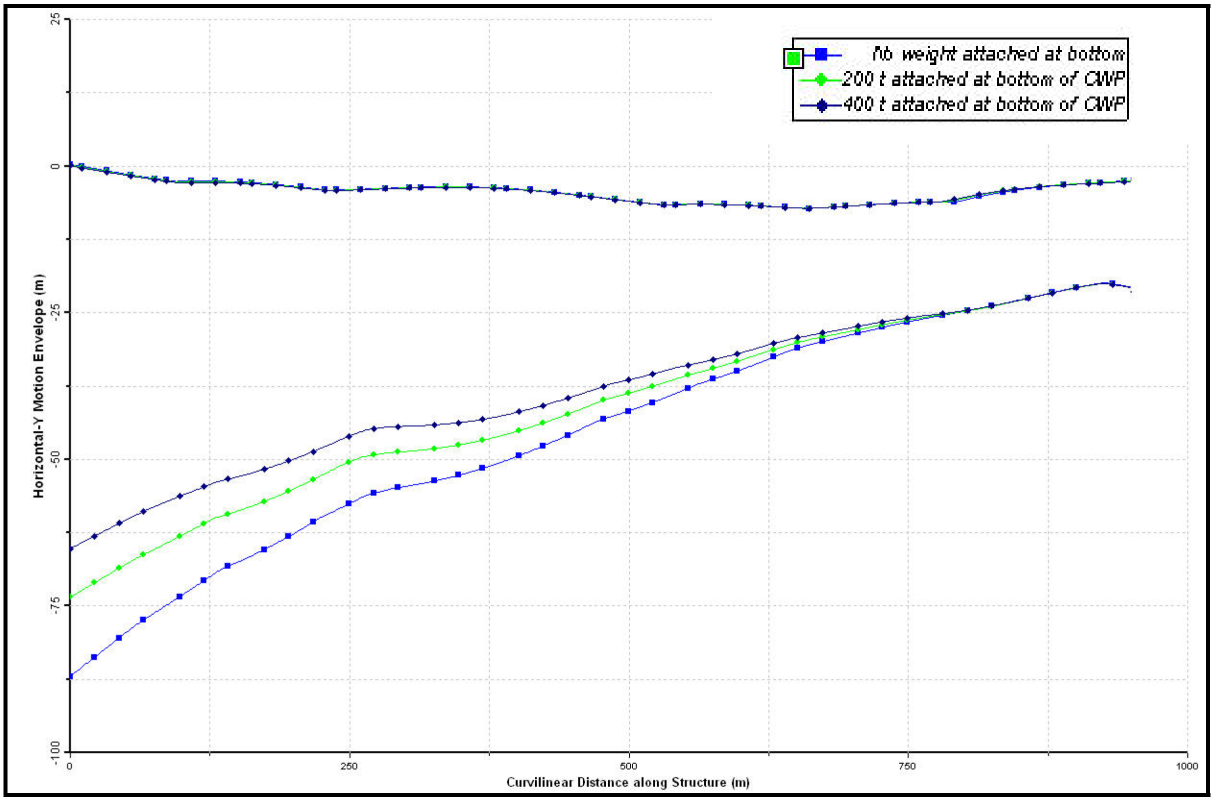


Figure 13: Motion Envelope for CWP Rigid Connected to Semi (from Bottom to Top)

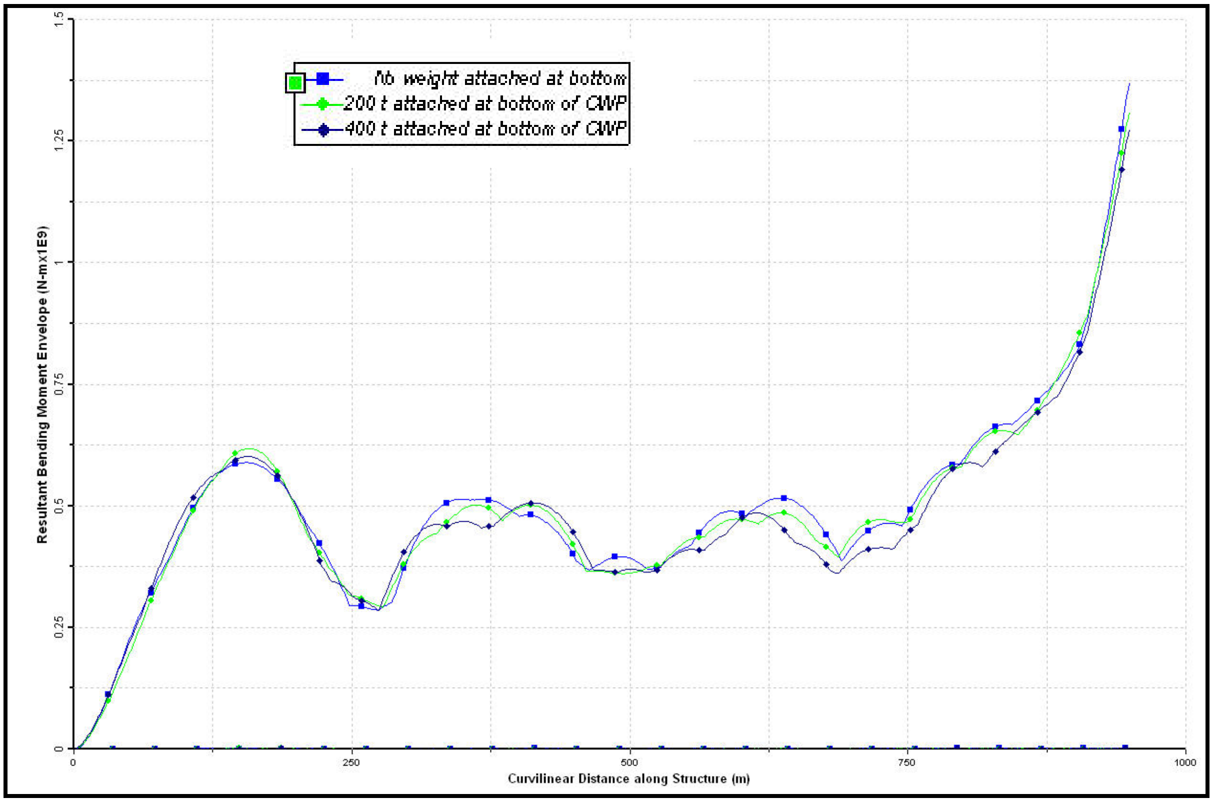


Figure 14: Bending Moment Envelope for CWP Rigid Connected to Semi (from Bottom to Top)

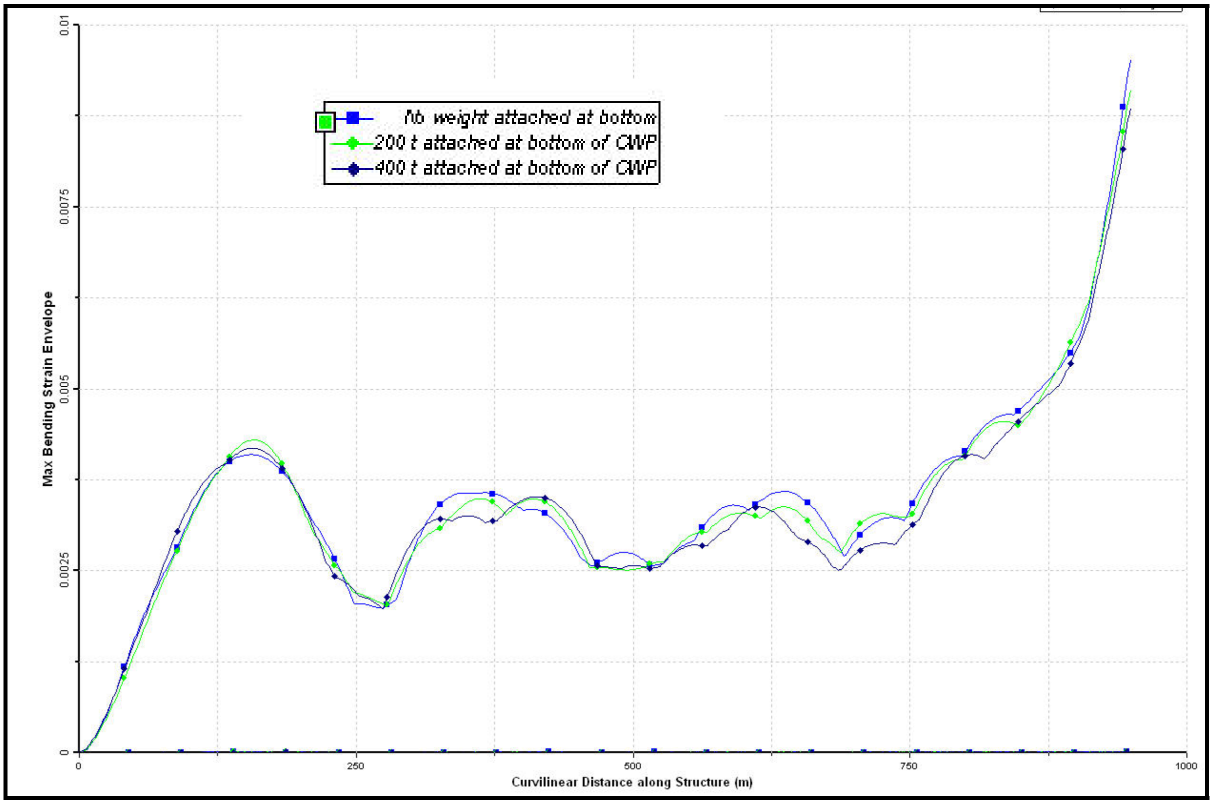


Figure 15: Bending Strain Envelope for CWP Rigid Connected to Semi (from Bottom to Top)

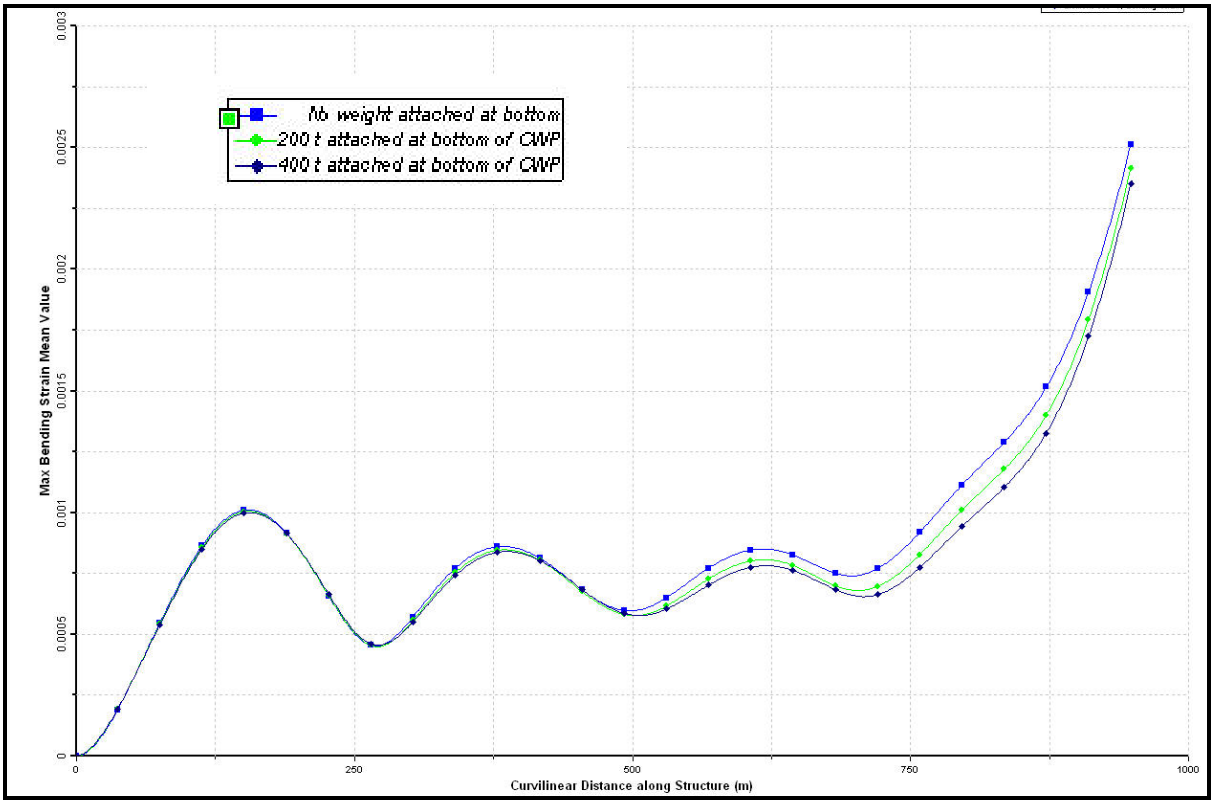


Figure 16: Mean Bending Strain for CWP Rigid Connected to Semi (from Bottom to Top)

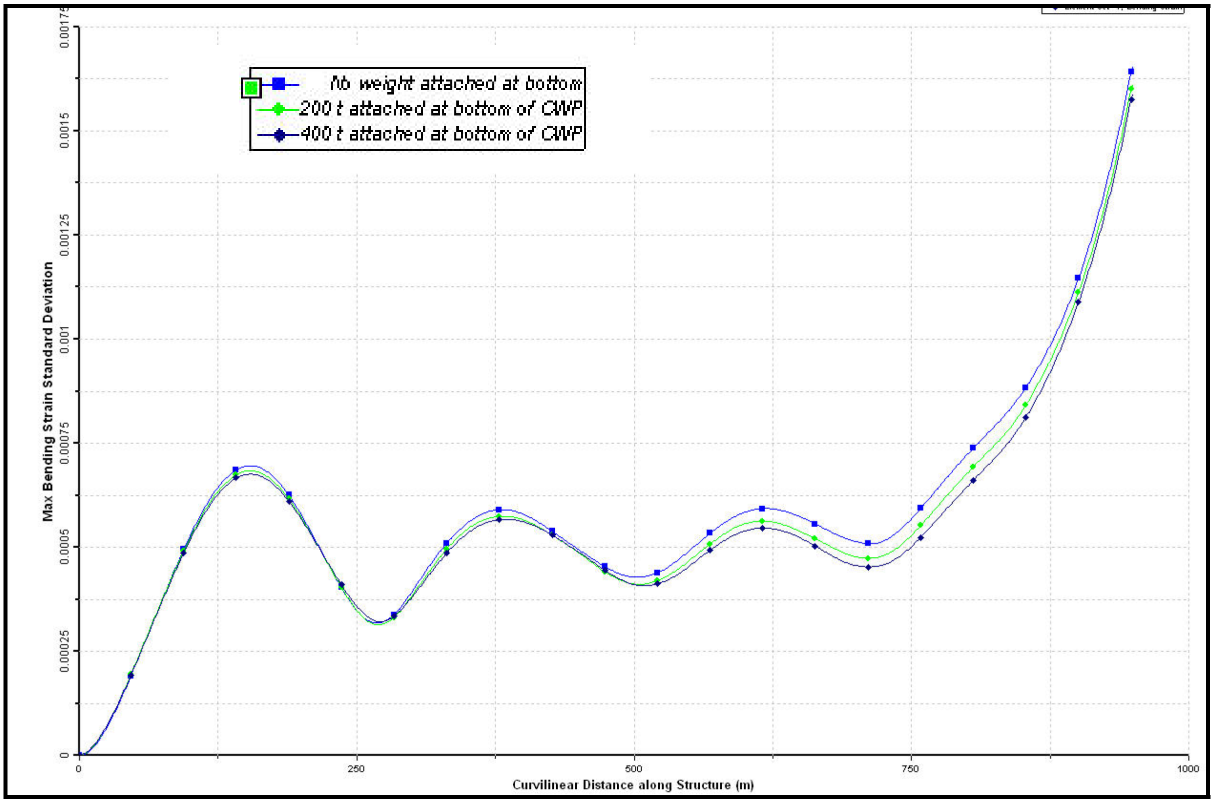


Figure 17: Std Dev of Bending Strain for CWP Rigid Connected to Semi (from Bottom to Top)

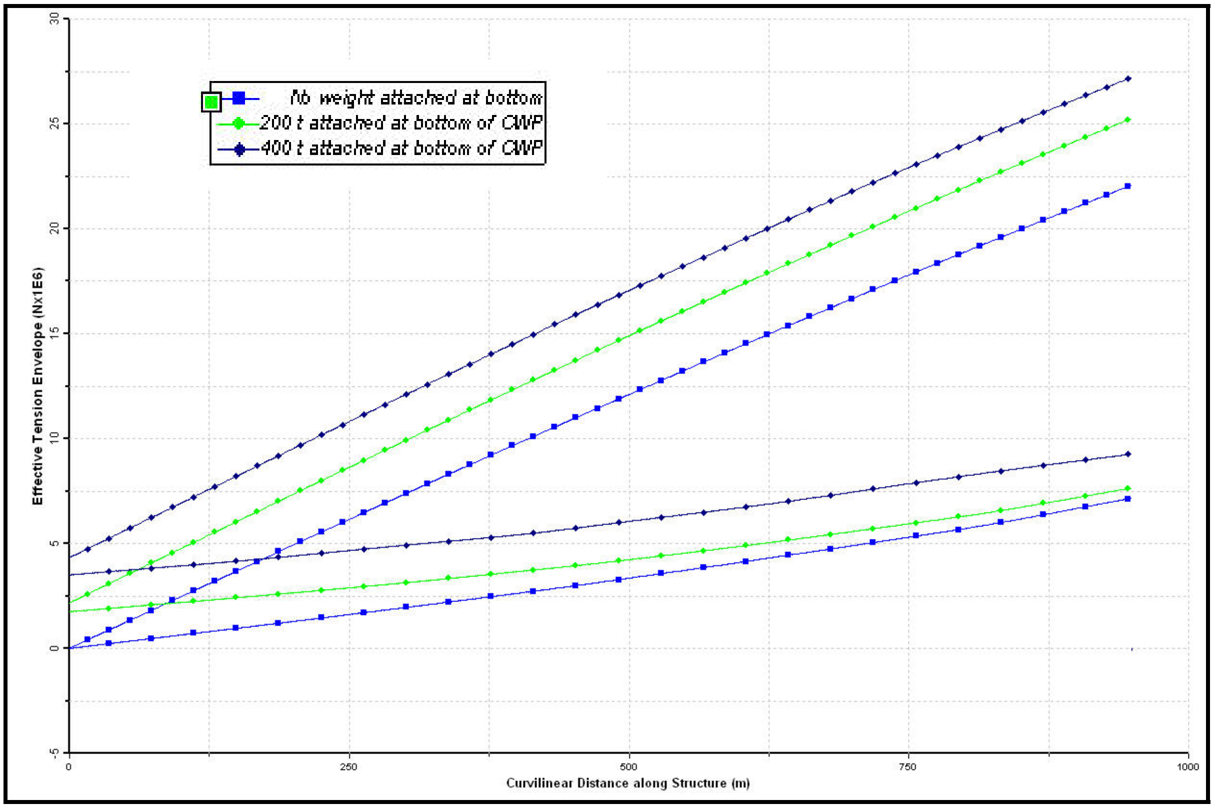


Figure 18: Effective Tension Envelope for CWP Rigid Connected to Semi (from Bottom to Top)

4.2 100 year cyclone (Pin Connected to keel)

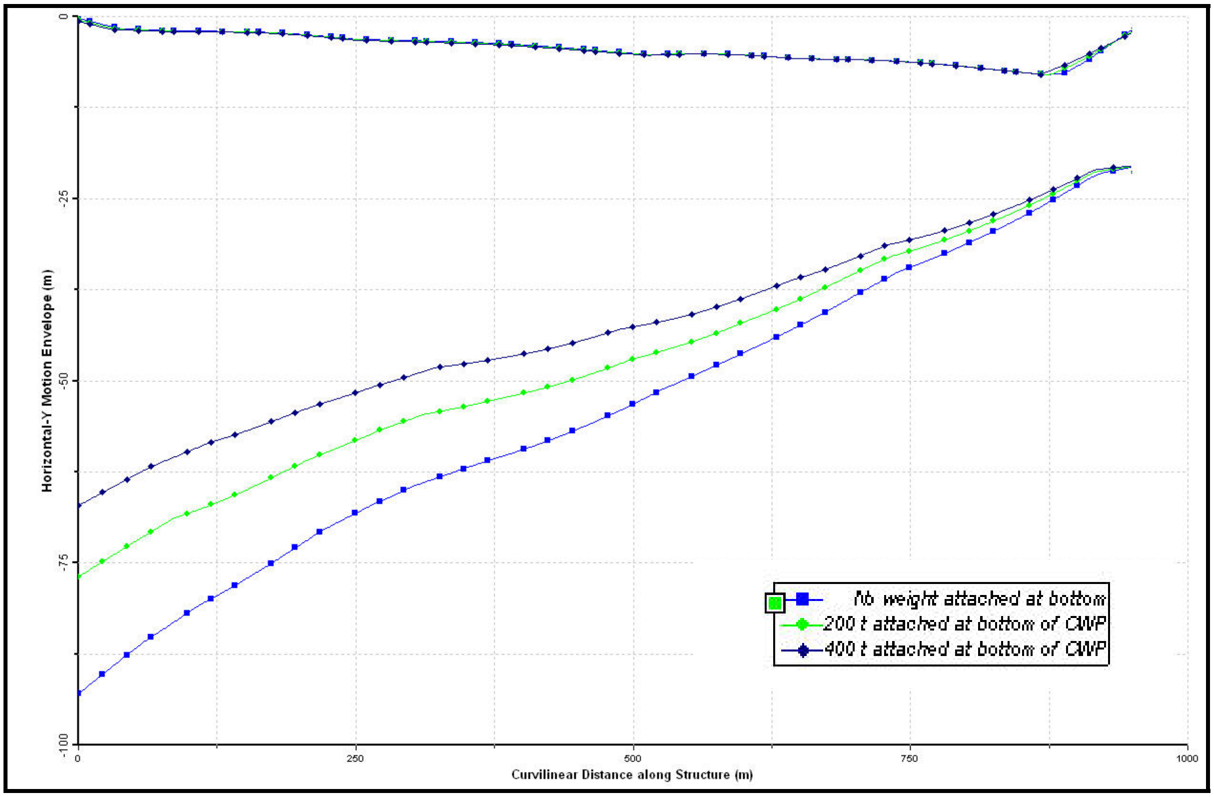


Figure 19: Motion Envelope for CWP Pin Connected to Semi (from Bottom to Top)

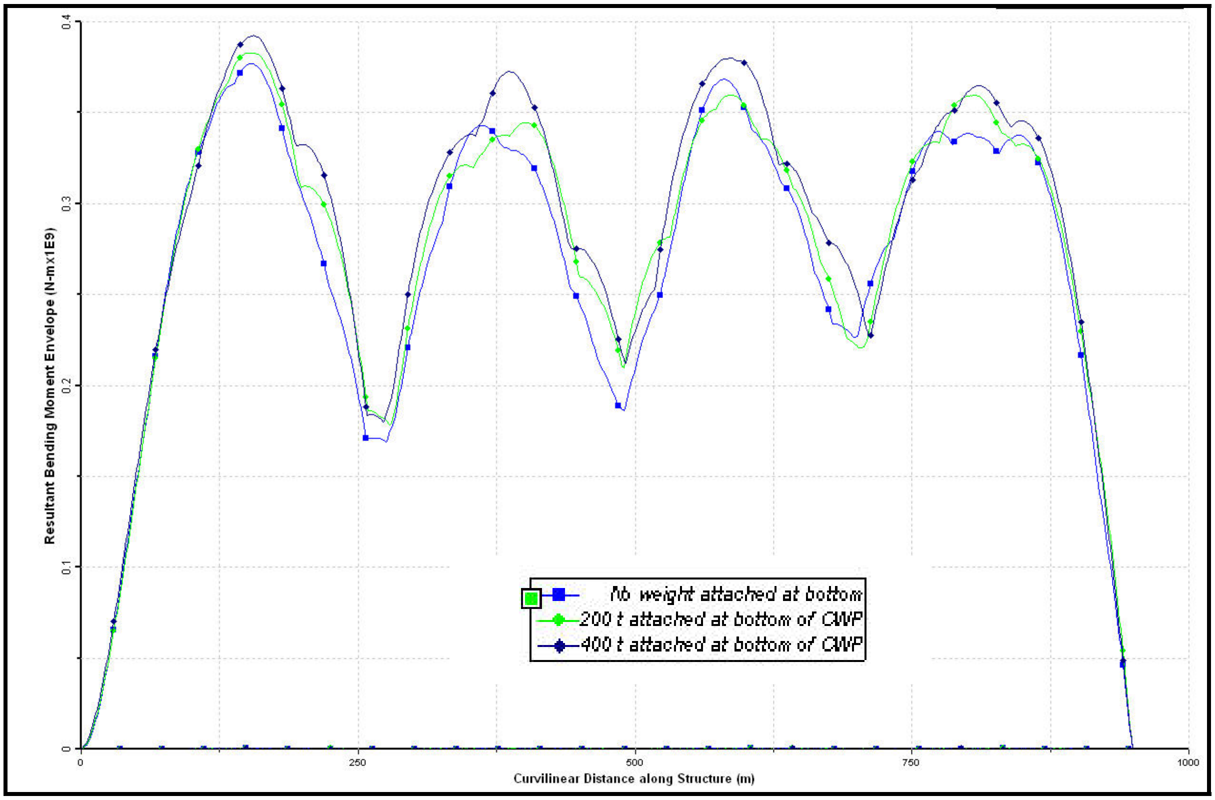


Figure 20: Bending Moment Envelope for CWP Pin Connected to Semi (from Bottom to Top)

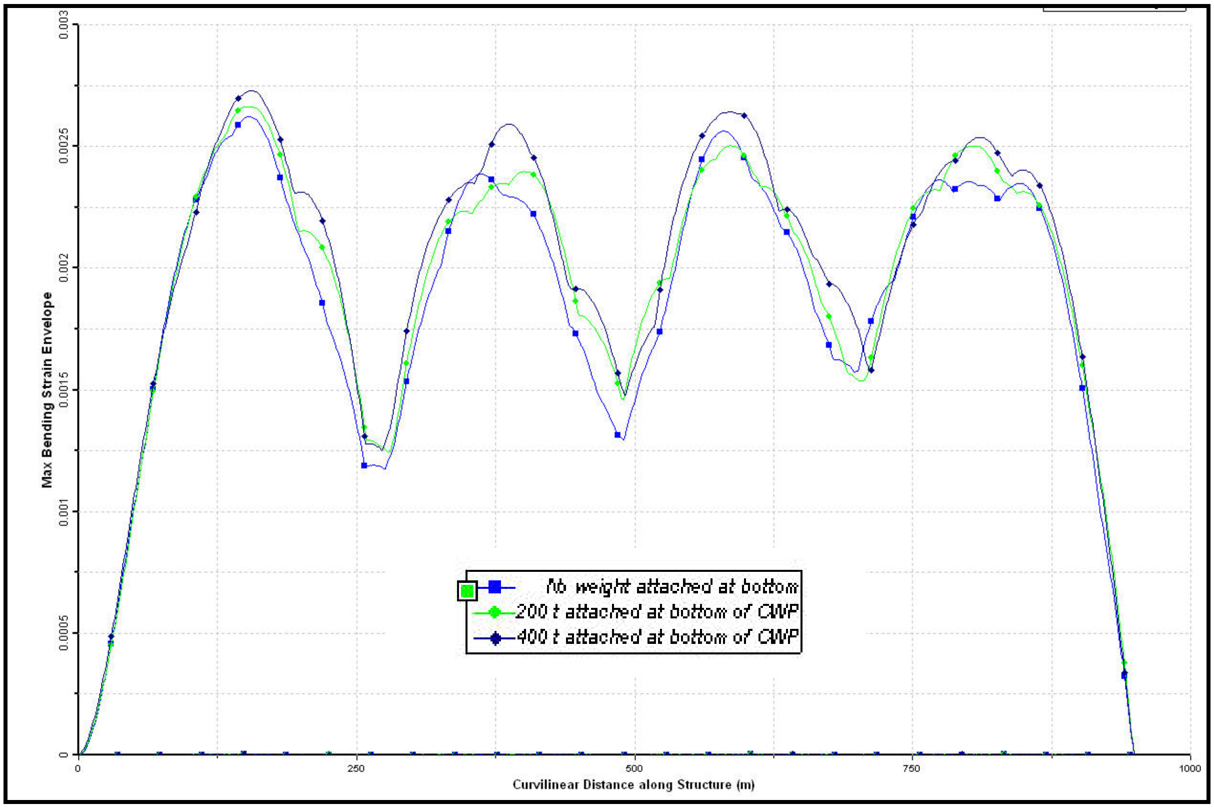


Figure 21: Bending Strain Envelope for CWP Pin Connected to Semi (from Bottom to Top)

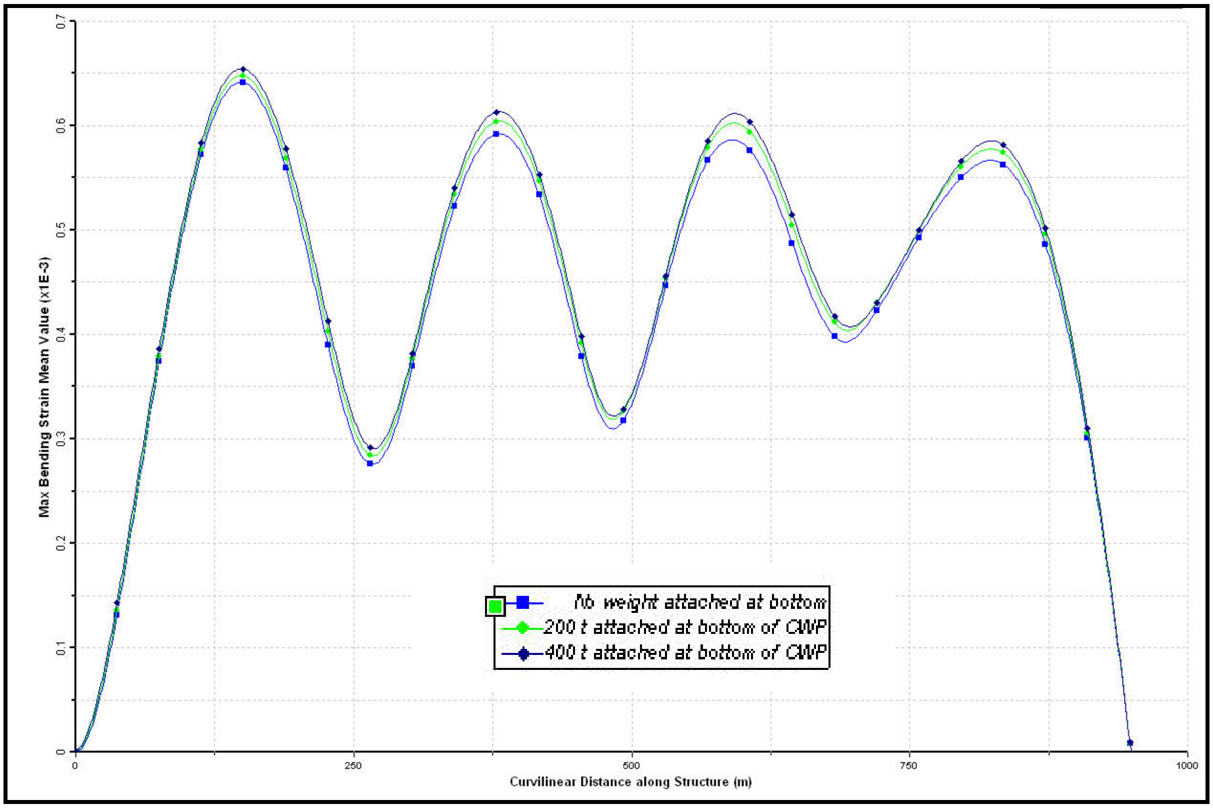


Figure 22: Mean Bending Strain for CWP Pin Connected to Semi (from Bottom to Top)

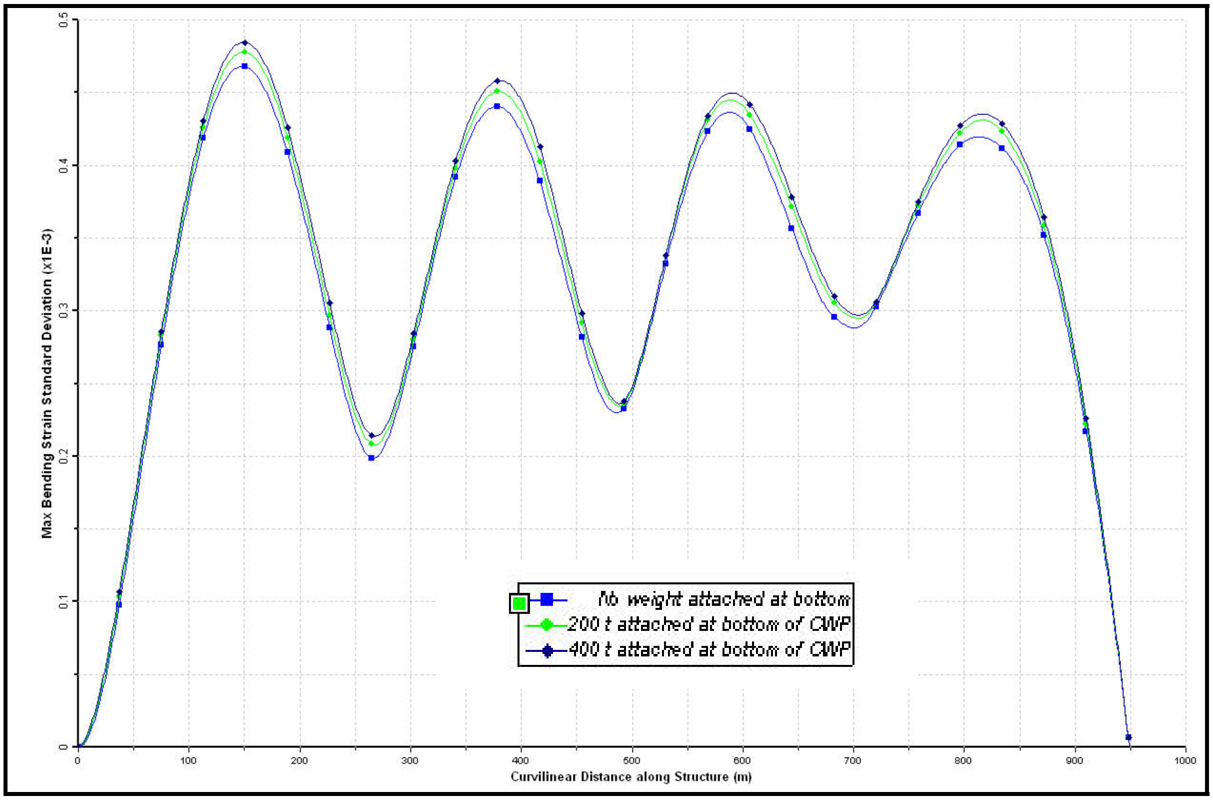


Figure 23: Std Dev of Bending Strain for CWP Pin Connected to Semi (from Bottom to Top)

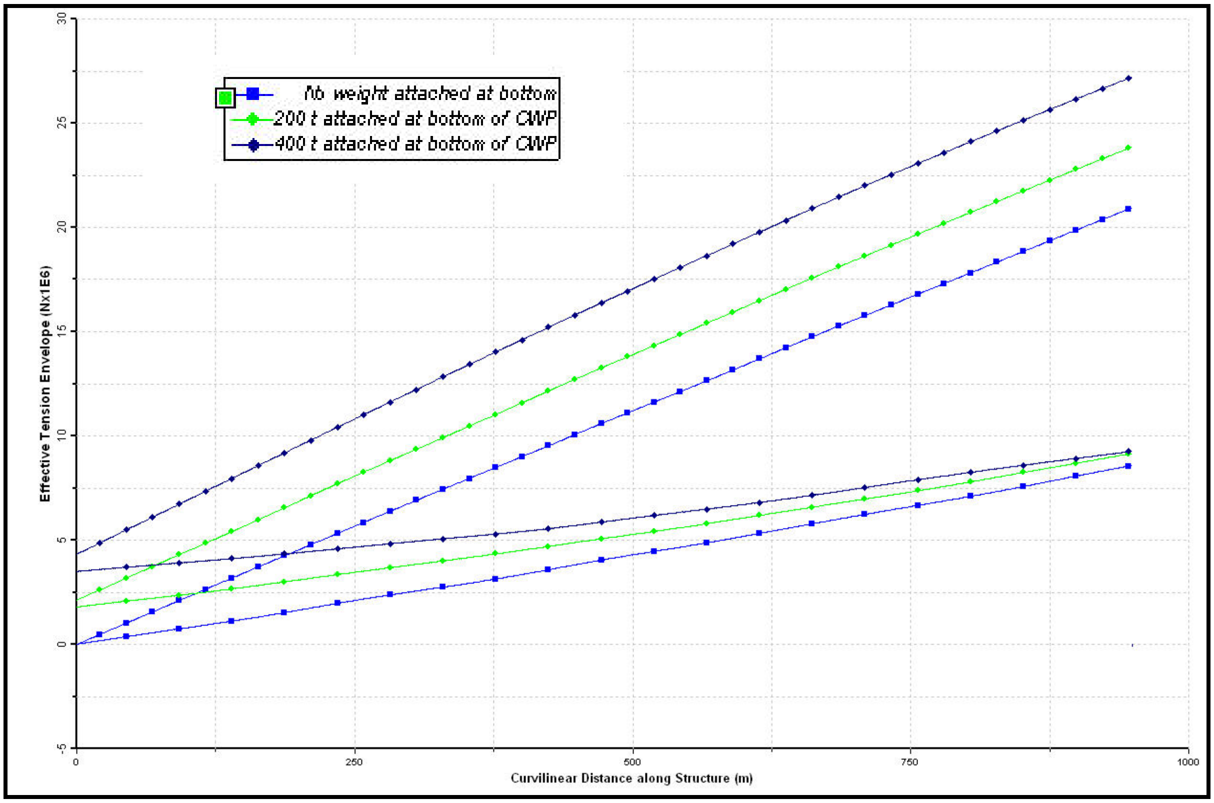


Figure 24: Effective Tension Envelope for CWP Pin Connected to Semi (from Bottom to Top)

4.3 Maximum Current for CWP Design (Rigid Connected to keel)

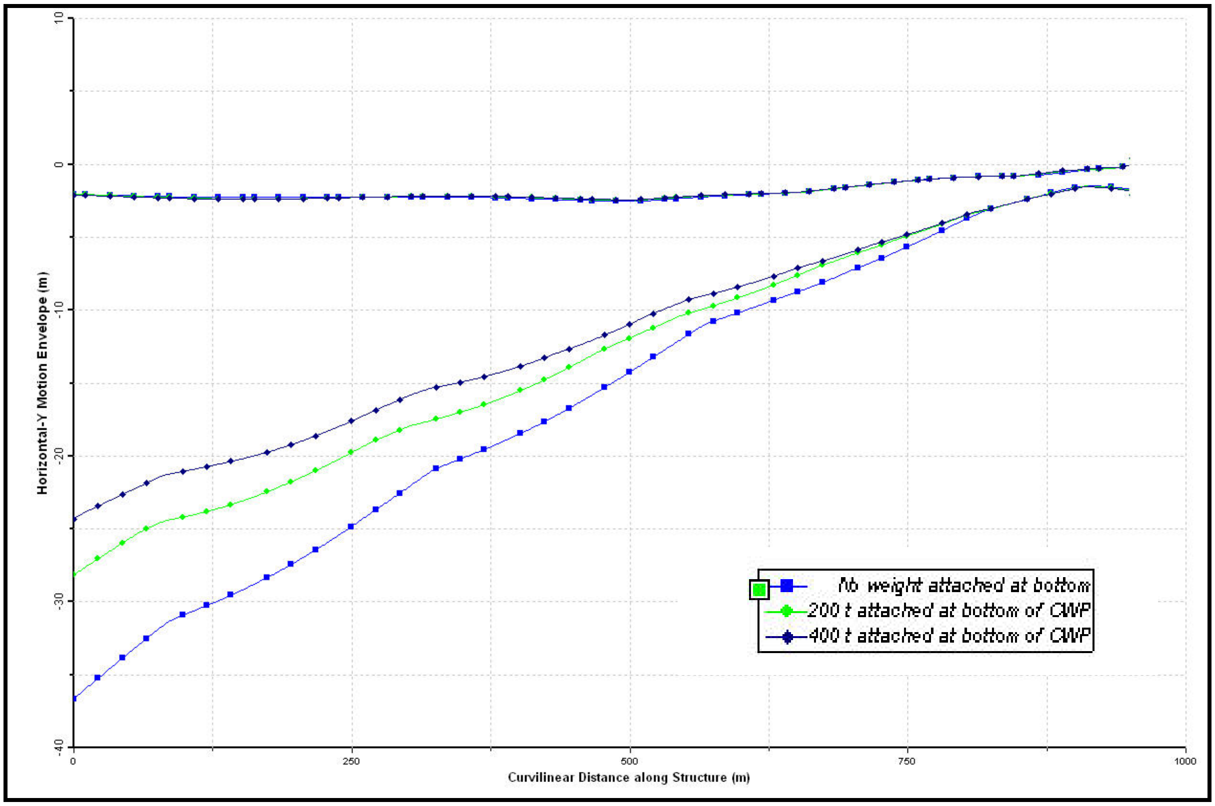


Figure 25: Motion Envelope for CWP Rigid Connected to Semi (from Bottom to Top)

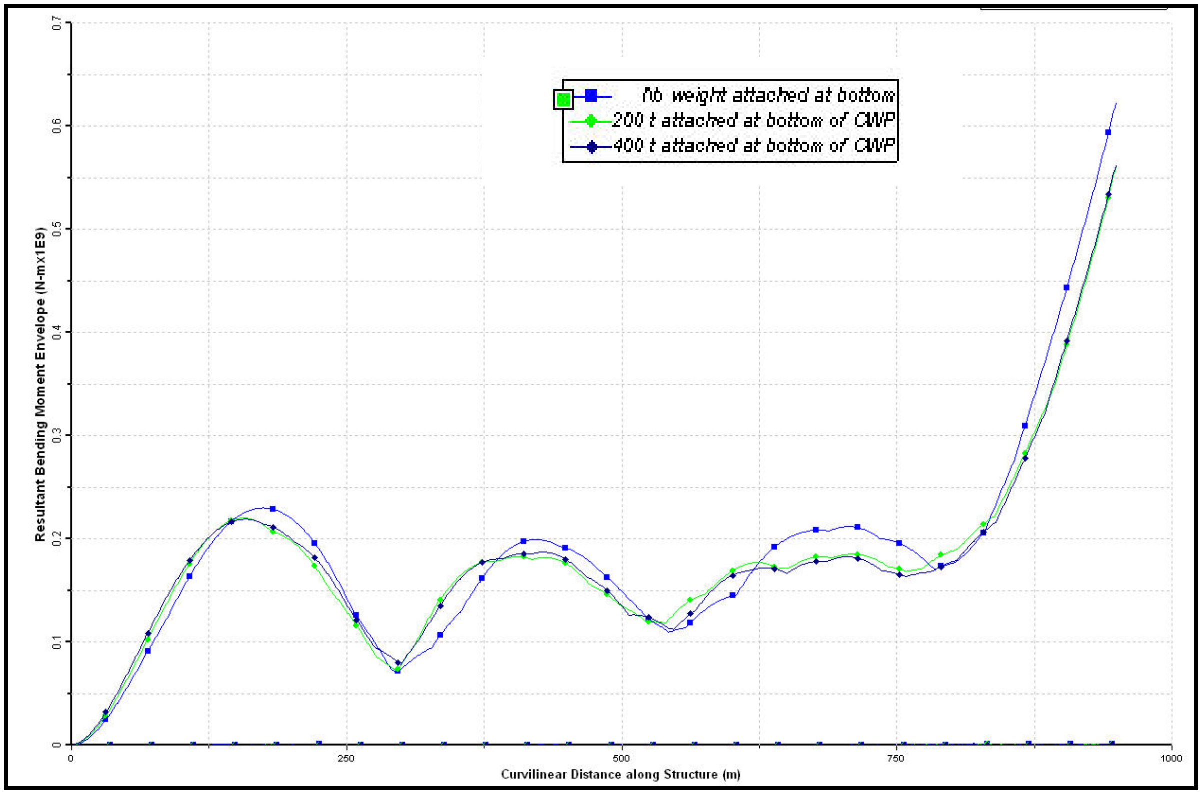


Figure 26: Bending Moment Envelope for CWP Rigid Connected to Semi (from Bottom to Top)

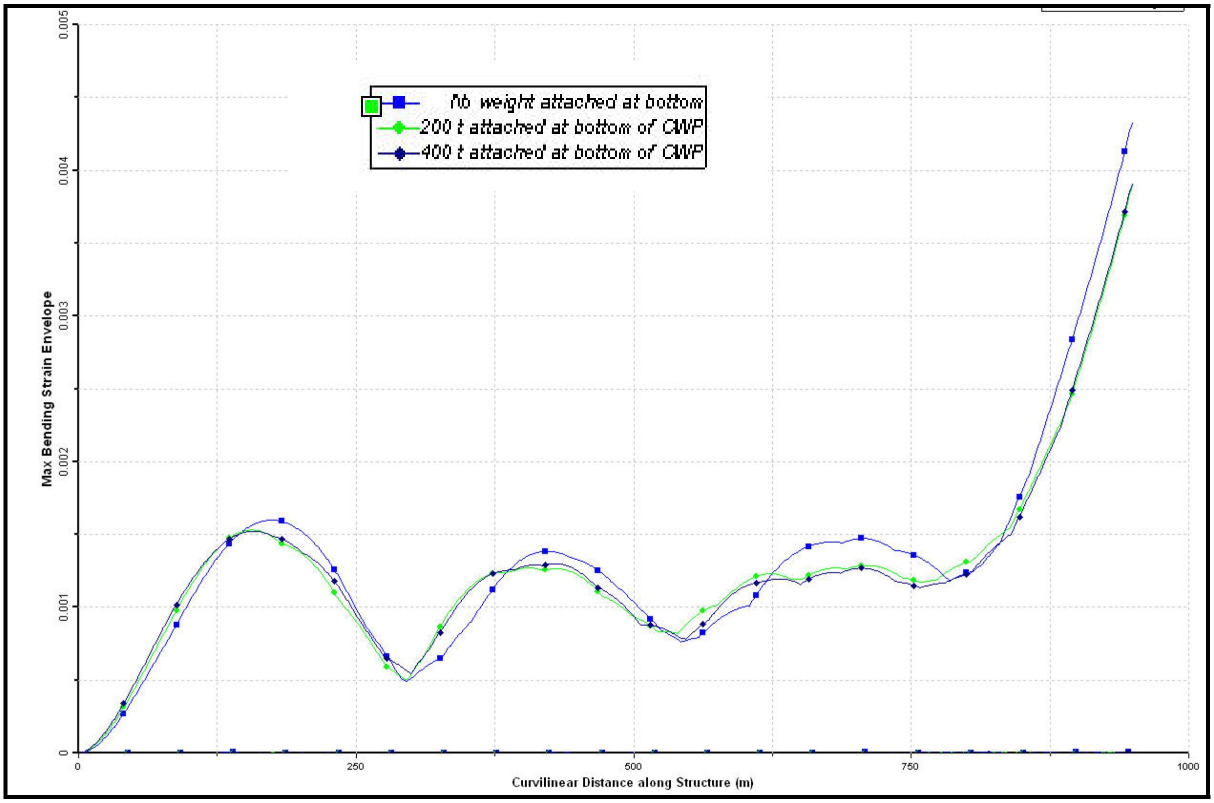


Figure 27: Bending Strain Envelope for CWP Rigid Connected to Semi (from Bottom to Top)

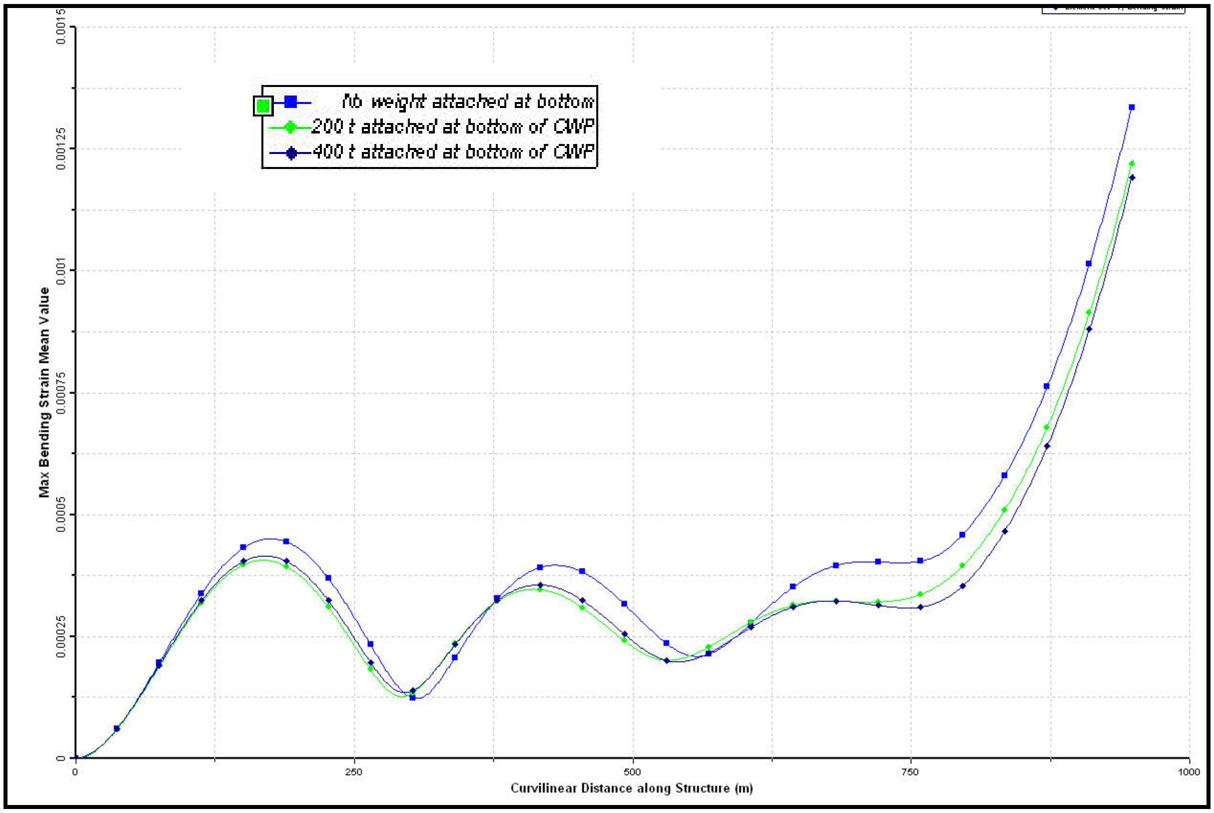


Figure 28: Mean Bending Strain for CWP Rigid Connected to Semi (from Bottom to Top)

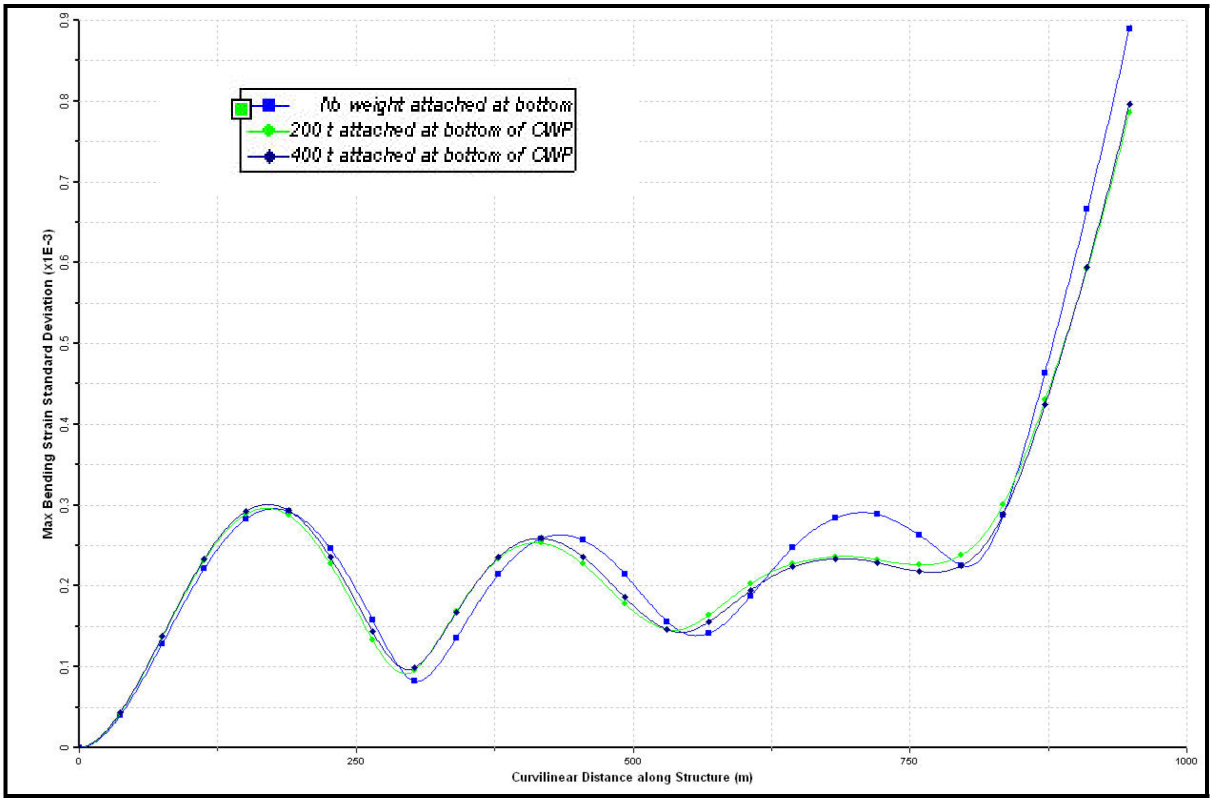


Figure 29: Std Dev of Bending Strain for CWP Rigid Connected to Semi (from Bottom to Top)

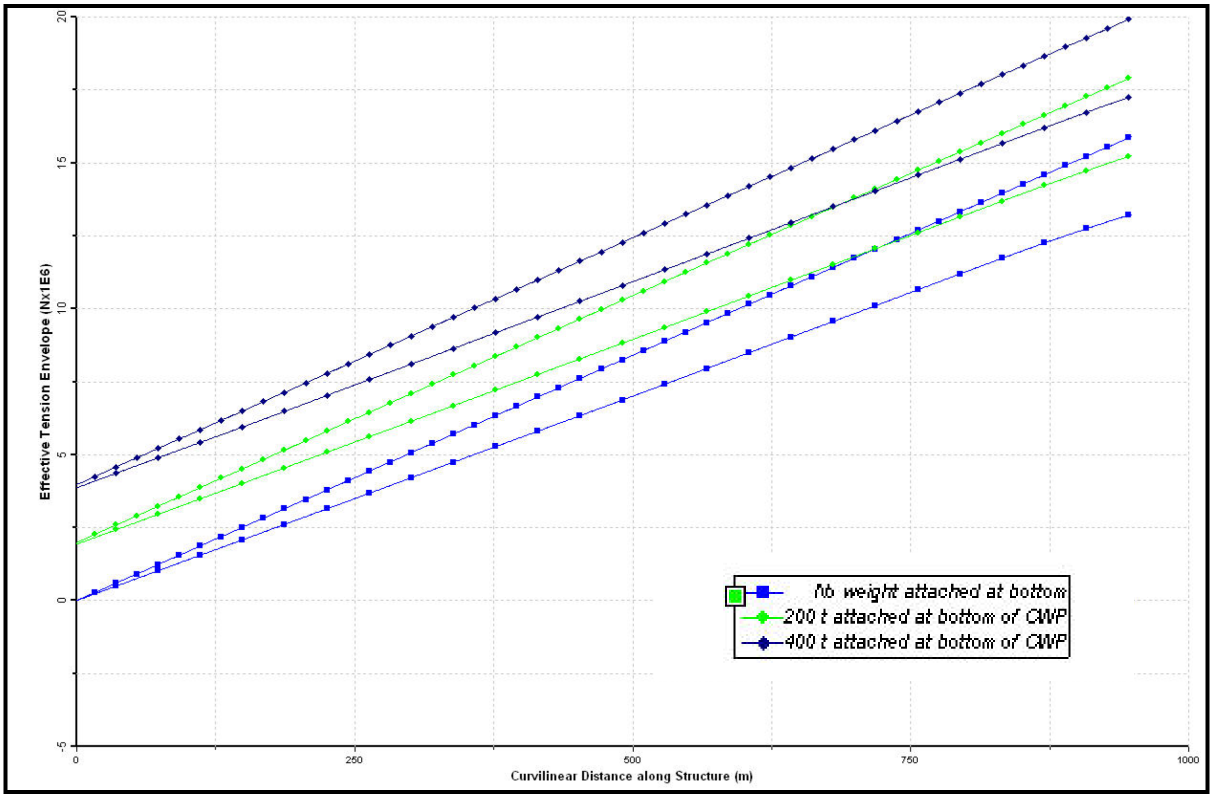


Figure 30: Effective Tension Envelope for CWP Rigid Connected to Semi (from Bottom to Top)

4.4 Maximum Current for CWP Design (Pin Connected to keel)

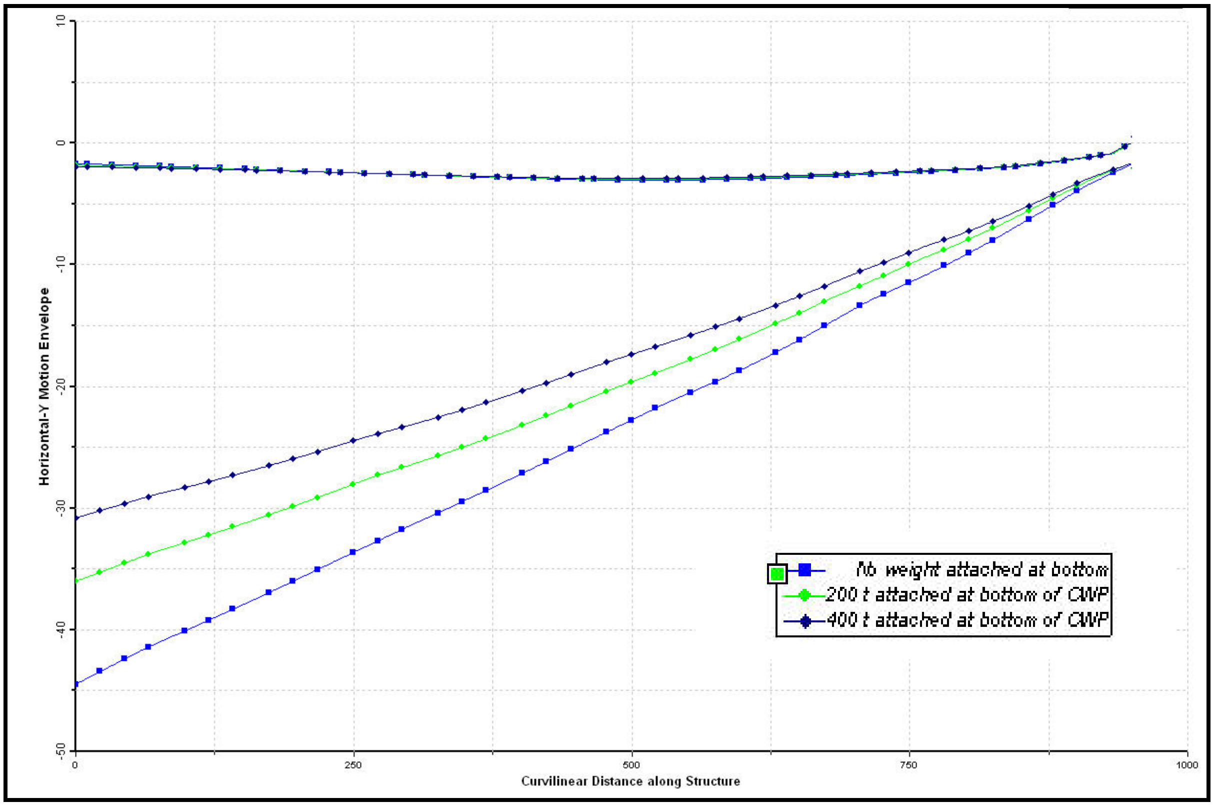


Figure 31: Motion Envelope for CWP Pin Connected to Semi (from Bottom to Top)

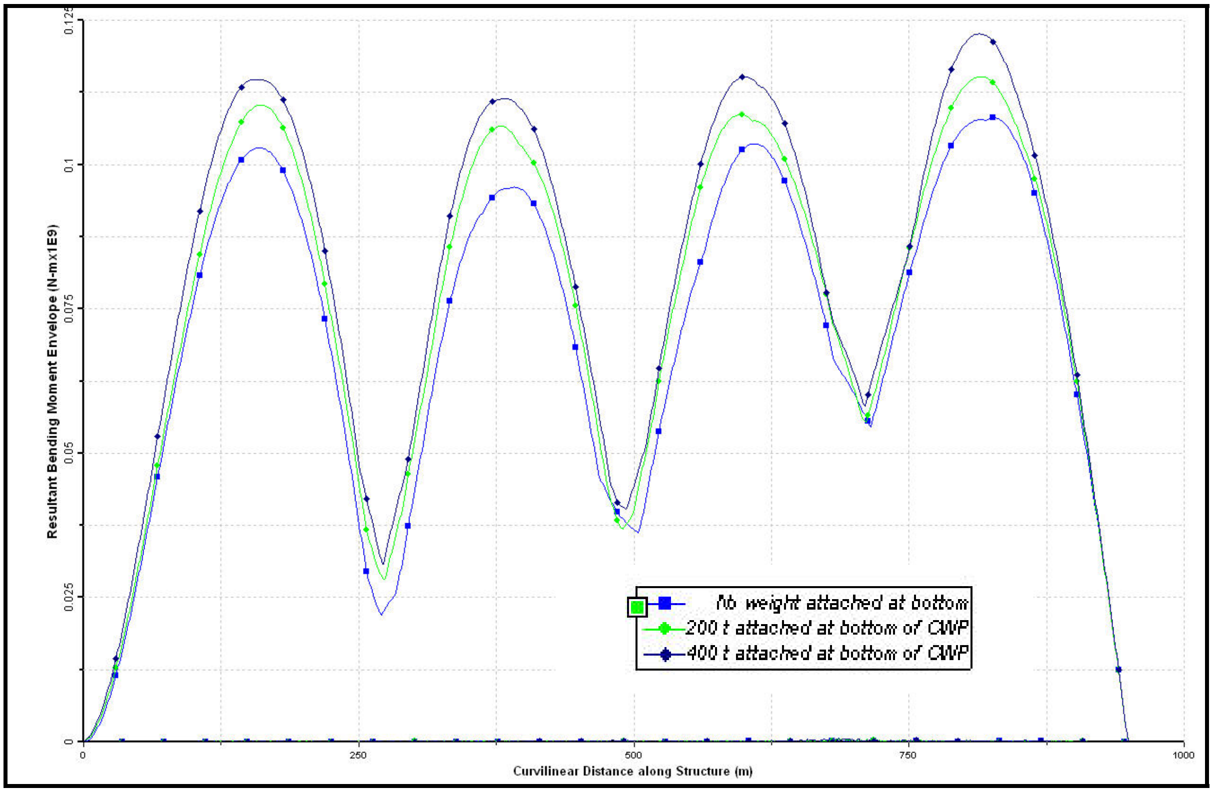


Figure 32: Bending Moment Envelope for CWP Pin Connected to Semi (from Bottom to Top)

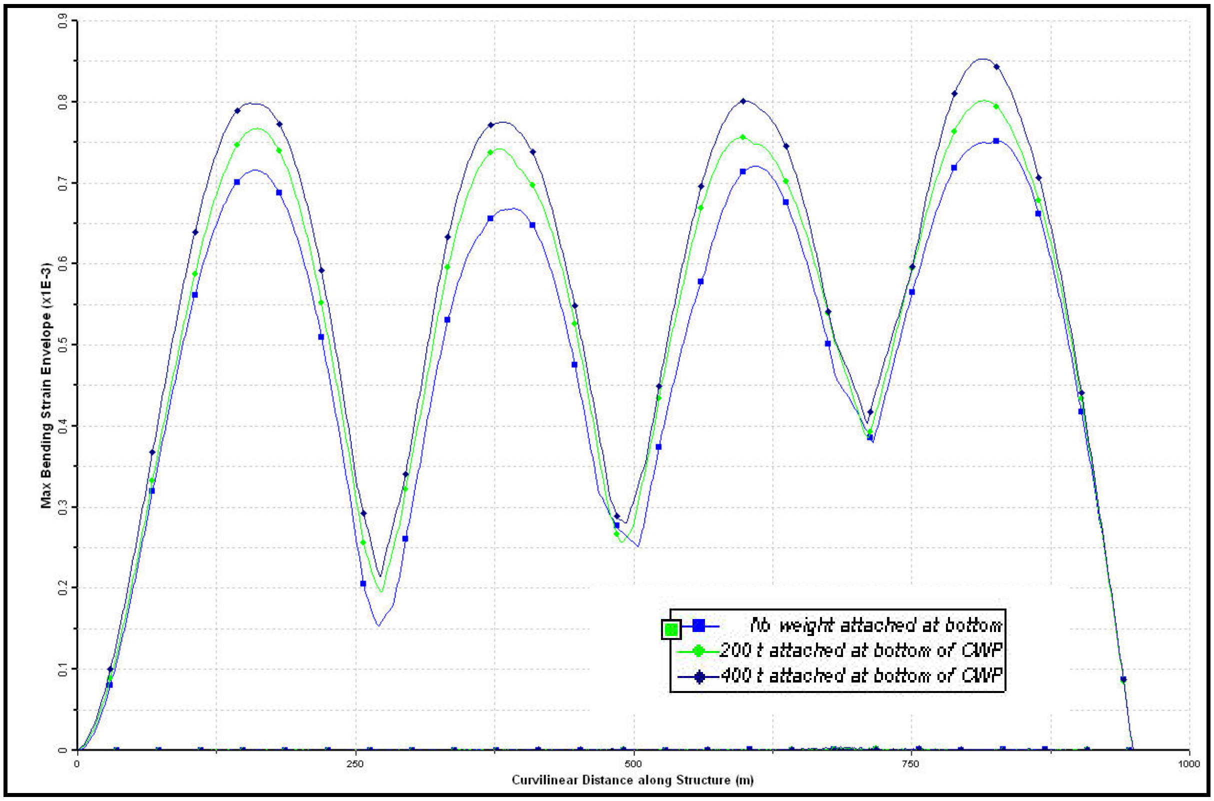


Figure 33: Bending Strain Envelope for CWP Pin Connected to Semi

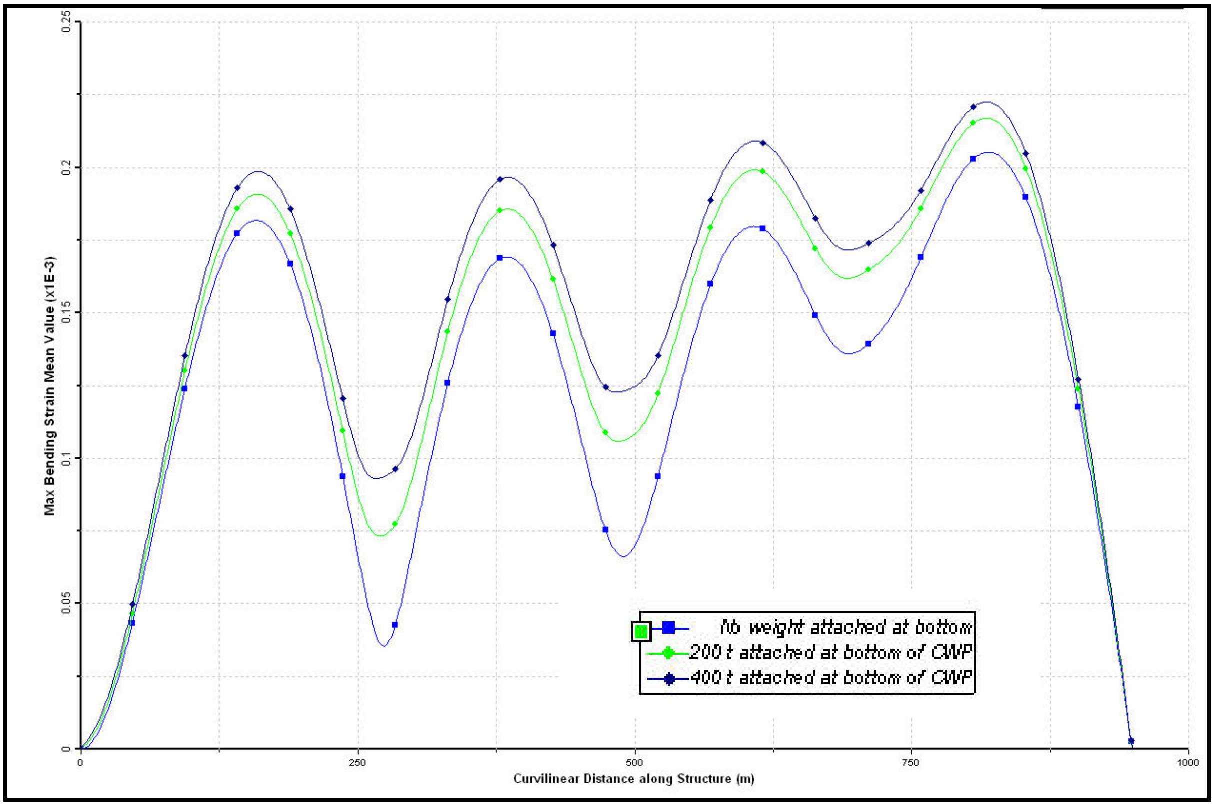


Figure 34: Mean Bending Strain for CWP Pin Connected to Semi

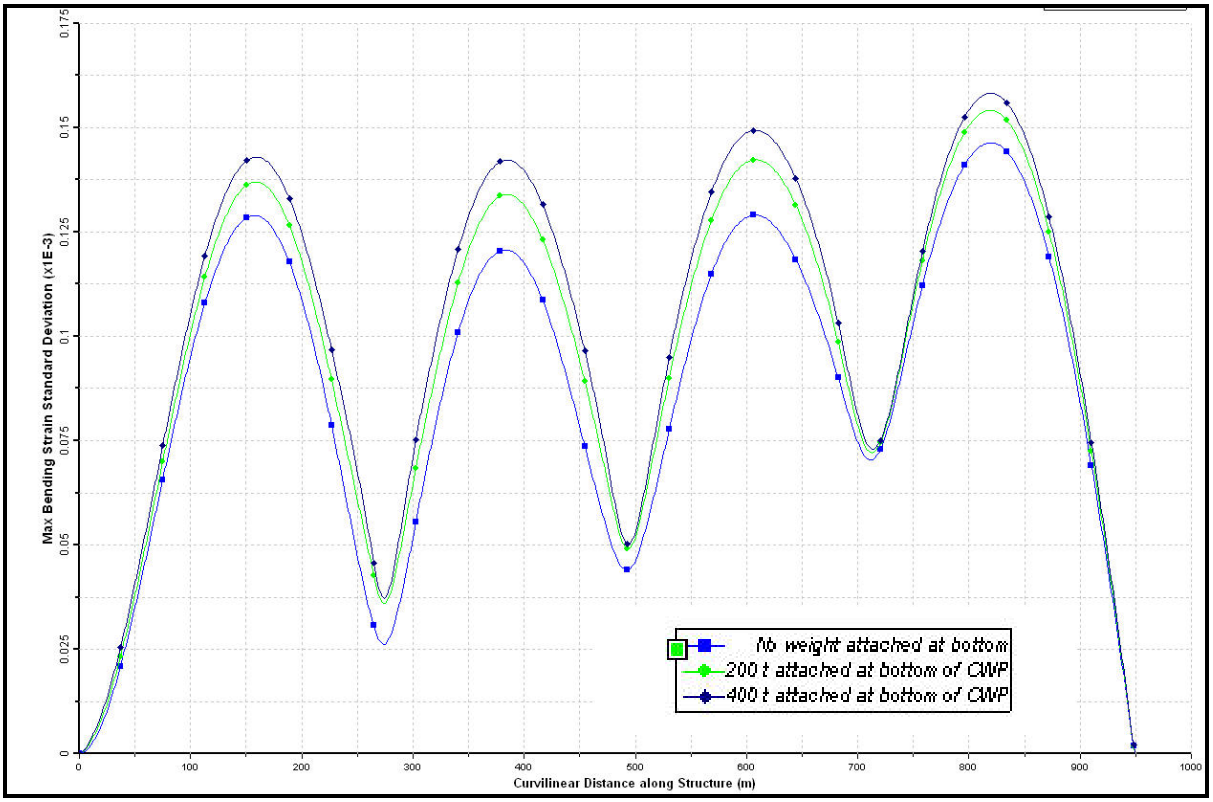


Figure 35: Std Dev of Bending Strain for CWP Pin Connected to Semi

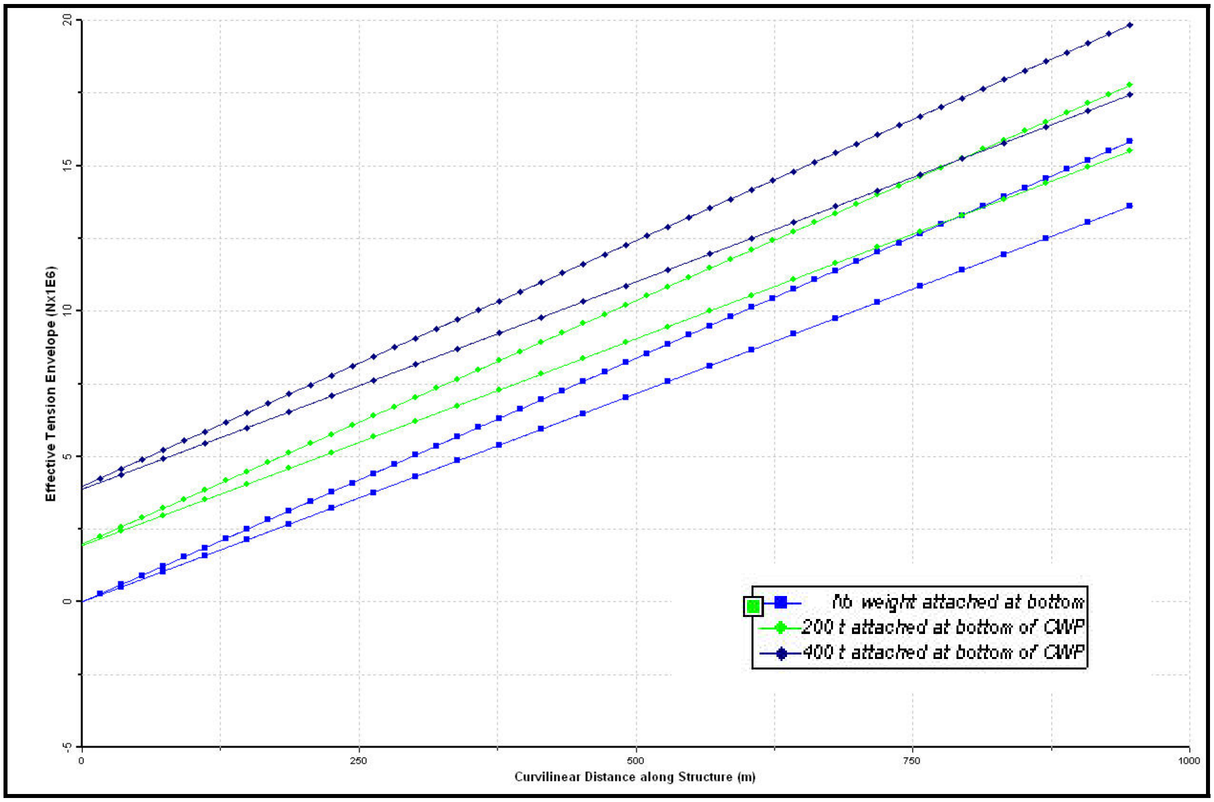
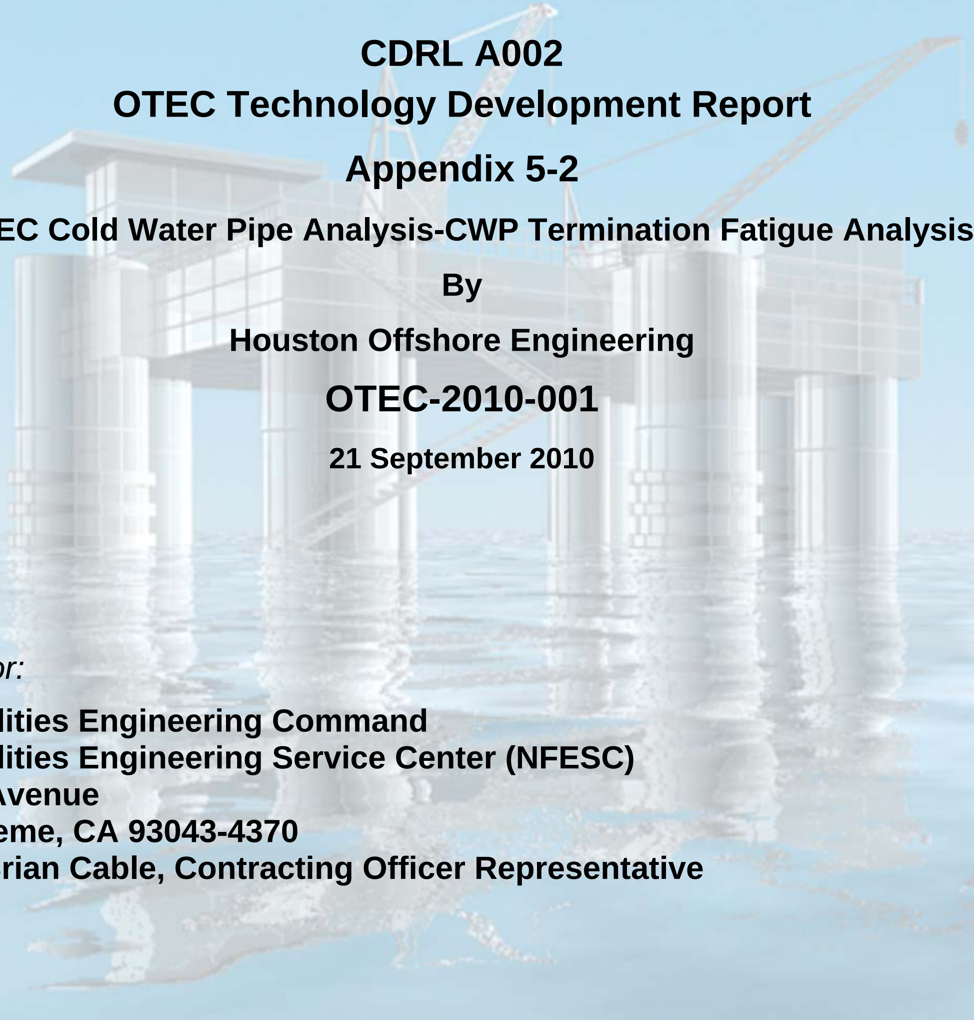


Figure 36: Effective Tension Envelope for CWP Pin Connected to Semi



NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report

Appendix 5-2

OTEC Cold Water Pipe Analysis-CWP Termination Fatigue Analysis

By

Houston Offshore Engineering

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
Naval Facilities Engineering Service Center (NFESC)
1100 23rd Avenue
Port Hueneme, CA 93043-4370
Attn: Mr. Brian Cable, Contracting Officer Representative

Prepared by:

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Distribution Statement A: Approved for public release; distribution is unlimited.

OTEC Cold Water Pipe Analysis

4th January, 2009

CWP Termination Fatigue Analysis

HOE-OTEC-3	A	4th January, 2009	Issue for information	NVK	SS	
Doc. No.	**Rev.**	**Date**	**Description**	**By**	**Appr.**	**Client**

Houston Offshore
ENGINEERING

Table of Contents

1 SUMMARY

The report presents the fatigue analysis results of the 10m OD Cold Water Pipe (CWP) for the 100MW OTEC semi. The CWP is fixed to the platform at the keel. Riser analysis program Flexcom3D is used for the study.

2 DESIGN DATA

2.1 CWP properties

The CWP properties for version 2 are presented in Table 1.

Property			
Inside Diameter	394 in		10.01 m
Outside Diameter	413.8 in		10.509 m
Wall Thickness	9.9 in		11.25 m
Outside Circumference	1299.9 in		33.02 m
Length below transition	39400 in		1,000.8 m
Cross sectional area, solid:	3366.013706 in ^2		2.17162 m^2
Void inside core, cross sectional area	9167.70 in^2		5.91 m^2
% wall that is void	73%		73%
Density of composite, average	0.06716 lbm/in^3		1859 kg/m^3
Mass (excludes internal water)	226.1 lbm/in		4,036.9 kg/m
CWP (no bottom weight) Total Mass (excludes internal water)	8,906,625 lbm		4,039,977 kg
Mass including internal water in walls only	565.5 lbm/in		10,099 kg/m
Mass including internal water, FRP walls and interior wall water	5080.4 lbm/in		90,725 kg/m
Dry Weight CWP (no bottom weight)	226.1 lb/in		39,589 N/m
Total Dry Weight (no bottom weight)	8,906,625 lbs		39,619 kN
Total Dry Weight (no bottom weight)	8,906,625 lbs		4,040 tonnes
Wet weight (no bottom weight)	101.41 lb/in		1.811 tonnes/m
Total wet Weight (no bottom weight)	3,995,609 lbs		1,812 tonnes
Total wet Weight inc bottom weight	3,995,609 lbs		1,812 tonnes
EI of wall - bending (ignore internal ribs)	5.70E+07 lb-in^2/in		6.44E+03 kN-m^2/m
EA	1.47E+10 lbs		65,242,320 kN
EI	2.95E+14 lb-in^2		846,963,409 kN-m^2
Cm	2		2
Cd	1		1

Table 1 :10 m CWP Properties (Version 2)

2.2 Environment Conditions

Fatigue analyses are performed using platform motions associated with 16 wave conditions, wind speed of 7 m/s, and the mean current. The current profile is presented in Table 2 and plotted in Figure 1. The 16 wave fatigue bins are shown in Table 3.

Depth (m)	Mean Current (m/s)
0	0.232
-50	0.229
-100	0.161
-150	0.169
-350	0.106
-800	0.088
-1000	0.076

Table 2: **Mean Current Profile**

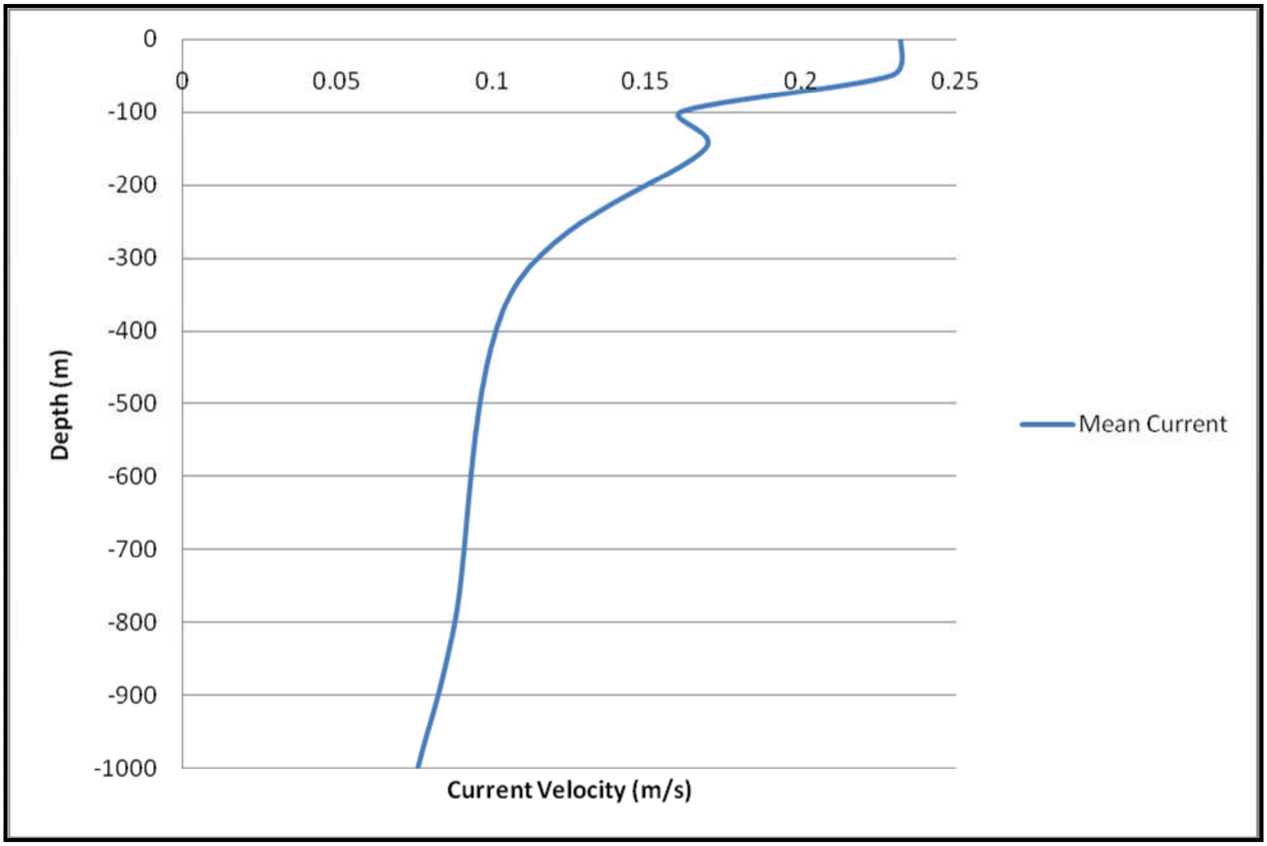
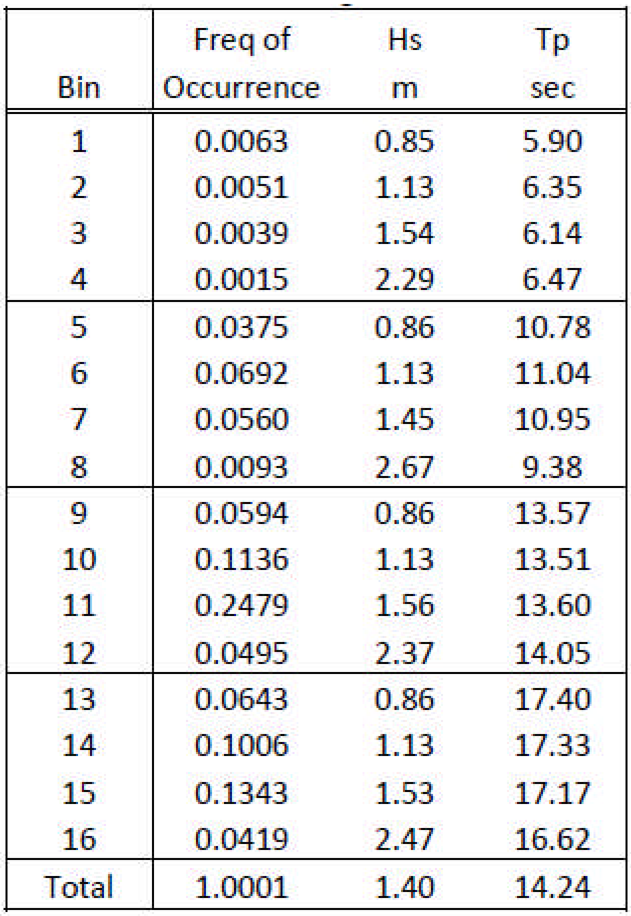


Figure 1 : Current Profile vs. Depth



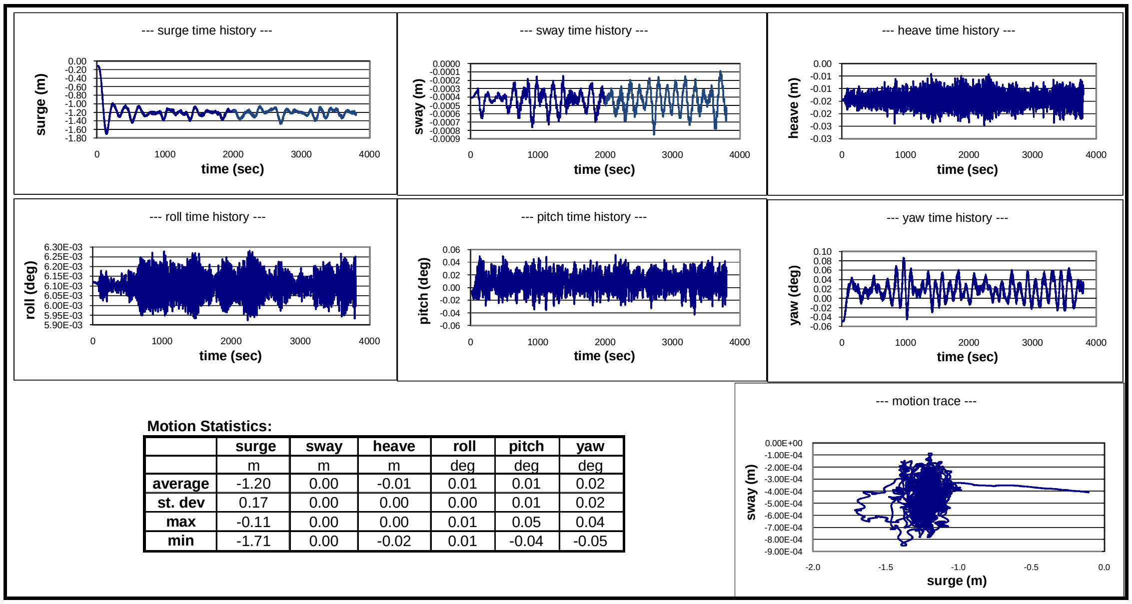
Bin	Freq of Occurrence	Hs m	Tp sec
1	0.0063	0.85	5.90
2	0.0051	1.13	6.35
3	0.0039	1.54	6.14
4	0.0015	2.29	6.47
5	0.0375	0.86	10.78
6	0.0692	1.13	11.04
7	0.0560	1.45	10.95
8	0.0093	2.67	9.38
9	0.0594	0.86	13.57
10	0.1136	1.13	13.51
11	0.2479	1.56	13.60
12	0.0495	2.37	14.05
13	0.0643	0.86	17.40
14	0.1006	1.13	17.33
15	0.1343	1.53	17.17
16	0.0419	2.47	16.62
Total	1.0001	1.40	14.24

Table 3: **Fatigue Bins for CWP Design**

3 MOTIONS OF SEMISUBMERSIBLE

The motions of the 100 MW Semi were generated using the program HARP.

3.1 Bin 1

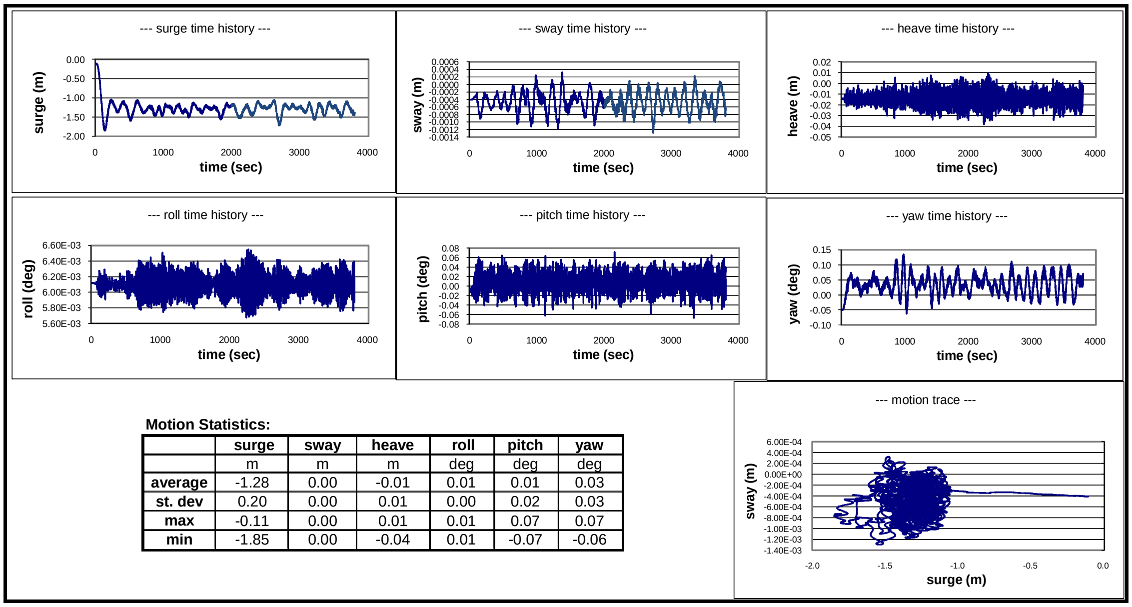


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.20	0.00	-0.01	0.01	0.01	0.02
st. dev	0.17	0.00	0.00	0.00	0.01	0.02
max	-0.11	0.00	0.00	0.01	0.05	0.04
min	-1.71	0.00	-0.02	0.01	-0.04	-0.05

Figure 2: Semi motions with 1000 m CWP Attached

3.2 Bin 2

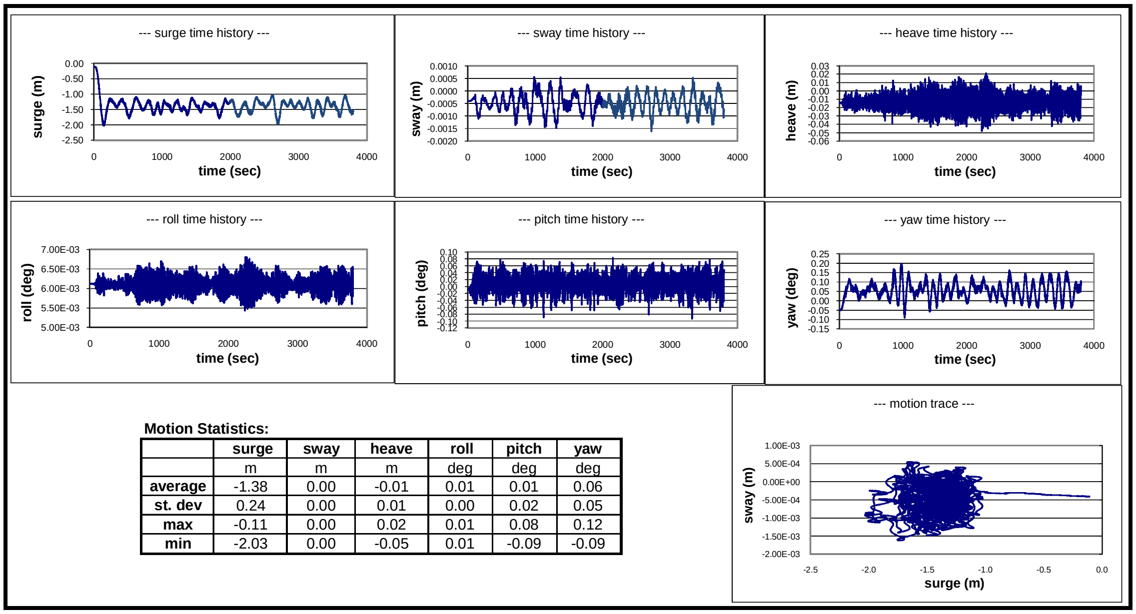


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.28	0.00	-0.01	0.01	0.01	0.03
st. dev	0.20	0.00	0.01	0.00	0.02	0.03
max	-0.11	0.00	0.01	0.01	0.07	0.07
min	-1.85	0.00	-0.04	0.01	-0.07	-0.06

Figure 3: Semi motions with 1000 m CWP Attached

3.3 Bin 3

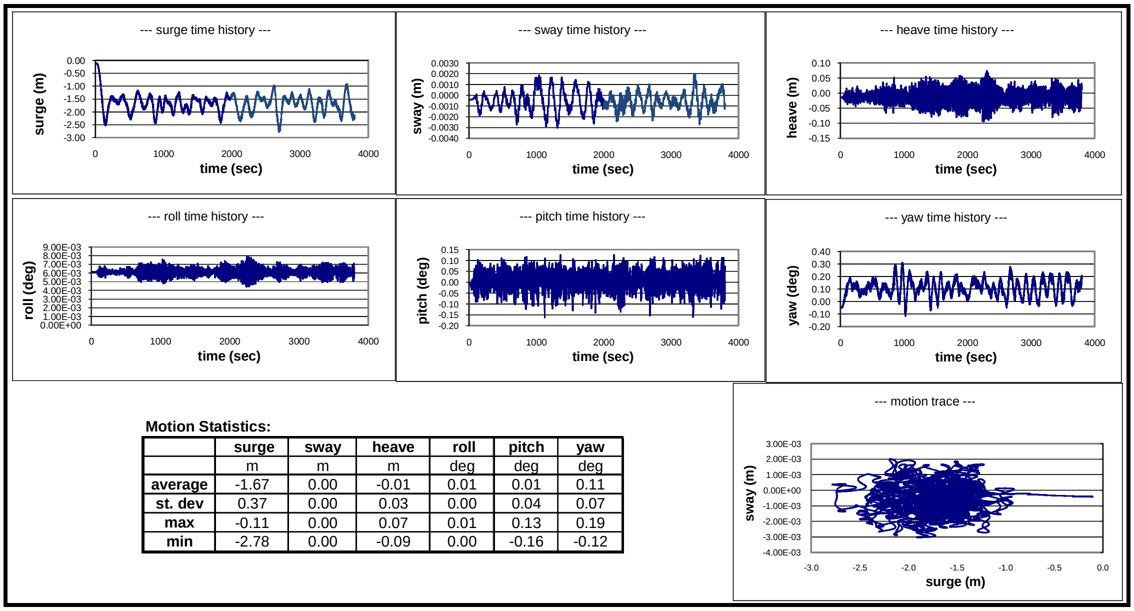


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.38	0.00	-0.01	0.01	0.01	0.06
st. dev	0.24	0.00	0.01	0.00	0.02	0.05
max	-0.11	0.00	0.02	0.01	0.08	0.12
min	-2.03	0.00	-0.05	0.01	-0.09	-0.09

Figure 4: Semi motions with 1000 m CWP Attached

3.4 Bin 4

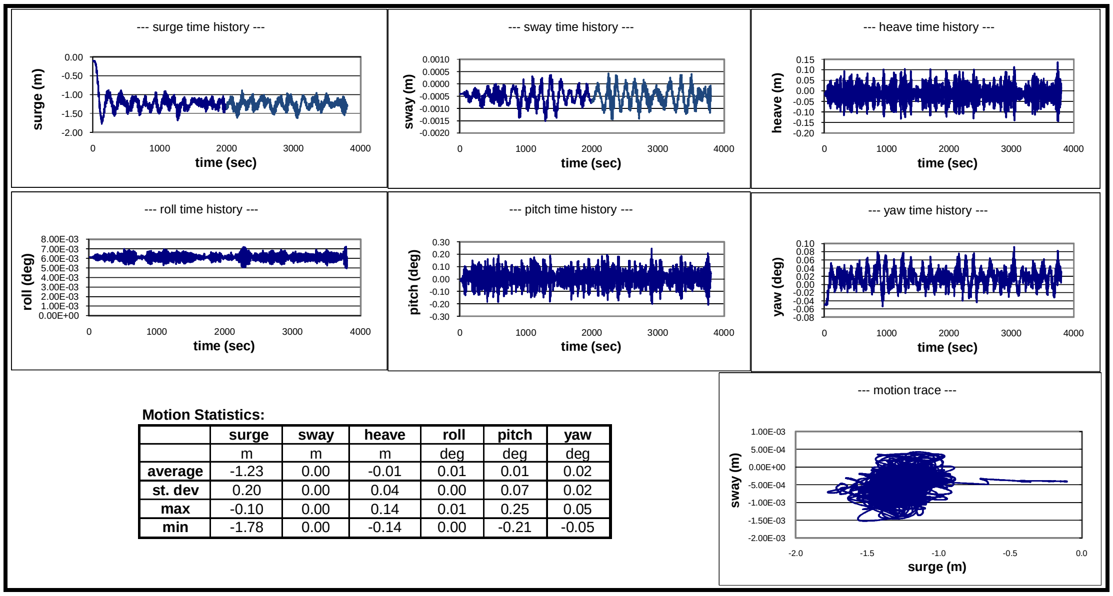


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.67	0.00	-0.01	0.01	0.01	0.11
st. dev	0.37	0.00	0.03	0.00	0.04	0.07
max	-0.11	0.00	0.07	0.01	0.13	0.19
min	-2.78	0.00	-0.09	0.00	-0.16	-0.12

Figure 5: Semi motions with 1000 m CWP Attached

3.5 Bin 5

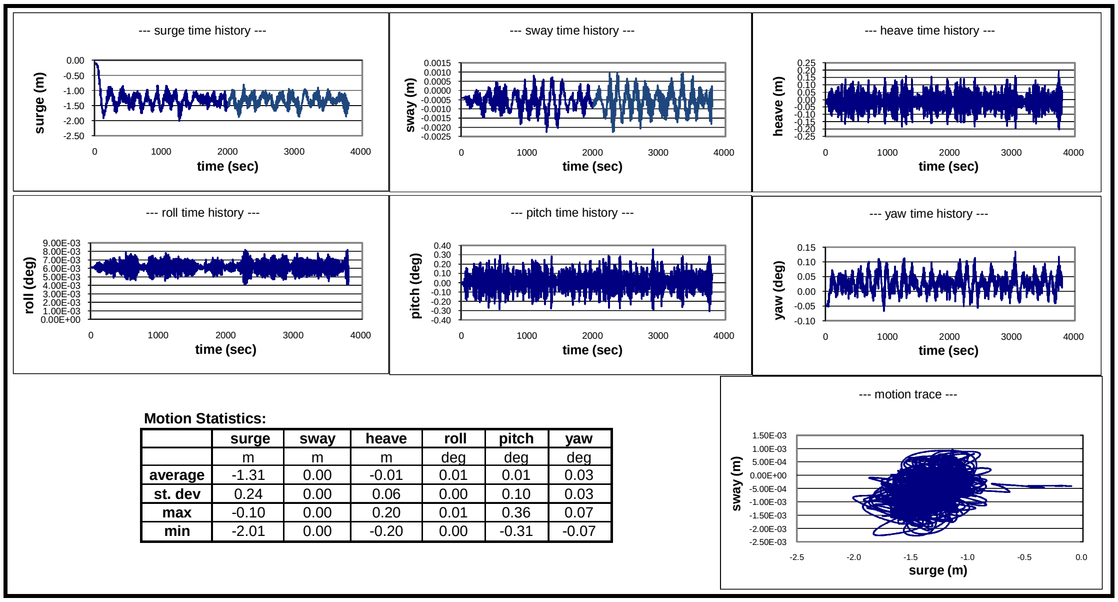


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.23	0.00	-0.01	0.01	0.01	0.02
st. dev	0.20	0.00	0.04	0.00	0.07	0.02
max	-0.10	0.00	0.14	0.01	0.25	0.05
min	-1.78	0.00	-0.14	0.00	-0.21	-0.05

Figure 6: Semi motions with 1000 m CWP Attached

3.6 Bin 6

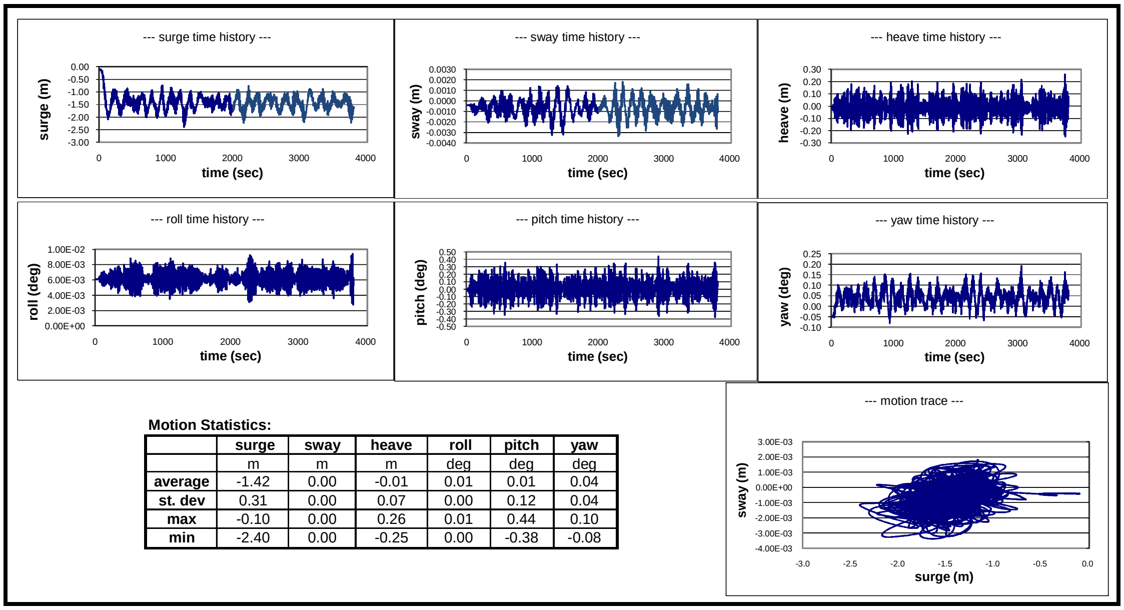


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.31	0.00	-0.01	0.01	0.01	0.03
st. dev	0.24	0.00	0.06	0.00	0.10	0.03
max	-0.10	0.00	0.20	0.01	0.36	0.07
min	-2.01	0.00	-0.20	0.00	-0.31	-0.07

Figure 7: Semi motions with 1000 m CWP Attached

3.7 Bin 7

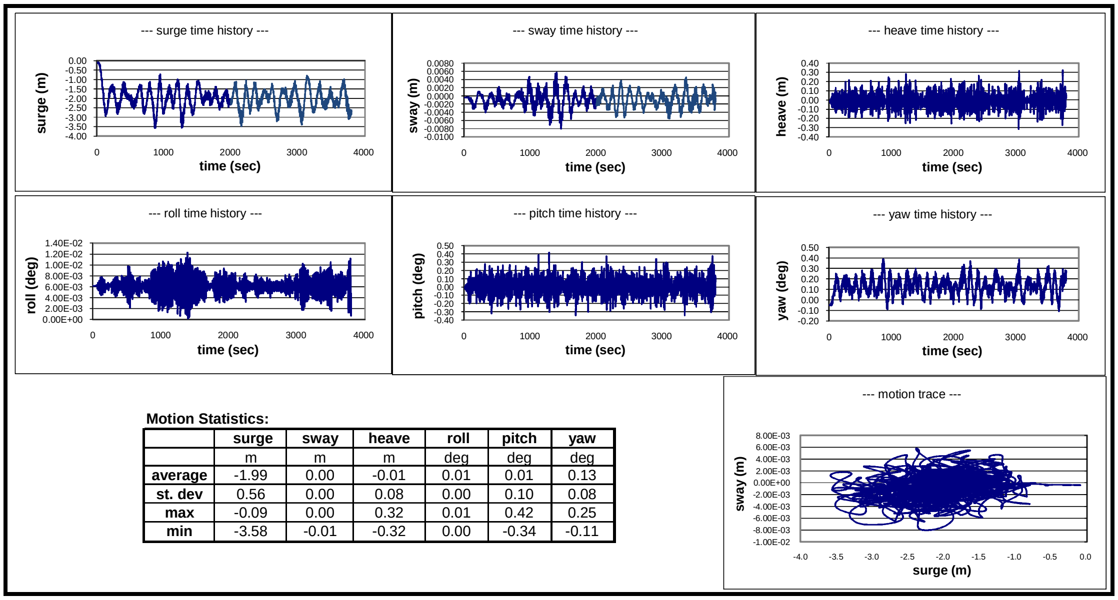


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.42	0.00	-0.01	0.01	0.01	0.04
st. dev	0.31	0.00	0.07	0.00	0.12	0.04
max	-0.10	0.00	0.26	0.01	0.44	0.10
min	-2.40	0.00	-0.25	0.00	-0.38	-0.08

Figure 8: Semi motions with 1000 m CWP Attached

3.8 Bin 8

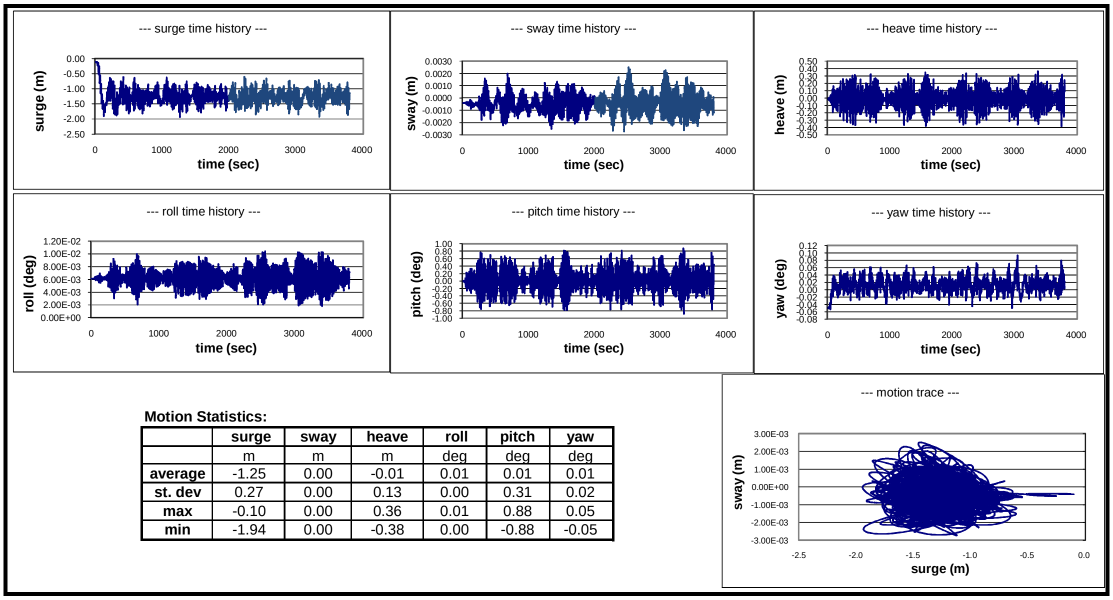


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.99	0.00	-0.01	0.01	0.01	0.13
st. dev	0.56	0.00	0.08	0.00	0.10	0.08
max	-0.09	0.00	0.32	0.01	0.42	0.25
min	-3.58	-0.01	-0.32	0.00	-0.34	-0.11

Figure 9: Semi motions with 1000 m CWP Attached

3.9 Bin 9

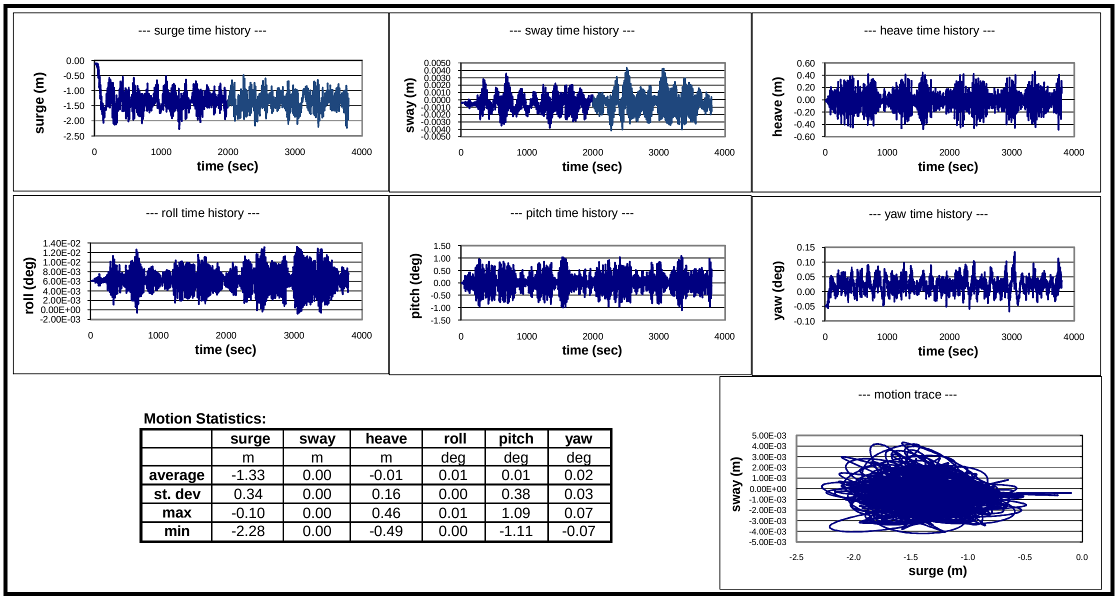


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.25	0.00	-0.01	0.01	0.01	0.01
st. dev	0.27	0.00	0.13	0.00	0.31	0.02
max	-0.10	0.00	0.36	0.01	0.88	0.05
min	-1.94	0.00	-0.38	0.00	-0.88	-0.05

Figure 10: Semi motions with 1000 m CWP Attached

3.10 Bin 10

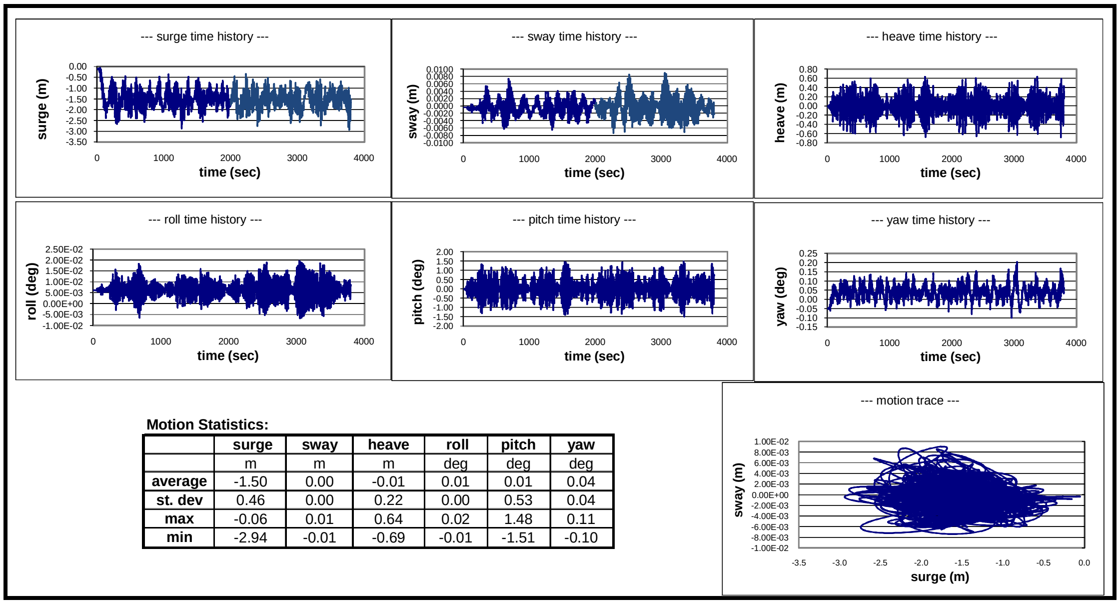


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.33	0.00	-0.01	0.01	0.01	0.02
st. dev	0.34	0.00	0.16	0.00	0.38	0.03
max	-0.10	0.00	0.46	0.01	1.09	0.07
min	-2.28	0.00	-0.49	0.00	-1.11	-0.07

Figure 11: Semi motions with 1000 m CWP Attached

3.11 Bin 11

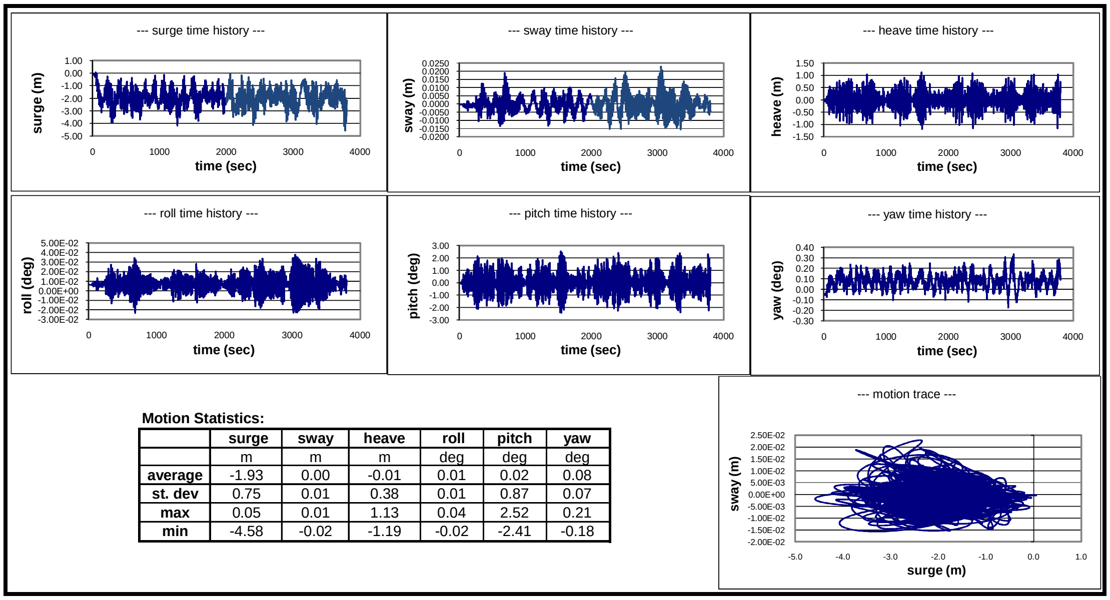


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.50	0.00	-0.01	0.01	0.01	0.04
st. dev	0.46	0.00	0.22	0.00	0.53	0.04
max	-0.06	0.01	0.64	0.02	1.48	0.11
min	-2.94	-0.01	-0.69	-0.01	-1.51	-0.10

Figure 12: Semi motions with 1000 m CWP Attached

3.12 Bin 12

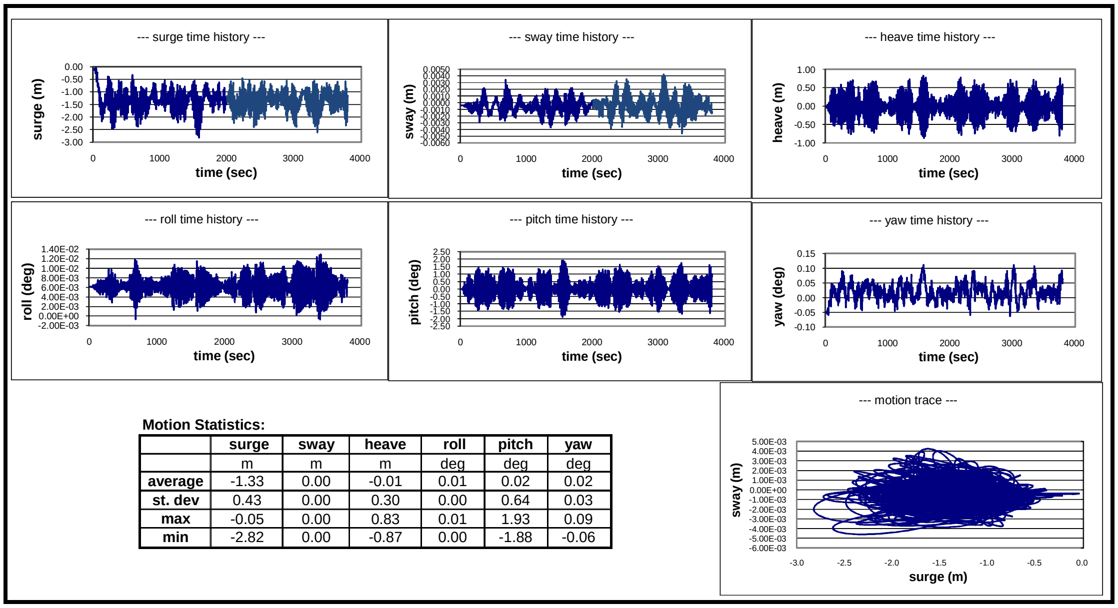


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.93	0.00	-0.01	0.01	0.02	0.08
st. dev	0.75	0.01	0.38	0.01	0.87	0.07
max	0.05	0.01	1.13	0.04	2.52	0.21
min	-4.58	-0.02	-1.19	-0.02	-2.41	-0.18

Figure 13: Semi motions with 1000 m CWP Attached

3.13 Bin 13

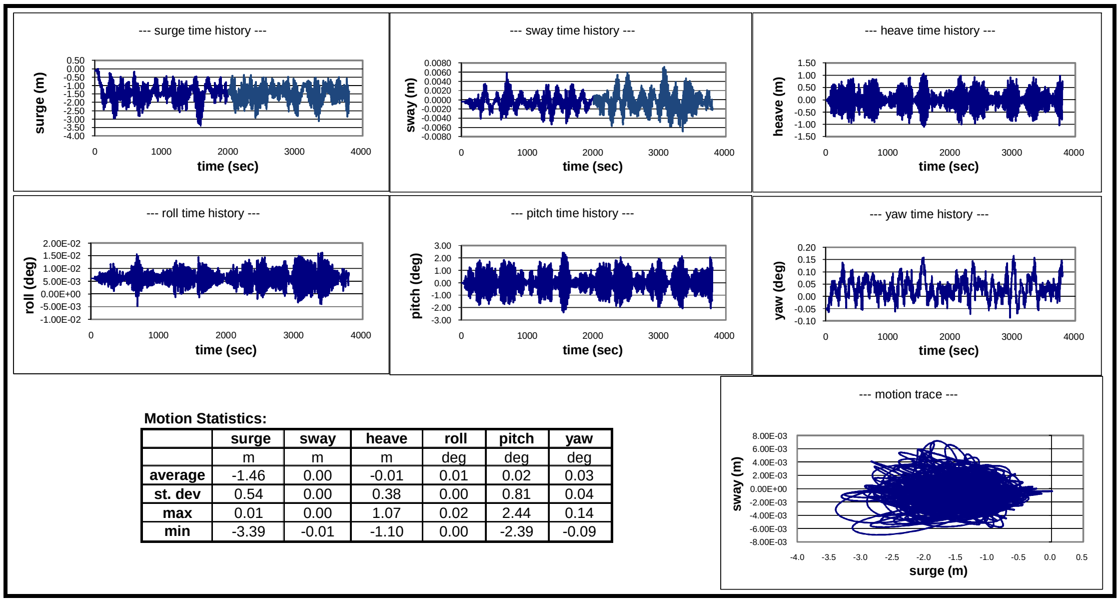


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.33	0.00	-0.01	0.01	0.02	0.02
st. dev	0.43	0.00	0.30	0.00	0.64	0.03
max	-0.05	0.00	0.83	0.01	1.93	0.09
min	-2.82	0.00	-0.87	0.00	-1.88	-0.06

Figure 14: Semi motions with 1000 m CWP Attached

3.14 Bin 14

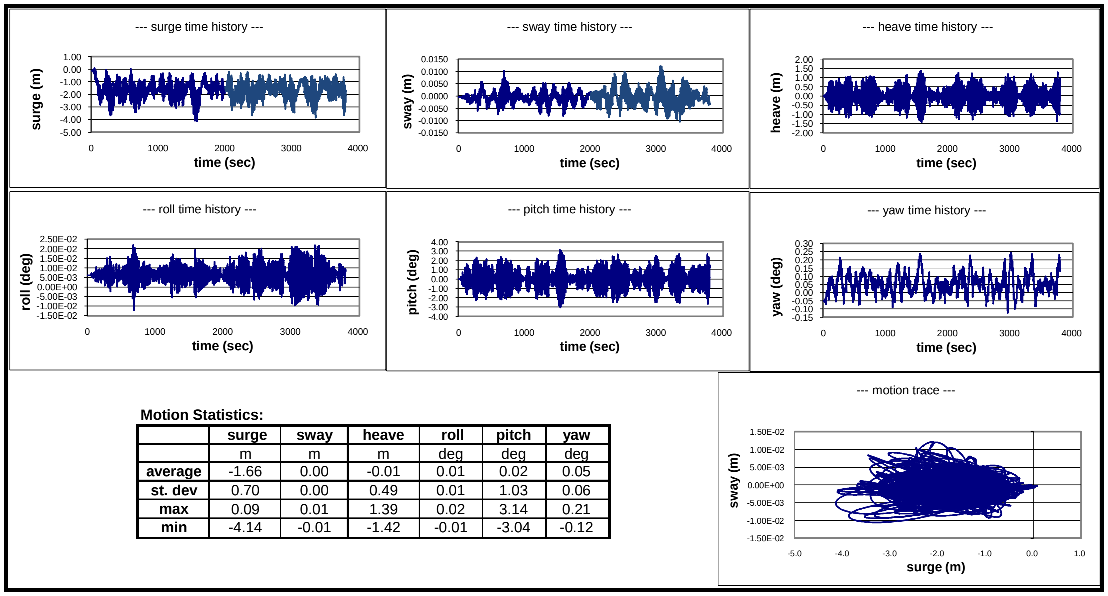


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.46	0.00	-0.01	0.01	0.02	0.03
st. dev	0.54	0.00	0.38	0.00	0.81	0.04
max	0.01	0.00	1.07	0.02	2.44	0.14
min	-3.39	-0.01	-1.10	0.00	-2.39	-0.09

Figure 15: Semi motions with 1000m CWP attached

3.15 Bin 15

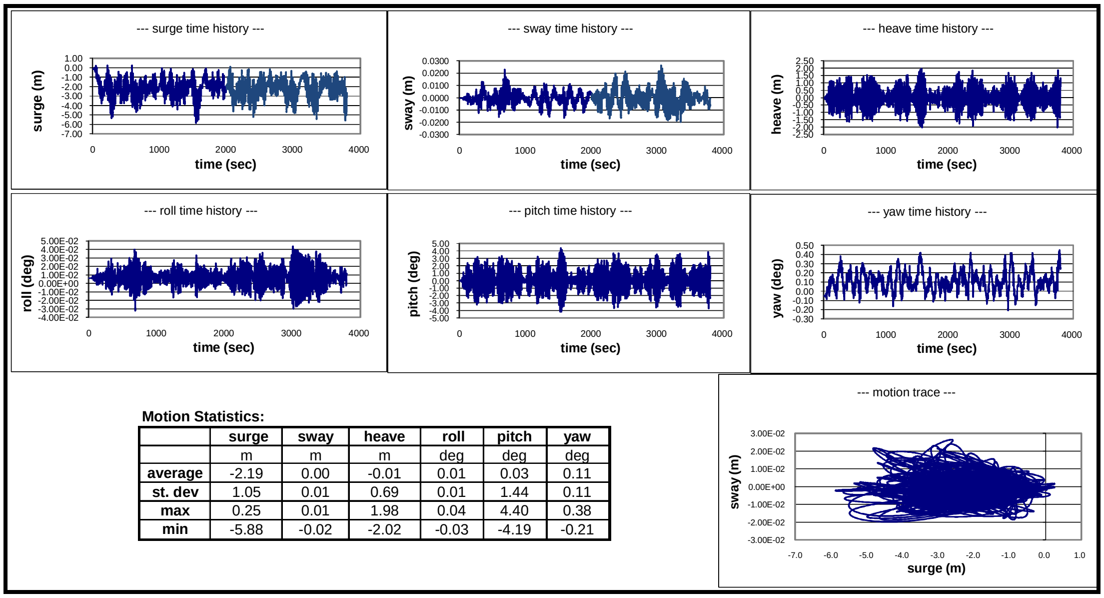


Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-1.66	0.00	-0.01	0.01	0.02	0.05
st. dev	0.70	0.00	0.49	0.01	1.03	0.06
max	0.09	0.01	1.39	0.02	3.14	0.21
min	-4.14	-0.01	-1.42	-0.01	-3.04	-0.12

Figure 16: Semi motions with 1000m CWP attached

3.16 Bin 16



Motion Statistics:

	surge	sway	heave	roll	pitch	yaw
	m	m	m	deg	deg	deg
average	-2.19	0.00	-0.01	0.01	0.03	0.11
st. dev	1.05	0.01	0.69	0.01	1.44	0.11
max	0.25	0.01	1.98	0.04	4.40	0.38
min	-5.88	-0.02	-2.02	-0.03	-4.19	-0.21

Figure 17: Semi motions with 1000m CWP attached

4 CWP FREQUENCY ANALYSIS

A frequency analysis of the CWP is performed with the Modes module of riser analysis program Flexcom3D. The eigenvalues and corresponding frequencies are presented in Table 4. There are 2 eigenpairs for each mode corresponding to the inplane and out of plane directions. The mode shapes for the first five modes are plotted in Figures 18-21.

Eigenpair No.	Eigenvalue	Frequency (Hz)	Period (s)
1	0.0002	0.0024	410.8593
2	0.0002	0.0024	410.8593
3	0.0037	0.0097	103.0663
4	0.0037	0.0097	103.0663
5	0.0247	0.0250	39.9764
6	0.0247	0.0250	39.9764
7	0.0903	0.0478	20.9107
8	0.0903	0.0478	20.9107
9	0.2413	0.0782	12.7919
10	0.2413	0.0782	12.7919
11	0.5320	0.1161	8.6146
12	0.5320	0.1161	8.6146
13	1.0304	0.1616	6.1899
14	1.0304	0.1616	6.1899
15	1.8180	0.2146	4.6600
16	1.8180	0.2146	4.6600
17	2.9899	0.2752	3.6337
18	2.9899	0.2752	3.6337
19	4.6548	0.3434	2.9123
20	4.6548	0.3434	2.9123
21	6.9350	0.4191	2.3859
22	6.9350	0.4191	2.3859
23	9.9665	0.5024	1.9903
24	9.9665	0.5024	1.9903
25	13.8985	0.5933	1.6854
26	13.8985	0.5933	1.6854
27	17.6879	0.6694	1.4940
28	18.8943	0.6918	1.4455
29	18.8943	0.6918	1.4455
30	25.1305	0.7978	1.2534

Table 4: **Eigen Values and Frequencies of CWP Modal Analysis**

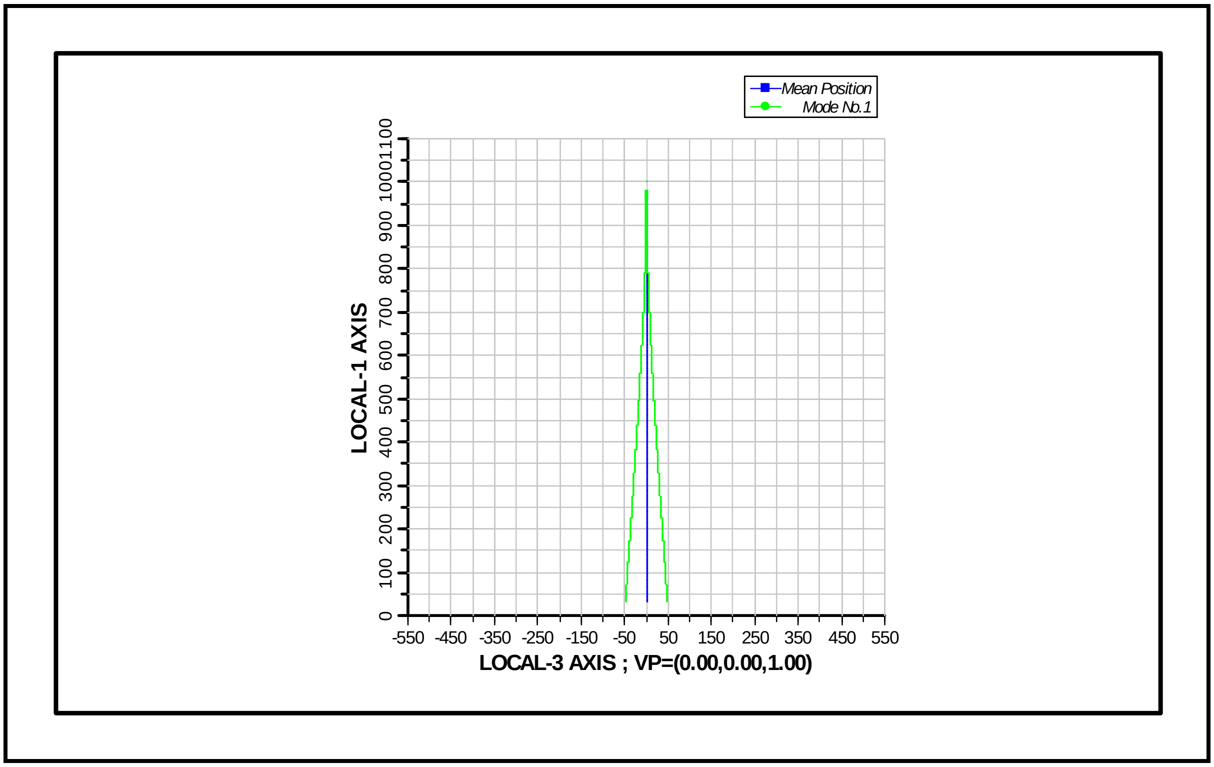


Figure 18: Mode 1 Shape of CWP

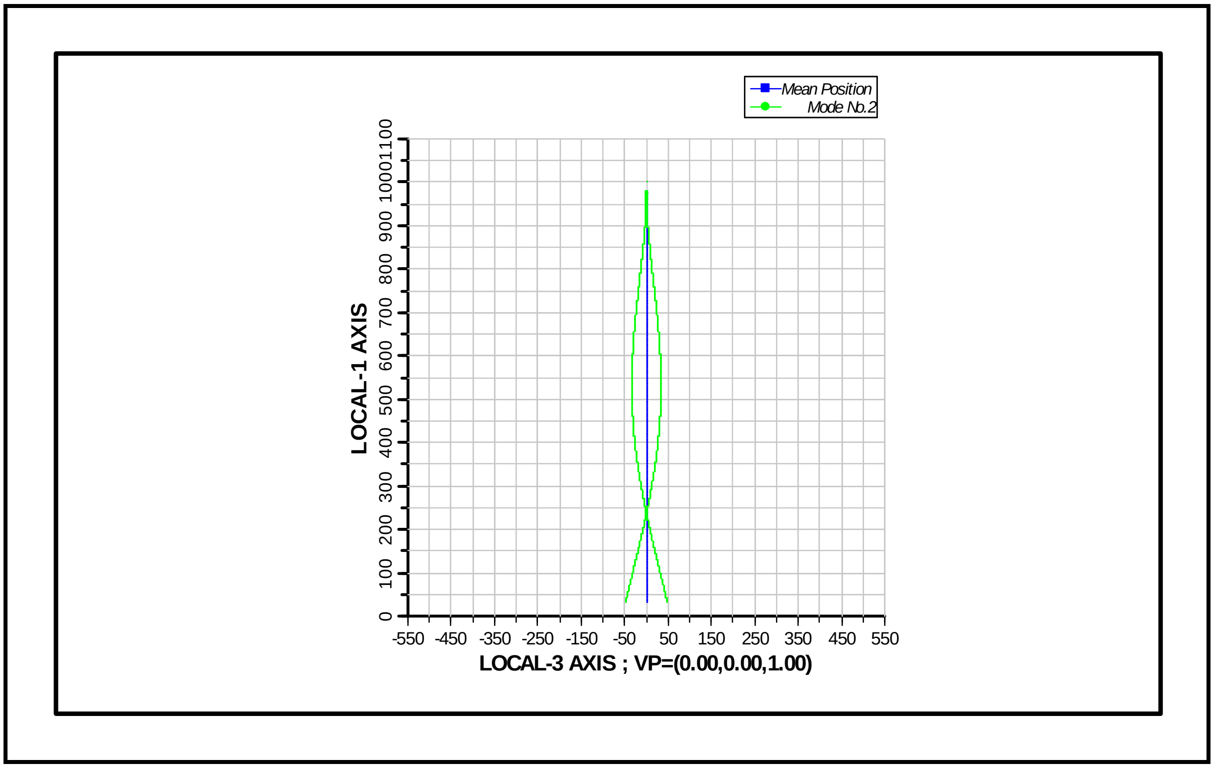


Figure 19: Mode 2 Shape of CWP

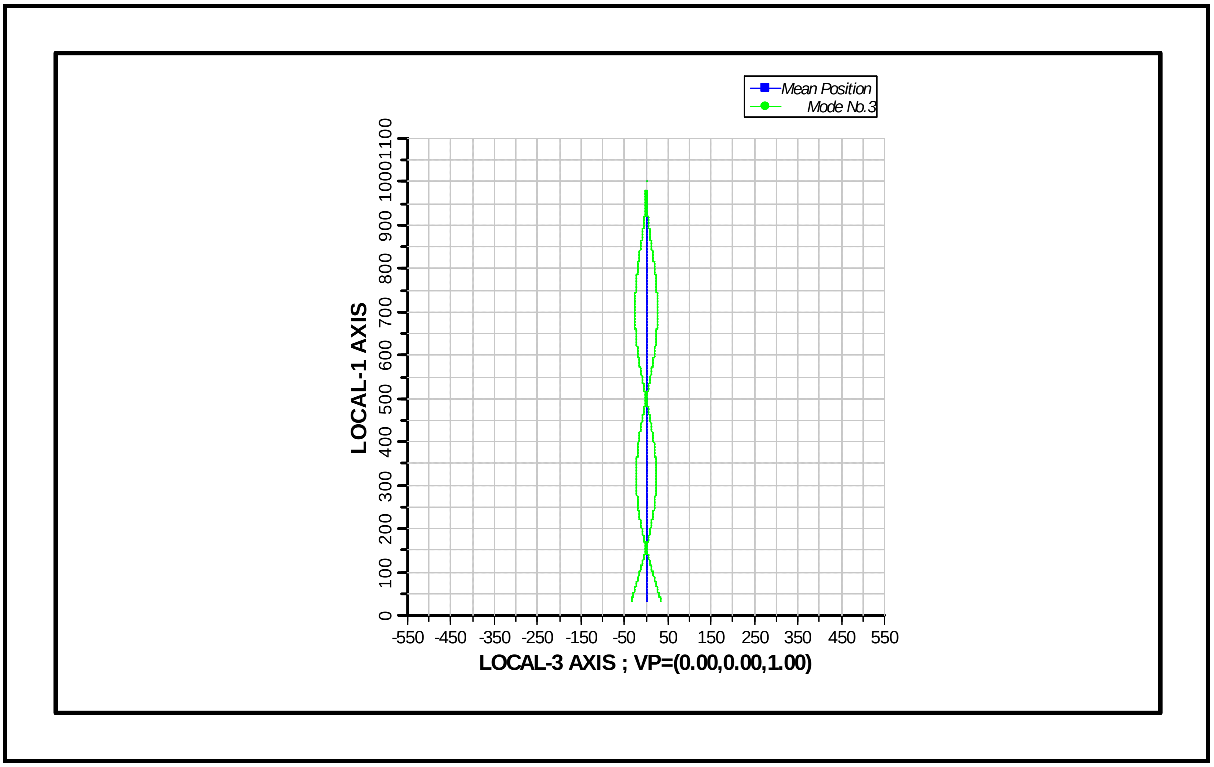


Figure 20: Mode 3 Shape of CWP

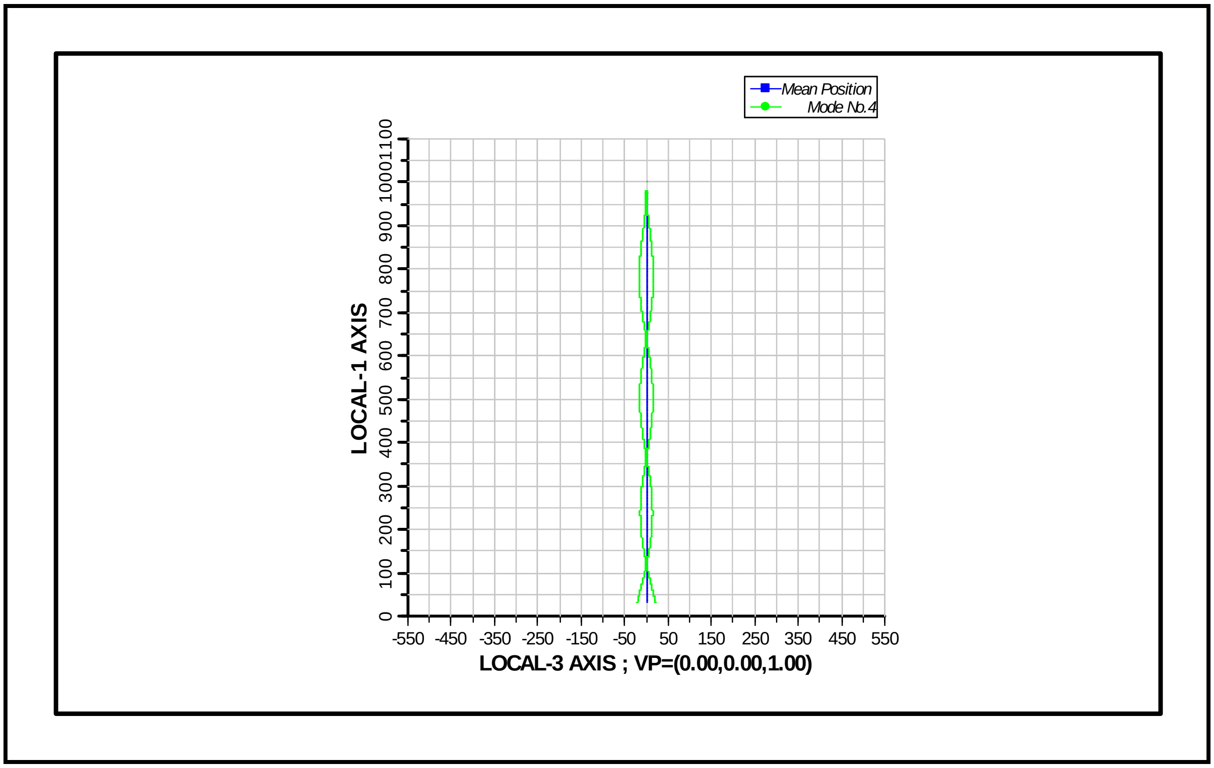


Figure 21: Mode 4 Shape of CWP

5 WAVE FATIGUE ANALYSIS RESULTS AND SUMMARY

The CWP maximum bottom offset, the maximum bending moment, the mean value and standard deviation of bending moment and the maximum bending strain is presented in Table 5. Since the CWP is fixed at the top the maximum bending moment and strains occur at the top of pipe. Figures 22-325 in the Appendix shows the maximum bending strain time history at the top along with the maximum, mean and standard deviation of motion, bending moment, bending strain, shear force, axial tension and axial strain. The maximum bending strain time history considers the maximum bending strain at the top of pipe which could occur at different places along the circumference. The minimum bending moment is observed for Bin 1 while the maximum occurs for Bin 16. The bending moment, strain and force time history can be utilized to calculate the fatigue using techniques like rainflow counting.

	Maximum Bottom Offset	Resultant Bending Moment Maximum	Resultant Bending Moment Mean Value	Resultant Bending Moment Std Dev	Maximum Bending Strain
	m	N-m	N-m	N-m	
Bin 1	6.125	1.50E+08	2.81E+07	2.16E+07	9.34E-04
Bin 2	6.427	1.67E+08	2.92E+07	2.23E+07	1.03E-03
Bin 3	6.757	1.41E+08	2.86E+07	2.14E+07	8.80E-04
Bin 4	7.56	1.62E+08	2.92E+07	2.20E+07	1.00E-03
Bin 5	6.417	1.79E+08	3.15E+07	2.35E+07	1.10E-03
Bin 6	6.79	1.91E+08	3.94E+07	2.96E+07	1.18E-03
Bin 7	7.305	2.42E+08	4.74E+07	3.53E+07	1.50E-03
Bin 8	9.2	2.74E+08	4.70E+07	3.54E+07	1.70E-03
Bin 9	9.55	4.65E+08	1.05E+08	7.73E+07	2.88E-03
Bin 10	11.22	5.34E+08	1.26E+08	9.28E+07	3.32E-03
Bin 11	14.38	7.16E+08	1.69E+08	1.23E+08	4.40E-03
Bin 12	22.49	1.00E+09	2.78E+08	1.97E+08	6.20E-03
Bin 13	21	8.92E+08	2.44E+08	1.74E+08	5.50E-03
Bin 14	25.11	1.04E+09	2.98E+08	2.10E+08	6.50E-03
Bin 15	30.03	1.27E+09	3.66E+08	2.55E+08	7.90E-03
Bin 16	37.92	1.65E+09	4.79E+08	3.28E+08	1.02E-02

Table 5: Pertinent results from CWP Analysis

6 Appendix

6.1 Bin 1

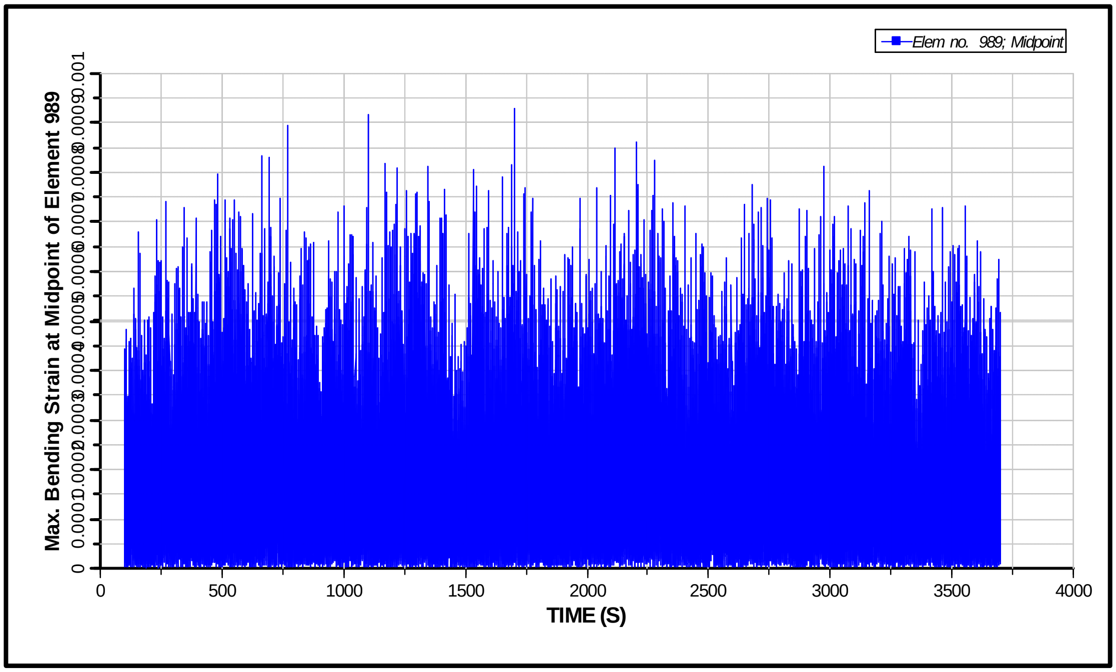


Figure 22: Maximum Bending Strain Time History at Top of CWP for Bin 1

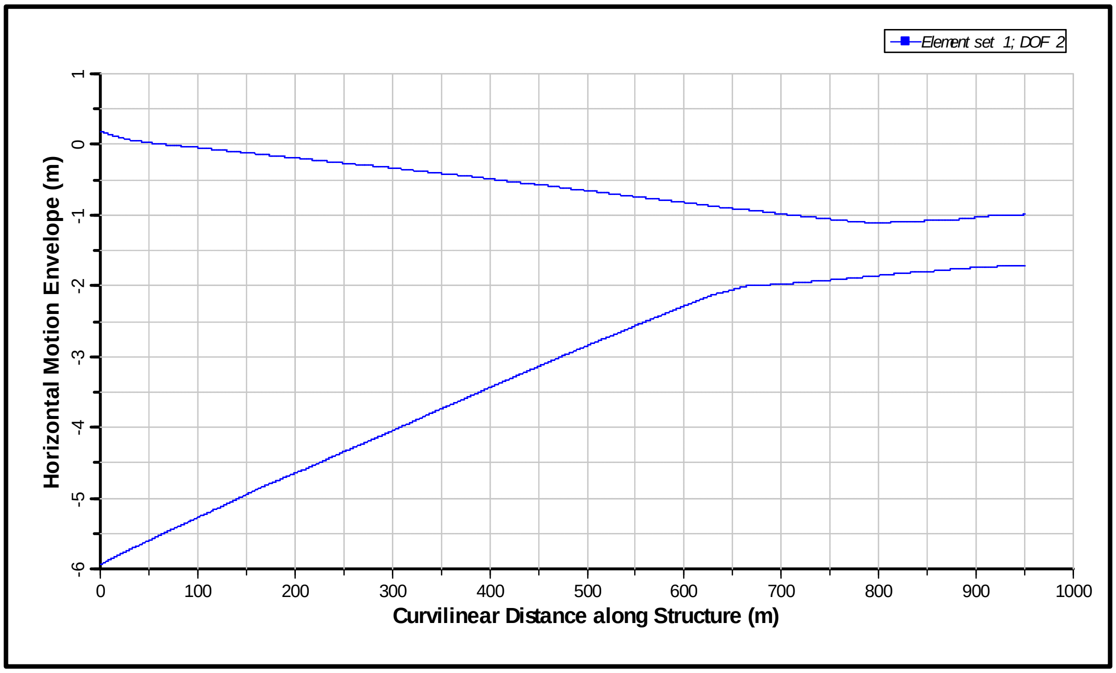


Figure 23: Motion Envelope for 1000 m CWP for Bin 1 (from Bottom to Top)

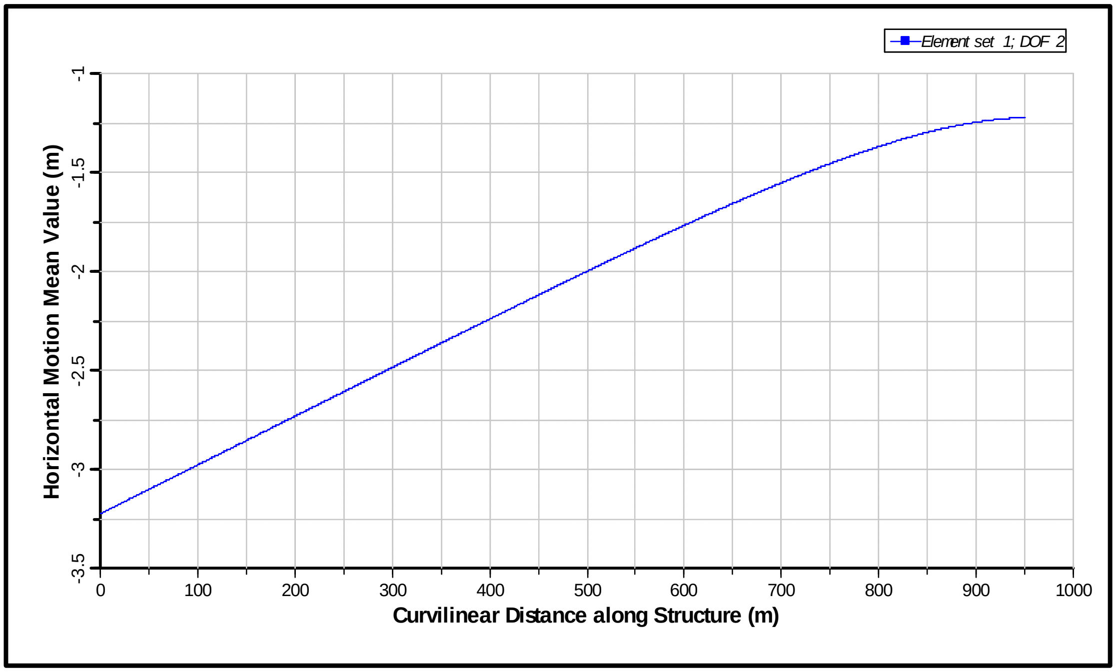


Figure 24: Mean Motion for 1000 m CWP for Bin 1 (from Bottom to Top)

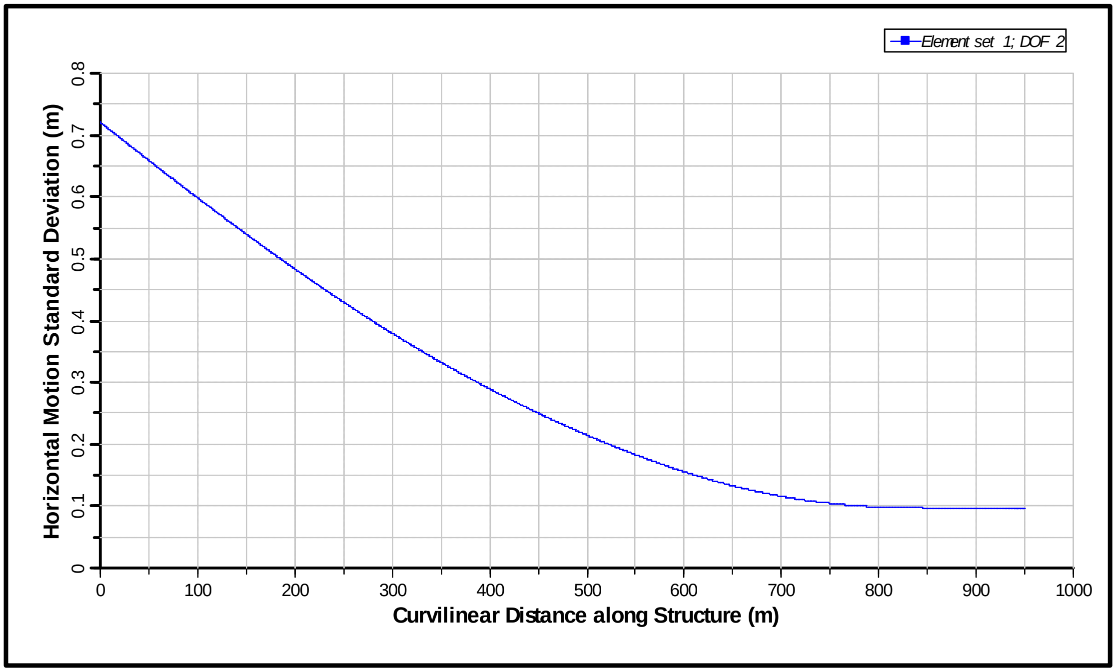


Figure 25: Standard Deviation of Motion for 1000 m CWP for Bin 1 (from Bottom to Top)

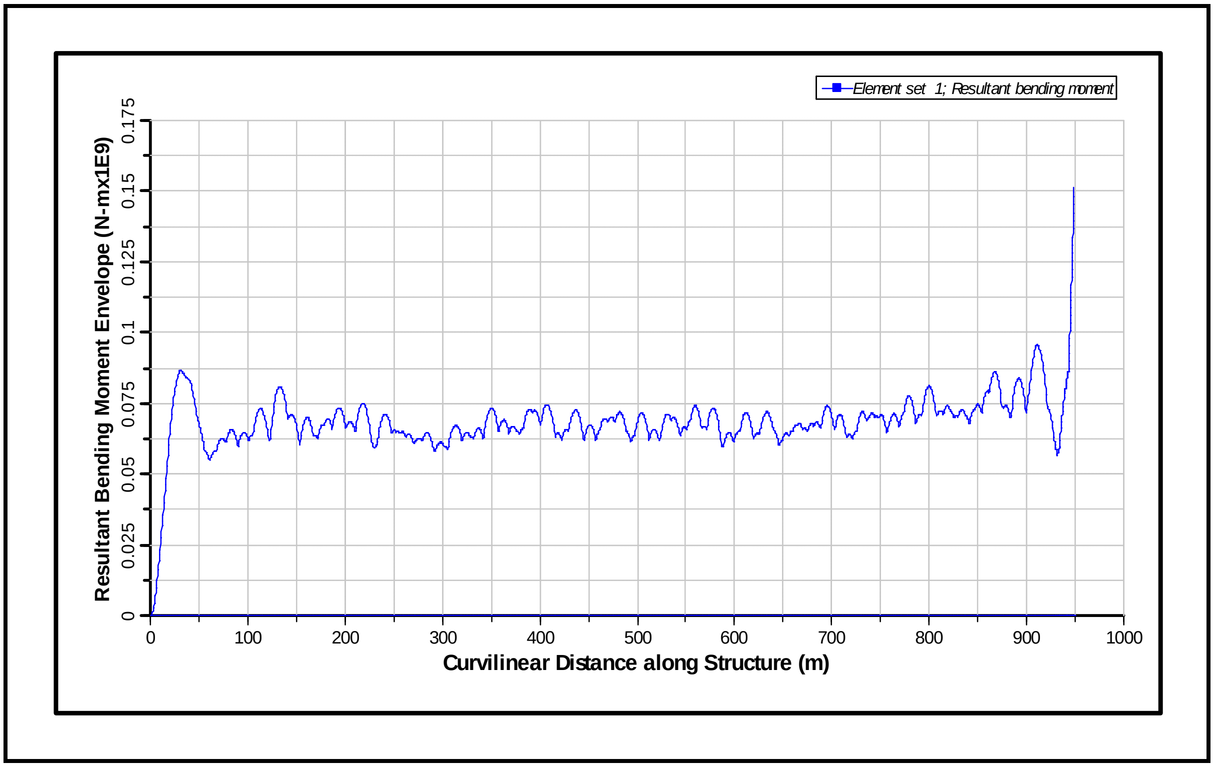


Figure 26: Bending Moment Envelope for 1000 m CWP for Bin 1 (from Bottom to Top)

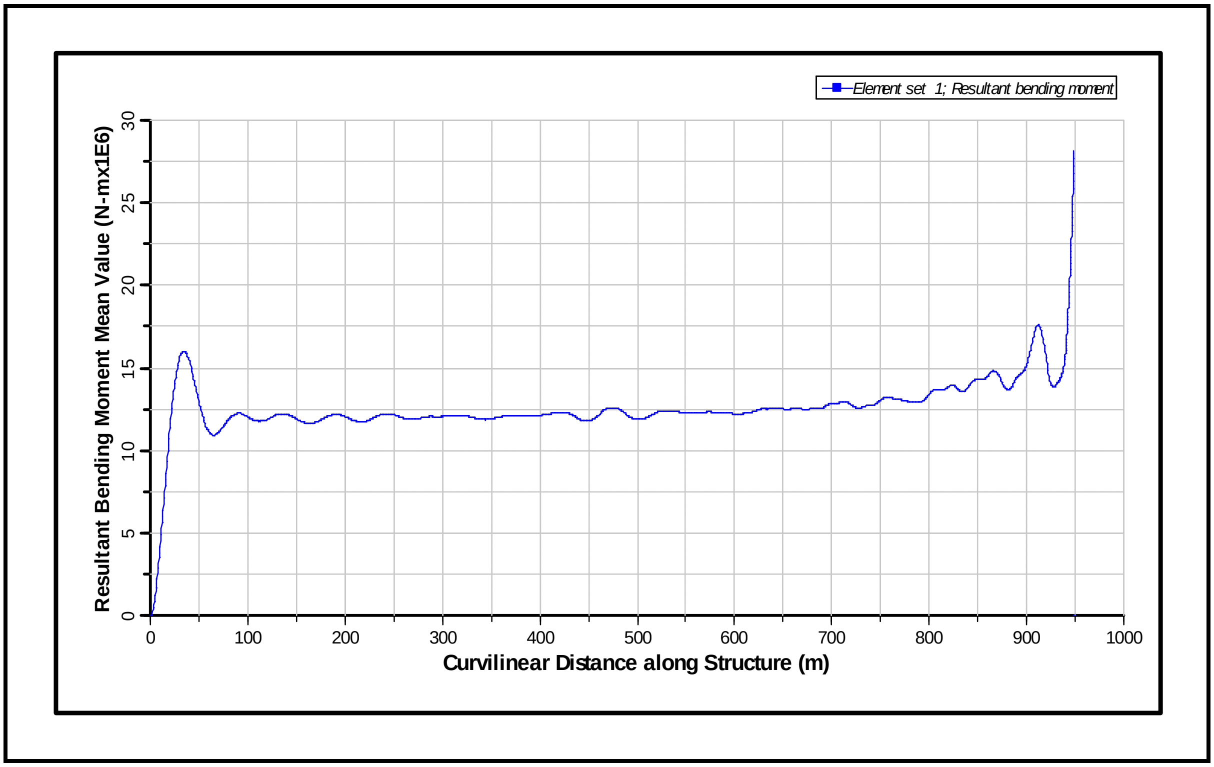


Figure 27: Mean Bending Moment for 1000 m CWP for Bin 1 (from Bottom to Top)

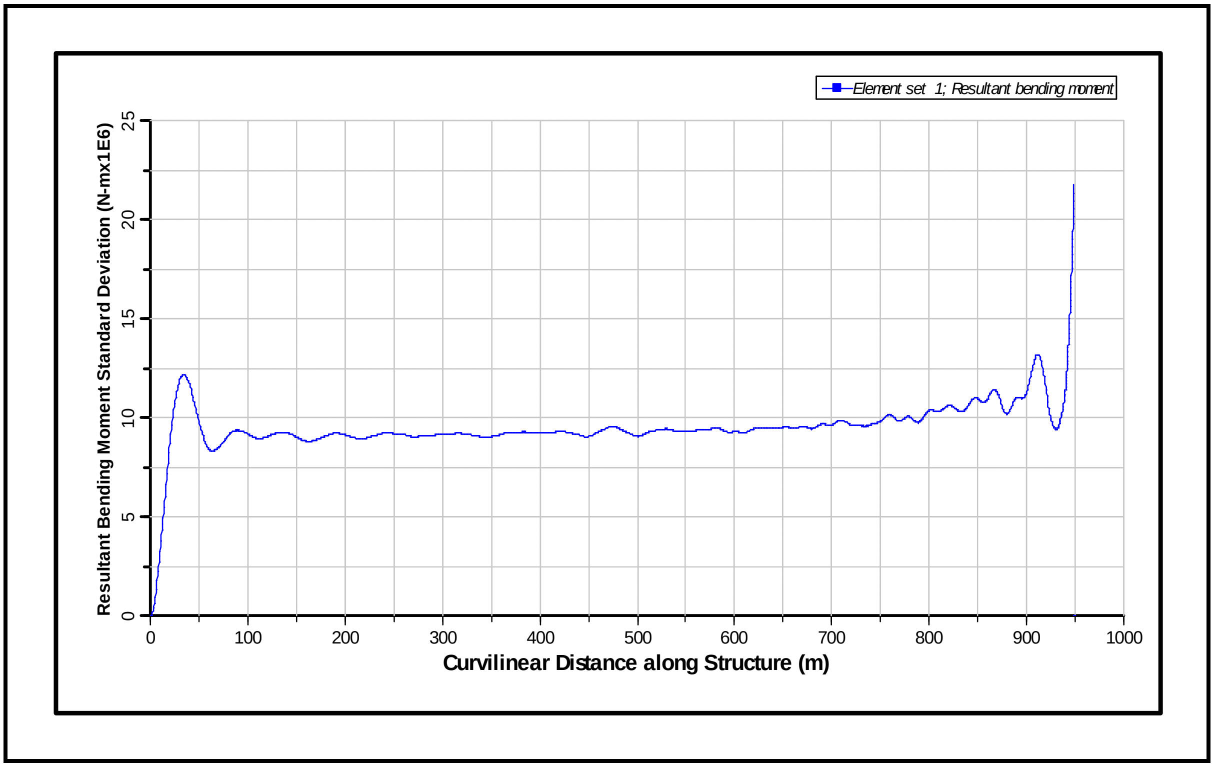


Figure 28: Standard Deviation of Bending Moment for 1000 m CWP for Bin 1 (from Bottom to Top)

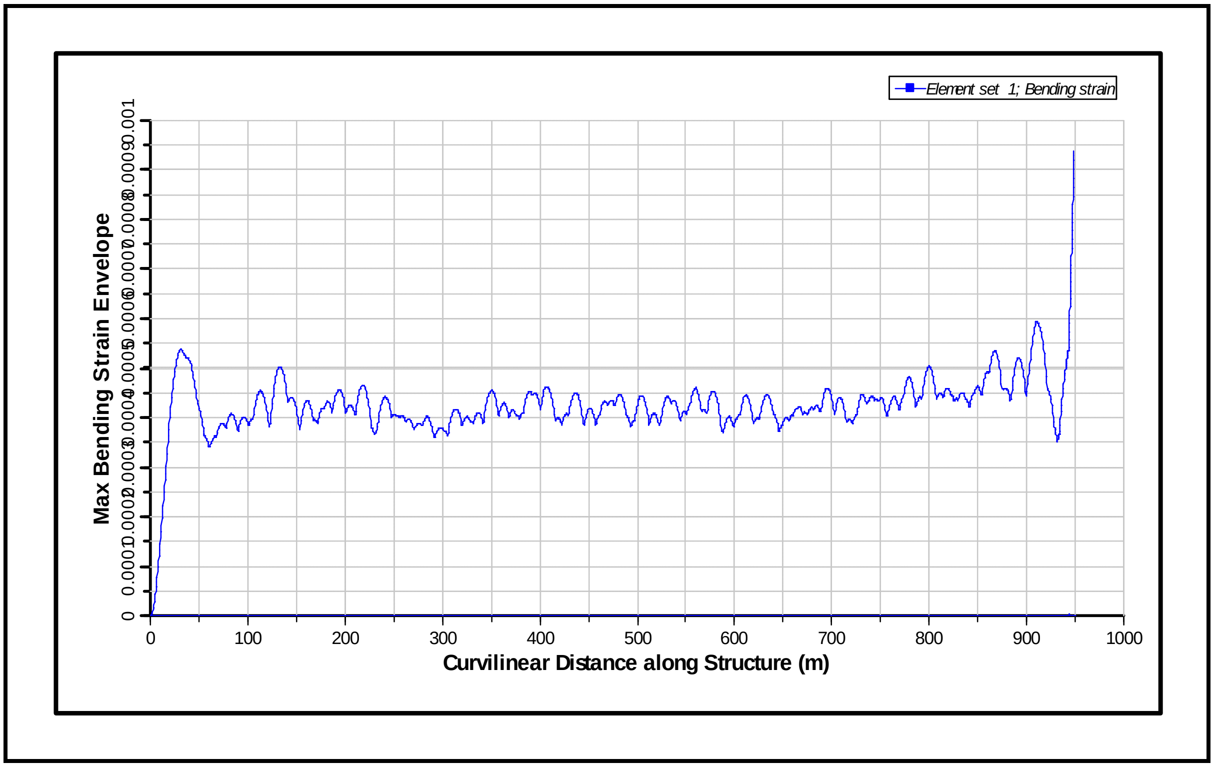


Figure 29: Bending Strain Envelope for 1000 m CWP for Bin 1 (from Bottom to Top)

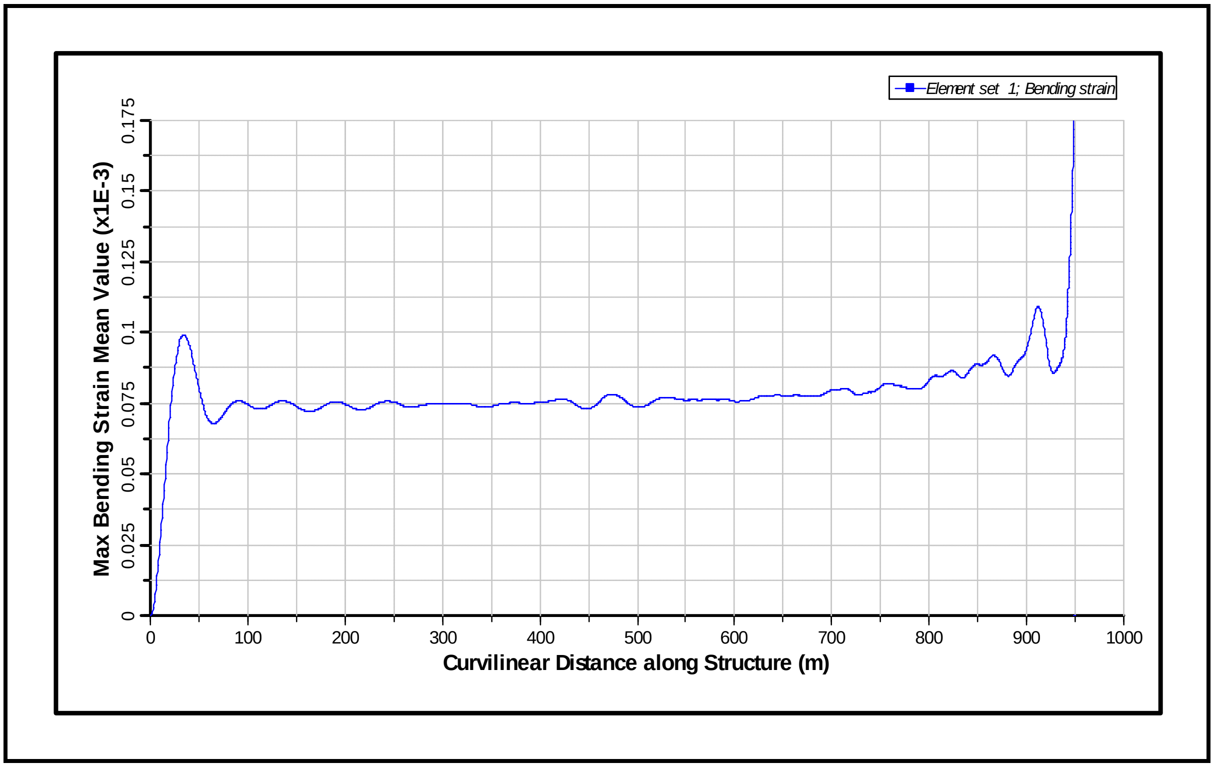


Figure 30: Mean Bending Strain for 1000 m CWP for Bin 1 (from Bottom to Top)

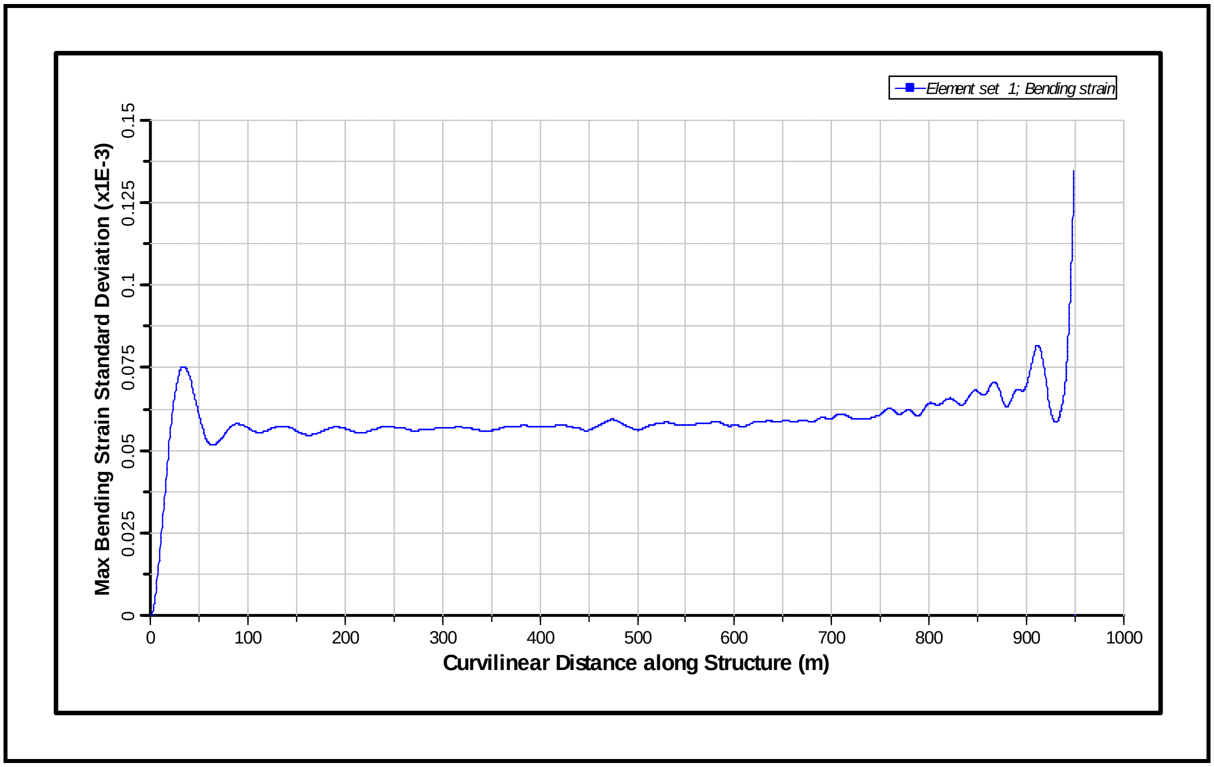


Figure 31: Standard Deviation of Bending Strain for 1000 m CWP for Bin 1 (from Bottom to Top)

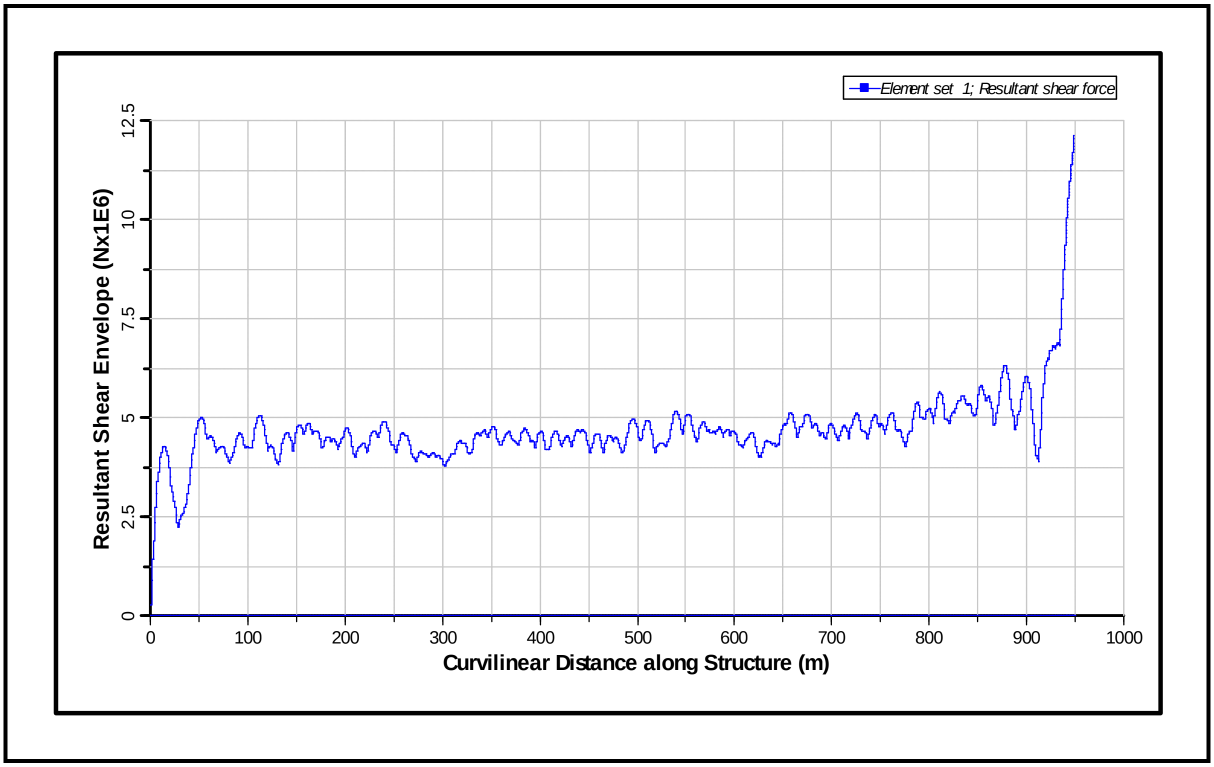


Figure 32: Shear Force Envelope for 1000 m CWP for Bin 1 (from Bottom to Top)

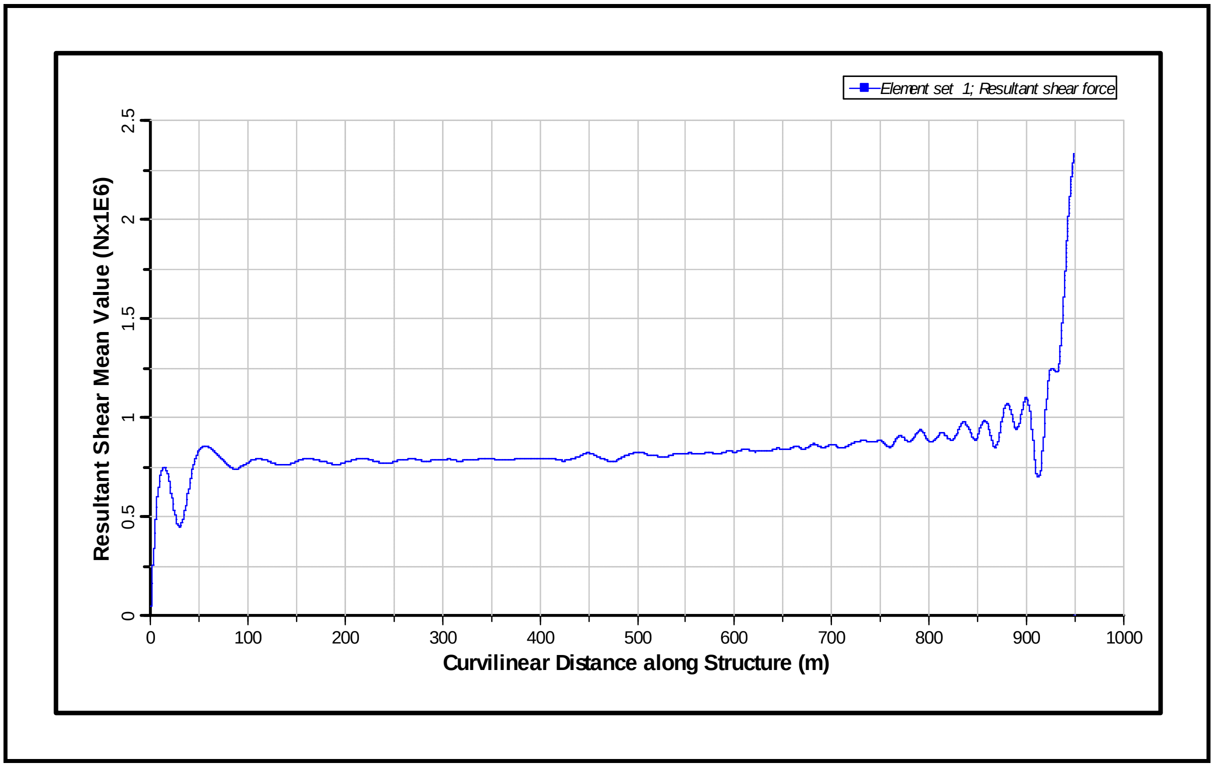


Figure 33: Mean Shear Force for 1000 m CWP for Bin 1 (from Bottom to Top)

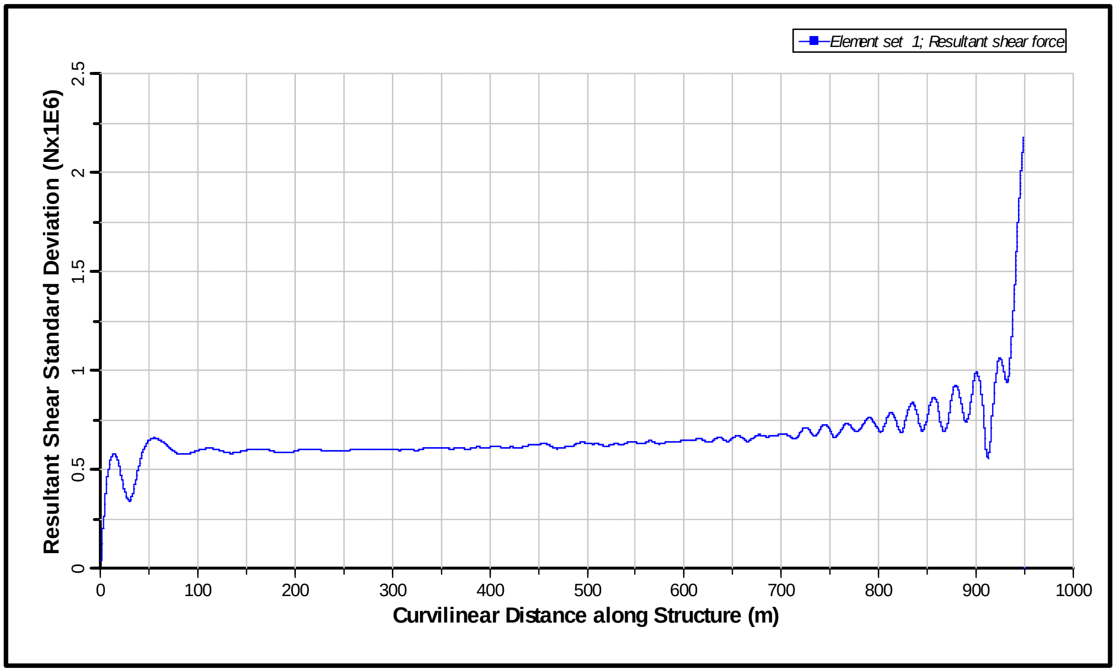


Figure 34: Standard Deviation of Shear Force for 1000 m CWP for Bin 1 (from Bottom to Top)

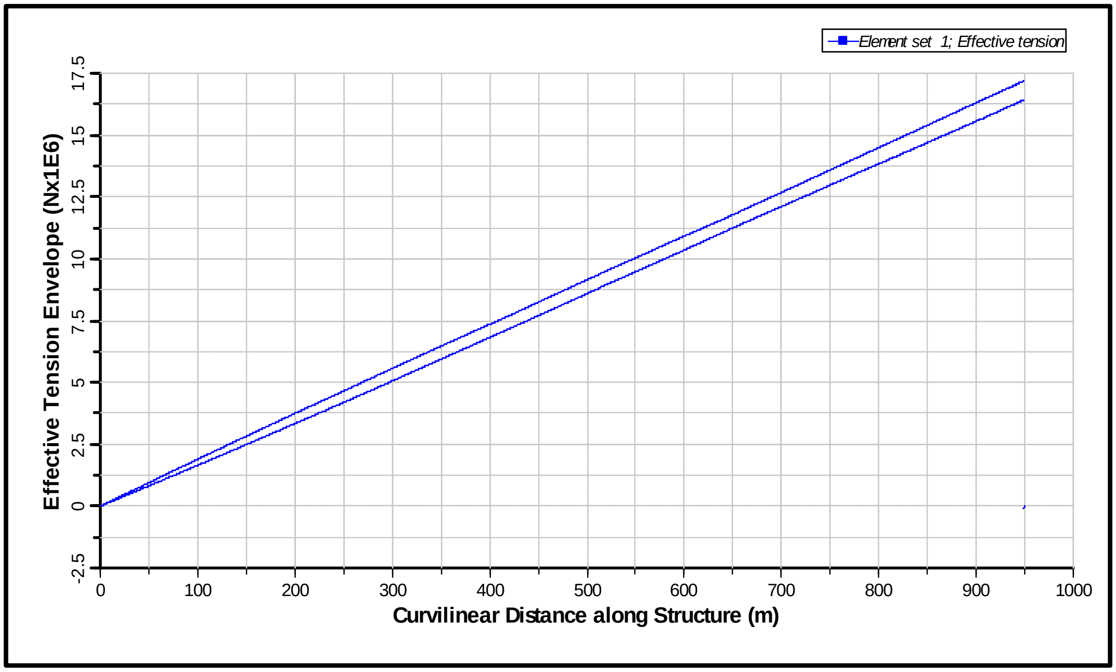


Figure 35: Axial Tension Envelope for 1000 m CWP for Bin 1 (from Bottom to Top)

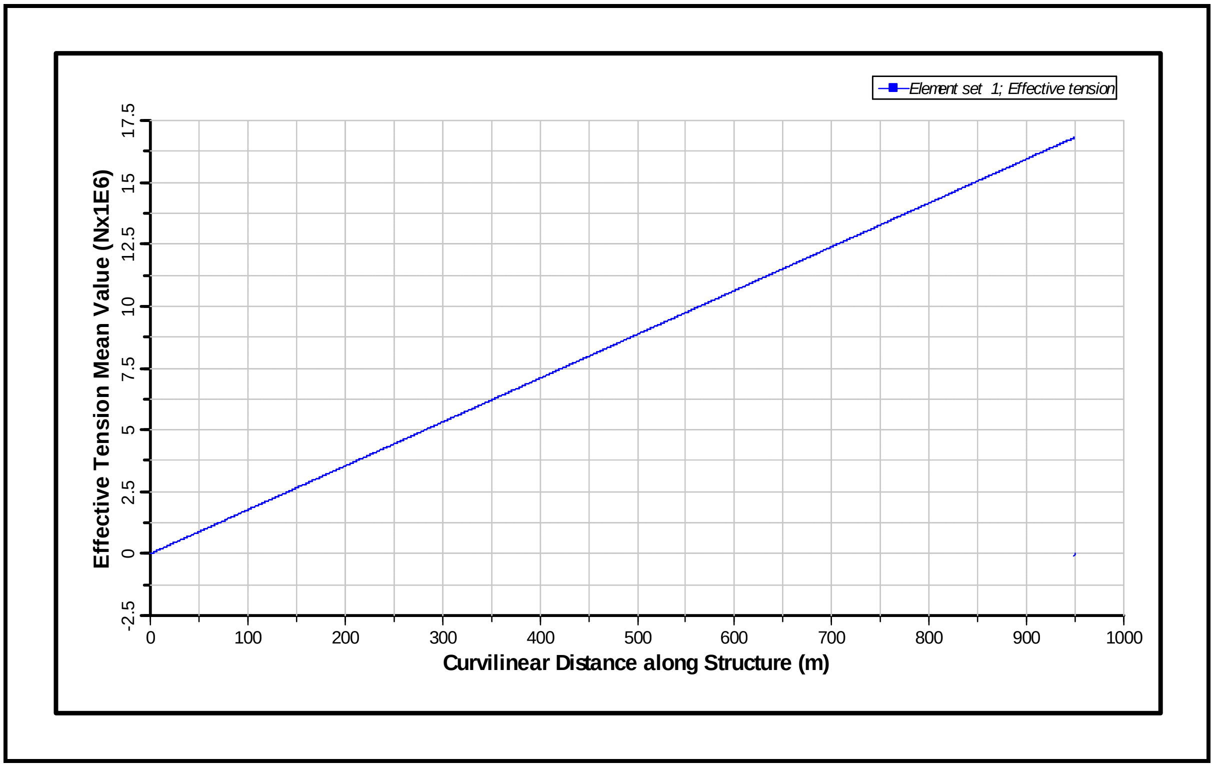


Figure 36: Mean Axial Tension for 1000 m CWP for Bin 1 (from Bottom to Top)

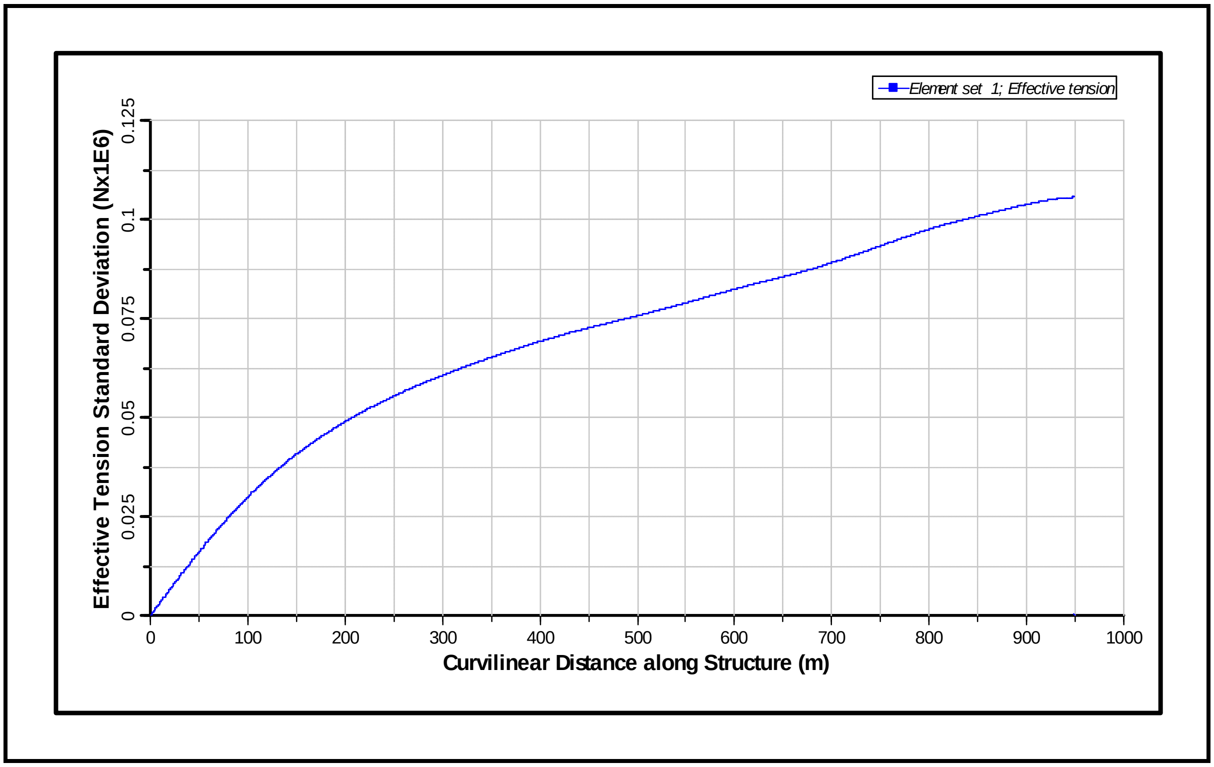


Figure 37: Standard Deviation of Axial Tension for 1000 m CWP for Bin 1 (from Bottom to Top)

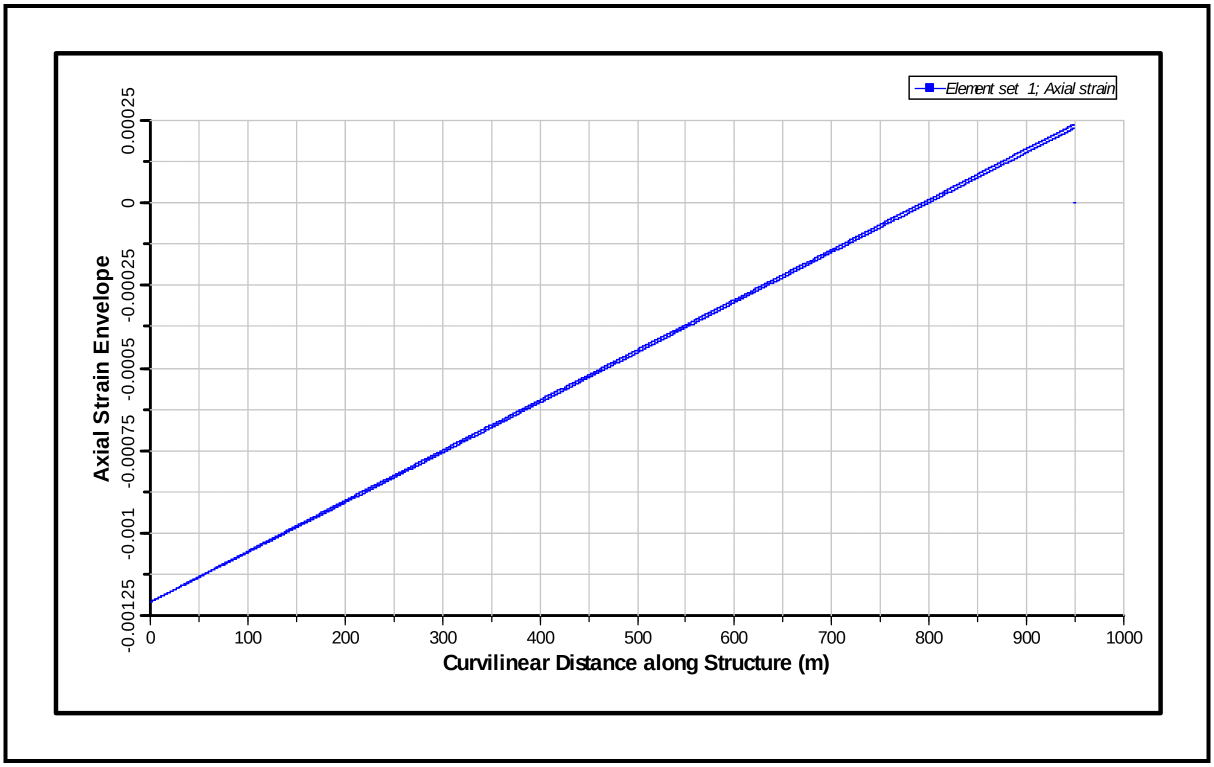


Figure 38: Axial Strain Envelope for 1000 m CWP for Bin 1 (from Bottom to Top)

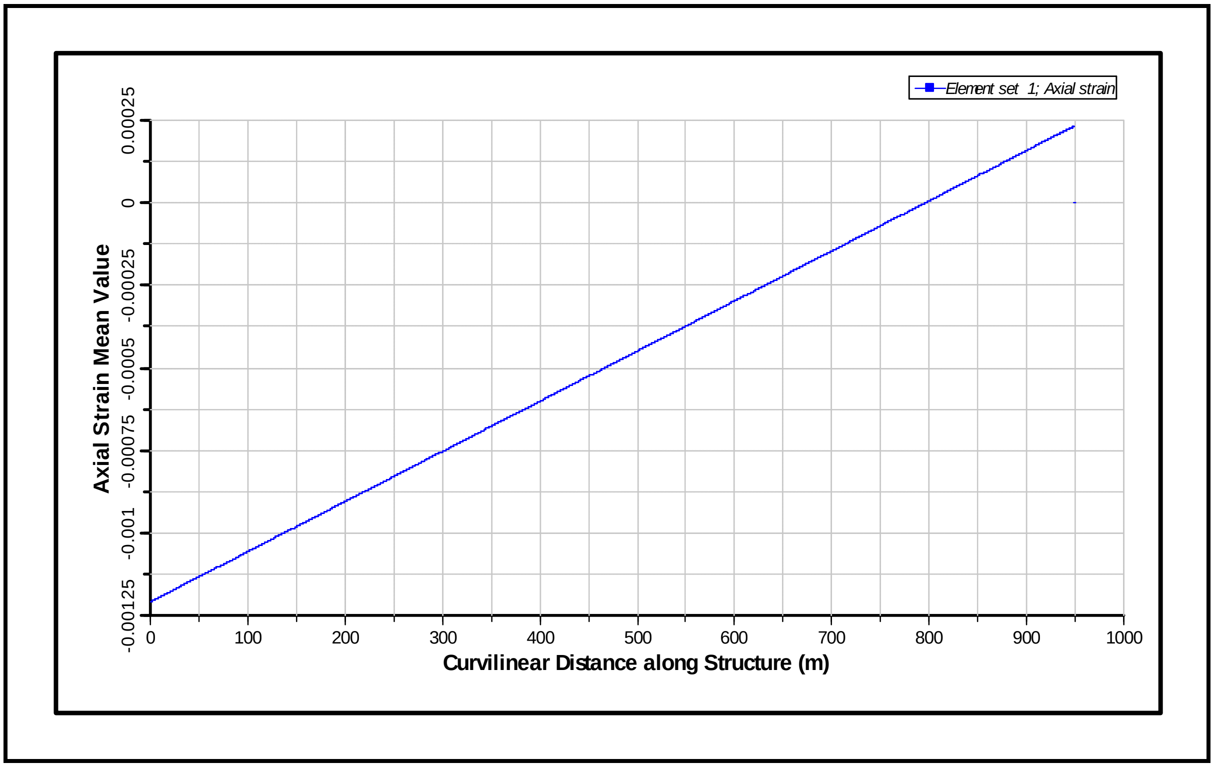


Figure 39: Mean Axial Strain for 1000 m CWP for Bin 1 (from Bottom to Top)

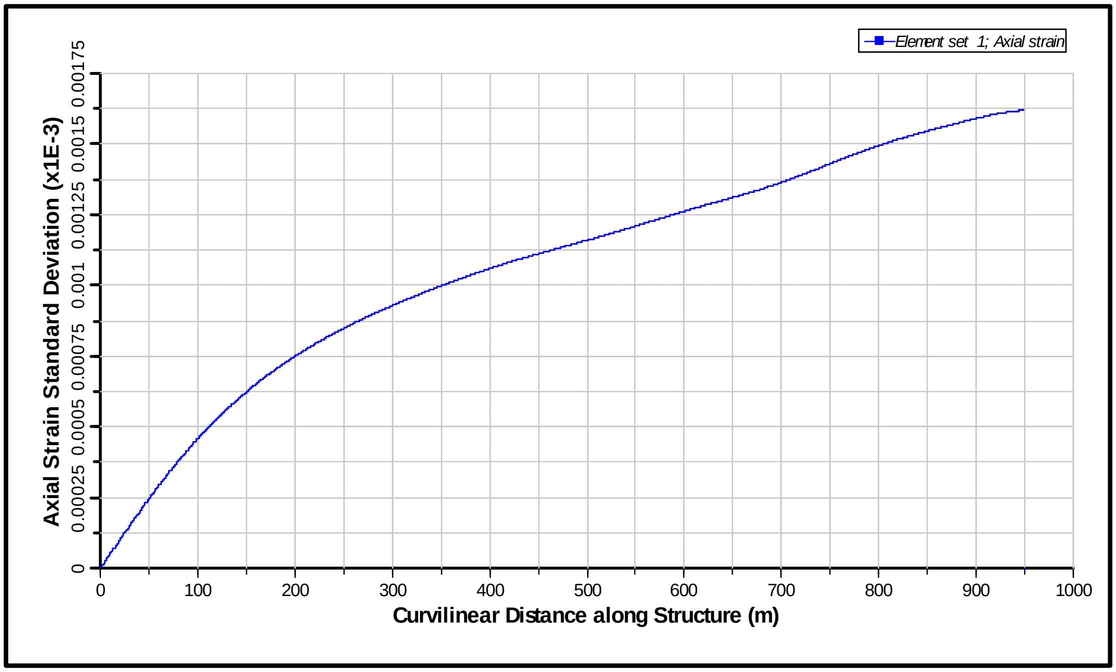


Figure 40: Standard Deviation of Axial Strain for 1000 m CWP for Bin 1 (from Bottom to Top)

6.2 Bin 2

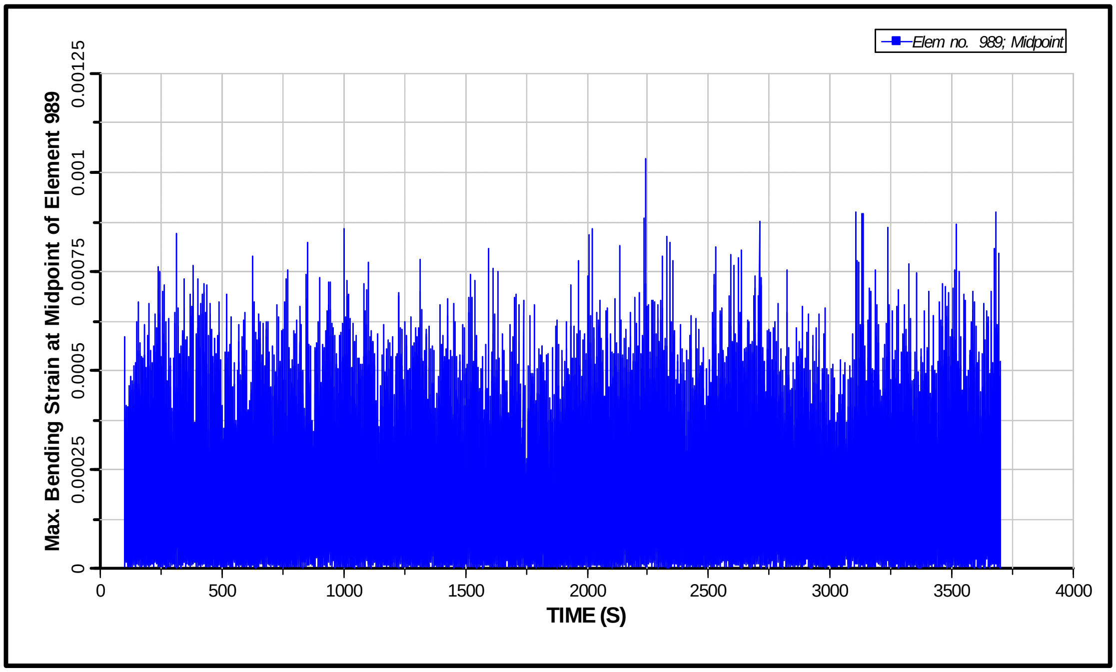


Figure 41: Maximum Bending Strain Time History at Top of CWP for Bin 2

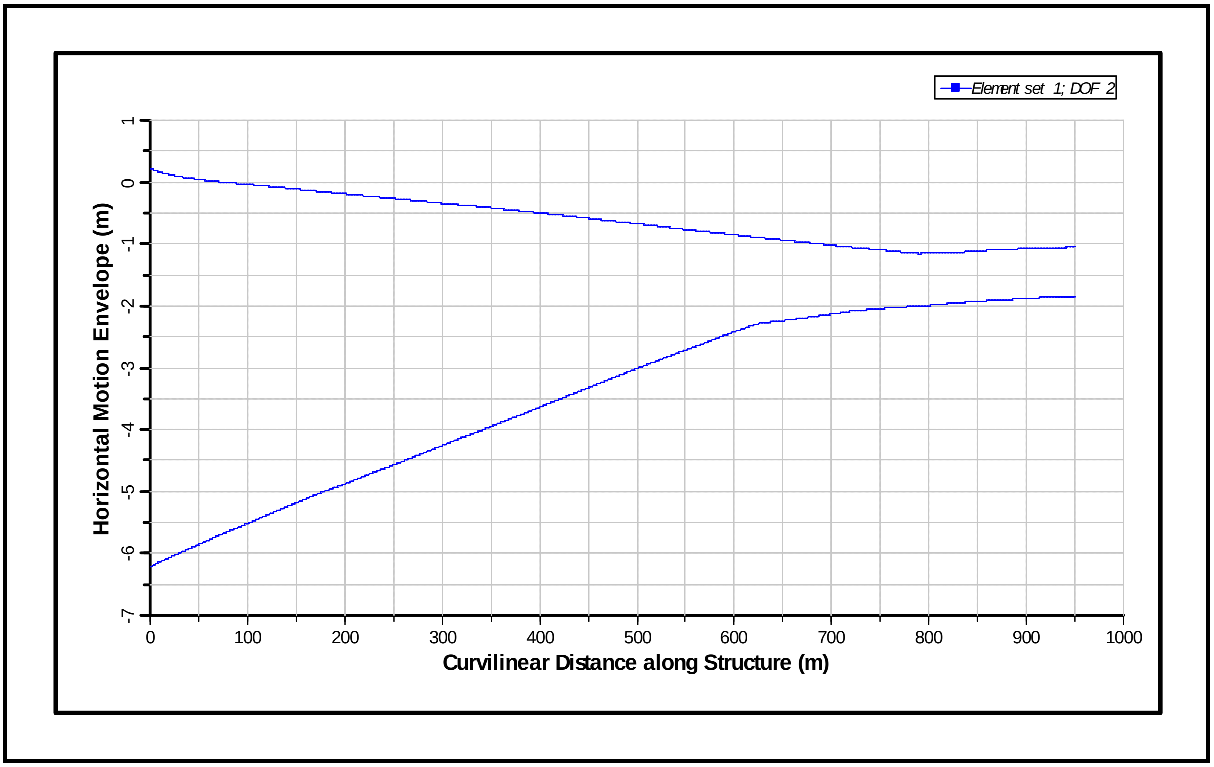


Figure 42: Motion Envelope for 1000 m CWP for Bin 2 (from Bottom to Top)

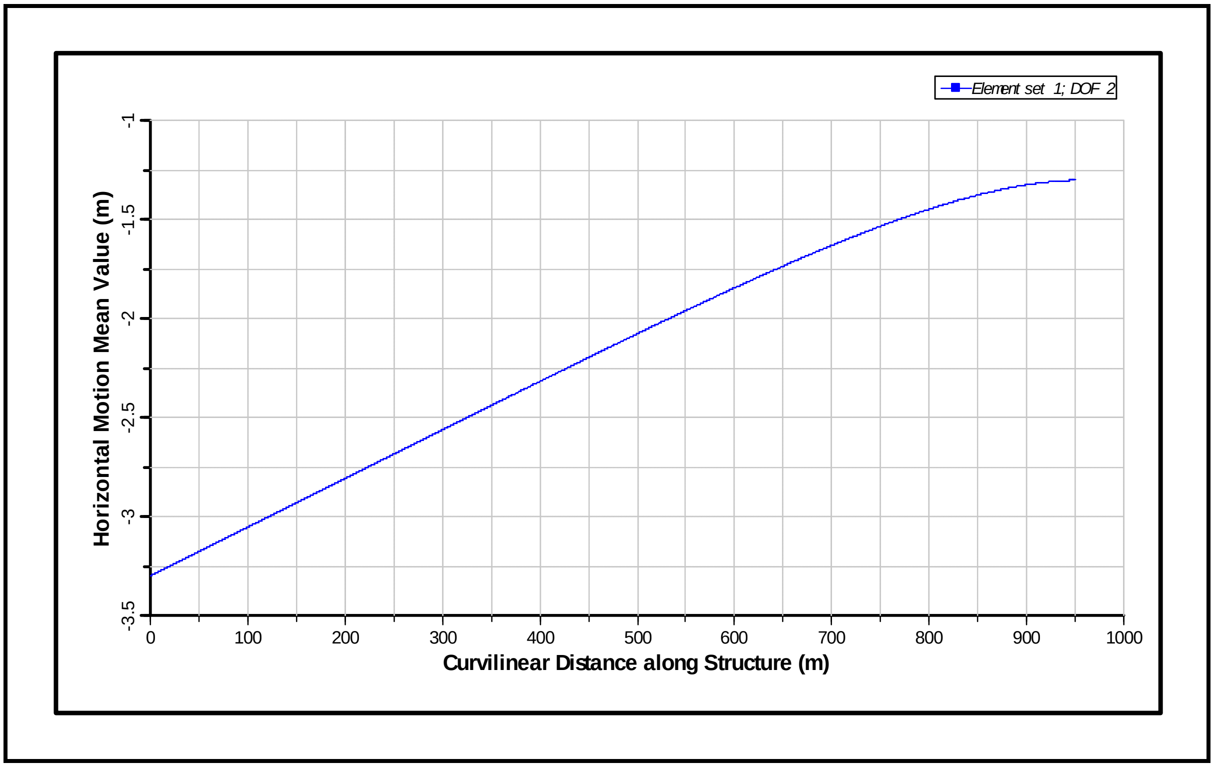


Figure 43: Mean Motion for 1000 m CWP for Bin 2 (from Bottom to Top)

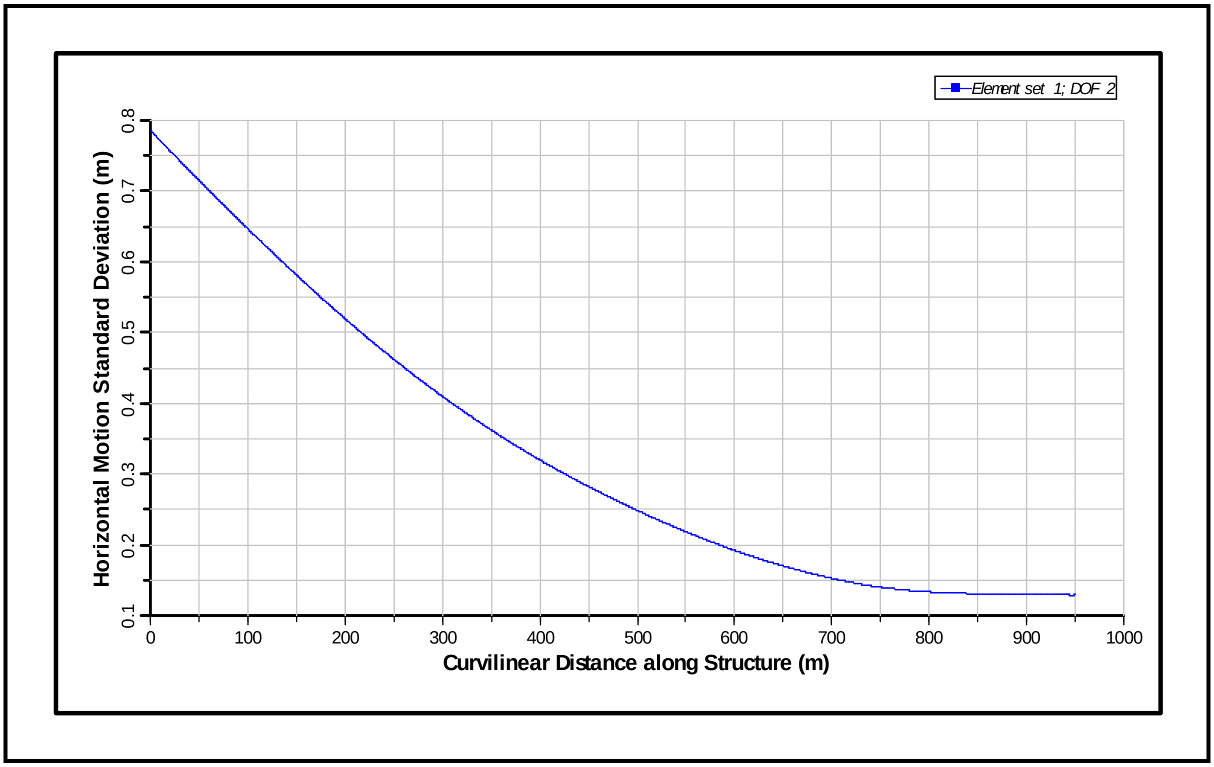


Figure 44: Standard Deviation of Motion for 1000 m CWP for Bin 2 (from Bottom to Top)

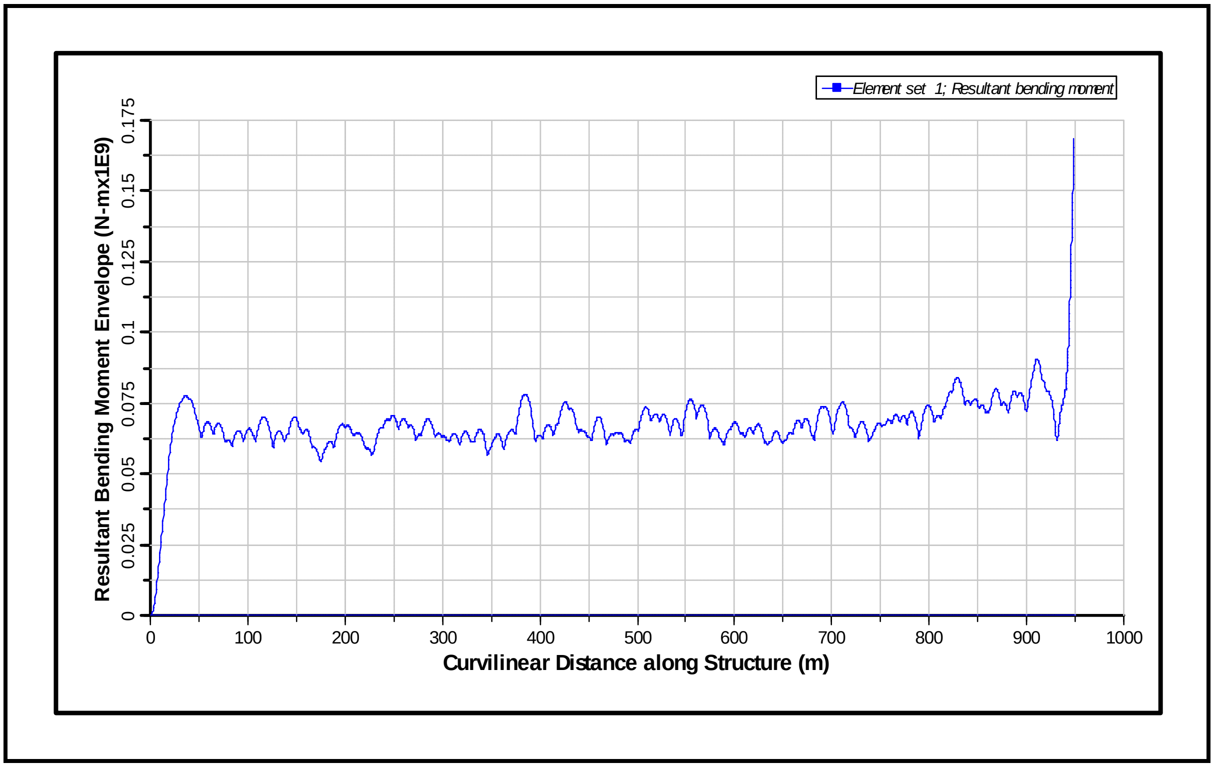


Figure 45: Bending Moment Envelope for 1000 m CWP for Bin 2 (from Bottom to Top)

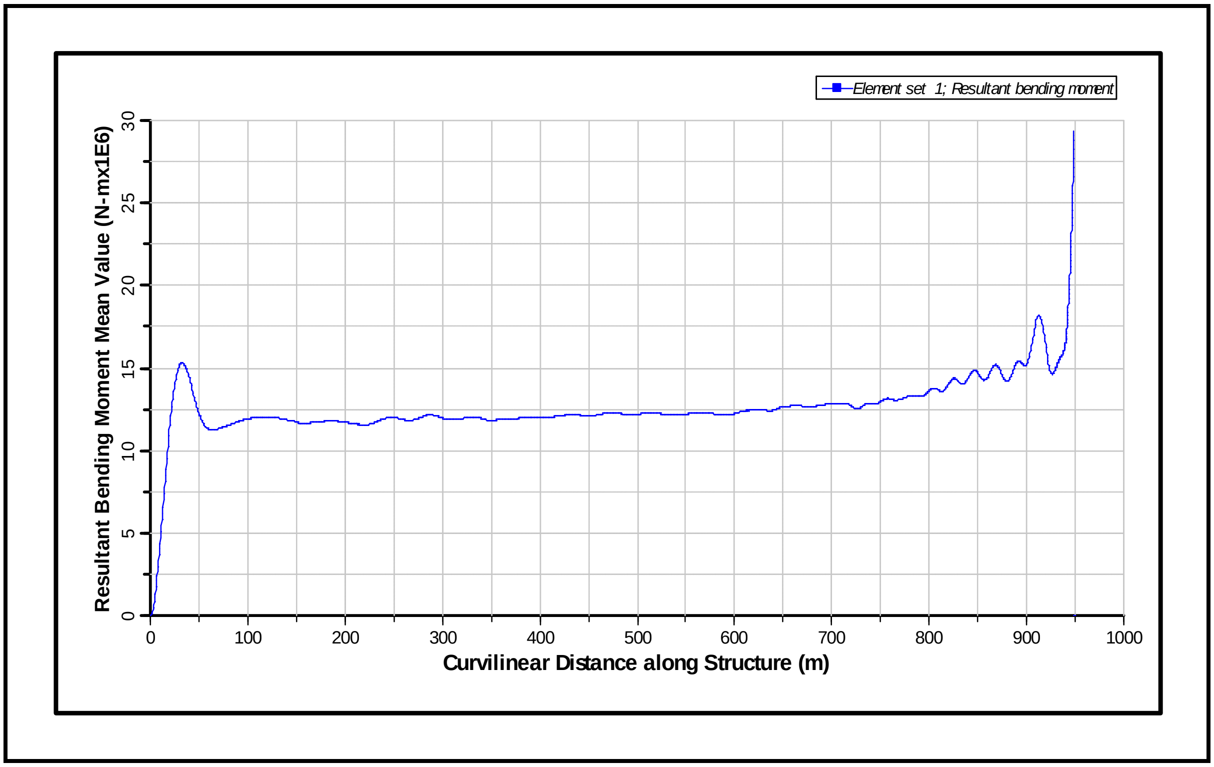


Figure 46: Mean Bending Moment for 1000 m CWP for Bin 2 (from Bottom to Top)

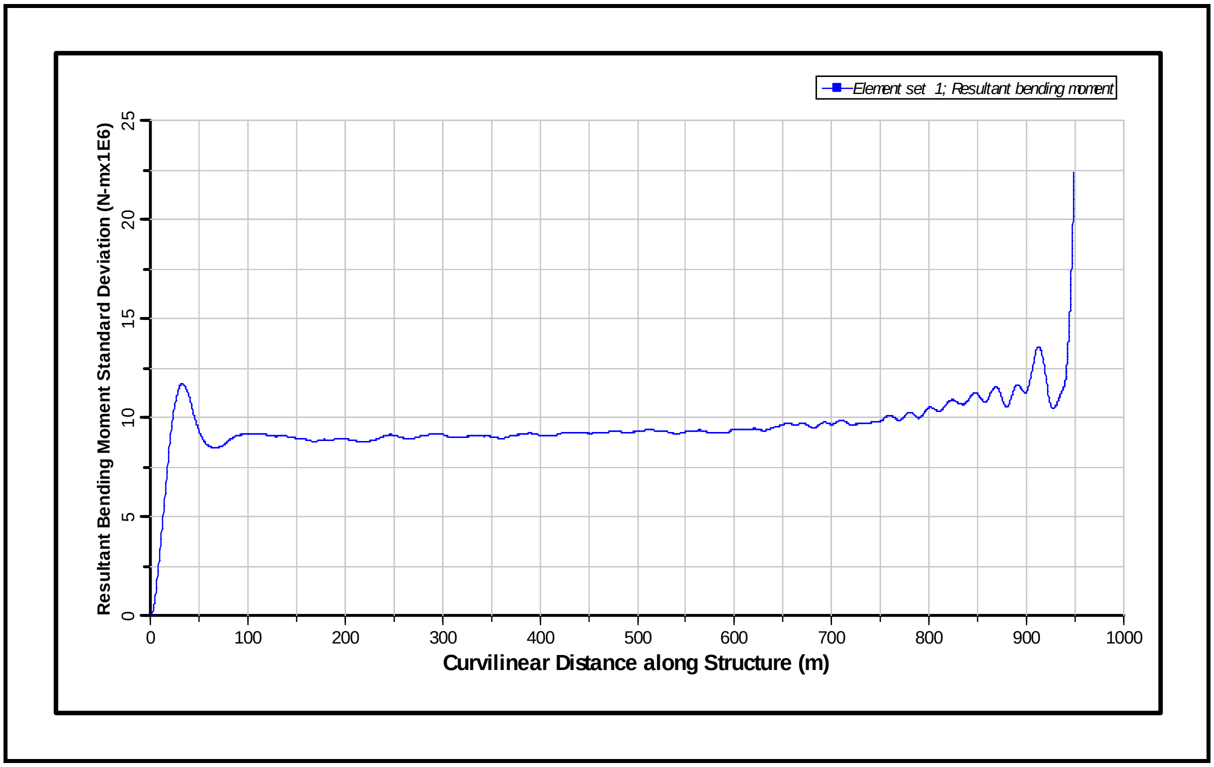


Figure 47: Standard Deviation of Bending Moment for 1000 m CWP for Bin 2 (from Bottom to Top)

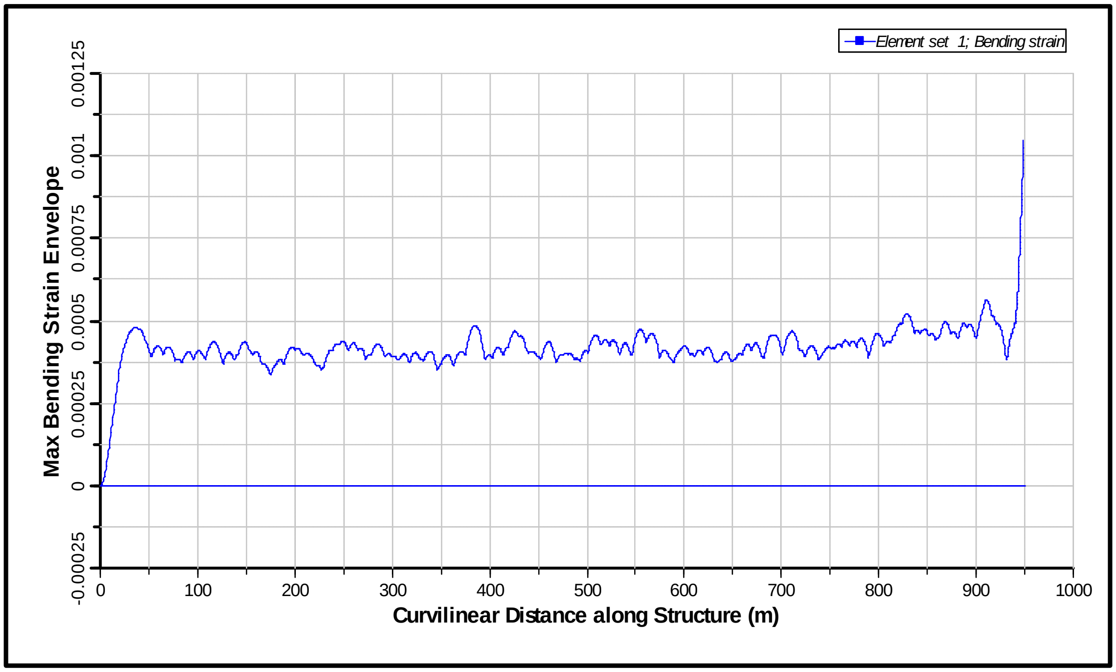


Figure 48: Bending Strain Envelope for 1000 m CWP for Bin 2 (from Bottom to Top)

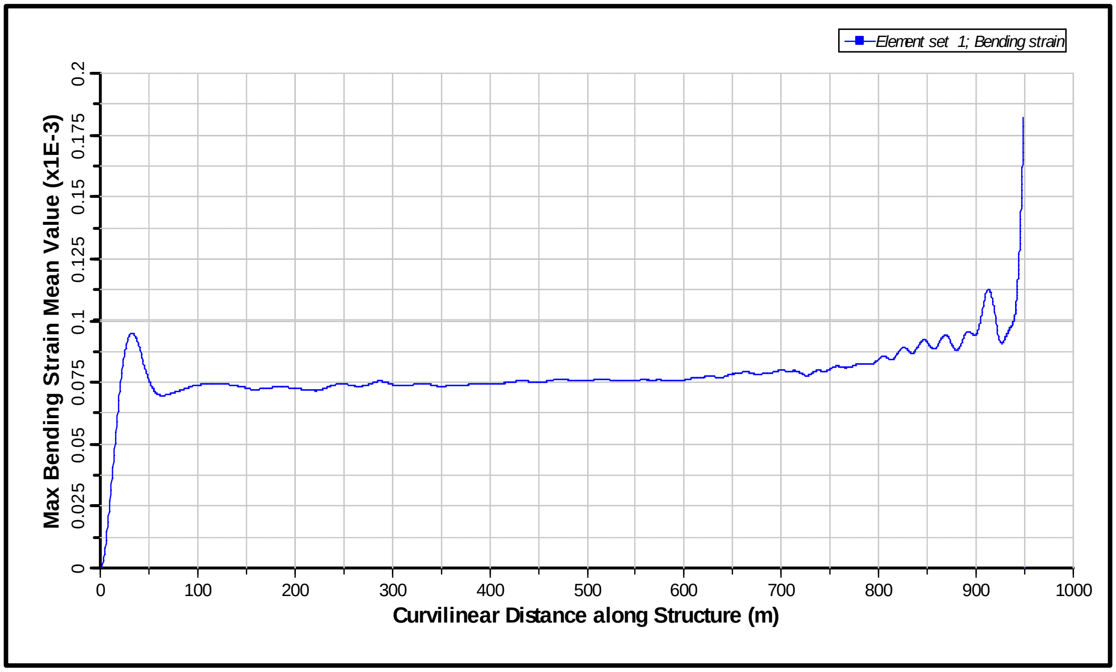


Figure 49: Mean Bending Strain for 1000 m CWP for Bin 2 (from Bottom to Top)

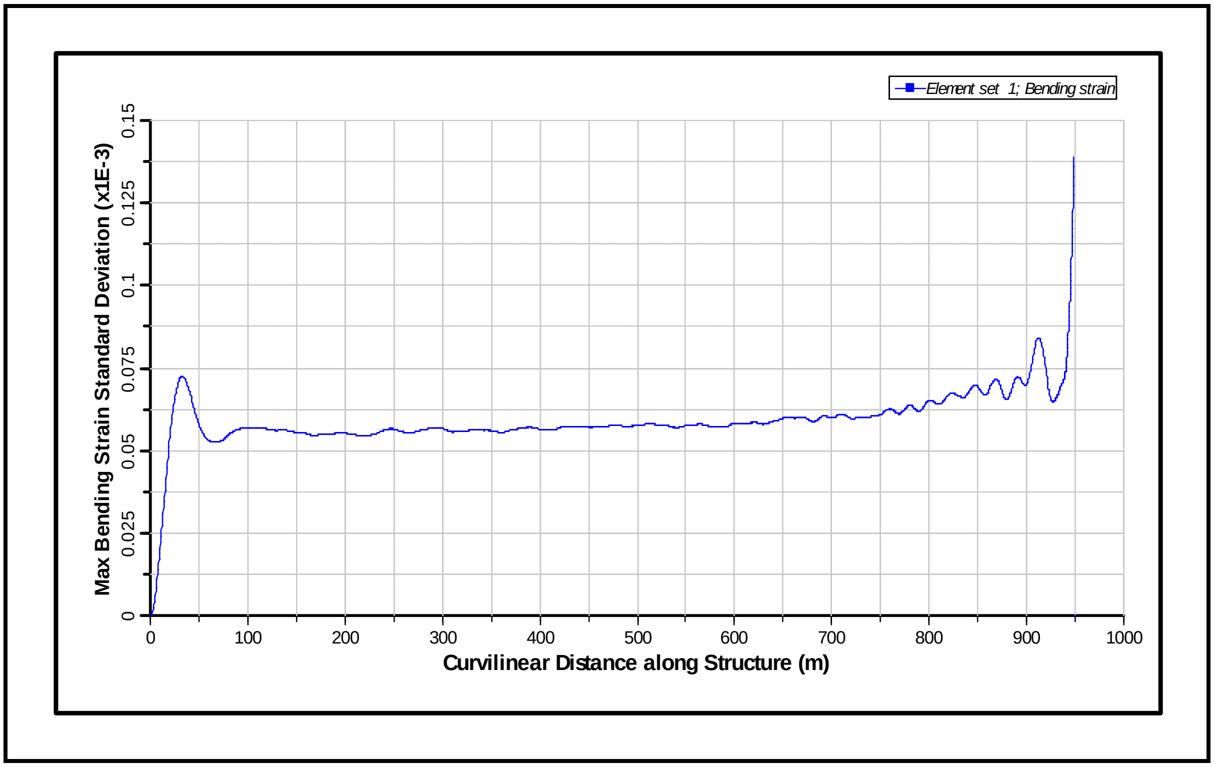


Figure 50: Standard Deviation of Bending Strain for 1000 m CWP for Bin 2 (from Bottom to Top)

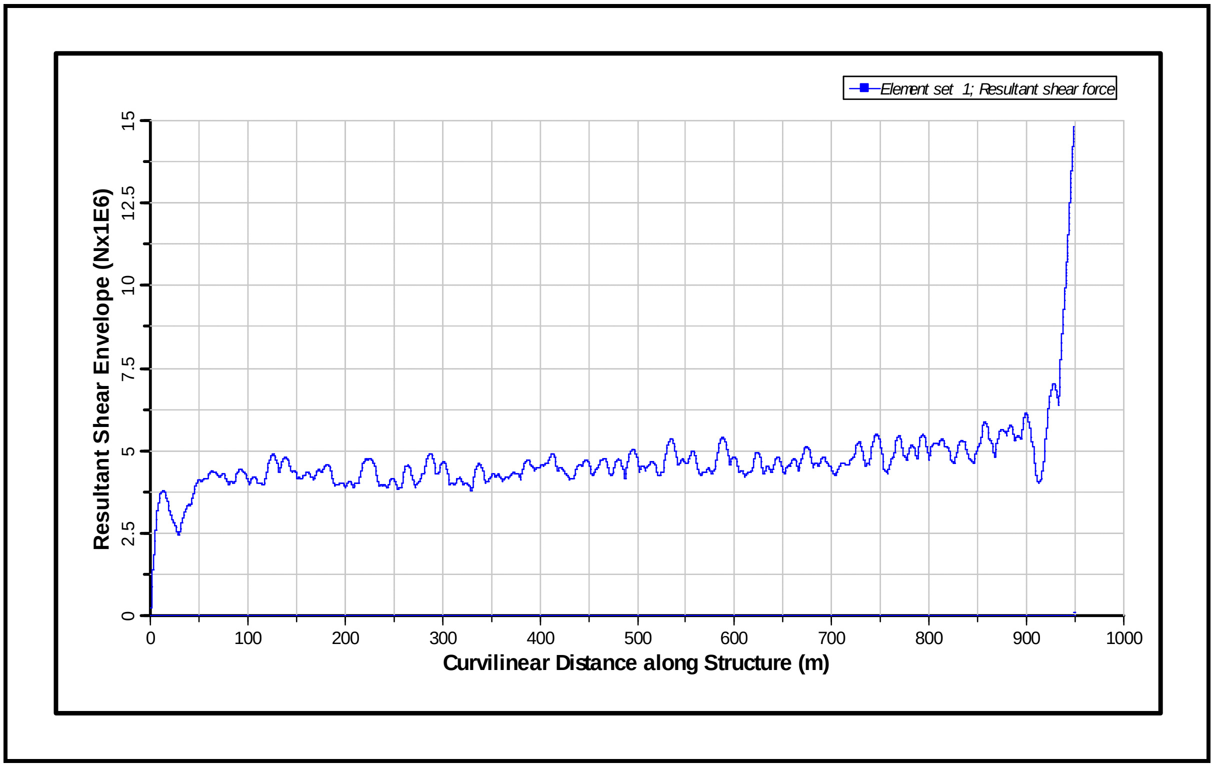


Figure 51: Shear Force Envelope for 1000 m CWP for Bin 2 (from Bottom to Top)

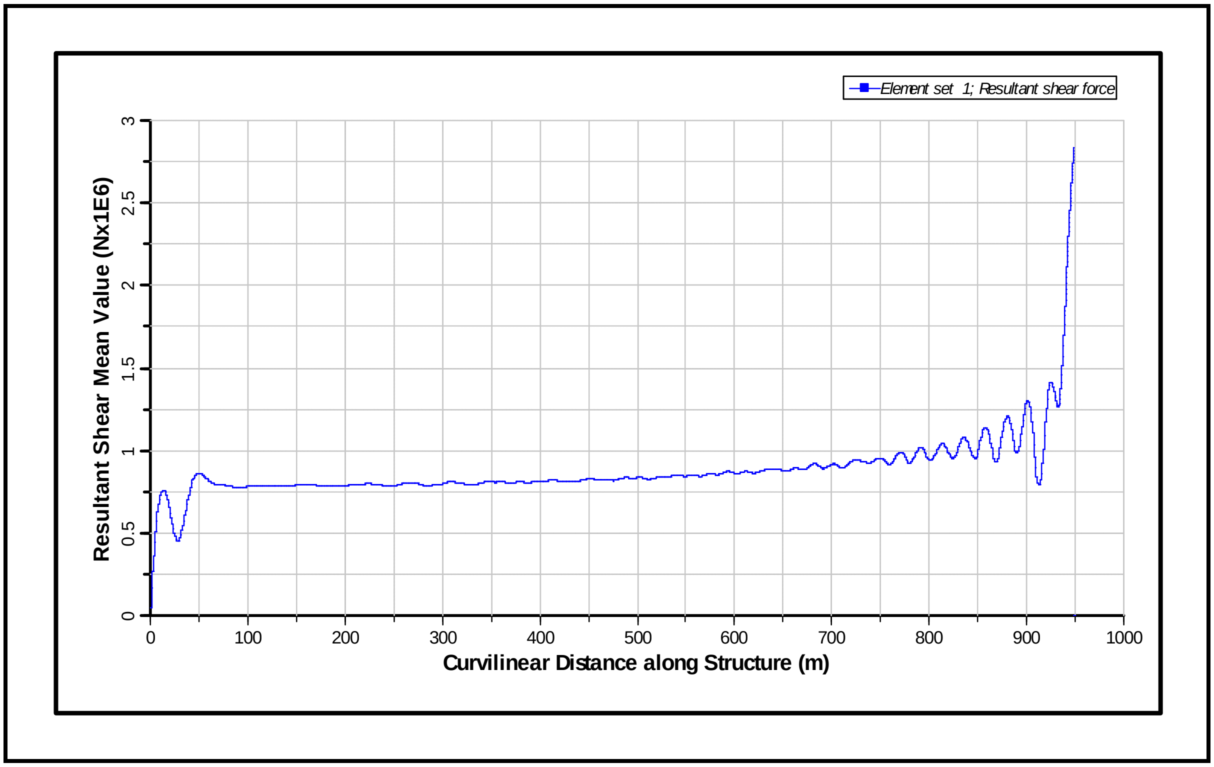


Figure 52: Mean Shear Force for 1000 m CWP for Bin 2 (from Bottom to Top)

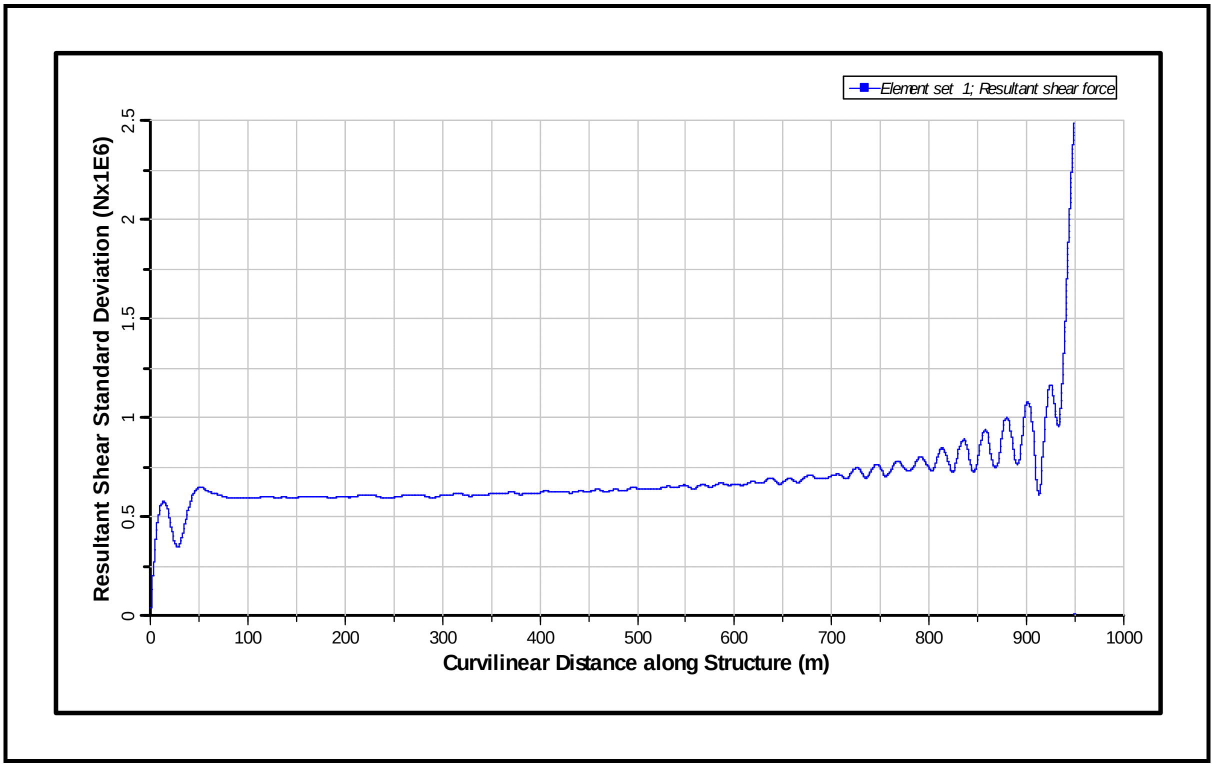


Figure 53: Standard Deviation of Shear Force for 1000 m CWP for Bin 2 (from Bottom to Top)

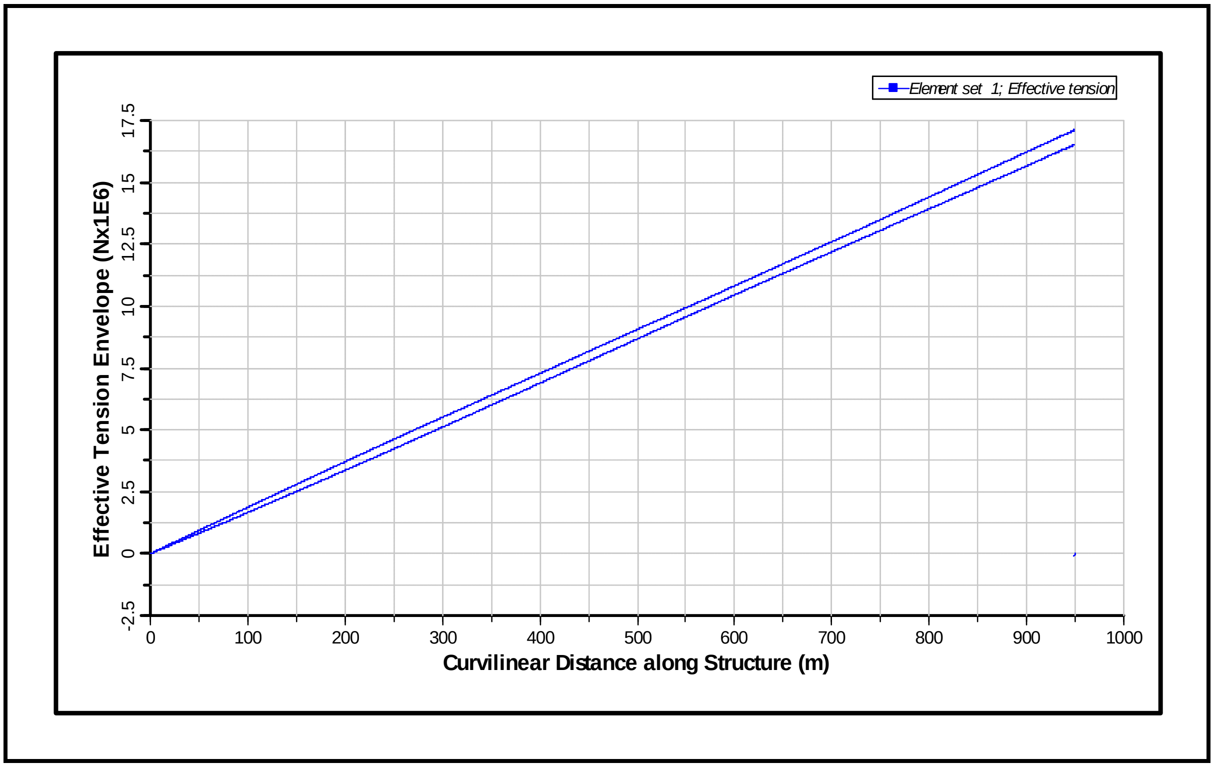


Figure 54: Axial Tension Envelope for 1000 m CWP for Bin 2 (from Bottom to Top)

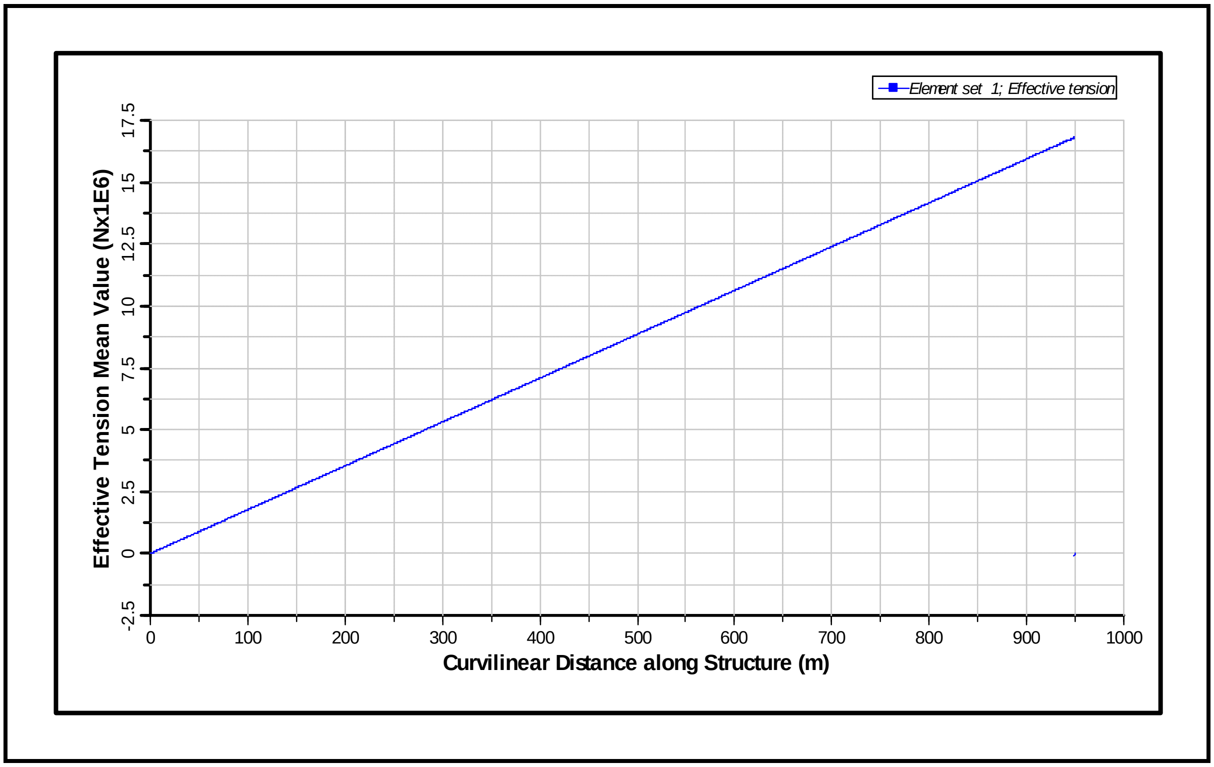


Figure 55: Mean Axial Tension for 1000 m CWP for Bin 2 (from Bottom to Top)

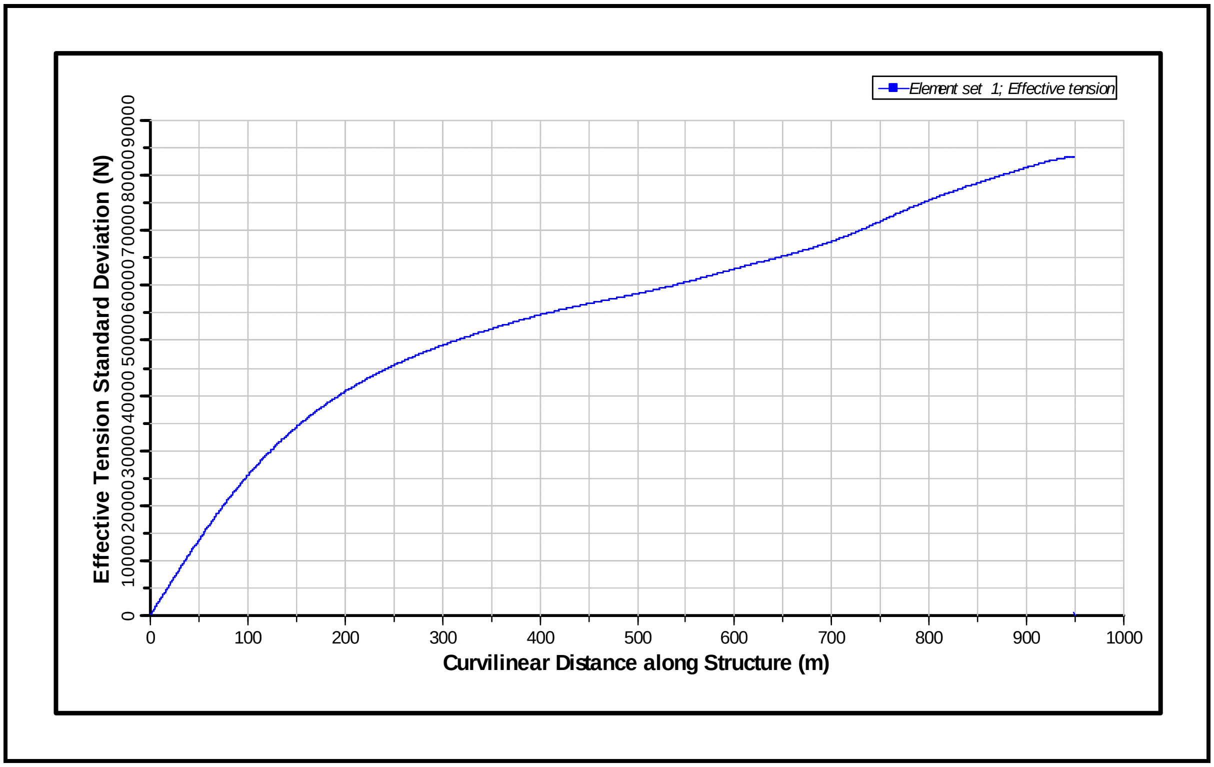


Figure 56: Standard Deviation of Axial Tension for 1000 m CWP for Bin 2 (from Bottom to Top)

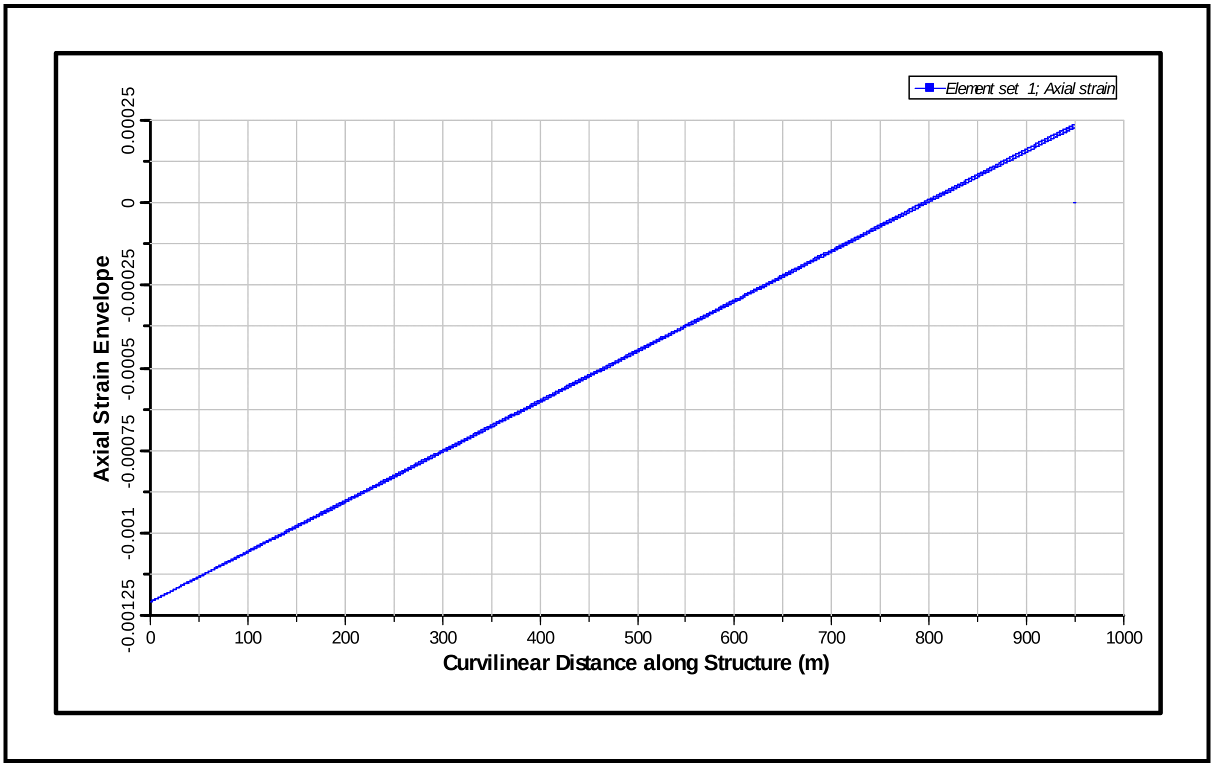


Figure 57: Axial Strain Envelope for 1000 m CWP for Bin 2 (from Bottom to Top)

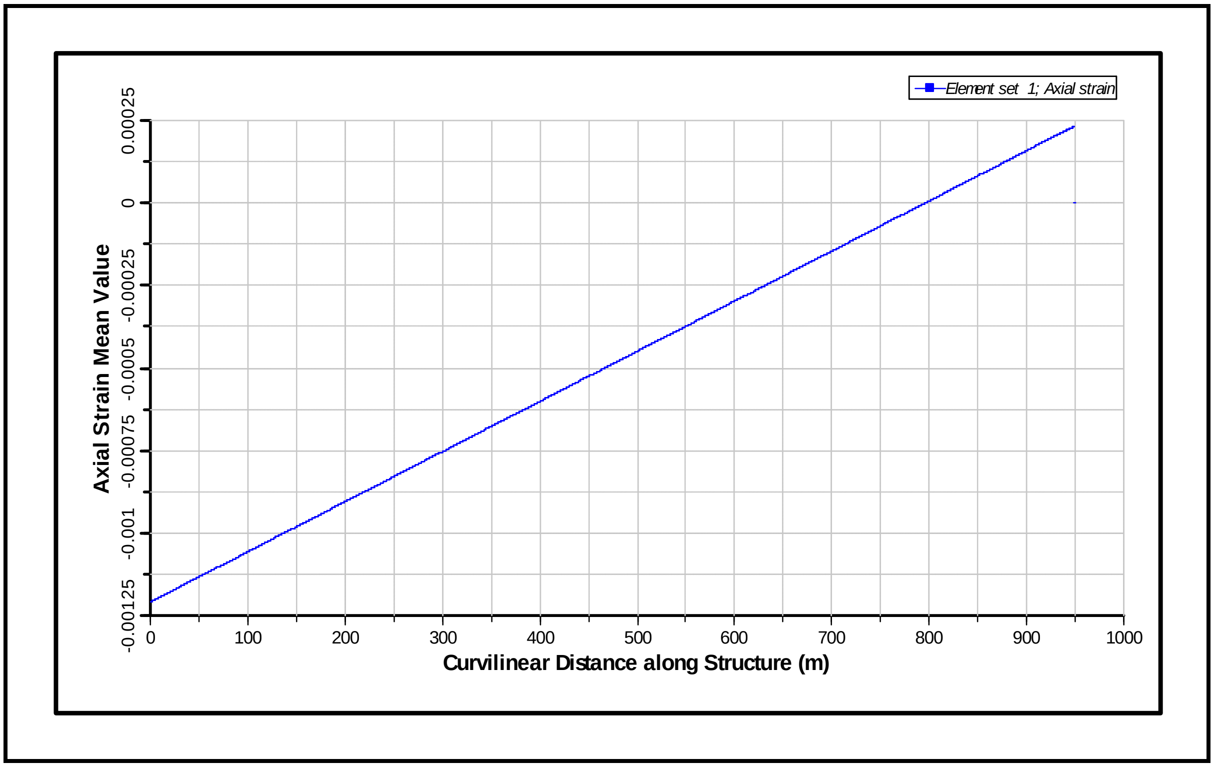


Figure 58: Mean Axial Strain for 1000 m CWP for Bin 2 (from Bottom to Top)

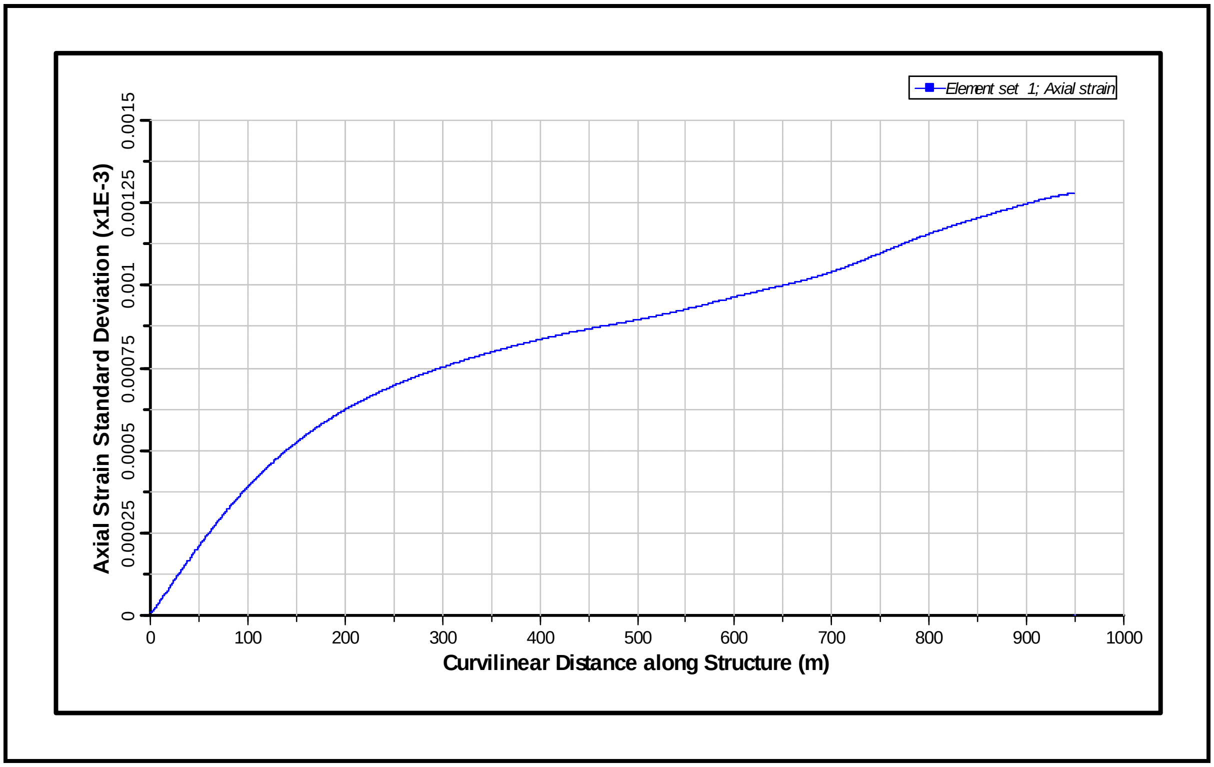


Figure 59: Standard Deviation of Axial Strain for 1000 m CWP for Bin 2 (from Bottom to Top)

6.3 Bin 3

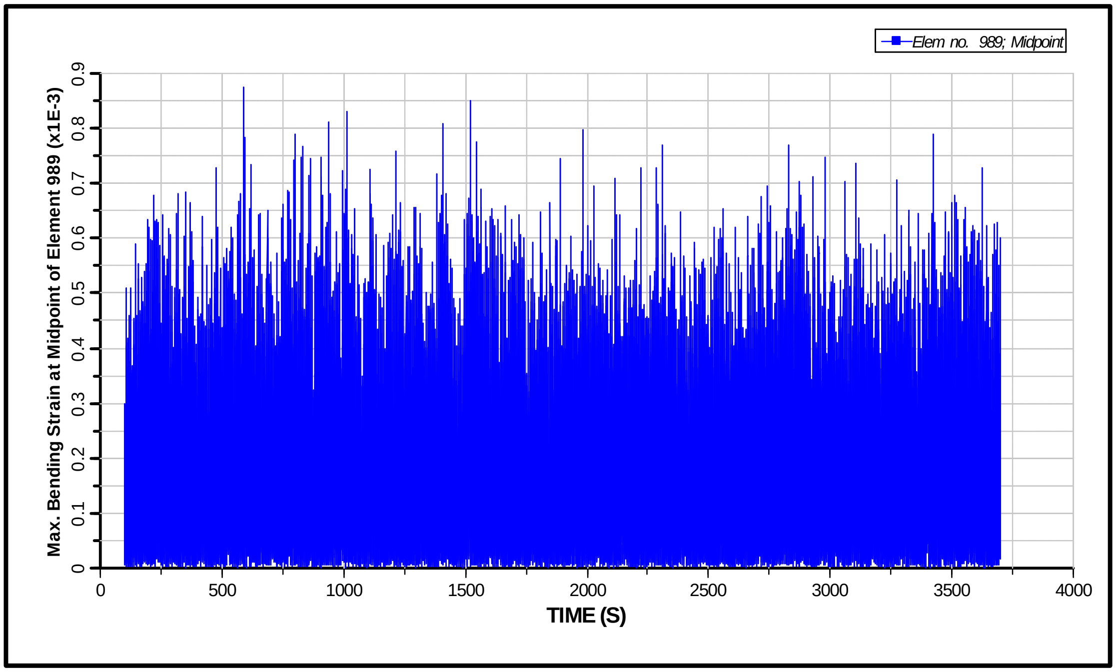


Figure 60: Maximum Bending Strain Time History at Top of CWP for Bin 3

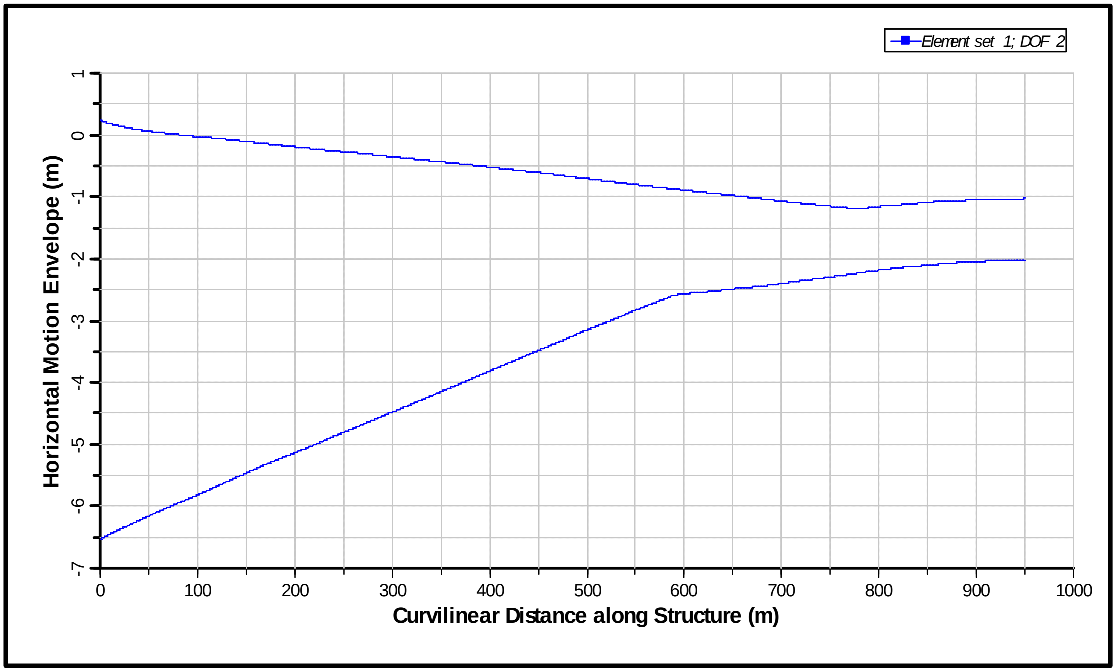


Figure 61: Motion Envelope for 1000 m CWP for Bin 3 (from Bottom to Top)

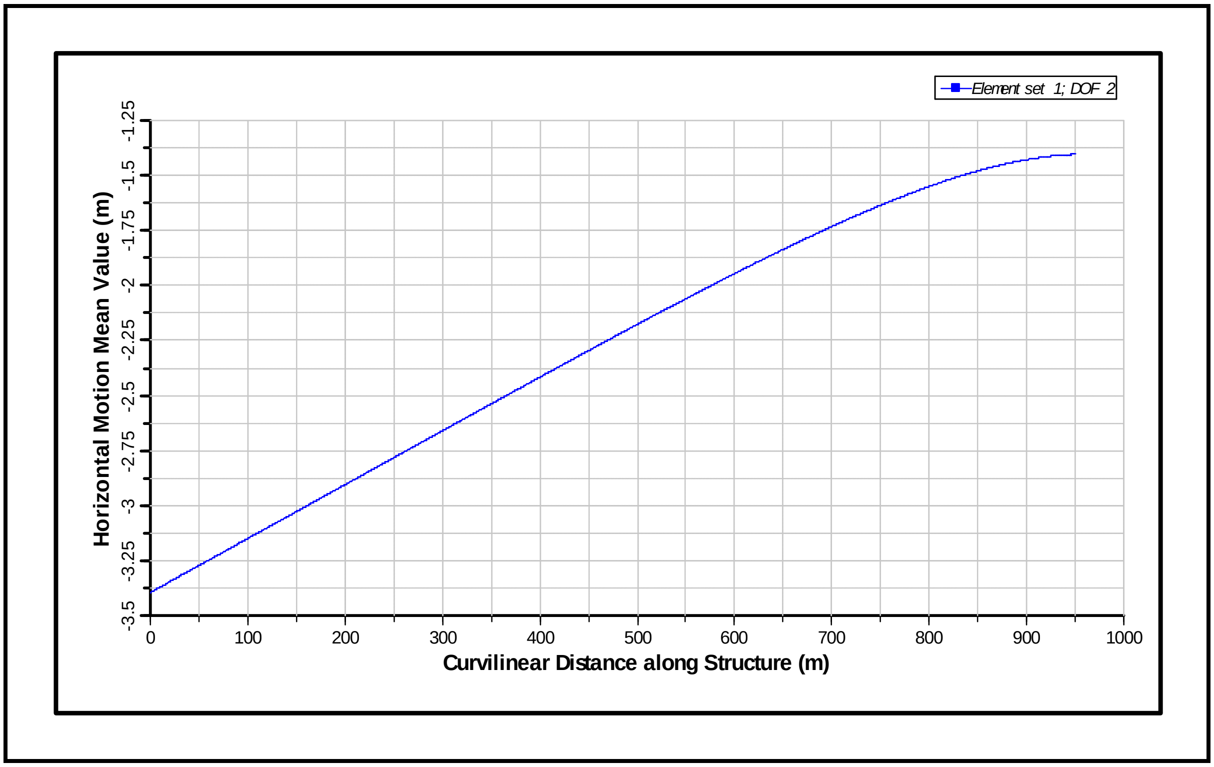


Figure 62: Mean Motion for 1000 m CWP for Bin 3 (from Bottom to Top)

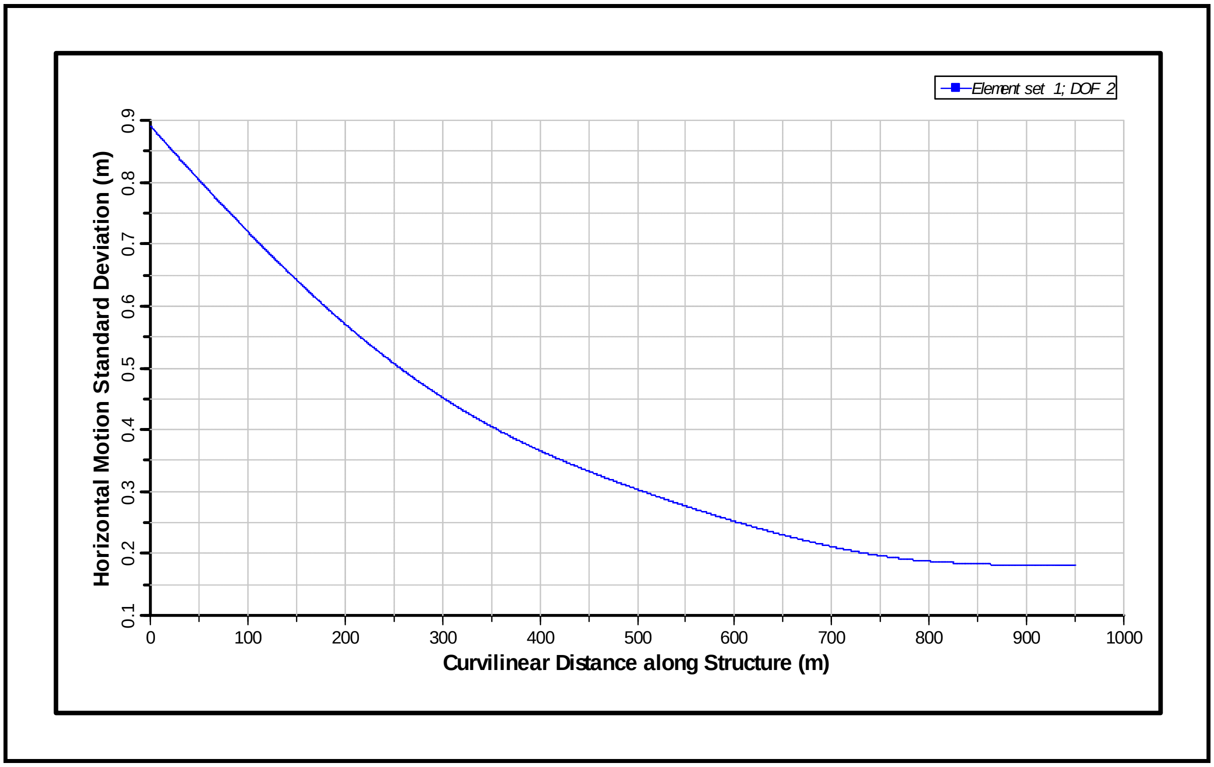


Figure 63: Standard Deviation of Motion for 1000 m CWP for Bin 3 (from Bottom to Top)

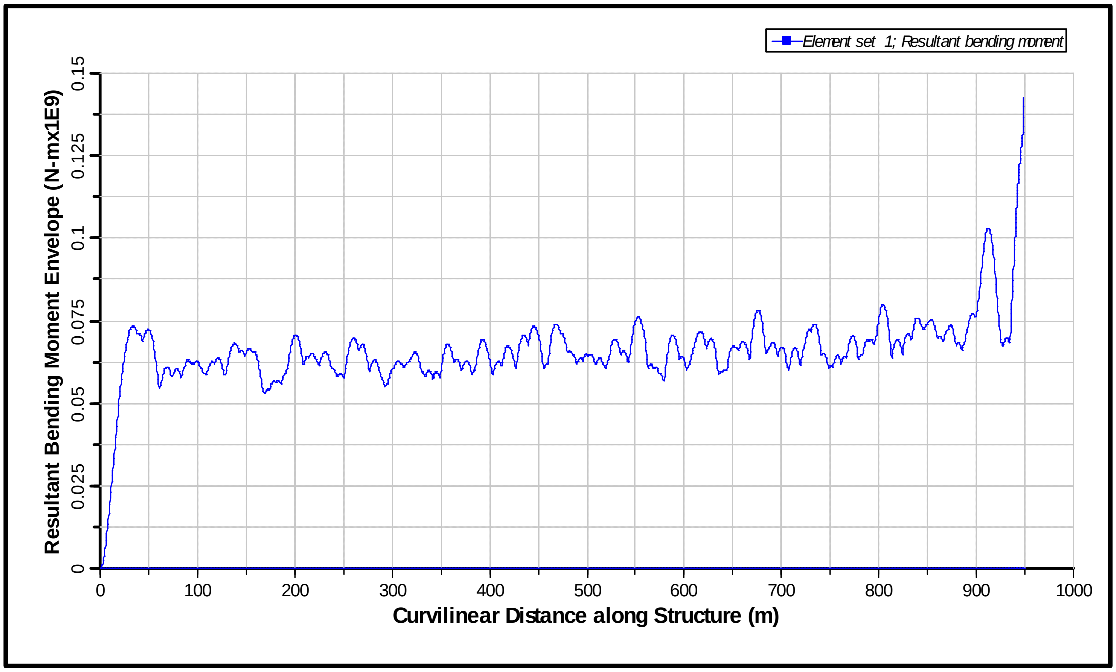


Figure 64: Bending Moment Envelope for 1000 m CWP for Bin 3 (from Bottom to Top)

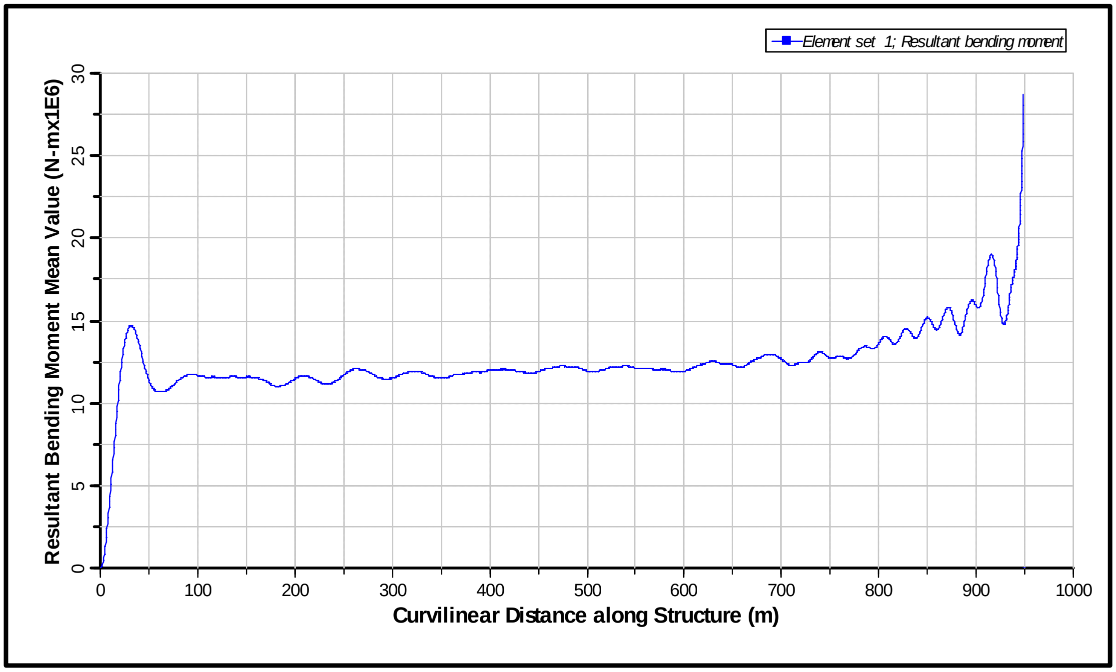


Figure 65: Mean Bending Moment for 1000 m CWP for Bin 3 (from Bottom to Top)

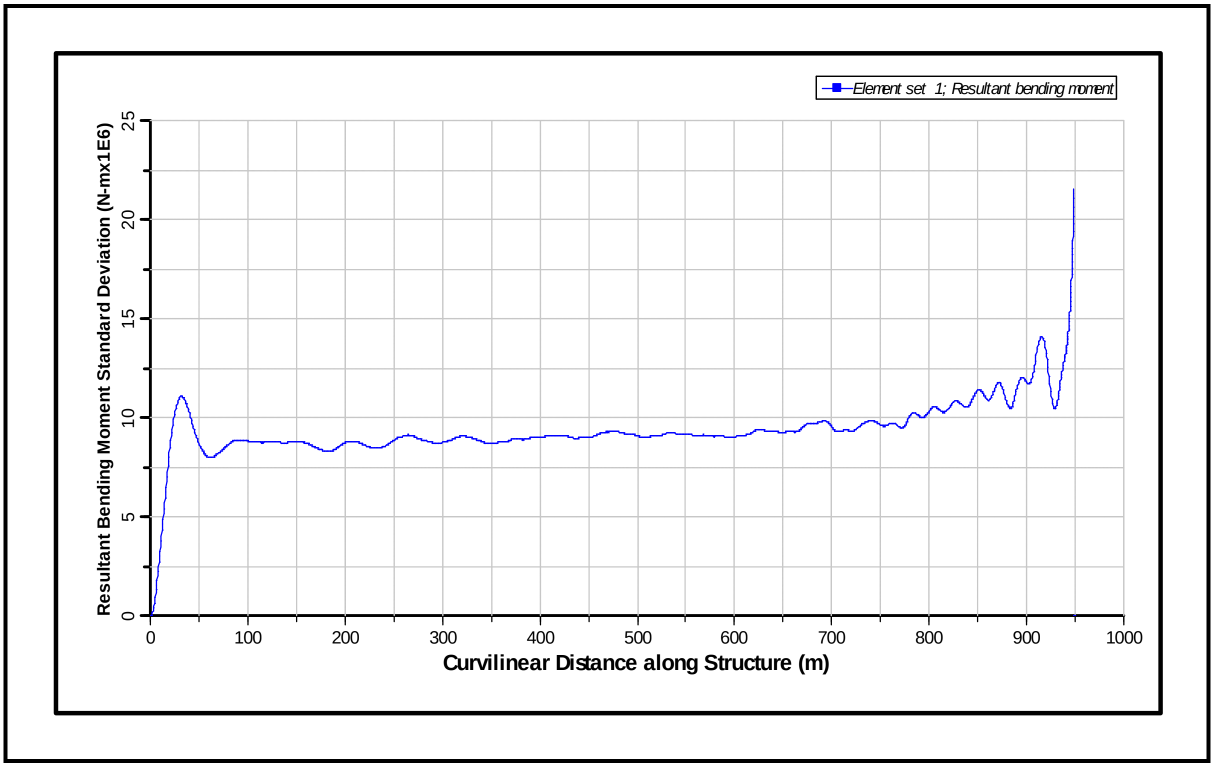


Figure 66: Standard Deviation of Bending Moment for 1000 m CWP for Bin 3 (from Bottom to Top)

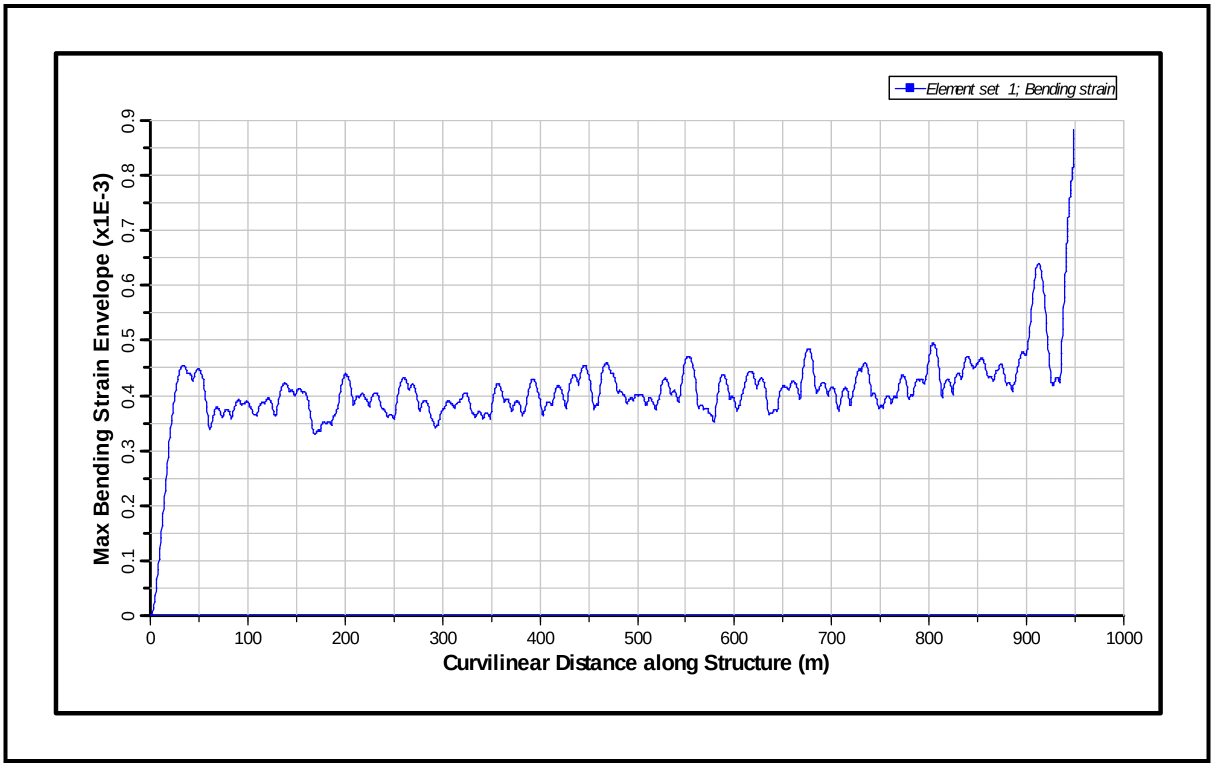


Figure 67: Bending Strain Envelope for 1000 m CWP for Bin 3 (from Bottom to Top)

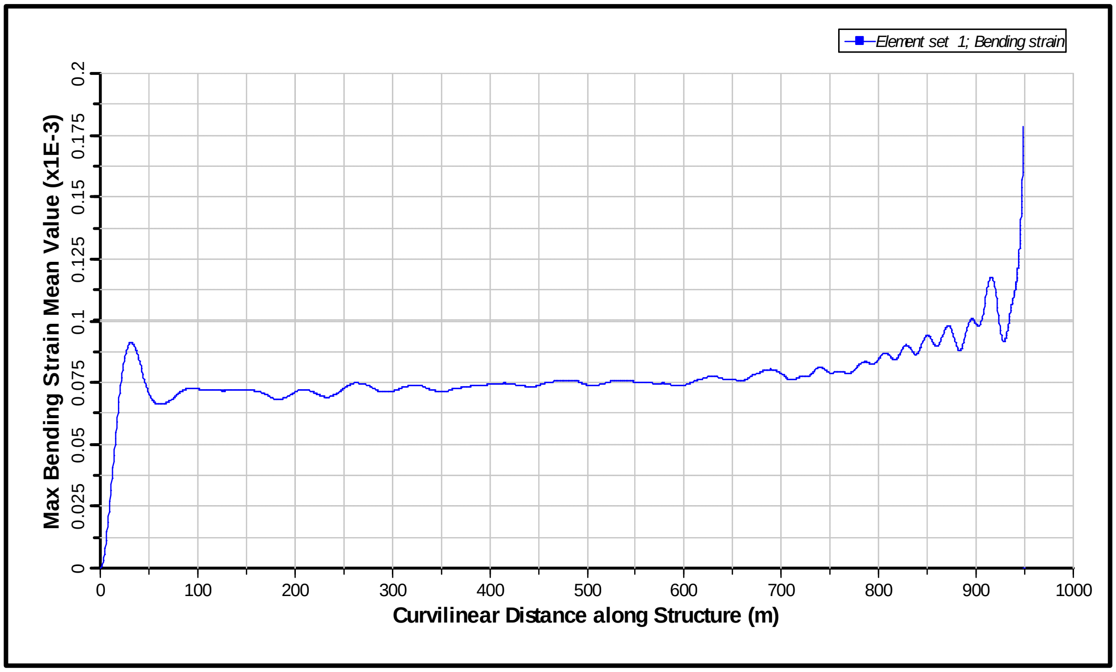


Figure 68: Mean Bending Strain for 1000 m CWP for Bin 3 (from Bottom to Top)

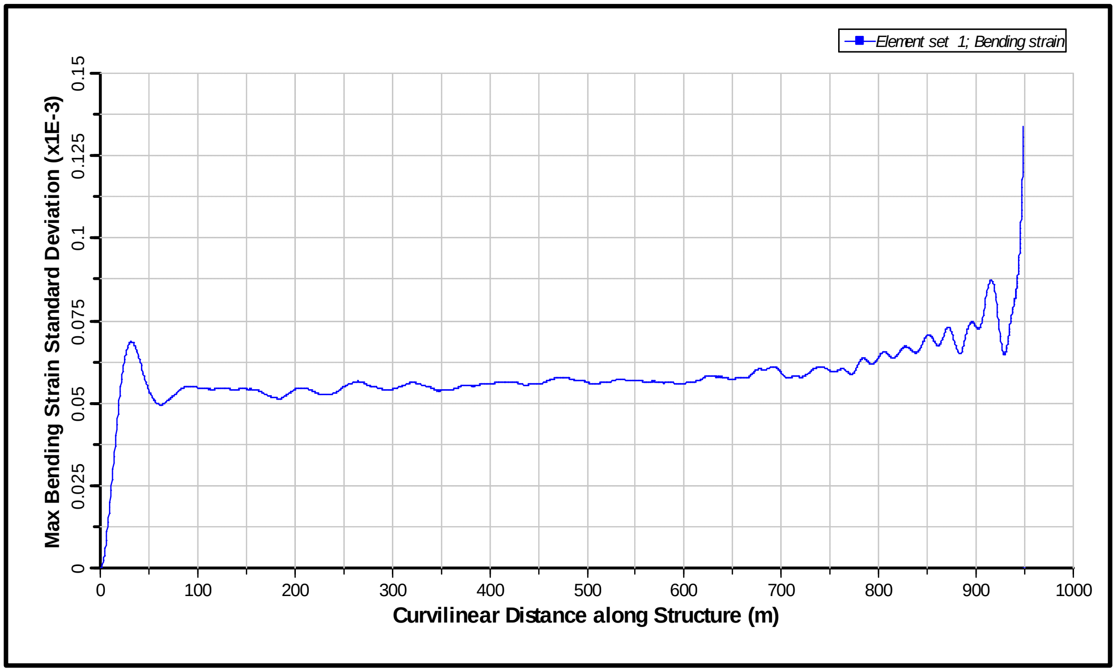


Figure 69: Standard Deviation of Bending Strain for 1000 m CWP for Bin 3 (from Bottom to Top)

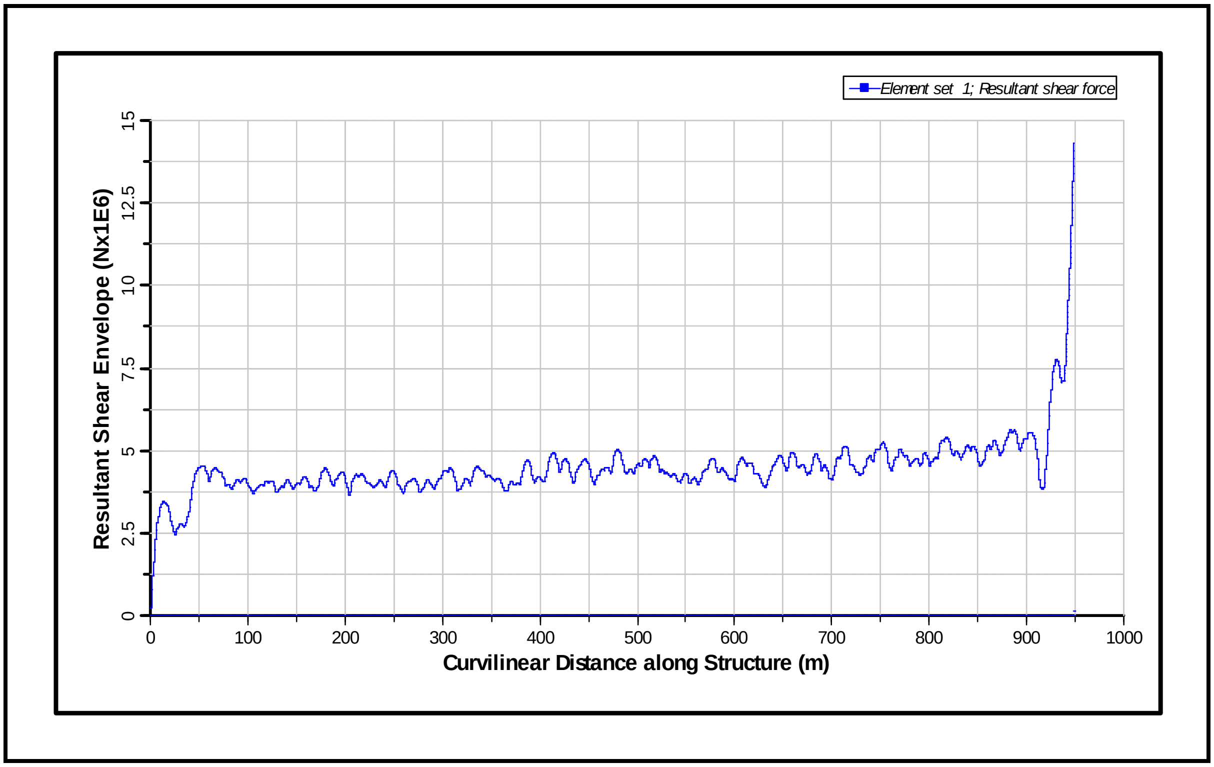


Figure 70: Shear Force Envelope for 1000 m CWP for Bin 3 (from Bottom to Top)

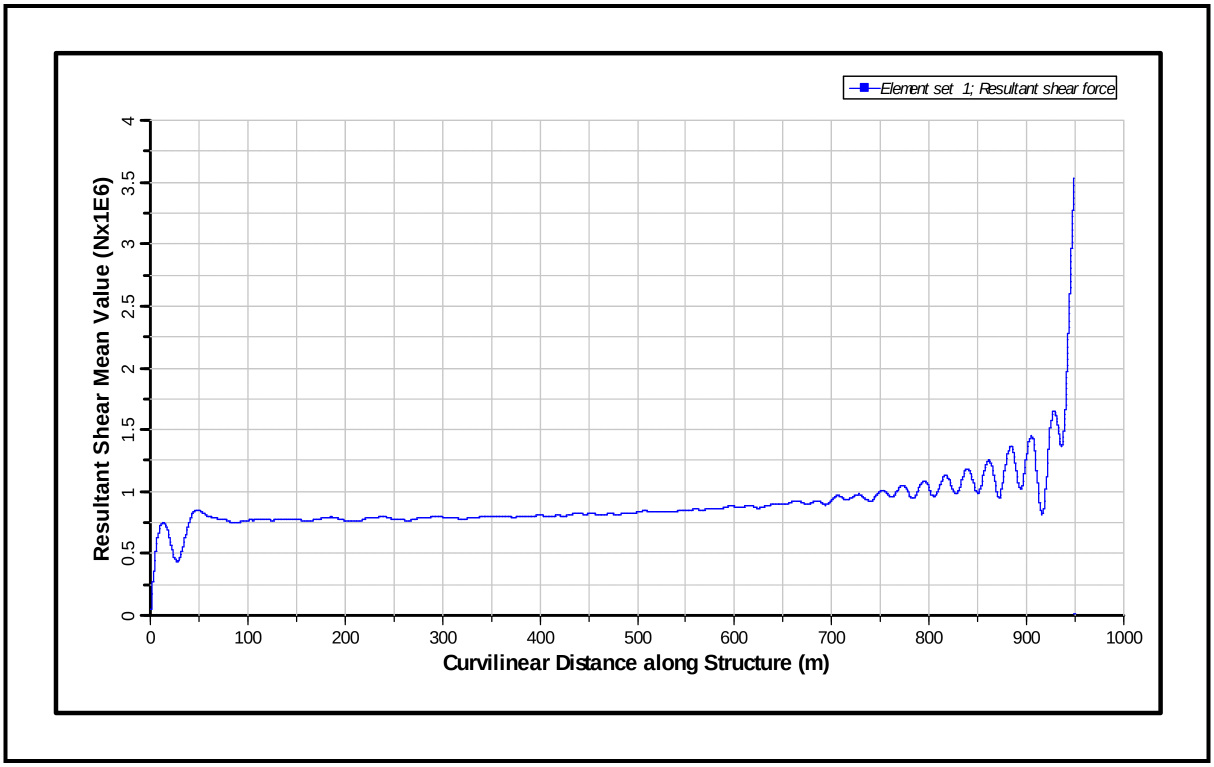


Figure 71: Mean Shear Force for 1000 m CWP for Bin 3 (from Bottom to Top)

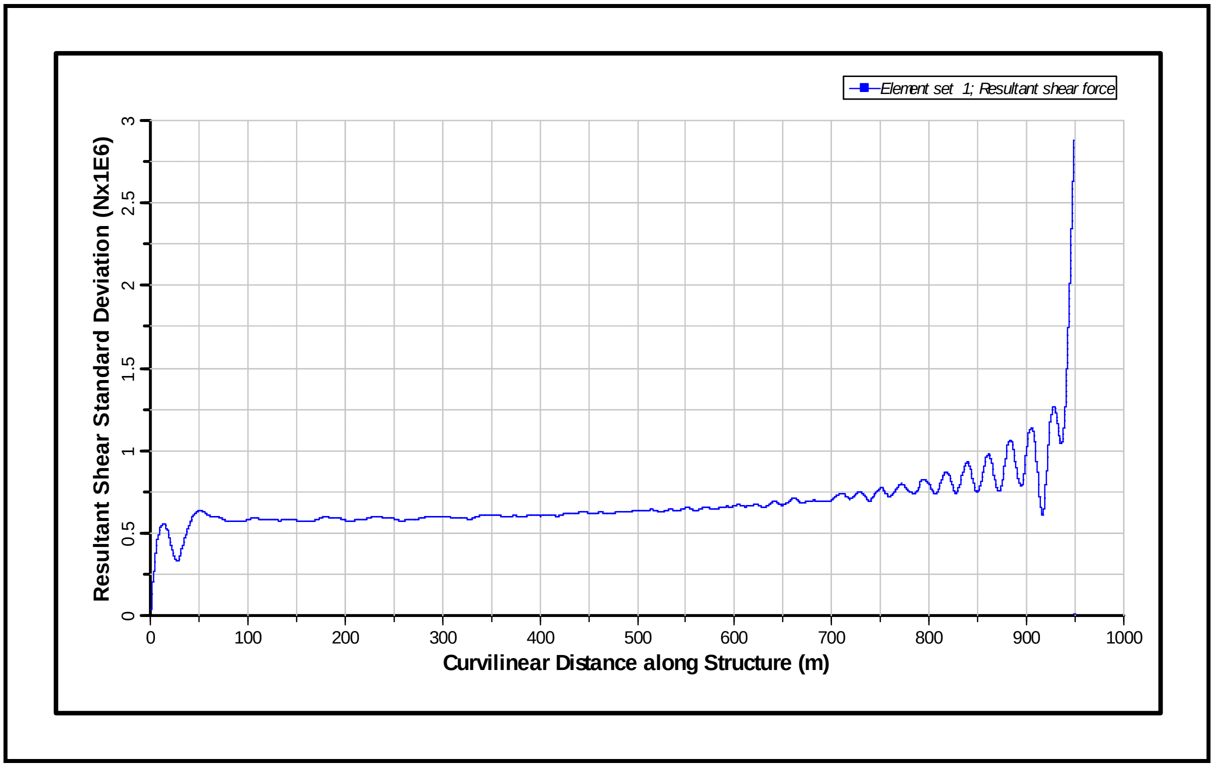


Figure 72: Standard Deviation of Shear Force for 1000 m CWP for Bin 3 (from Bottom to Top)

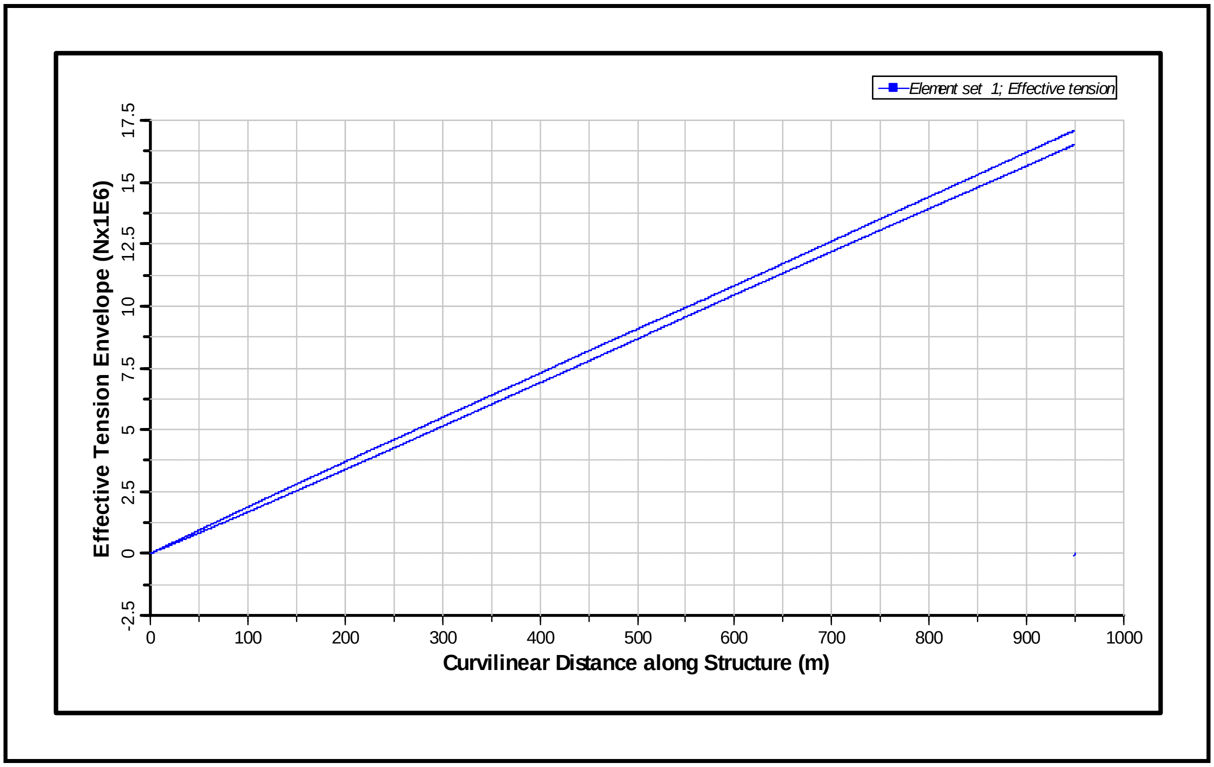


Figure 73: Axial Tension Envelope for 1000 m CWP for Bin 3 (from Bottom to Top)

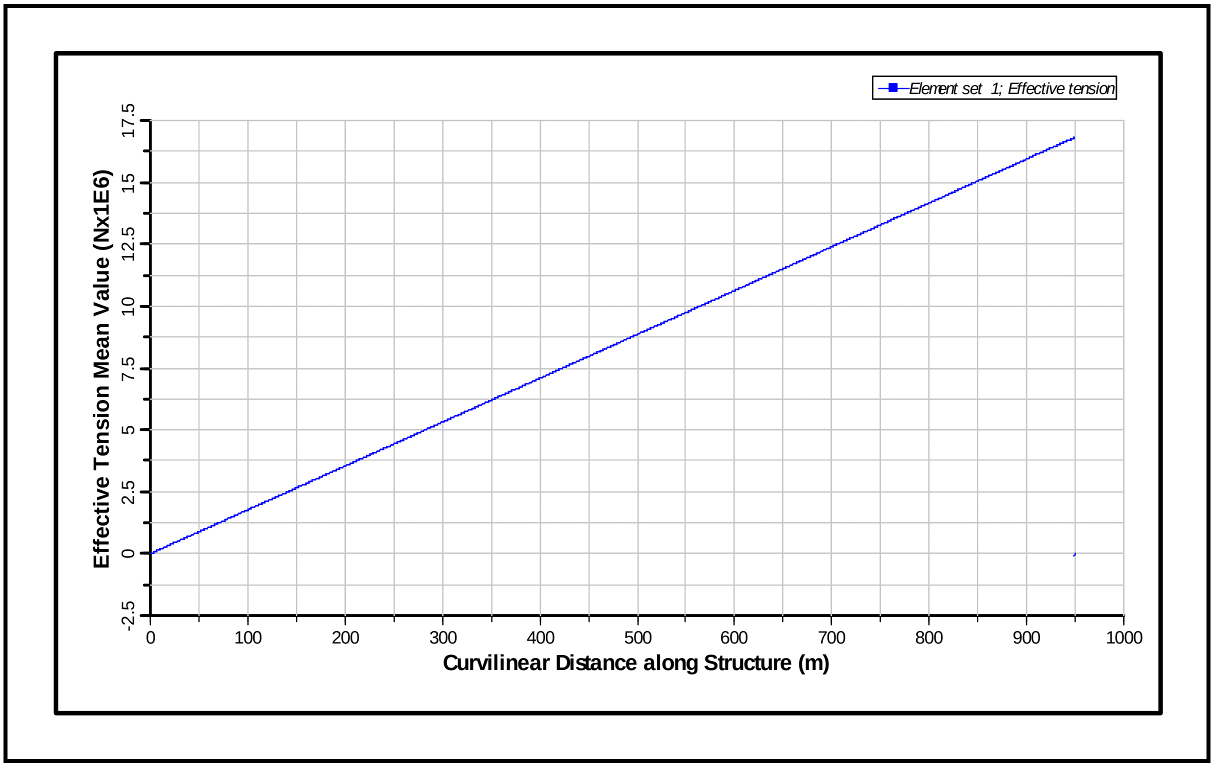


Figure 74: Mean Axial Tension for 1000 m CWP for Bin 3 (from Bottom to Top)

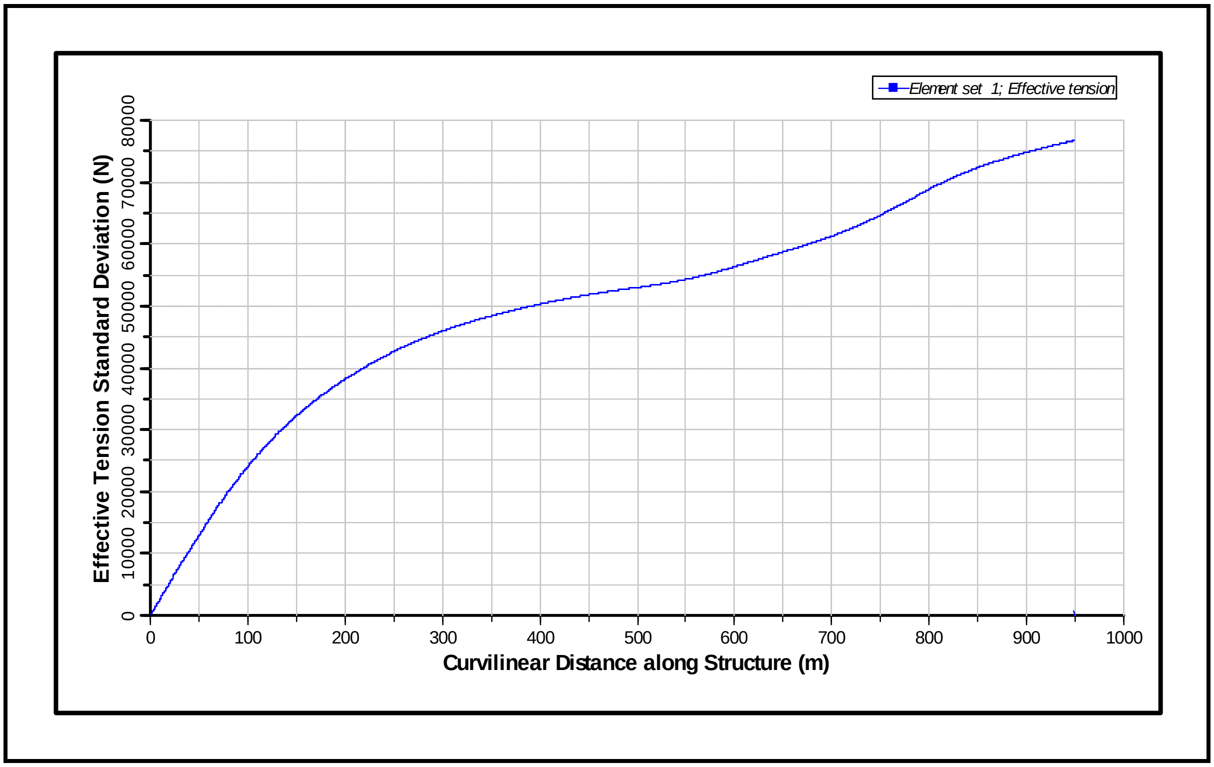


Figure 75: Standard Deviation of Axial Tension for 1000 m CWP for Bin 3 (from Bottom to Top)

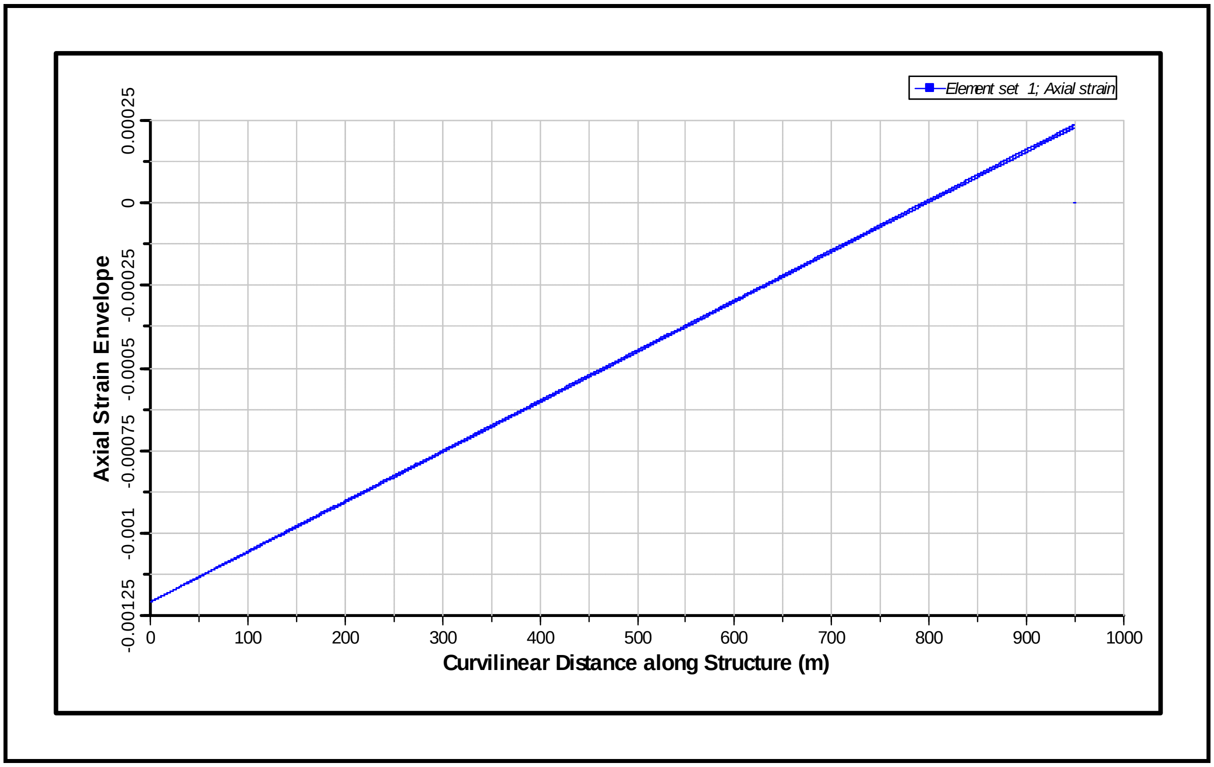


Figure 76: Axial Strain Envelope for 1000 m CWP for Bin 3 (from Bottom to Top)

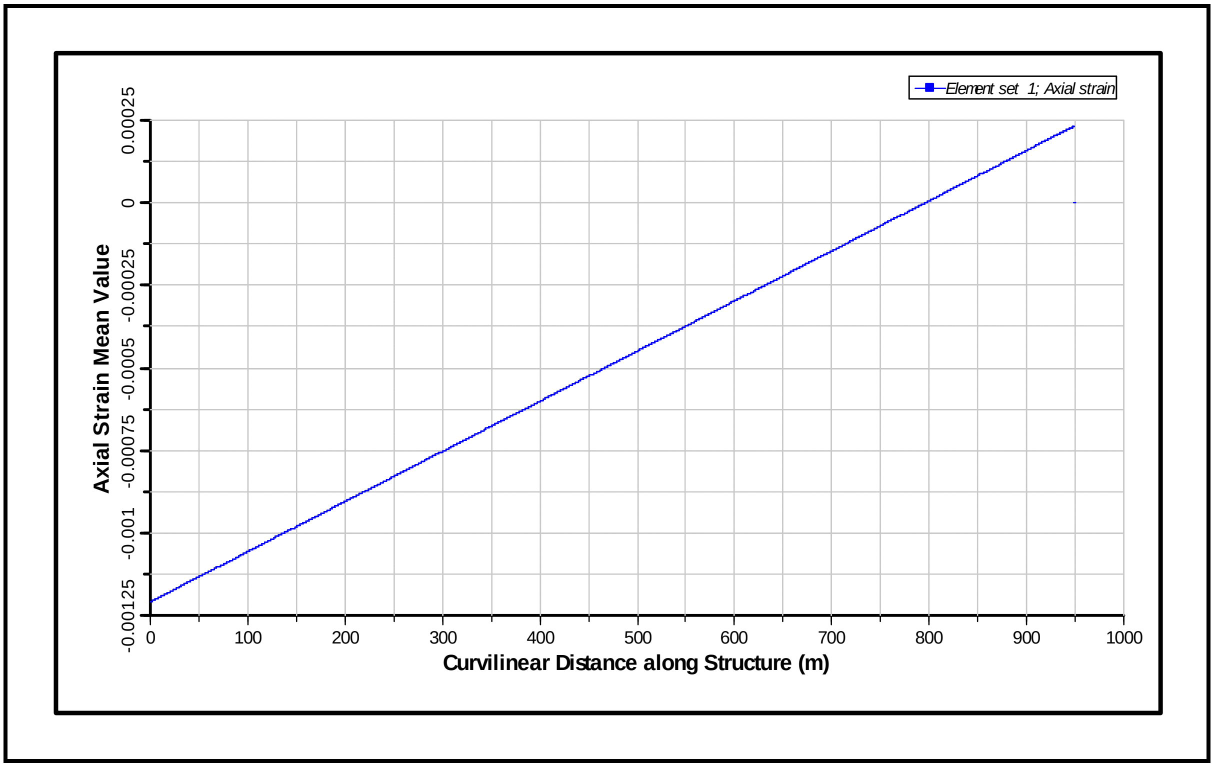


Figure 77: Mean Axial Strain for 1000 m CWP for Bin 3 (from Bottom to Top)

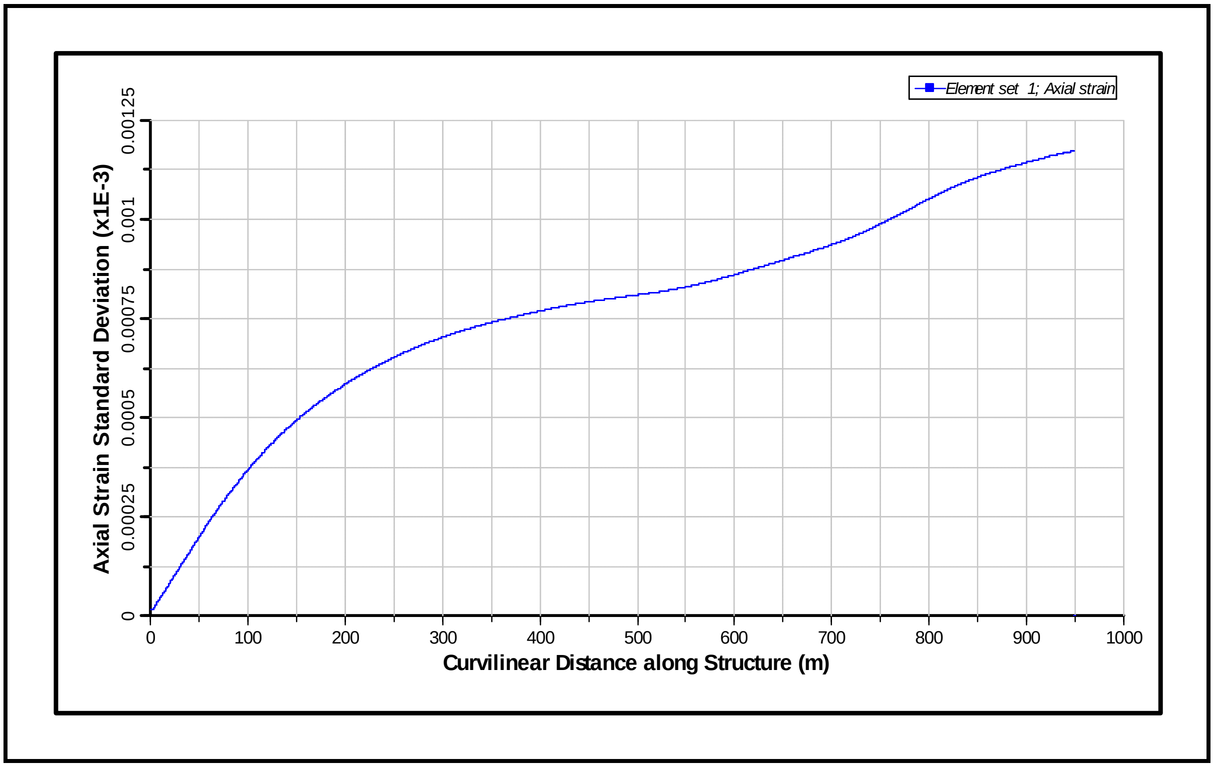


Figure 78: Standard Deviation of Axial Strain for 1000 m CWP for Bin 3 (from Bottom to Top)

6.4 Bin 4

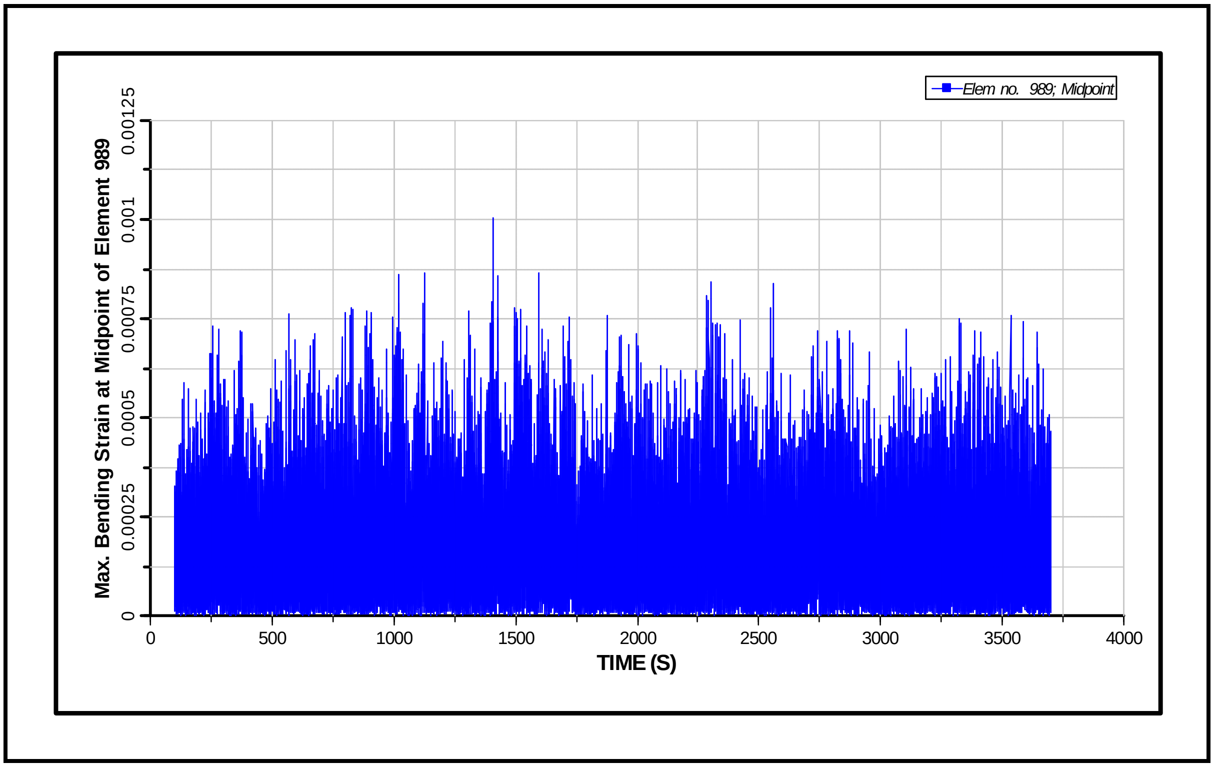


Figure 79: Maximum Bending Strain Time History at Top of CWP for Bin 4

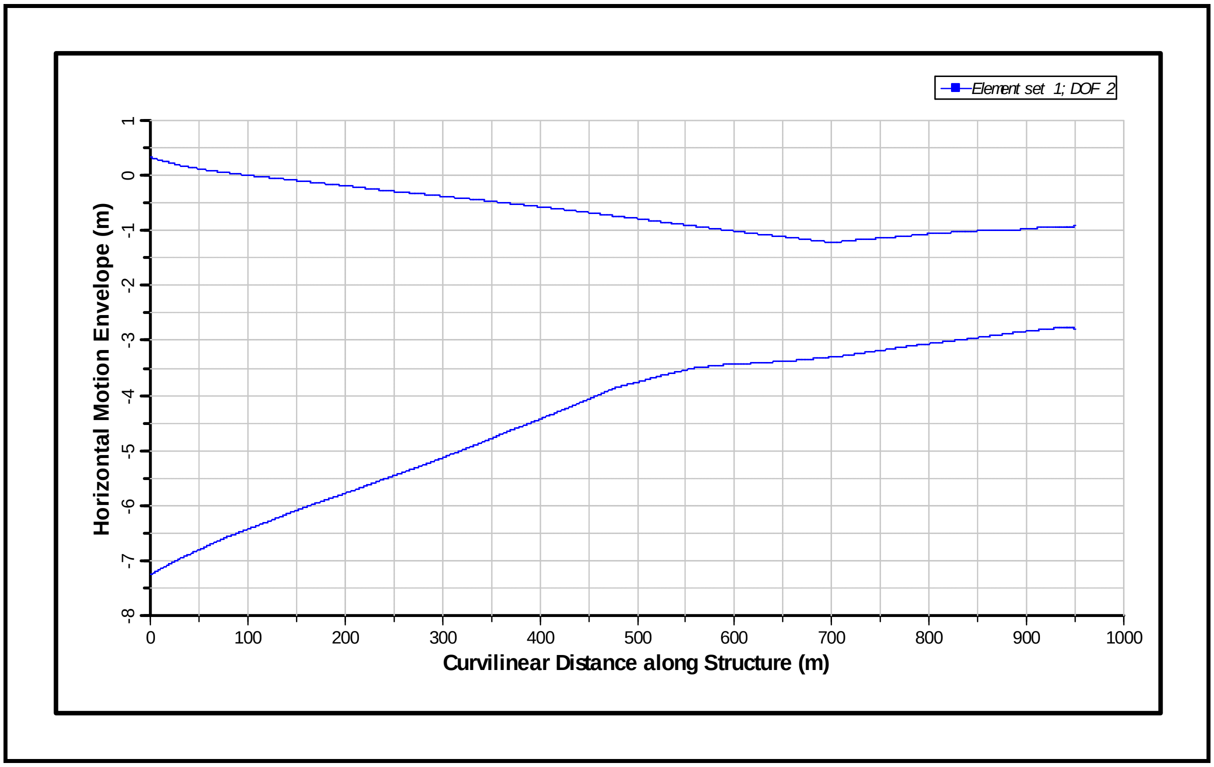


Figure 80: Motion Envelope for 1000 m CWP for Bin 4 (from Bottom to Top)

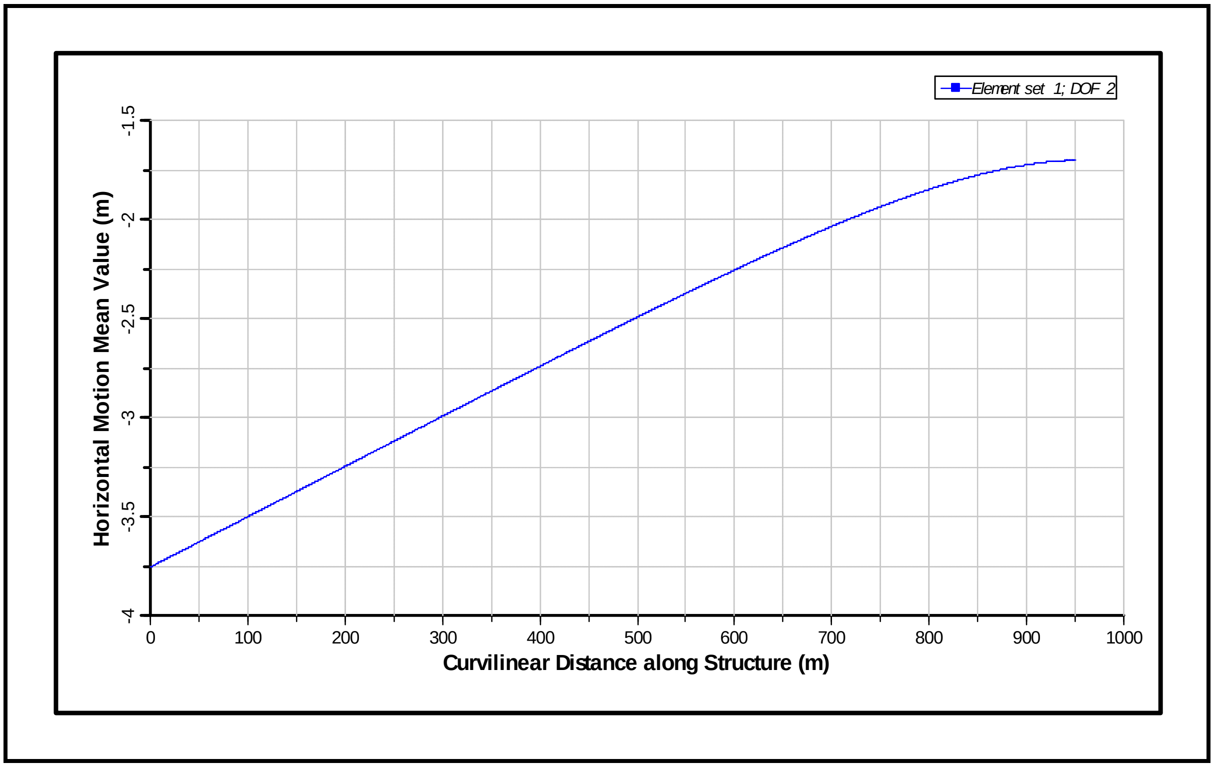


Figure 81: Mean Motion for 1000 m CWP for Bin 4 (from Bottom to Top)

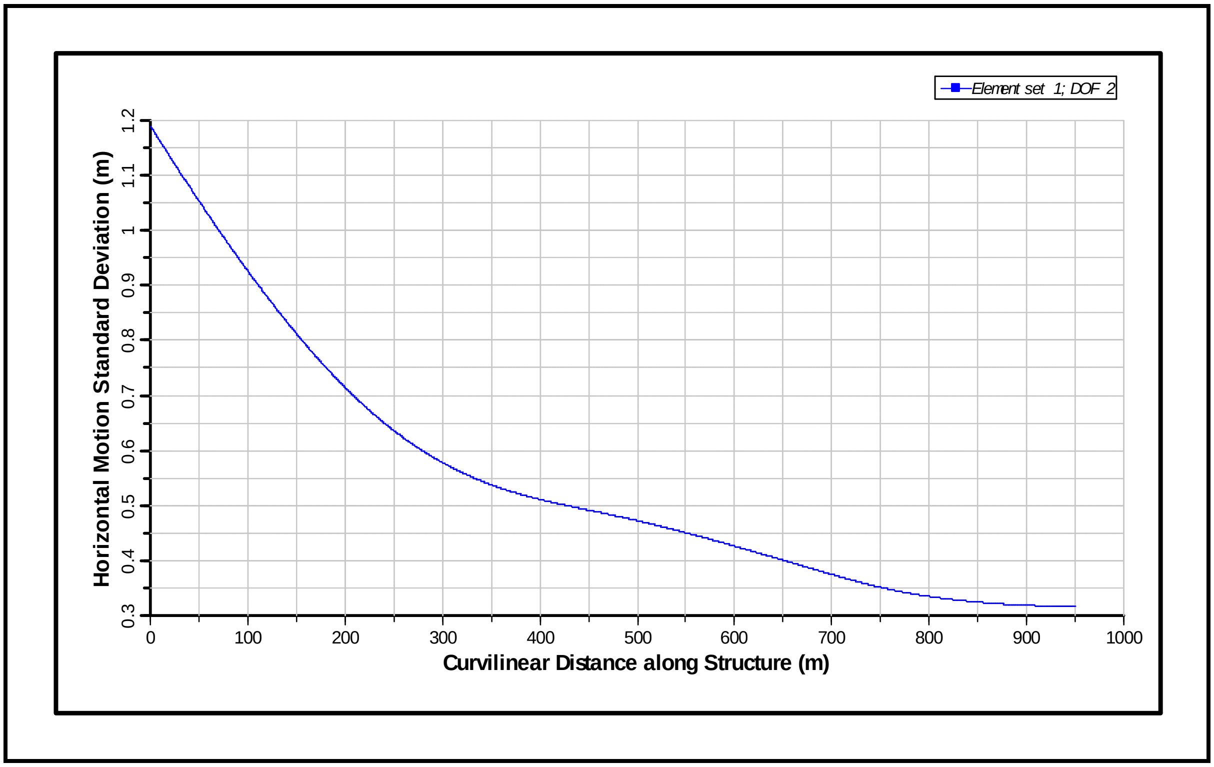


Figure 82: Standard Deviation of Motion for 1000 m CWP for Bin 4 (from Bottom to Top)

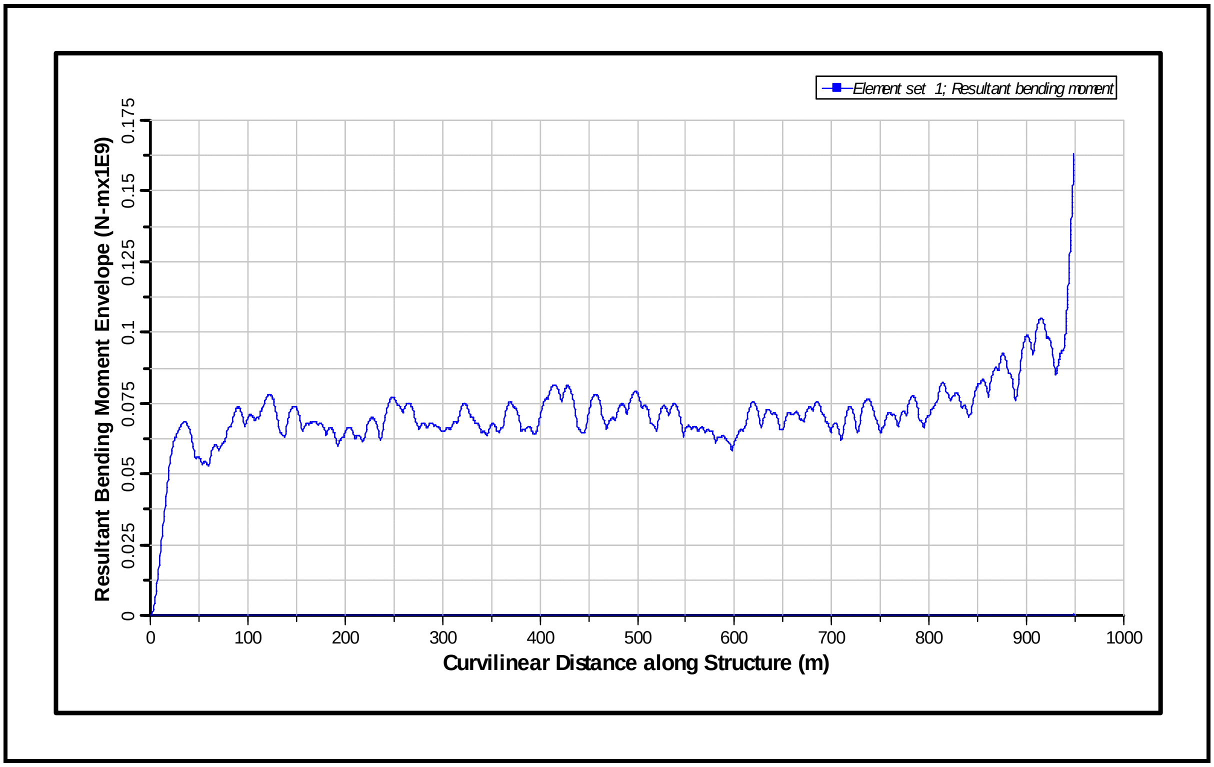


Figure 83: Bending Moment Envelope for 1000 m CWP for Bin 4 (from Bottom to Top)

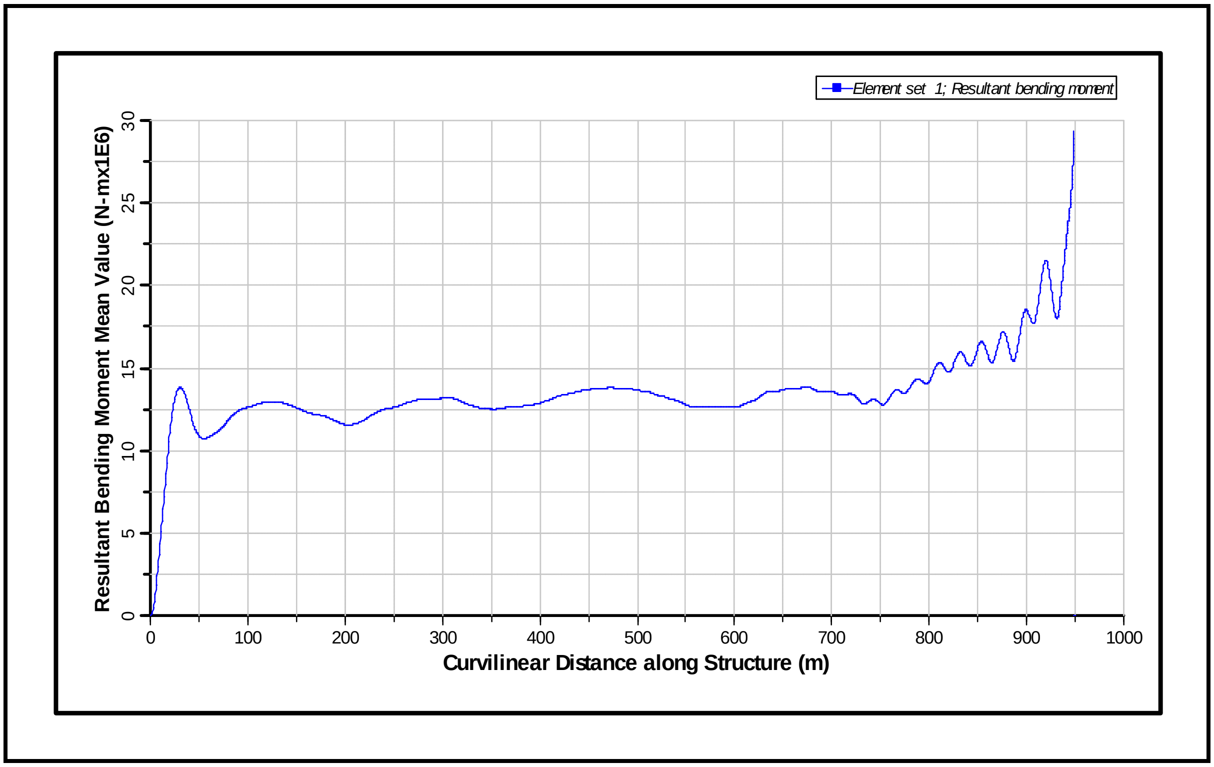


Figure 84: Mean Bending Moment for 1000 m CWP for Bin 4 (from Bottom to Top)

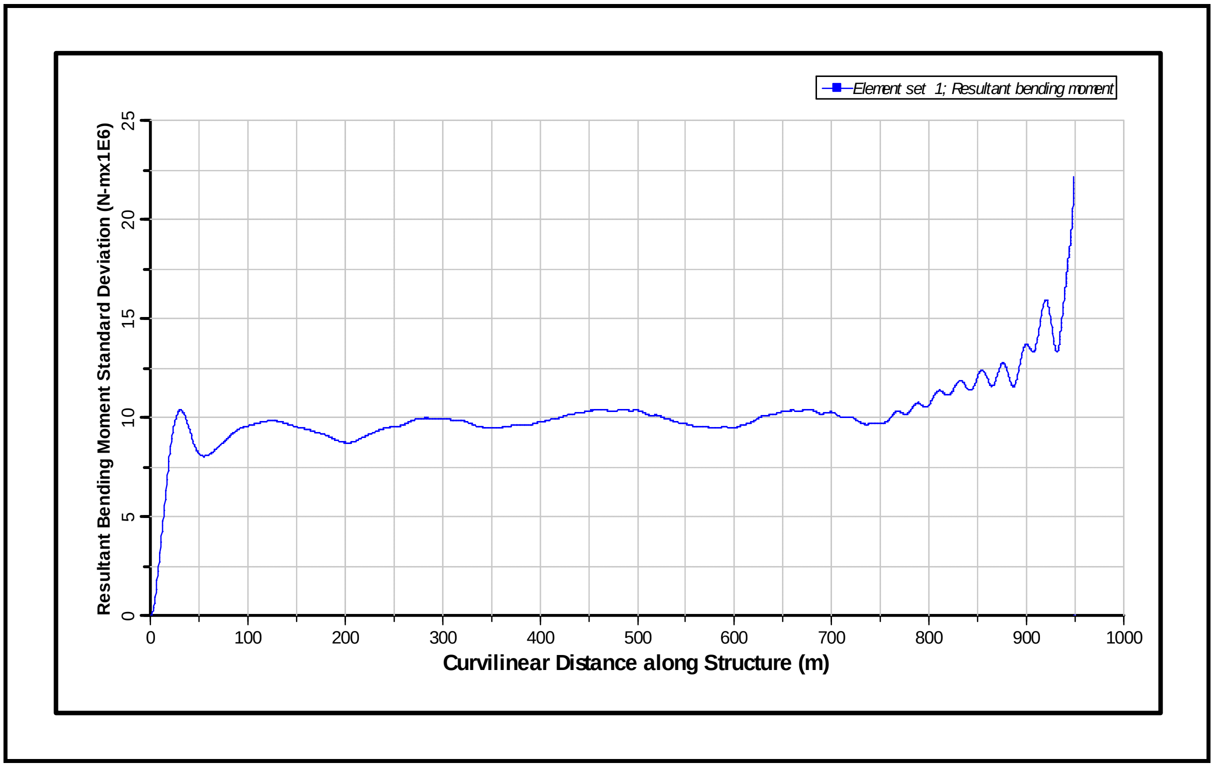


Figure 85: Standard Deviation of Bending Moment for 1000 m CWP for Bin 4 (from Bottom to Top)

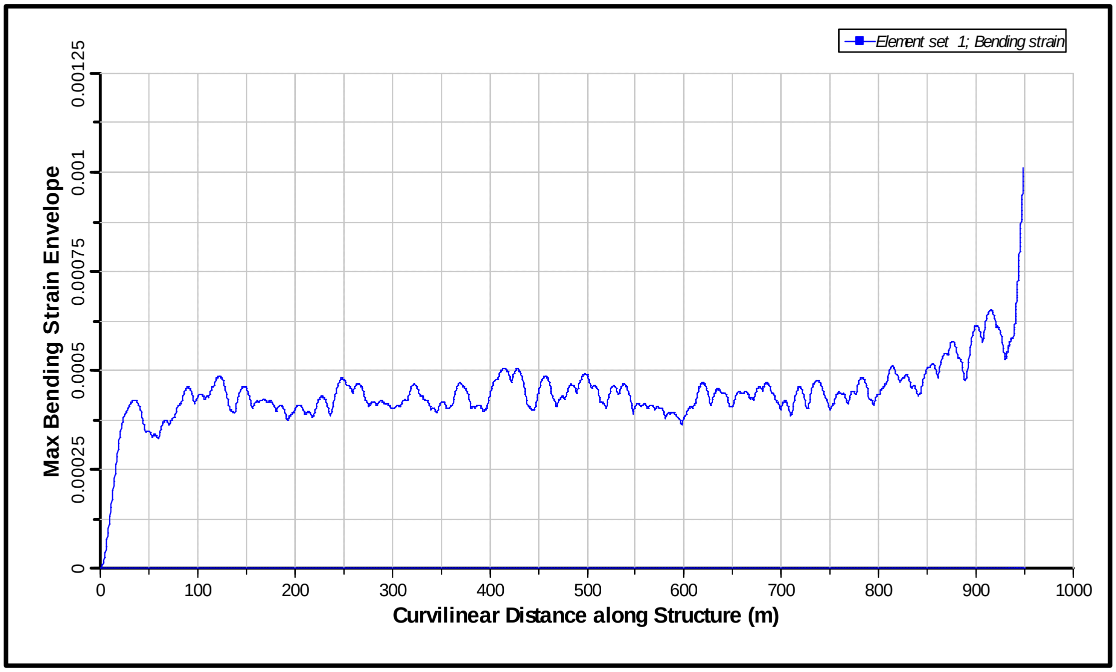


Figure 86: Bending Strain Envelope for 1000 m CWP for Bin 4 (from Bottom to Top)

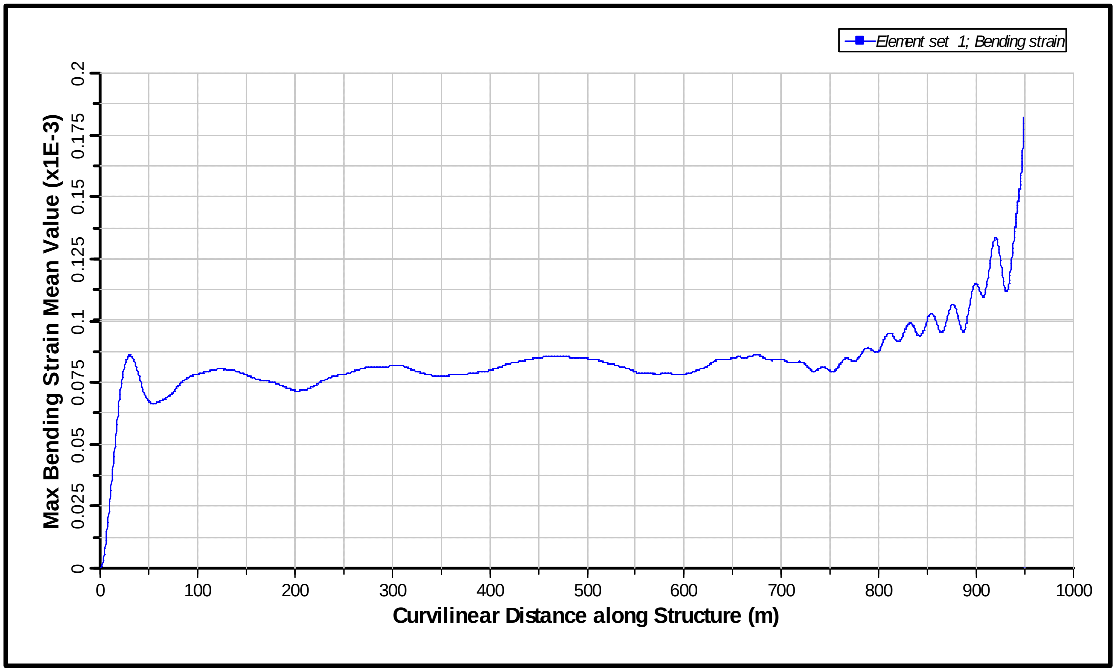


Figure 87: Mean Bending Strain for 1000 m CWP for Bin 4 (from Bottom to Top)

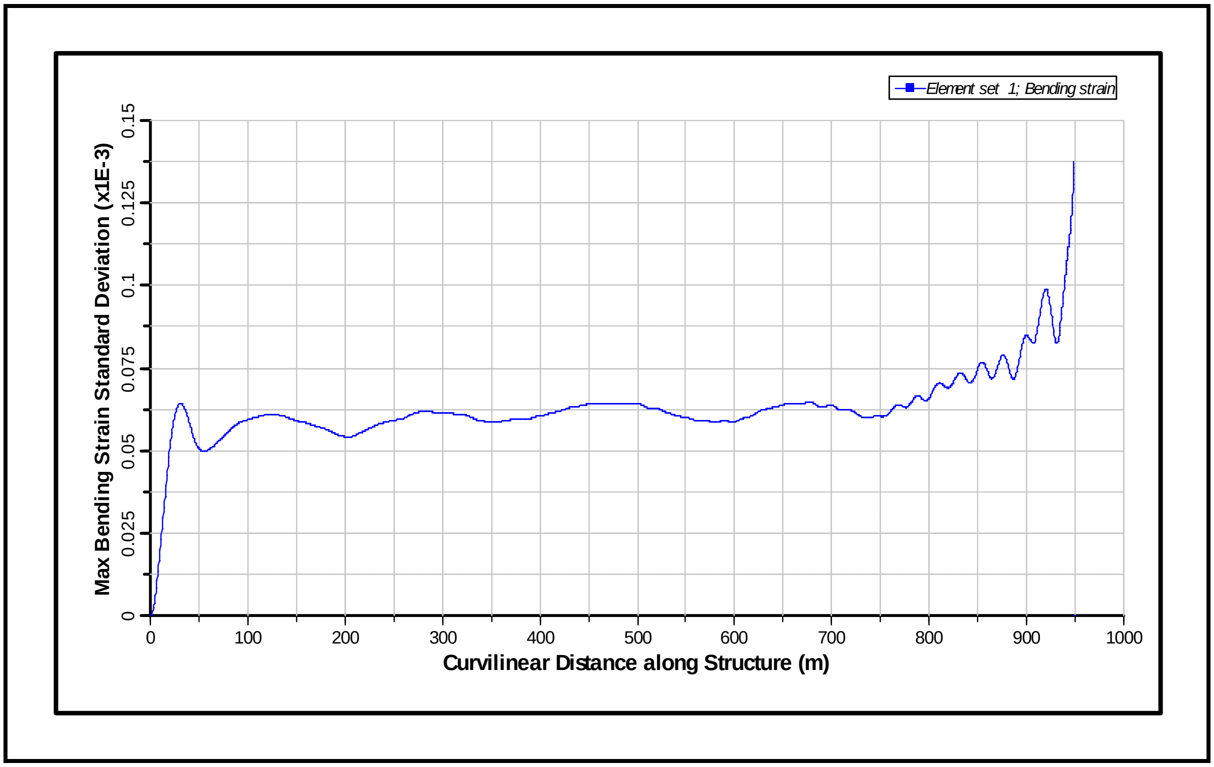


Figure 88: Standard Deviation of Bending Strain for 1000 m CWP for Bin 4 (from Bottom to Top)

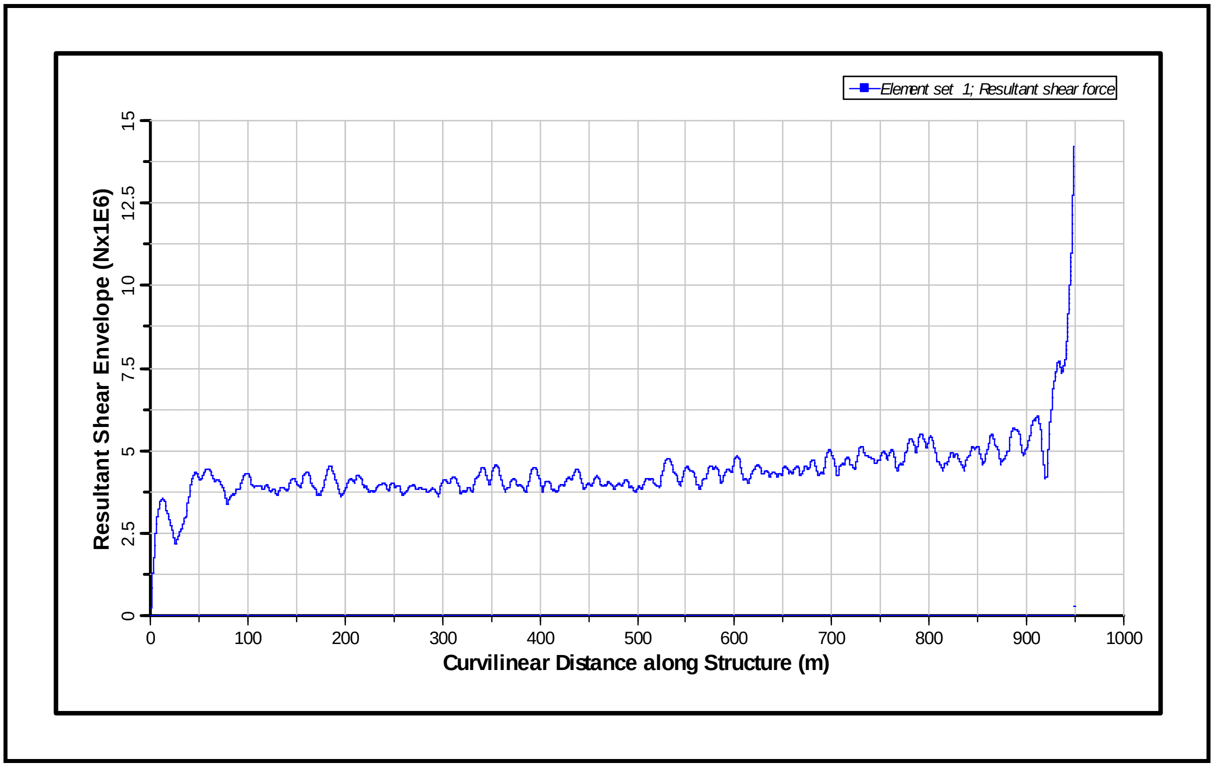


Figure 89: Shear Force Envelope for 1000 m CWP for Bin 4 (from Bottom to Top)

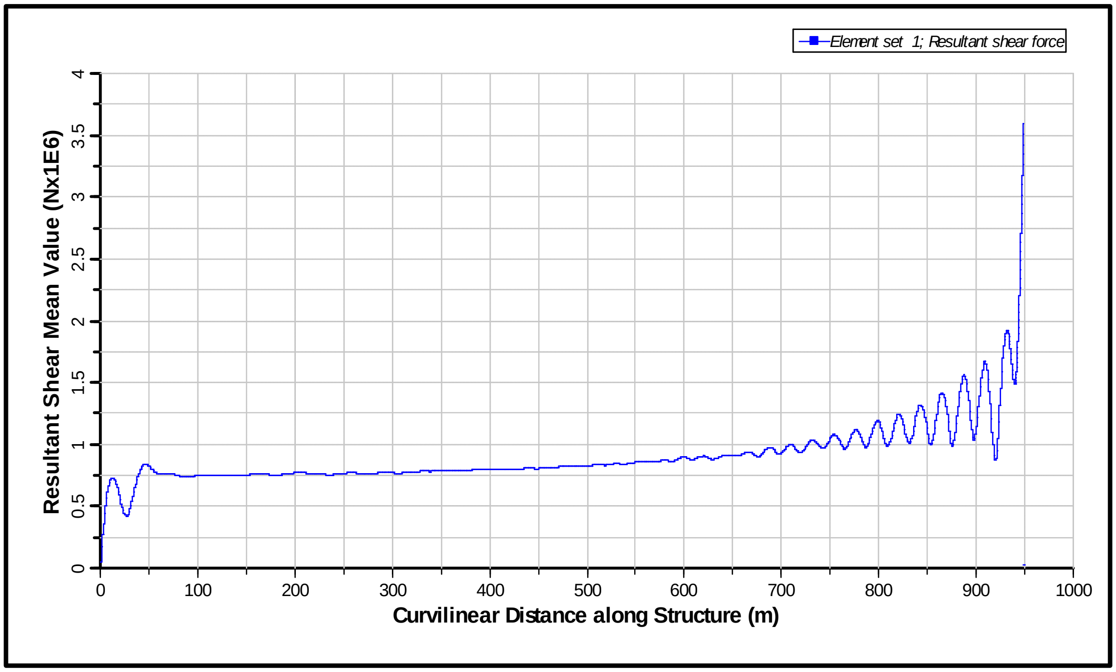


Figure 90: Mean Shear Force for 1000 m CWP for Bin 4 (from Bottom to Top)

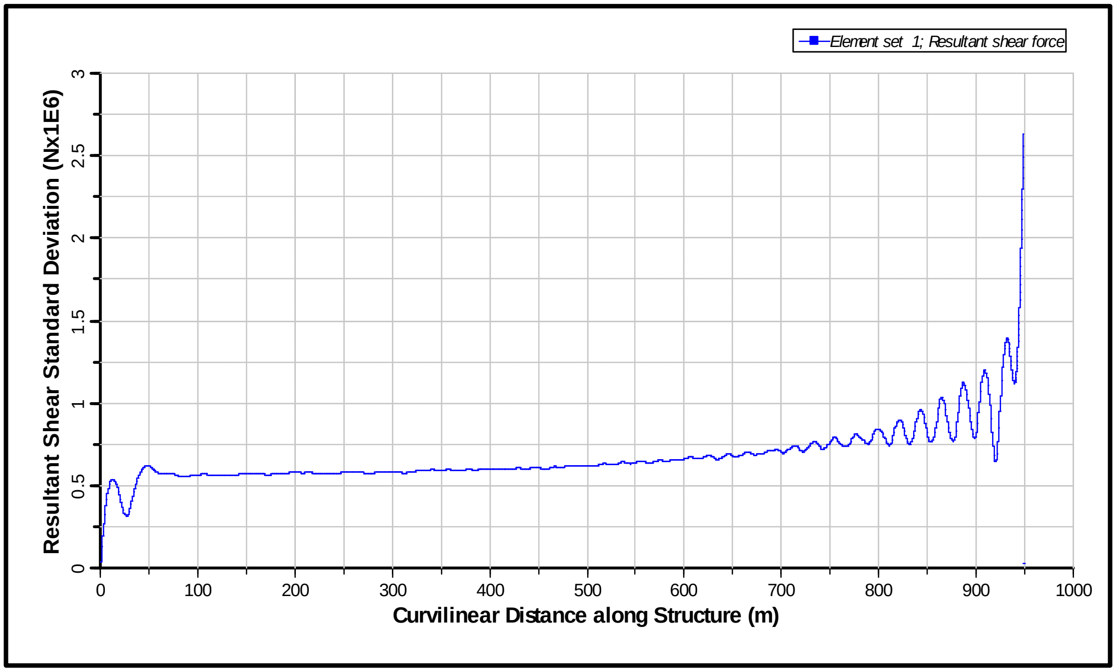


Figure 91: Standard Deviation of Shear Force for 1000 m CWP for Bin 4 (from Bottom to Top)

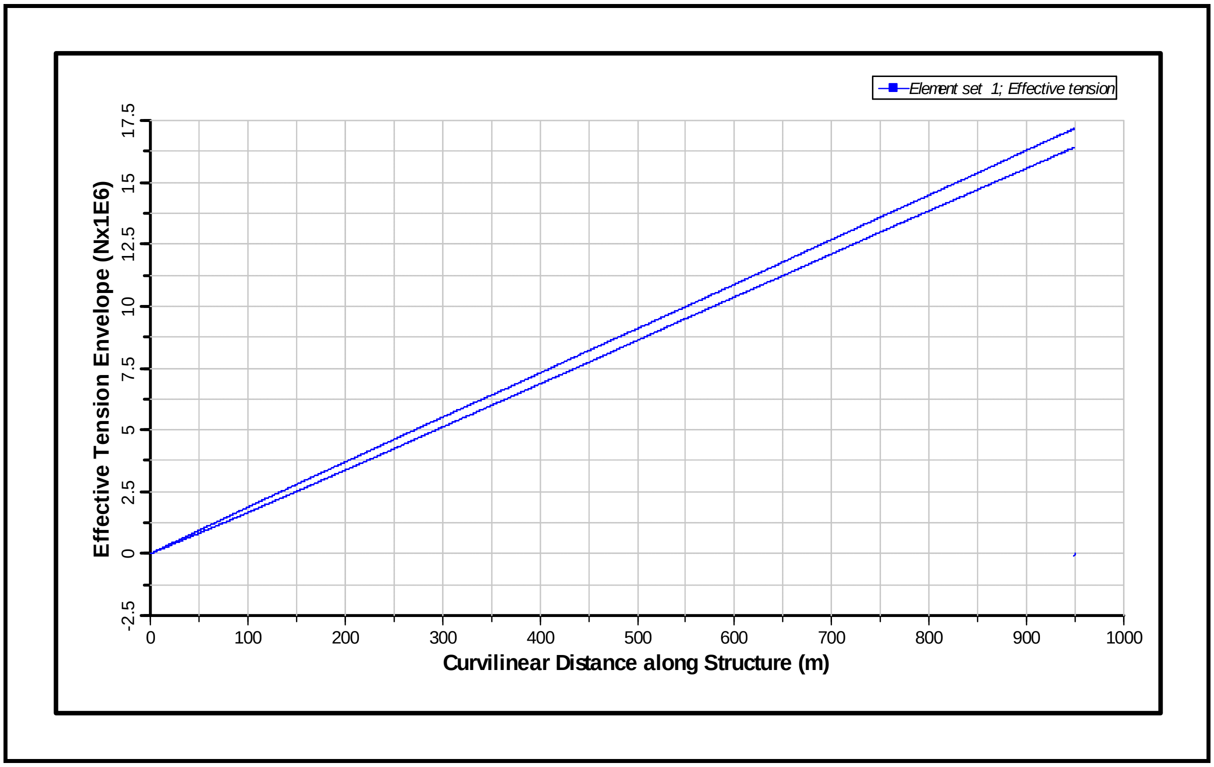


Figure 92: Axial Tension Envelope for 1000 m CWP for Bin 4 (from Bottom to Top)

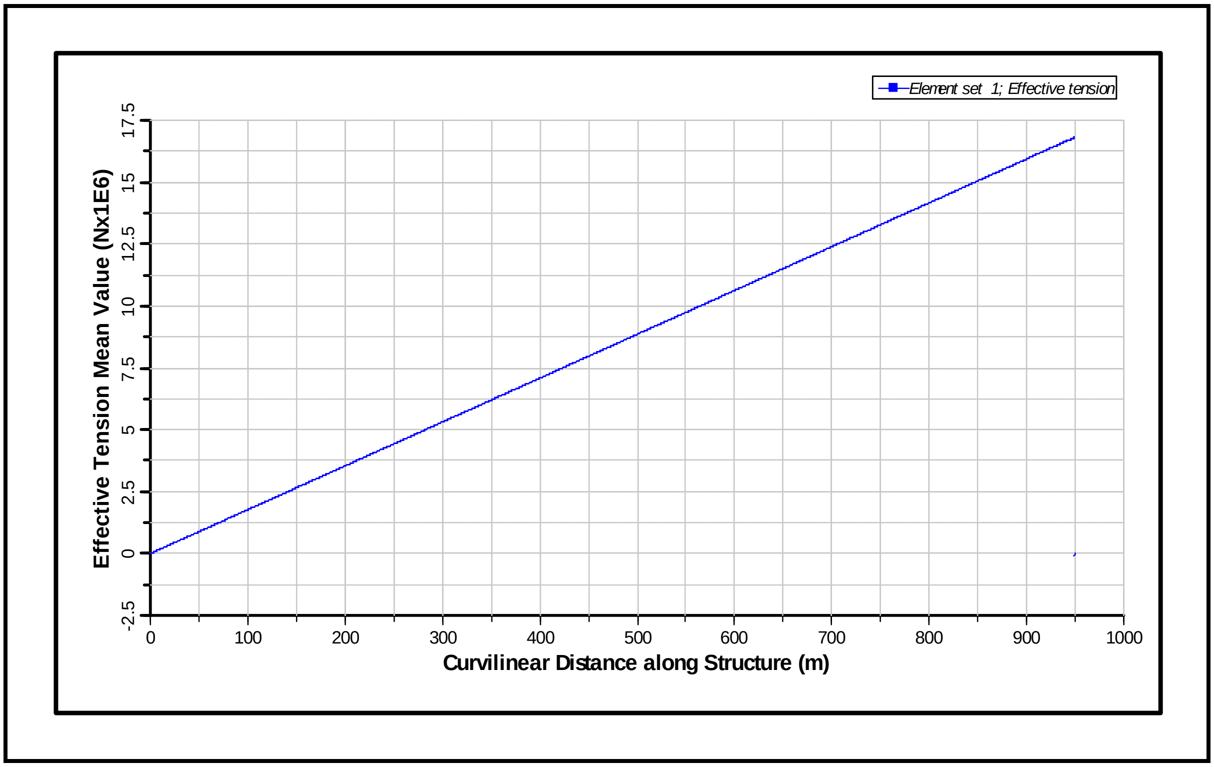


Figure 93: Mean Axial Tension for 1000 m CWP for Bin 4 (from Bottom to Top)

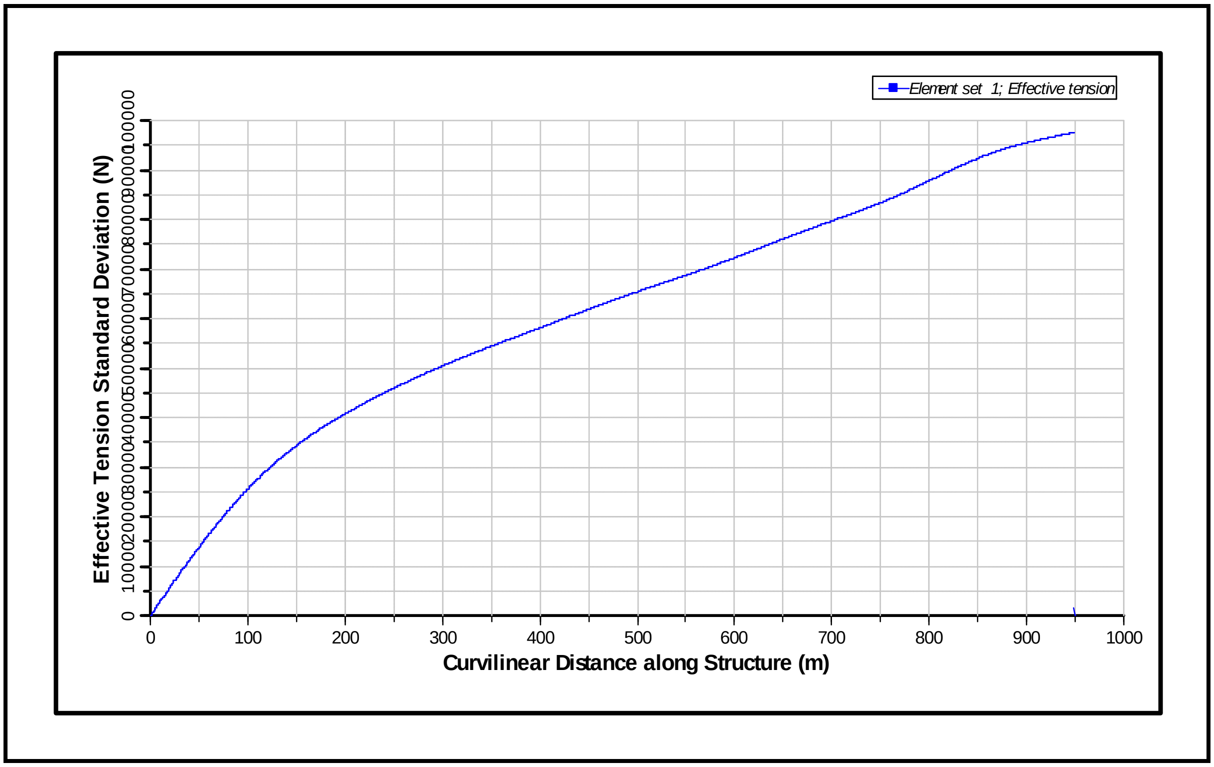


Figure 94: Standard Deviation of Axial Tension for 1000 m CWP for Bin 4 (from Bottom to Top)

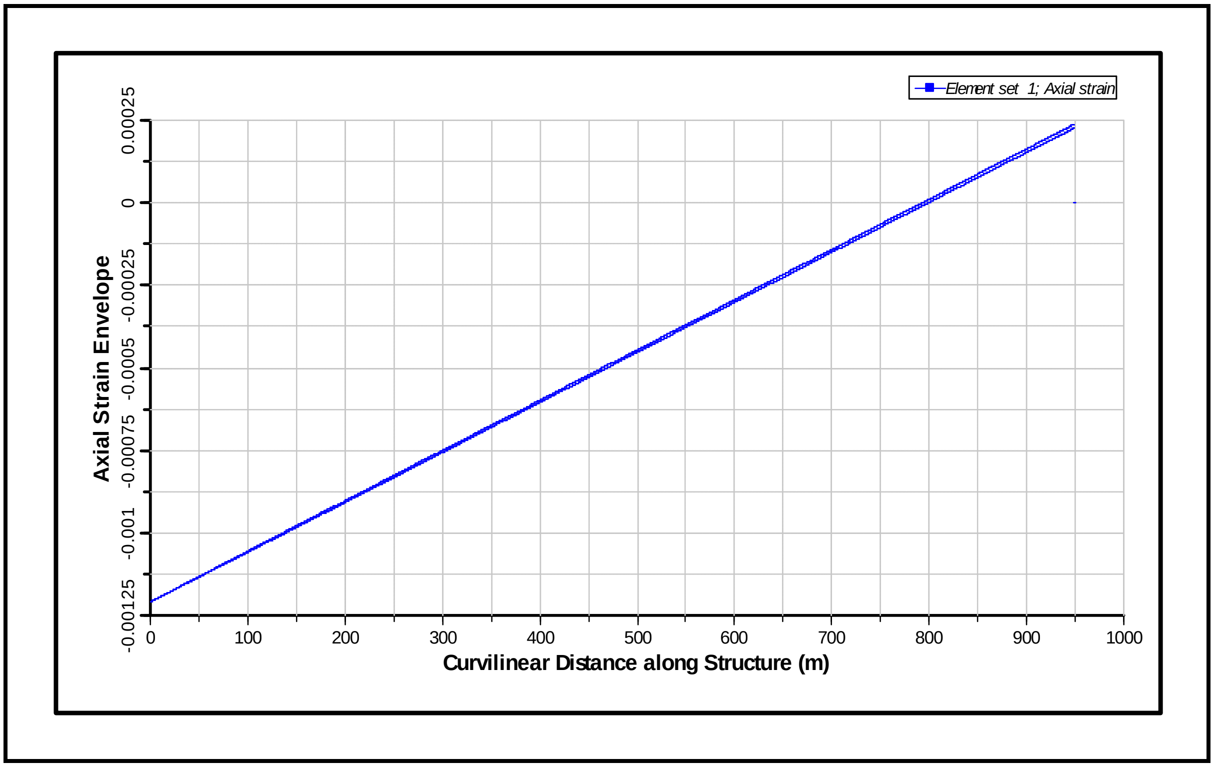


Figure 95: Axial Strain Envelope for 1000 m CWP for Bin 4 (from Bottom to Top)

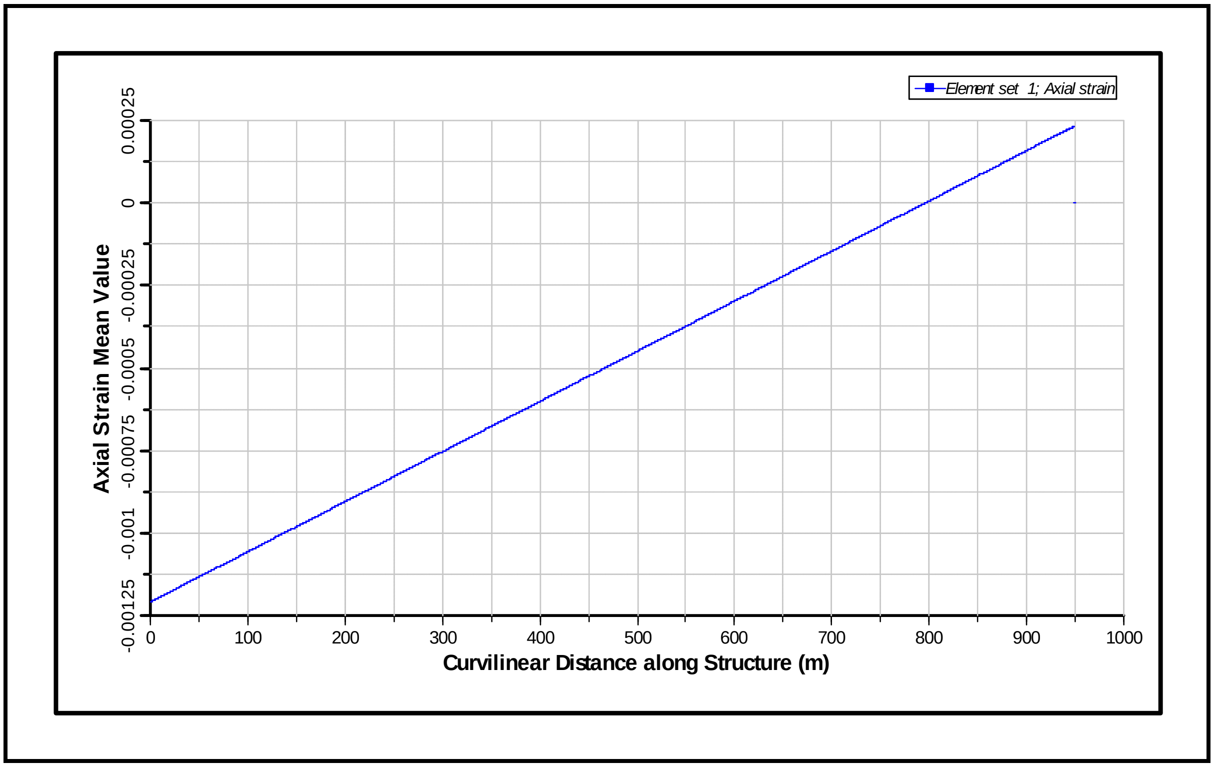


Figure 96: Mean Axial Strain for 1000 m CWP for Bin 4 (from Bottom to Top)

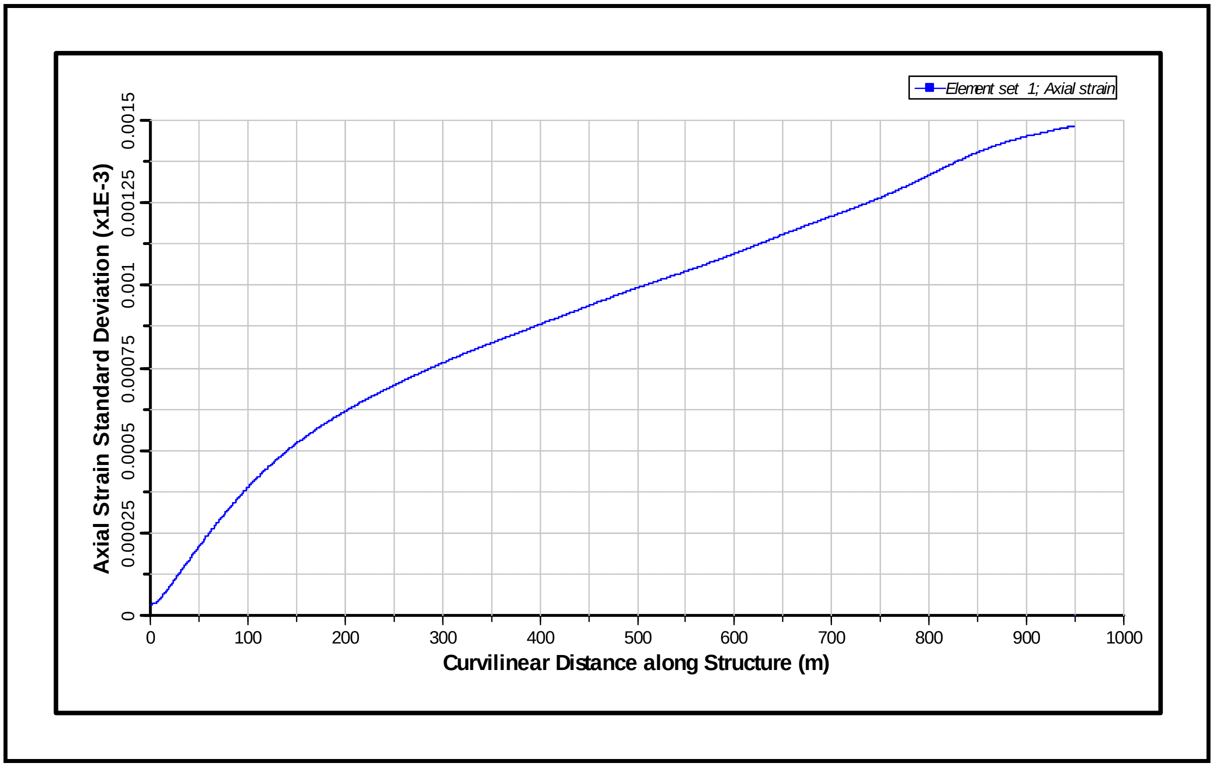


Figure 97: Standard Deviation of Axial Strain for 1000 m CWP for Bin 4 (from Bottom to Top)

6.5 Bin 5

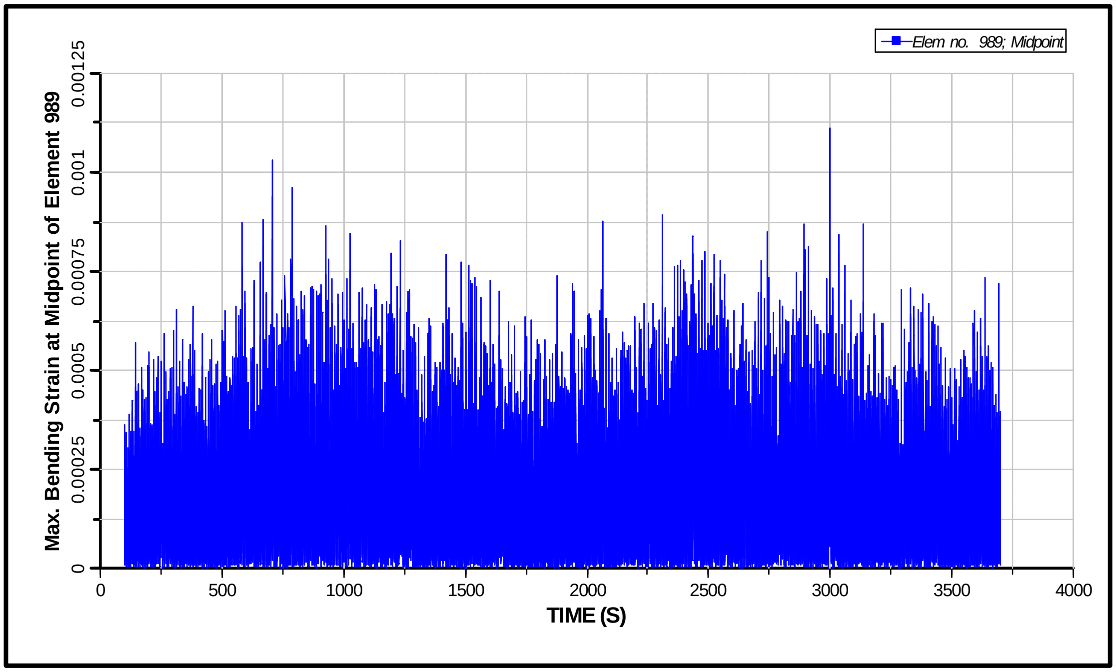


Figure 98: Maximum Bending Strain Time History at Top of CWP for Bin 5

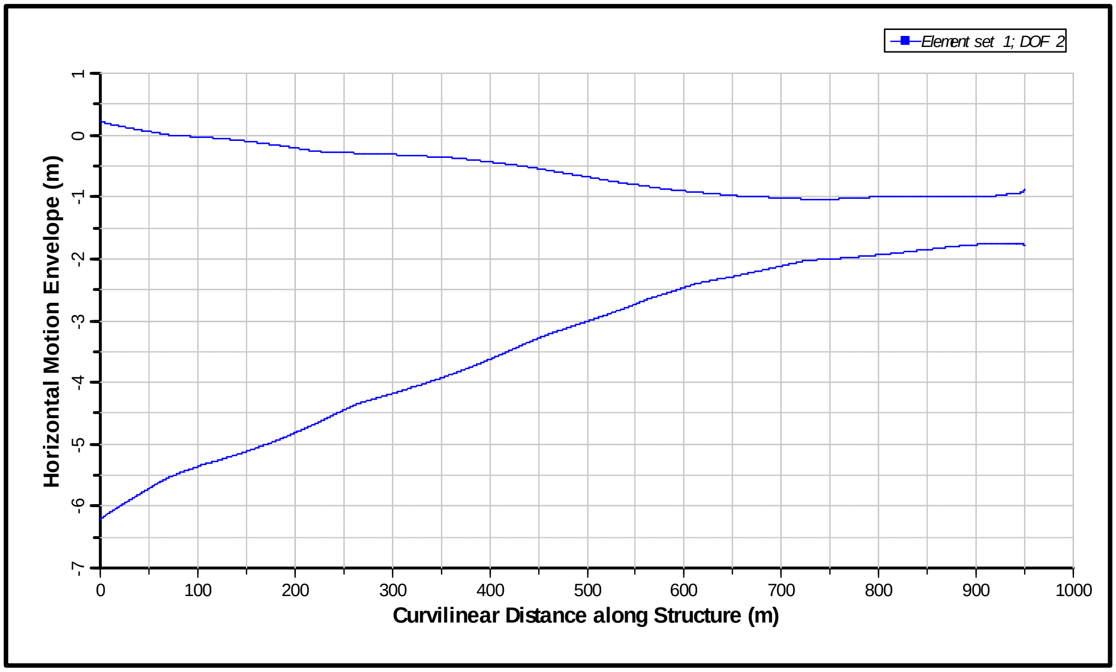


Figure 99: Motion Envelope for 1000 m CWP for Bin 5 (from Bottom to Top)

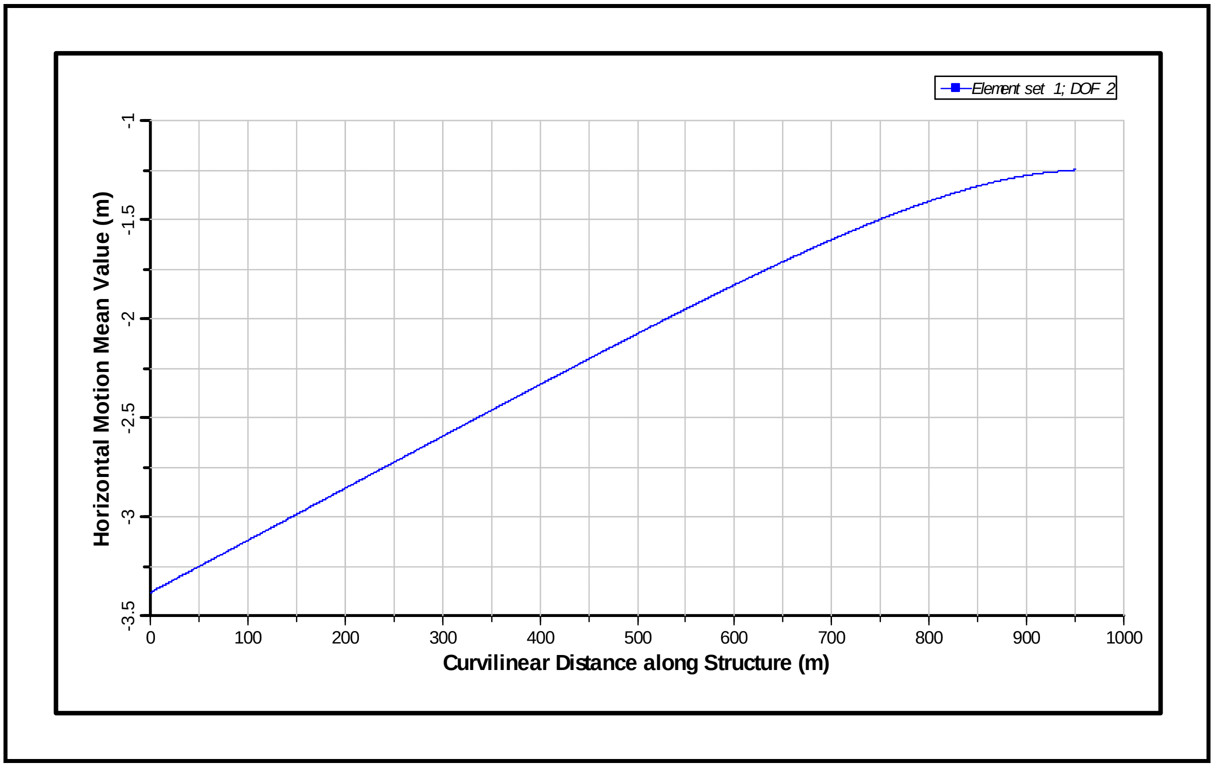


Figure 100: Mean Motion for 1000 m CWP for Bin 5 (from Bottom to Top)

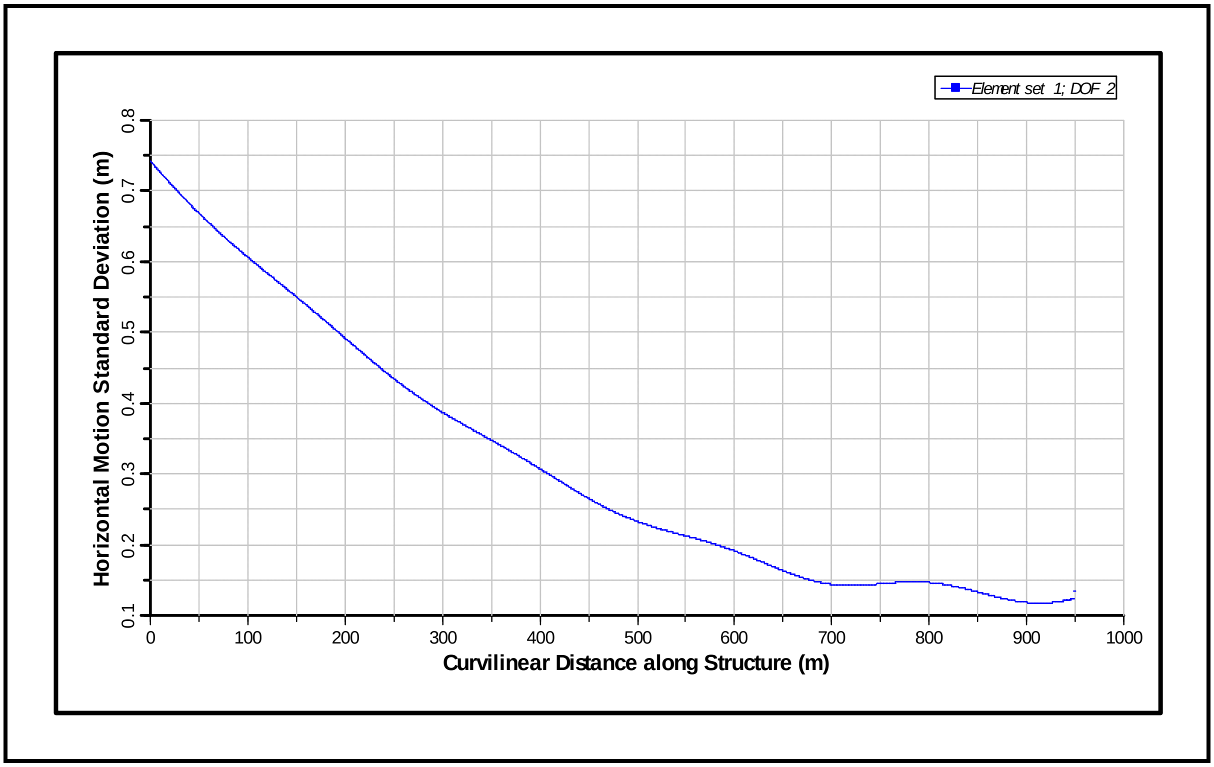


Figure 101: Standard Deviation of Motion for 1000 m CWP for Bin 5 (from Bottom to Top)

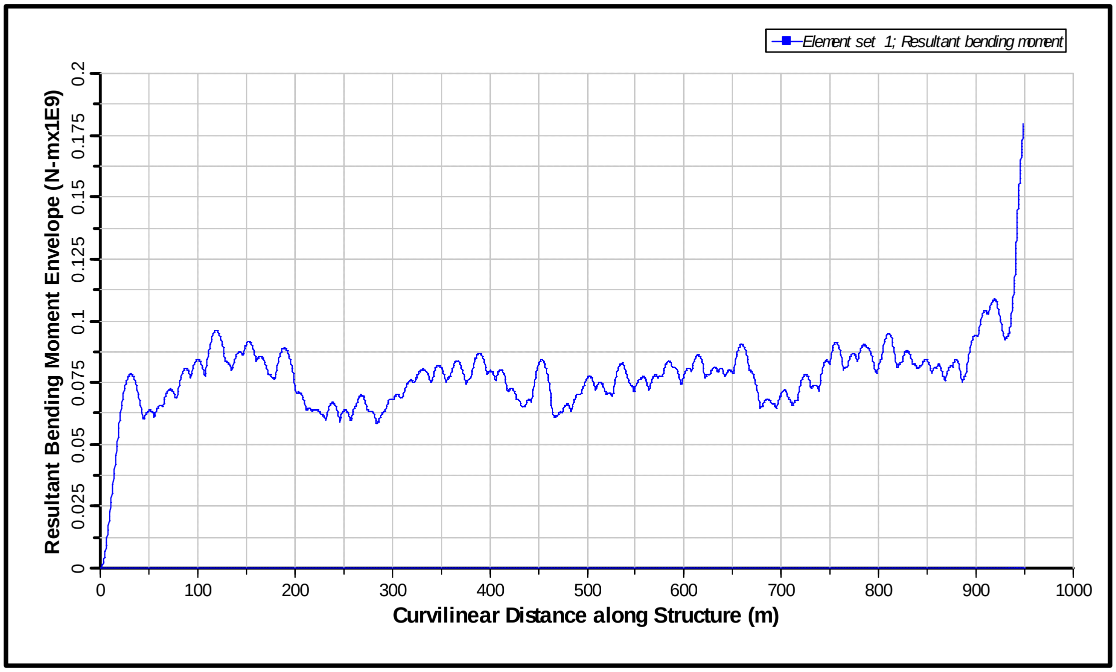


Figure 102: Bending Moment Envelope for 1000 m CWP for Bin 5 (from Bottom to Top)

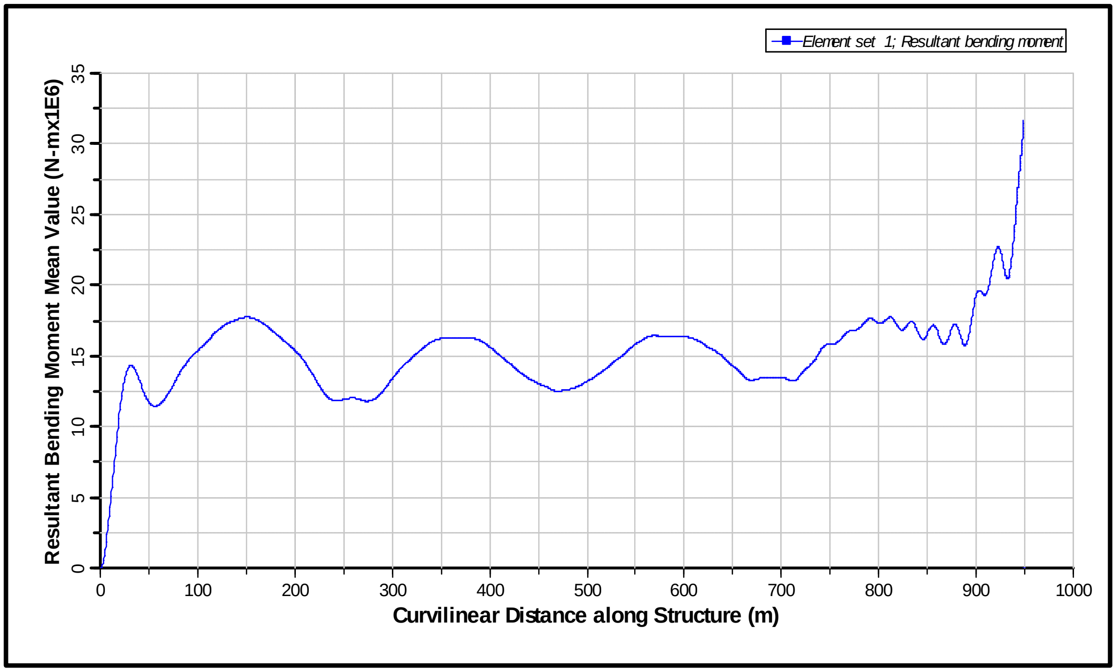


Figure 103: Mean Bending Moment for 1000 m CWP for Bin 5 (from Bottom to Top)

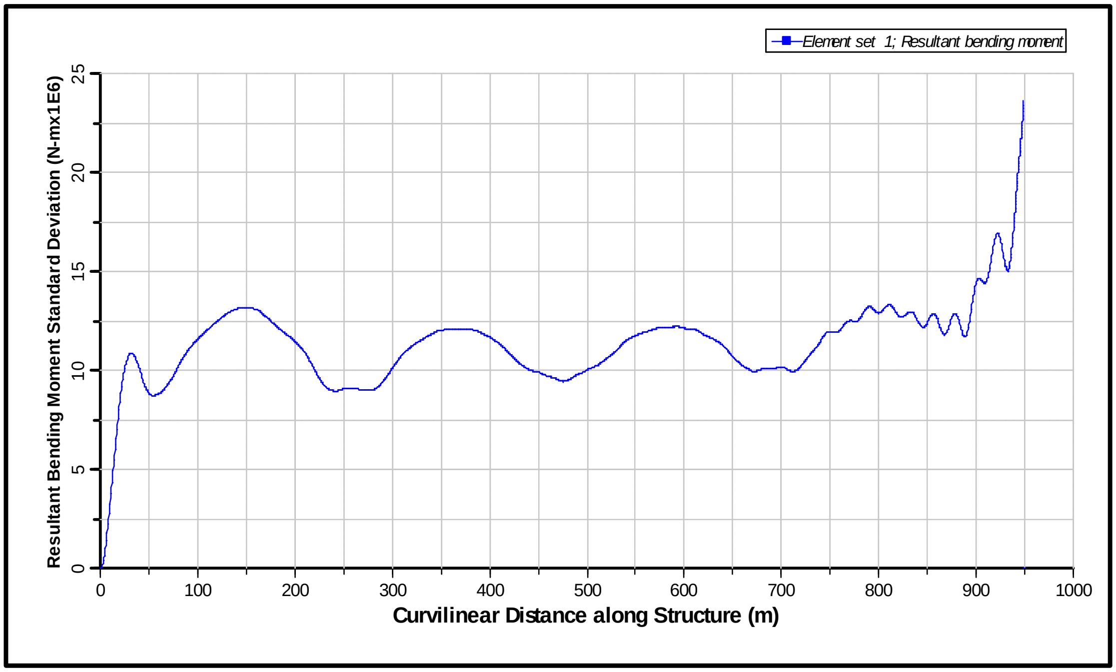


Figure 104: Standard Deviation of Bending Moment for 1000 m CWP for Bin 5 (from Bottom to Top)

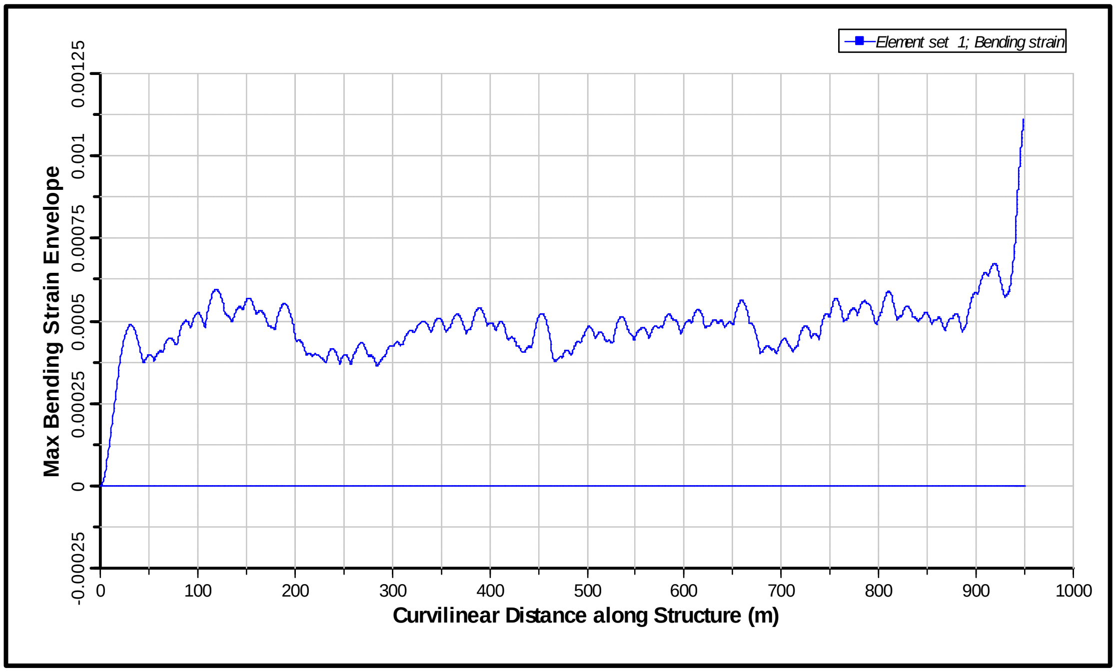


Figure 105: Bending Strain Envelope for 1000 m CWP for Bin 5 (from Bottom to Top)

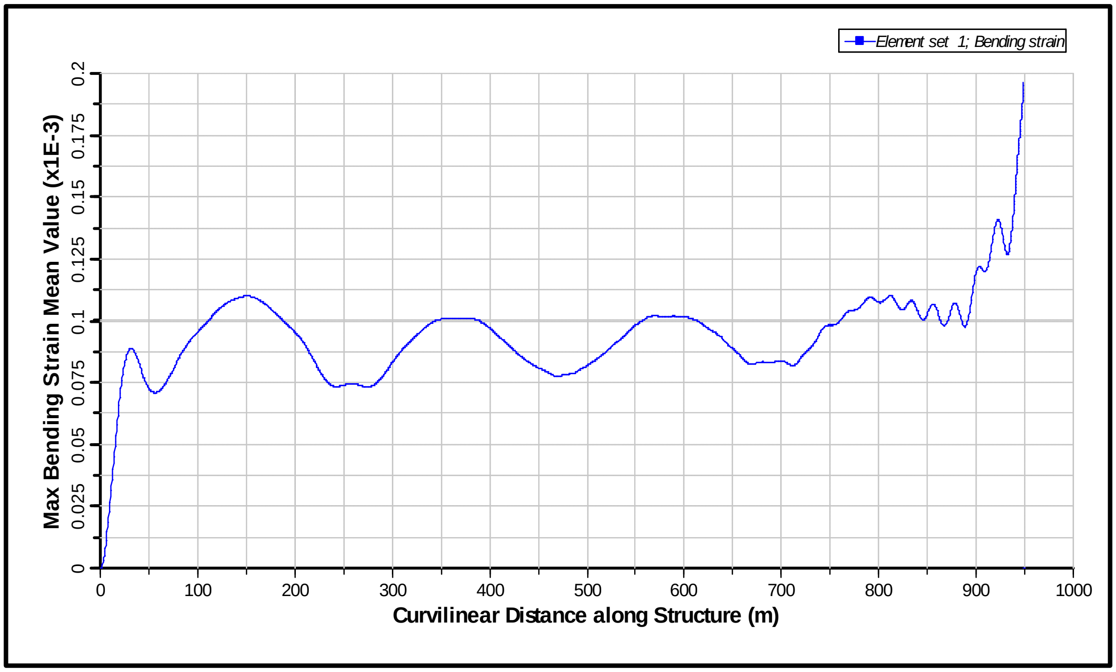


Figure 106: Mean Bending Strain for 1000 m CWP for Bin 5 (from Bottom to Top)

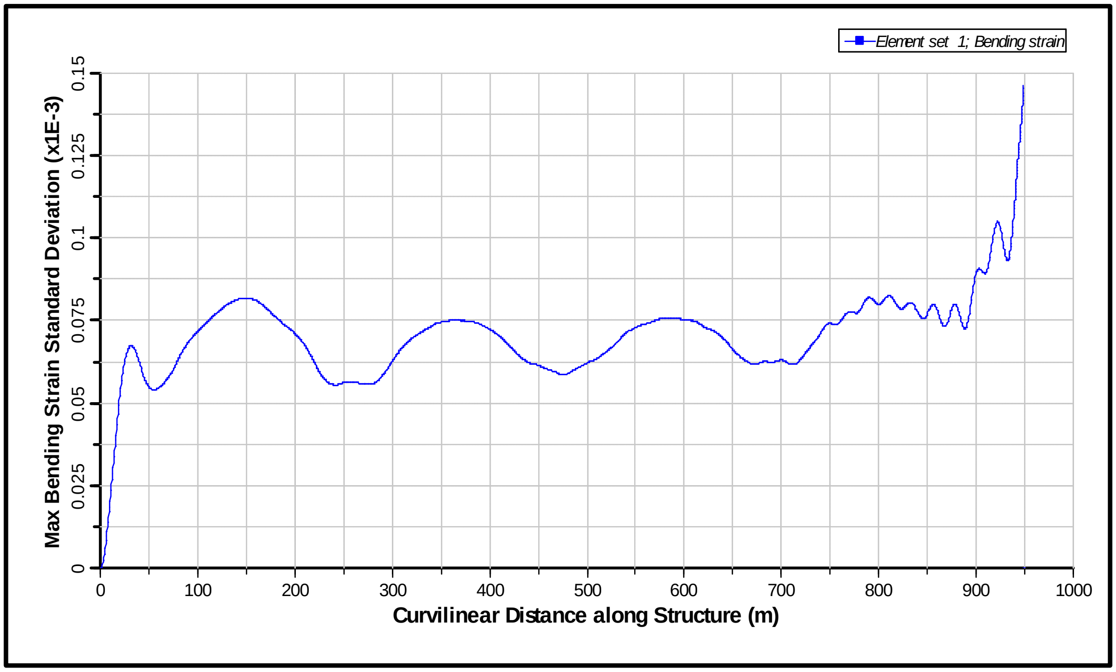


Figure 107: Standard Deviation of Bending Strain for 1000 m CWP for Bin 5 (from Bottom to Top)

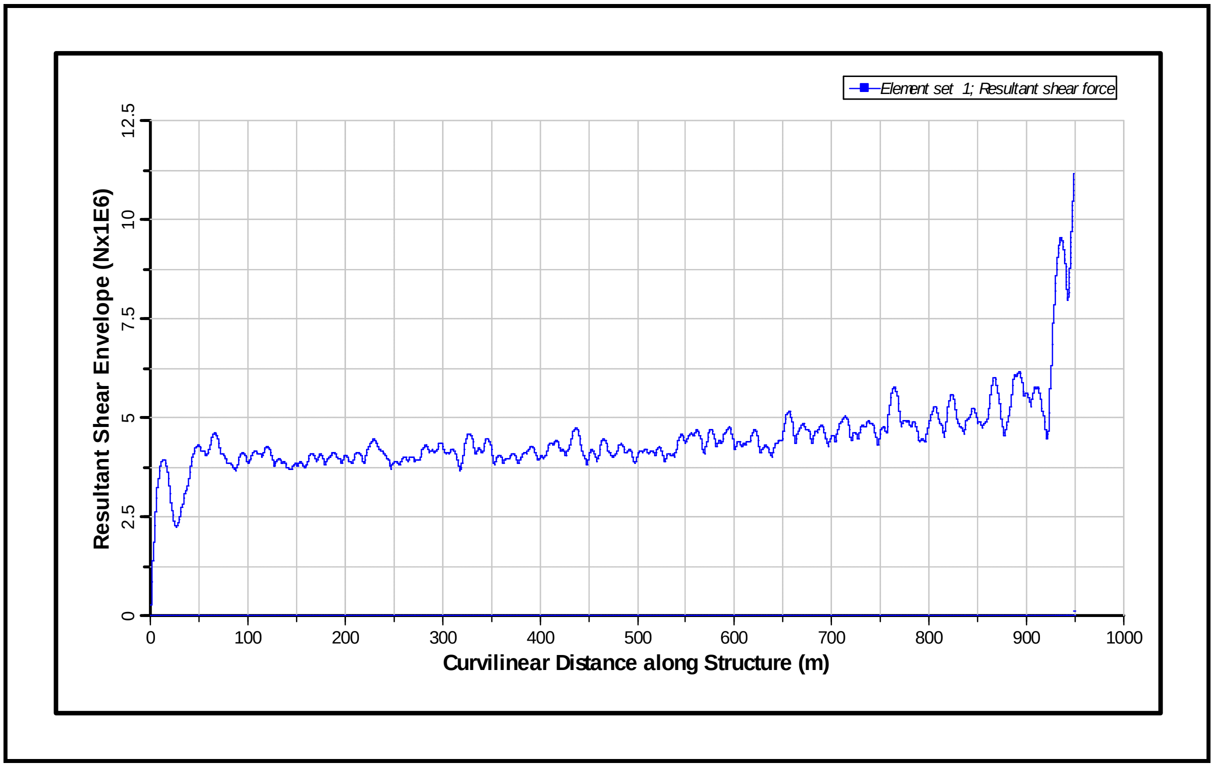


Figure 108: Shear Force Envelope for 1000 m CWP for Bin 5 (from Bottom to Top)

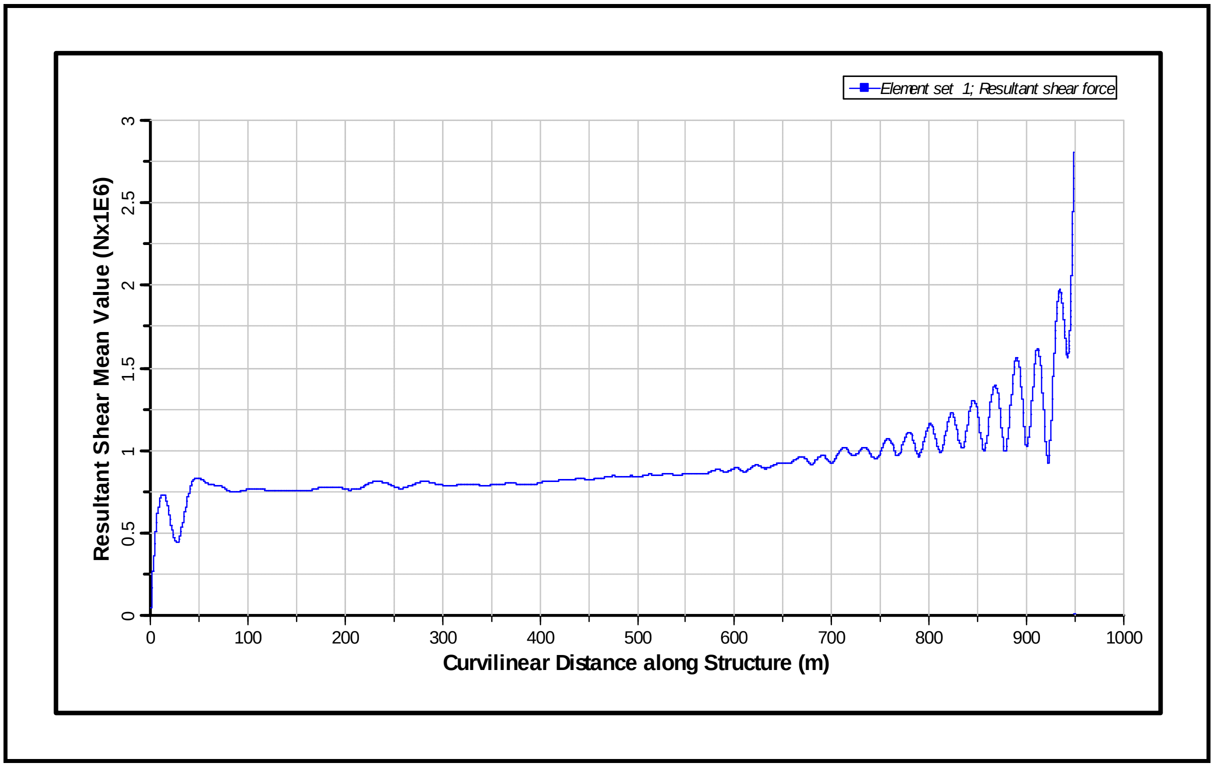


Figure 109: Mean Shear Force for 1000 m CWP for Bin 5 (from Bottom to Top)

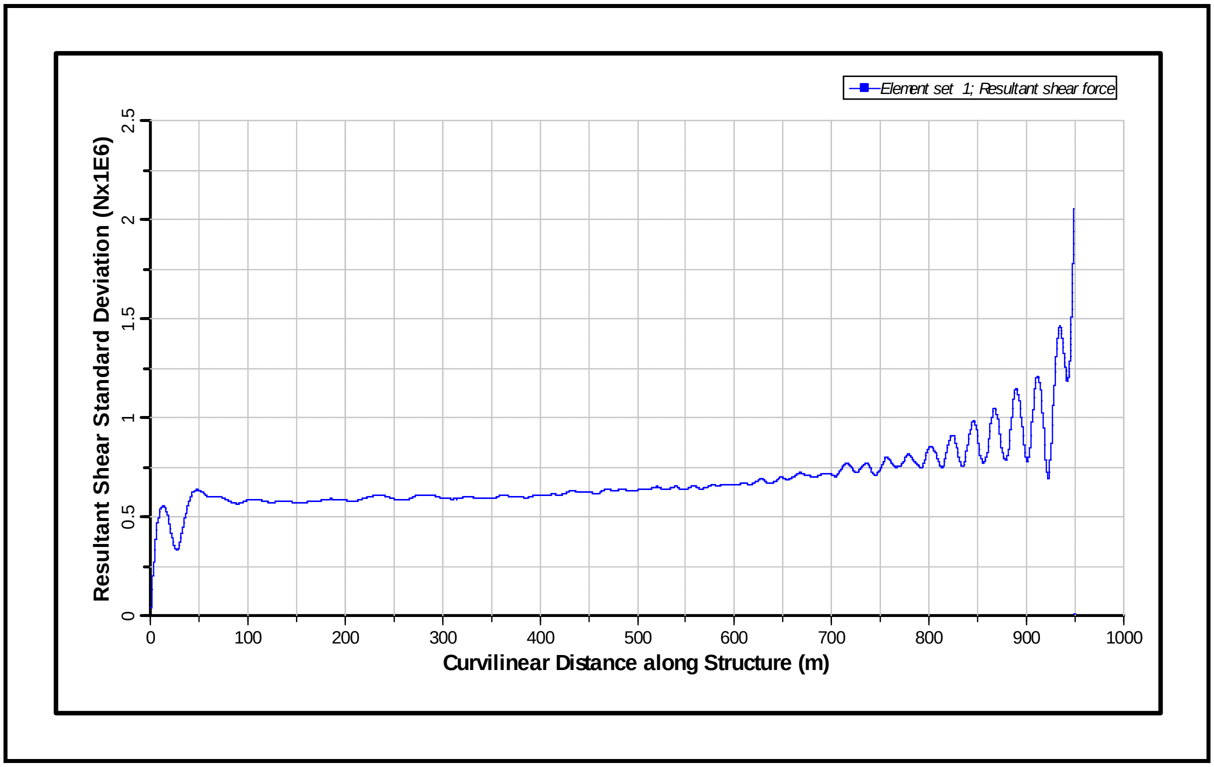


Figure 110: Standard Deviation of Shear Force for 1000 m CWP for Bin 5 (from Bottom to Top)

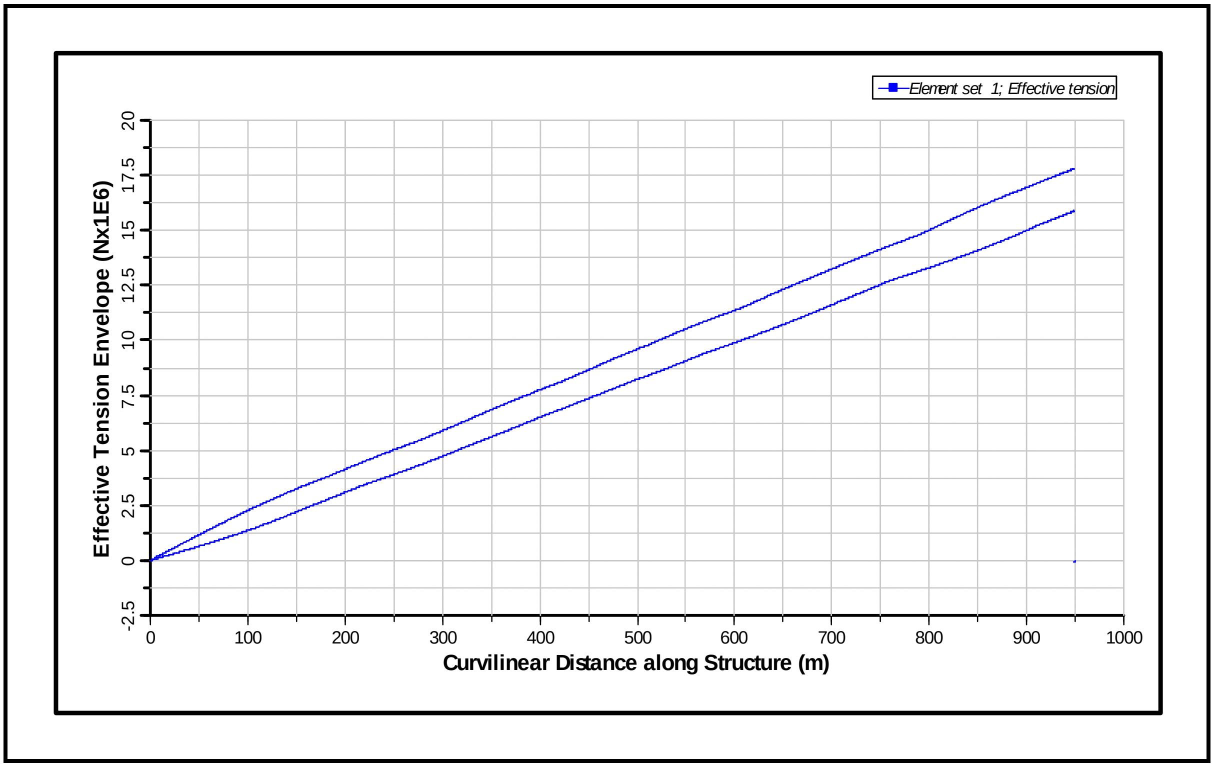


Figure 111: Axial Tension Envelope for 1000 m CWP for Bin 5 (from Bottom to Top)

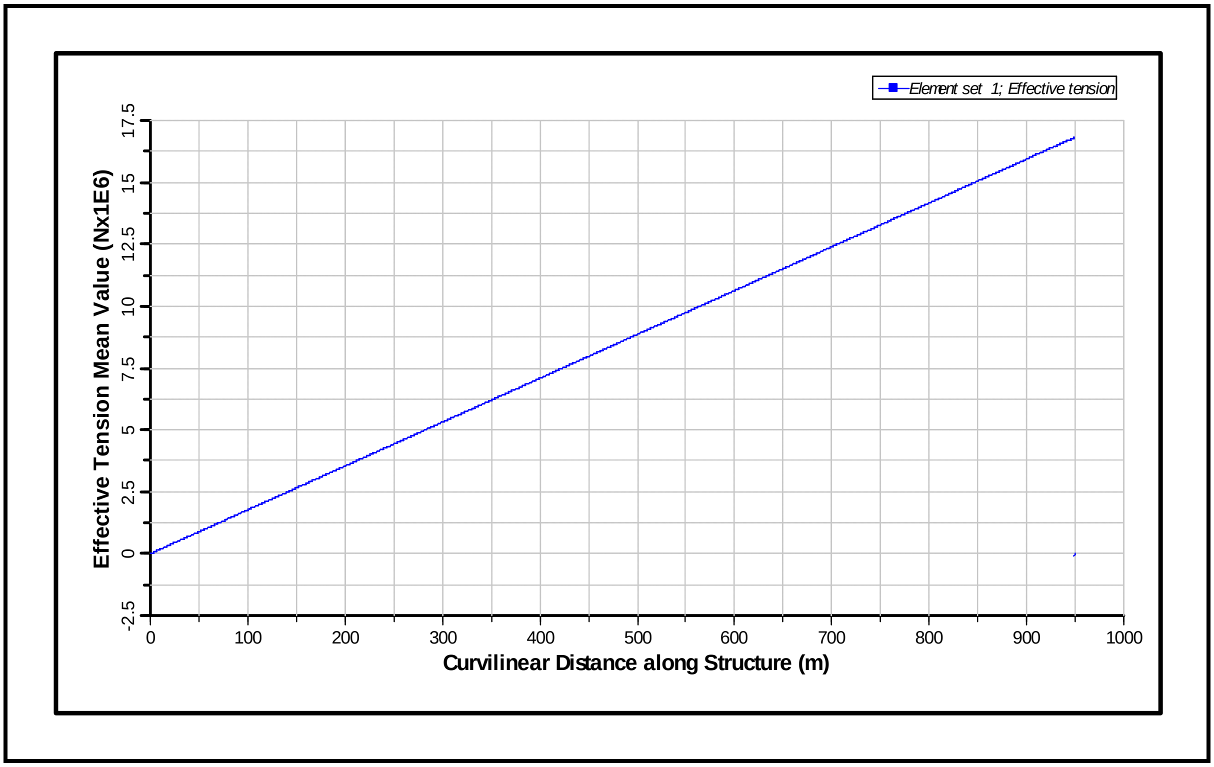


Figure 112: Mean Axial Tension for 1000 m CWP for Bin 5 (from Bottom to Top)

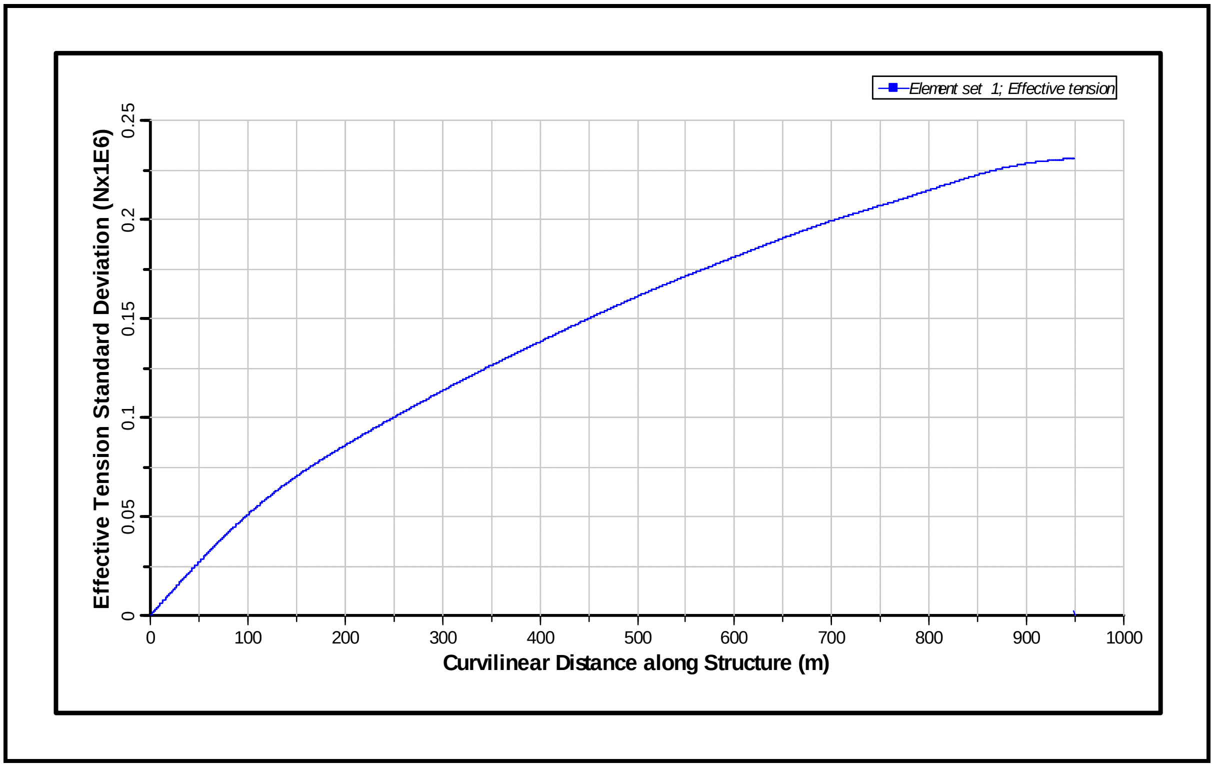


Figure 113: Standard Deviation of Axial Tension for 1000 m CWP for Bin 5 (from Bottom to Top)

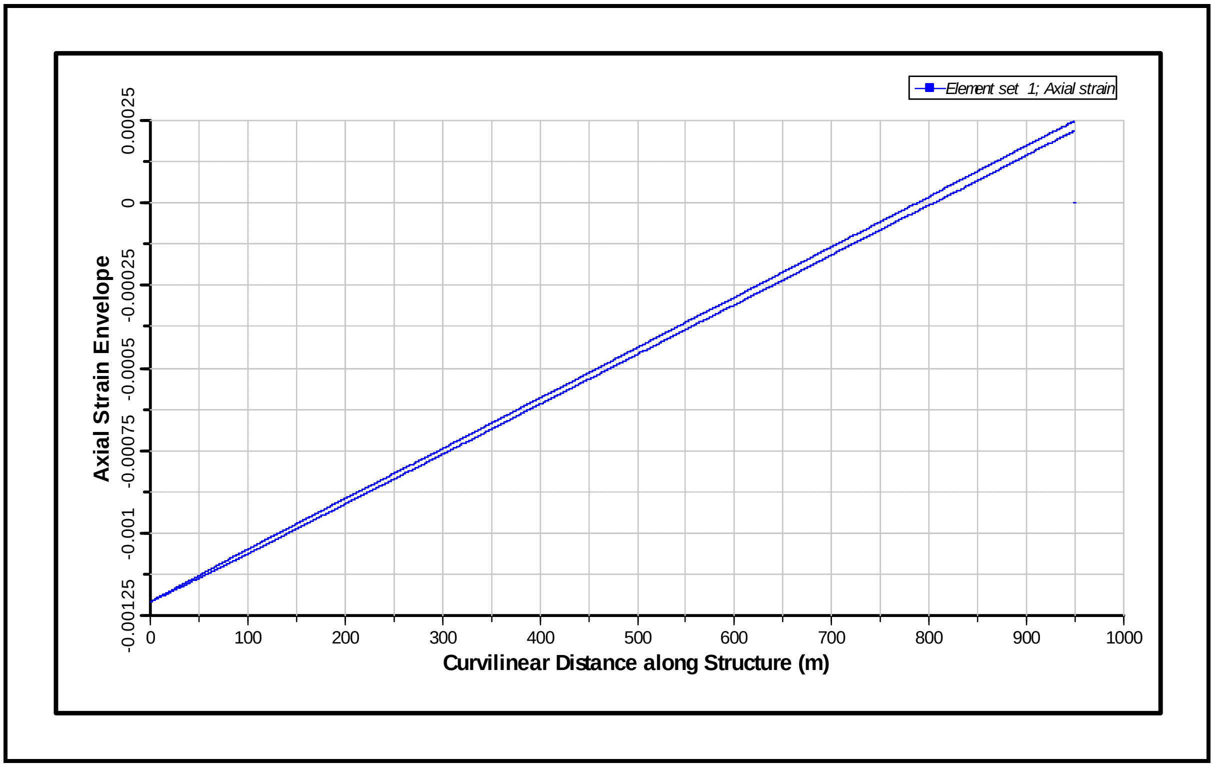


Figure 114: Axial Strain Envelope for 1000 m CWP for Bin 5 (from Bottom to Top)

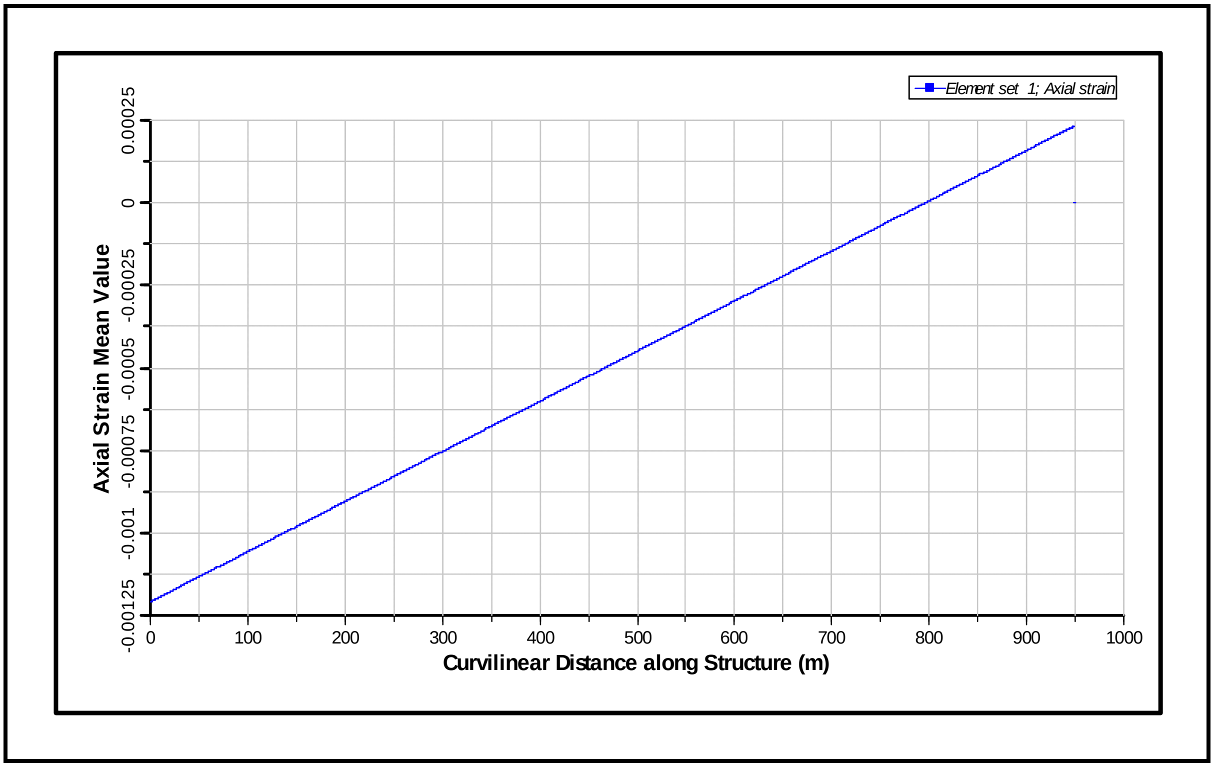


Figure 115: Mean Axial Strain for 1000 m CWP for Bin 5 (from Bottom to Top)

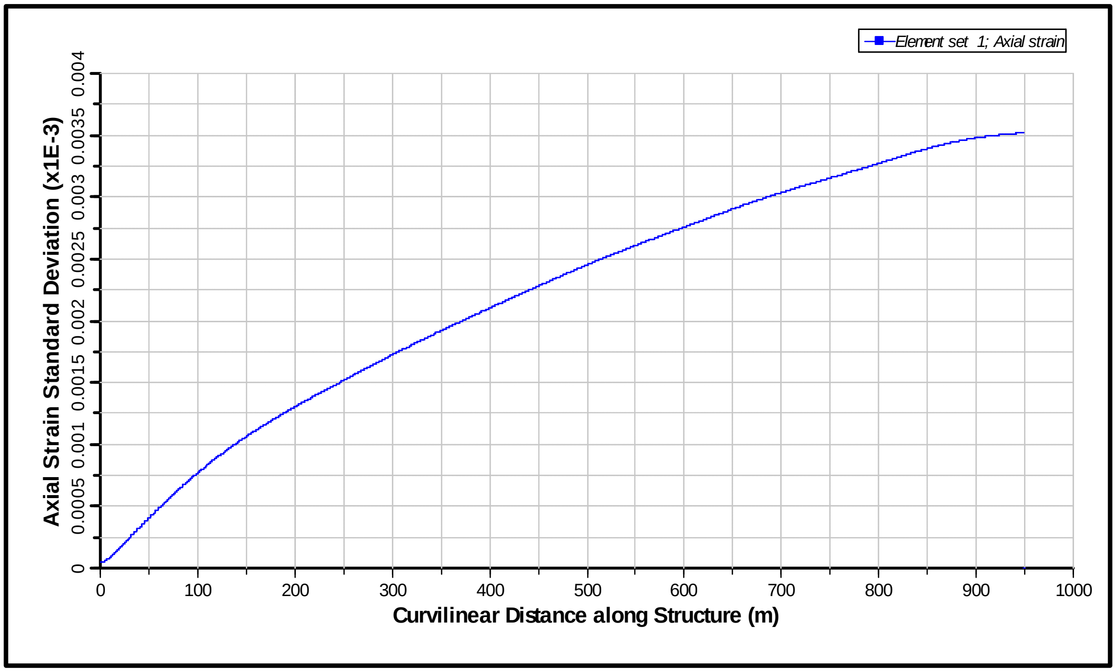


Figure 116: Standard Deviation of Axial Strain for 1000 m CWP for Bin 5 (from Bottom to Top)

6.6 Bin 6

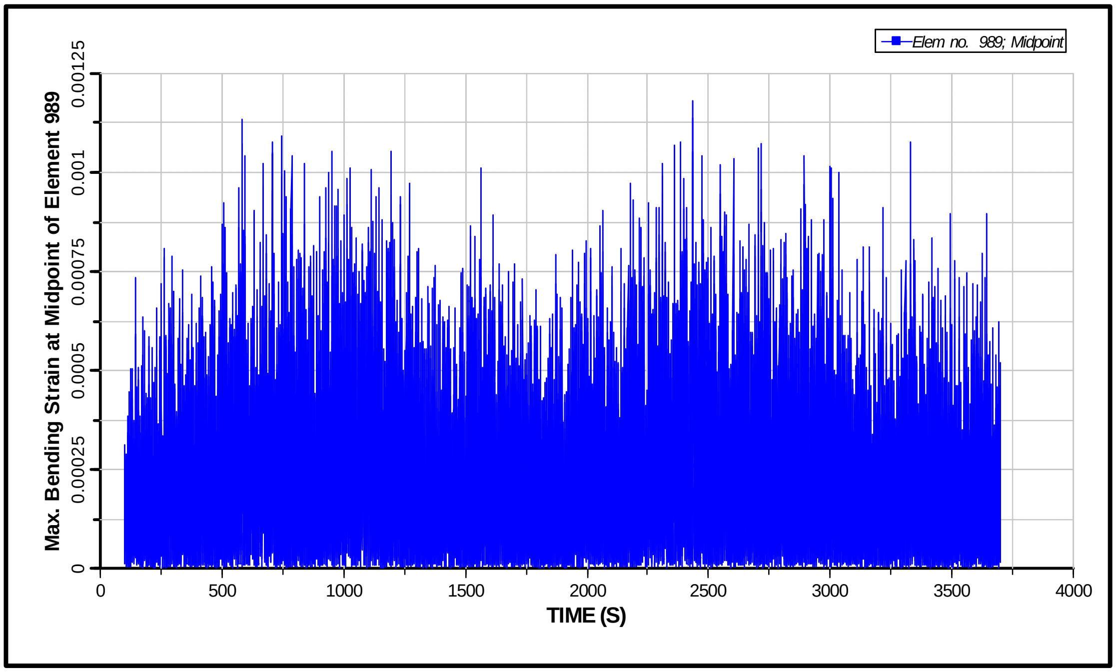


Figure 117: Maximum Bending Strain Time History at Top of CWP for Bin 6

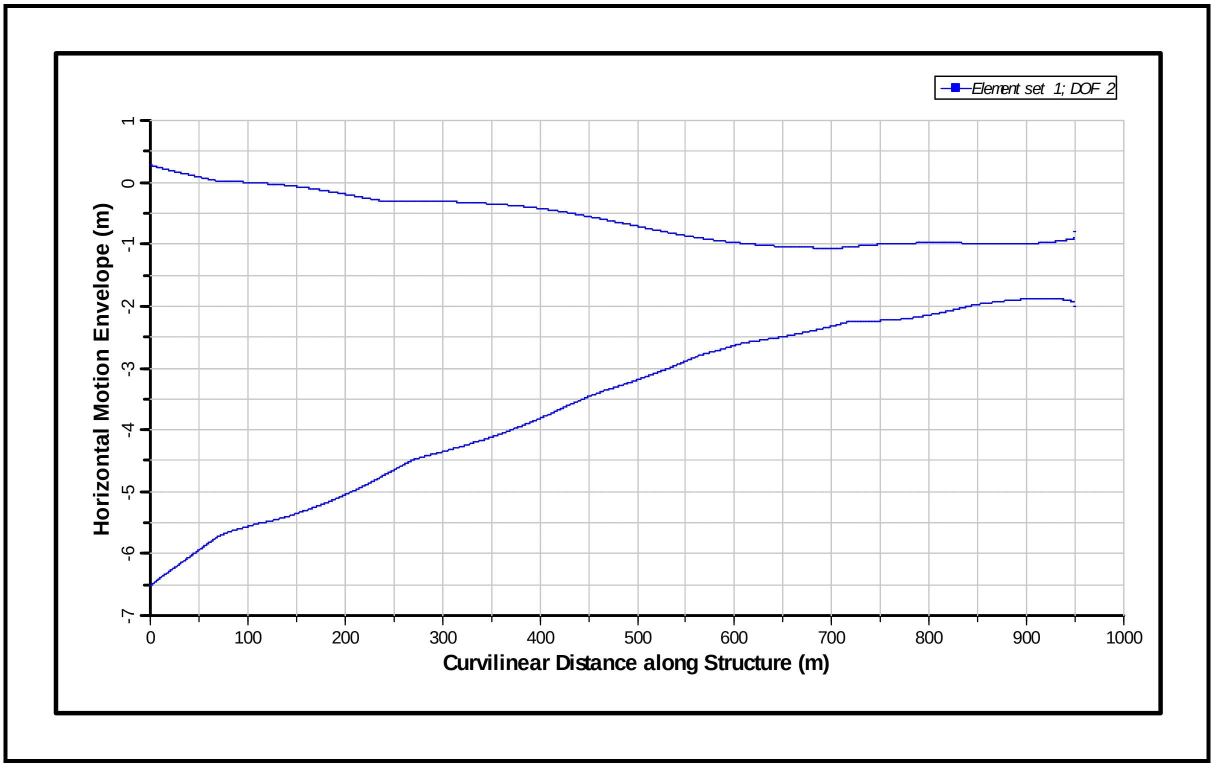


Figure 118: Motion Envelope for 1000 m CWP for Bin 6 (from Bottom to Top)

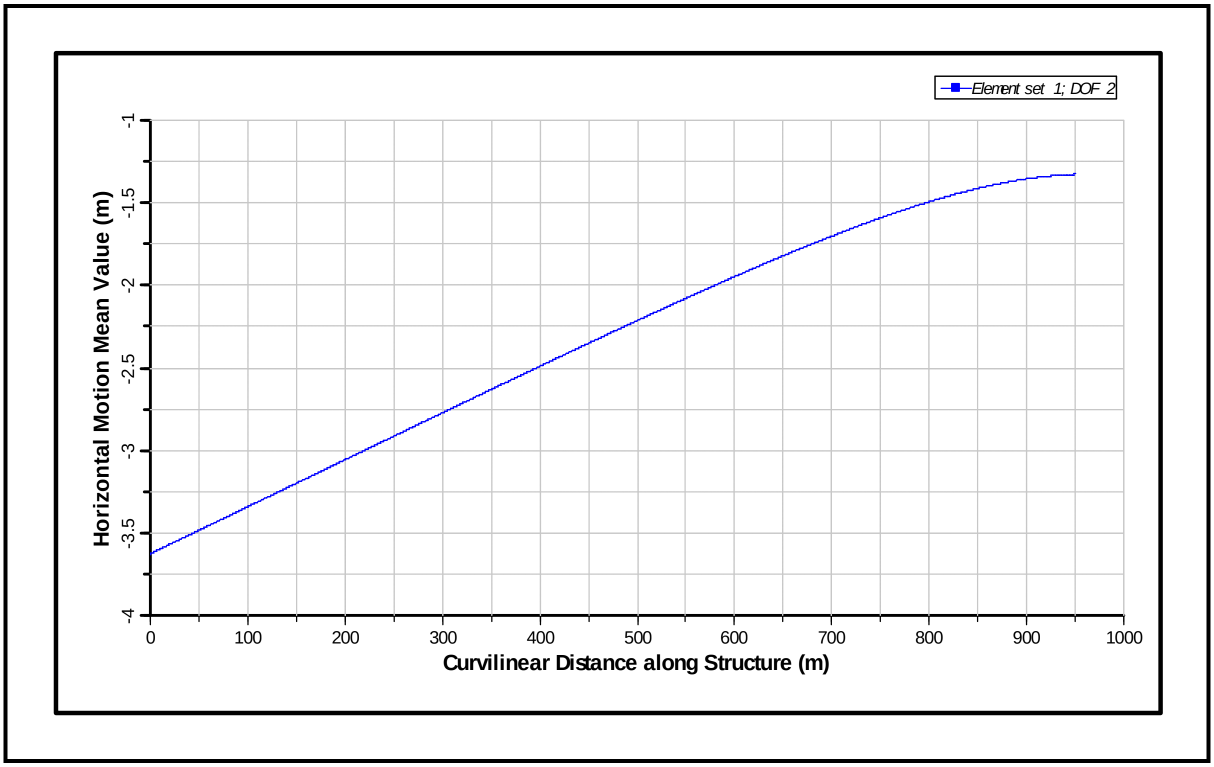


Figure 119: Mean Motion for 1000 m CWP for Bin 6 (from Bottom to Top)

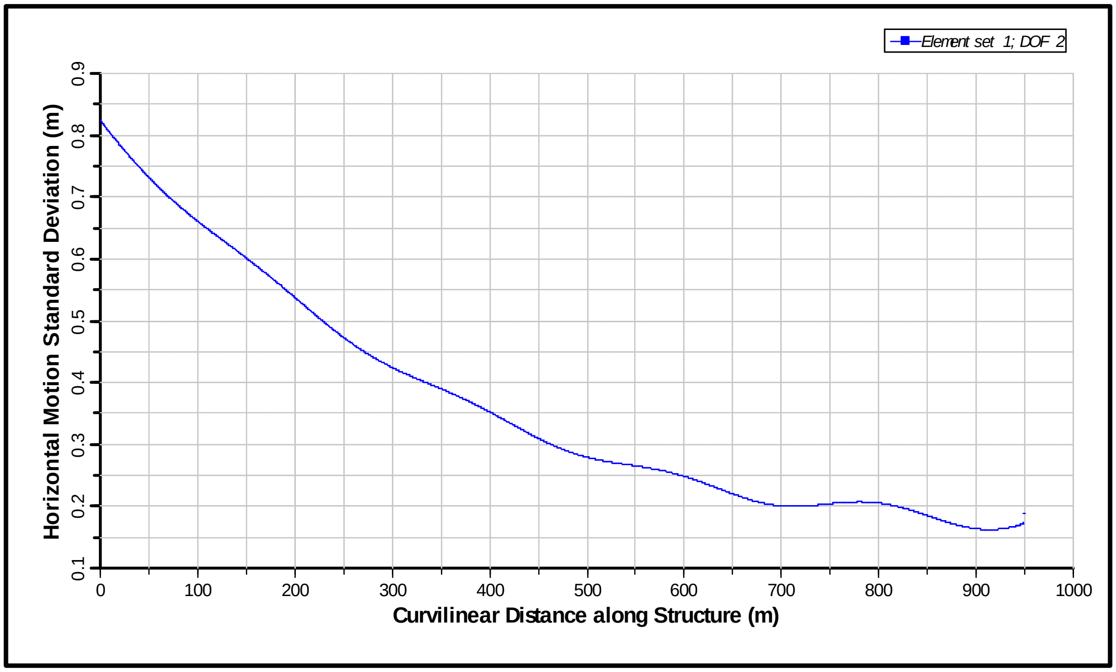


Figure 120: Standard Deviation of Motion for 1000 m CWP for Bin 6 (from Bottom to Top)

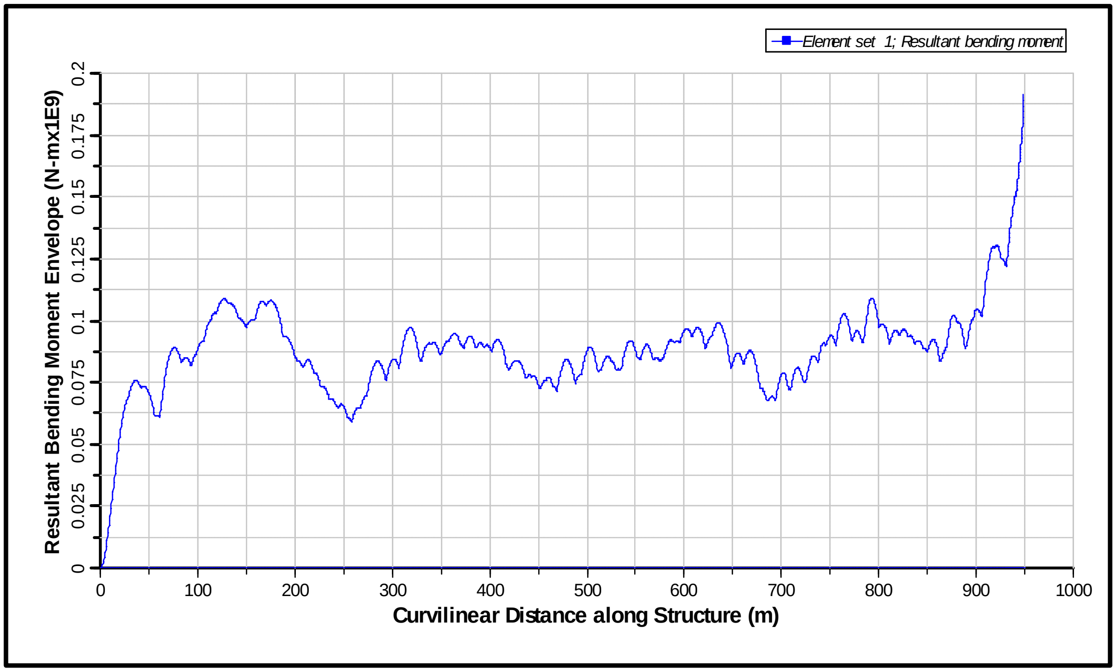


Figure 121: Bending Moment Envelope for 1000 m CWP for Bin 6 (from Bottom to Top)

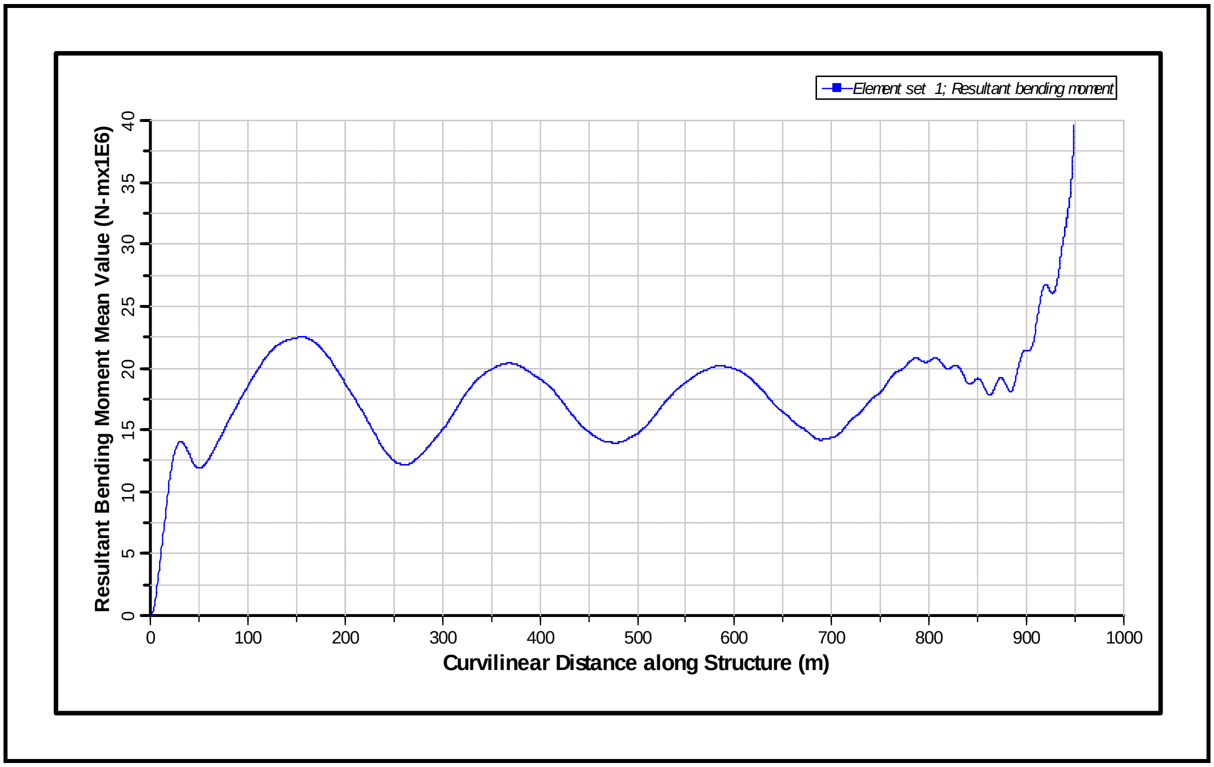


Figure 122: Mean Bending Moment for 1000 m CWP for Bin 6 (from Bottom to Top)

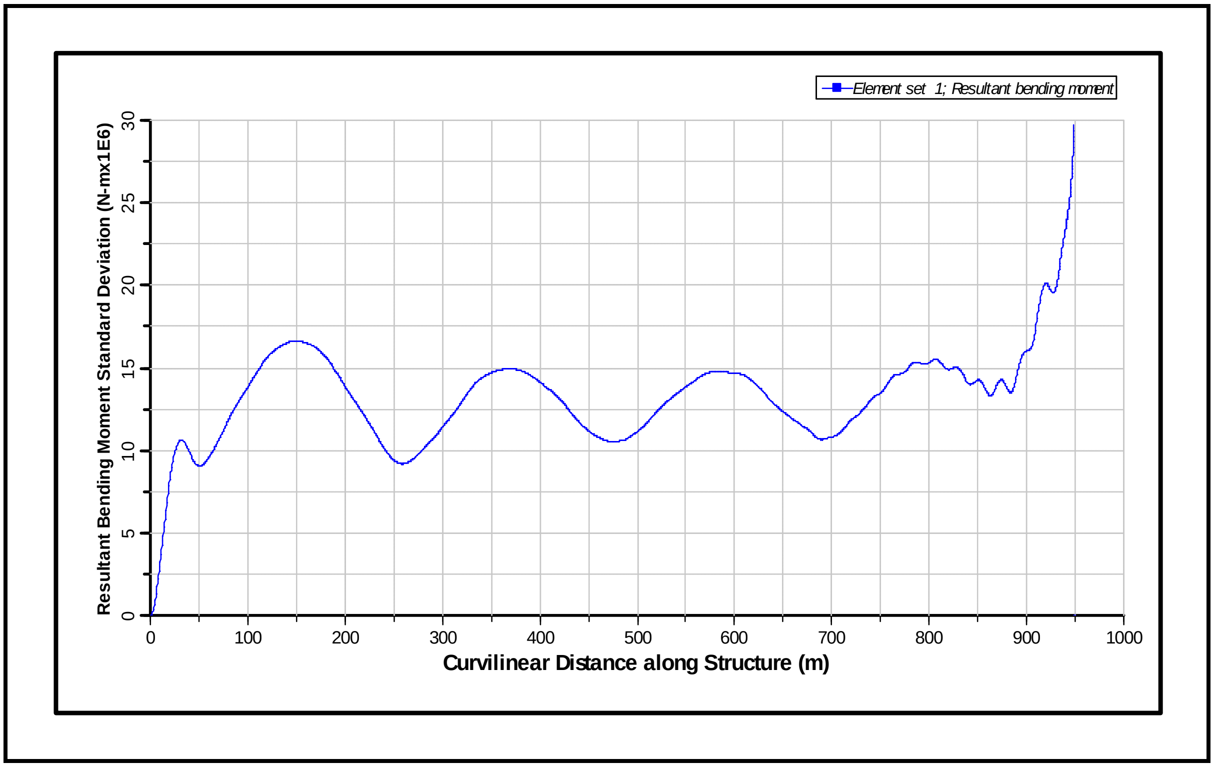


Figure 123: Standard Deviation of Bending Moment for 1000 m CWP for Bin 6 (from Bottom to Top)

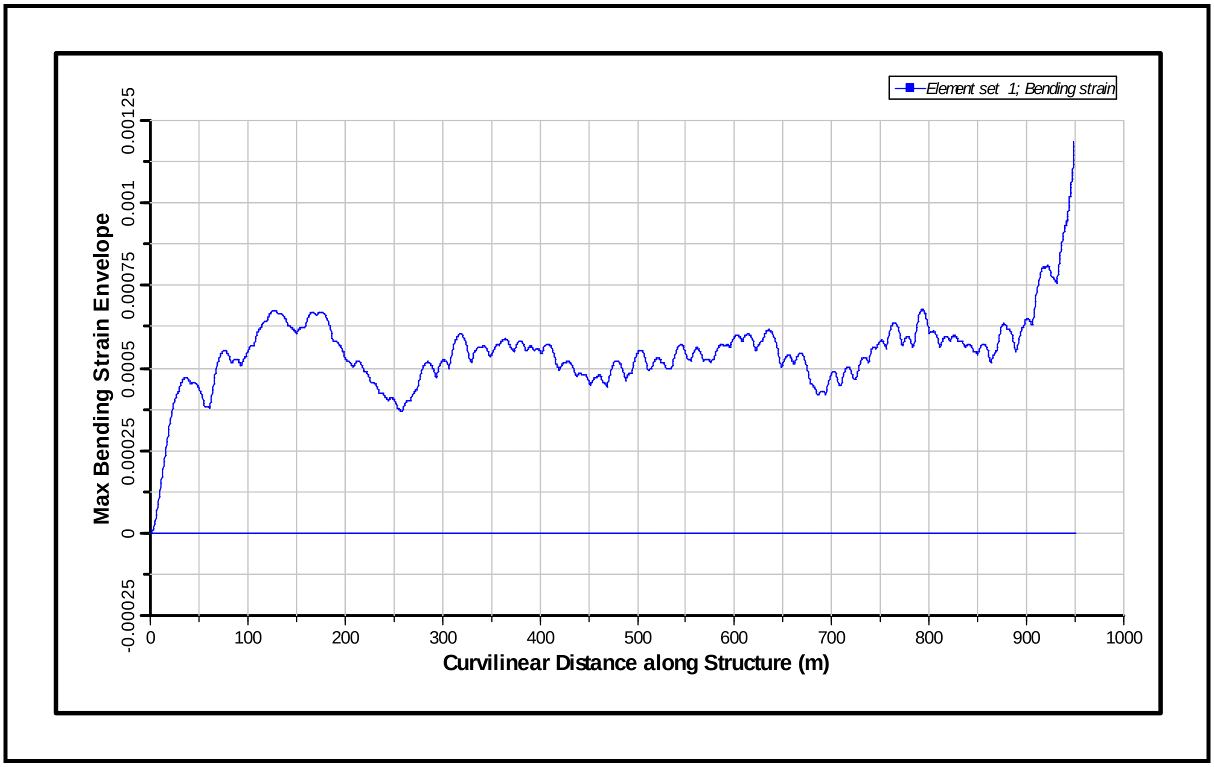


Figure 124: Bending Strain Envelope for 1000 m CWP for Bin 6 (from Bottom to Top)

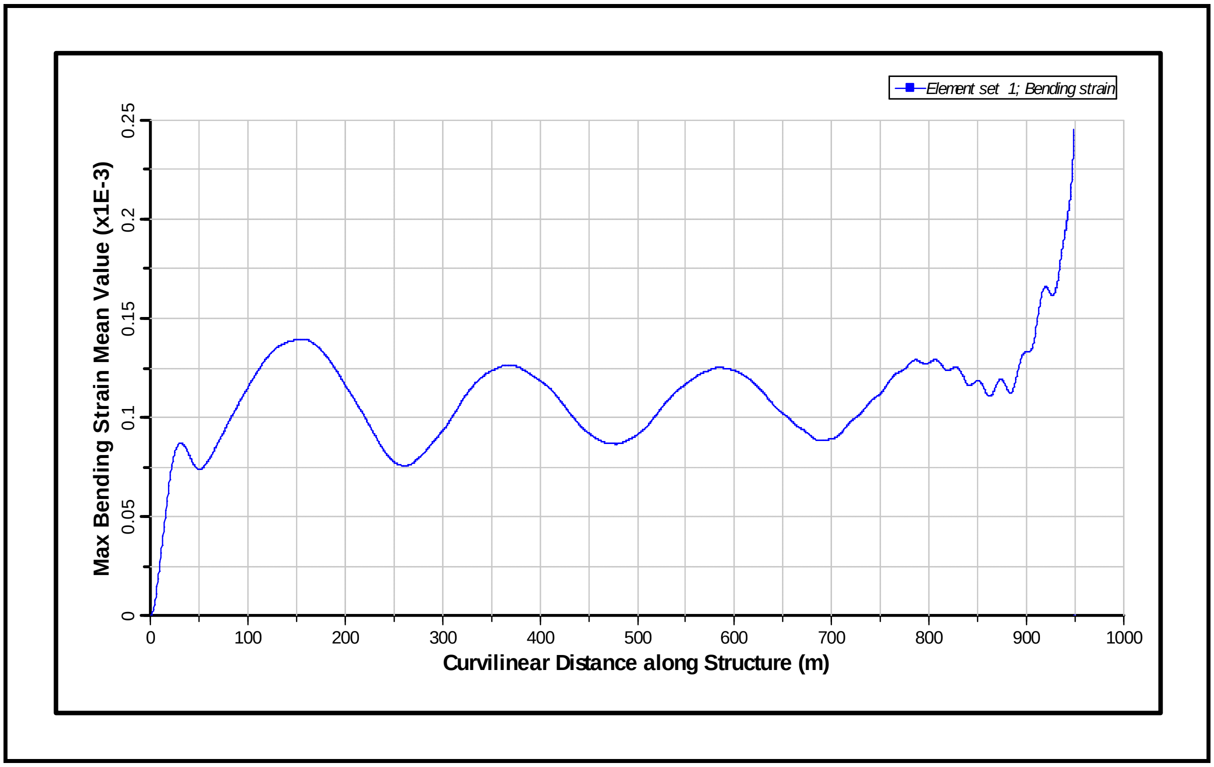


Figure 125: Mean Bending Strain for 1000 m CWP for Bin 6 (from Bottom to Top)

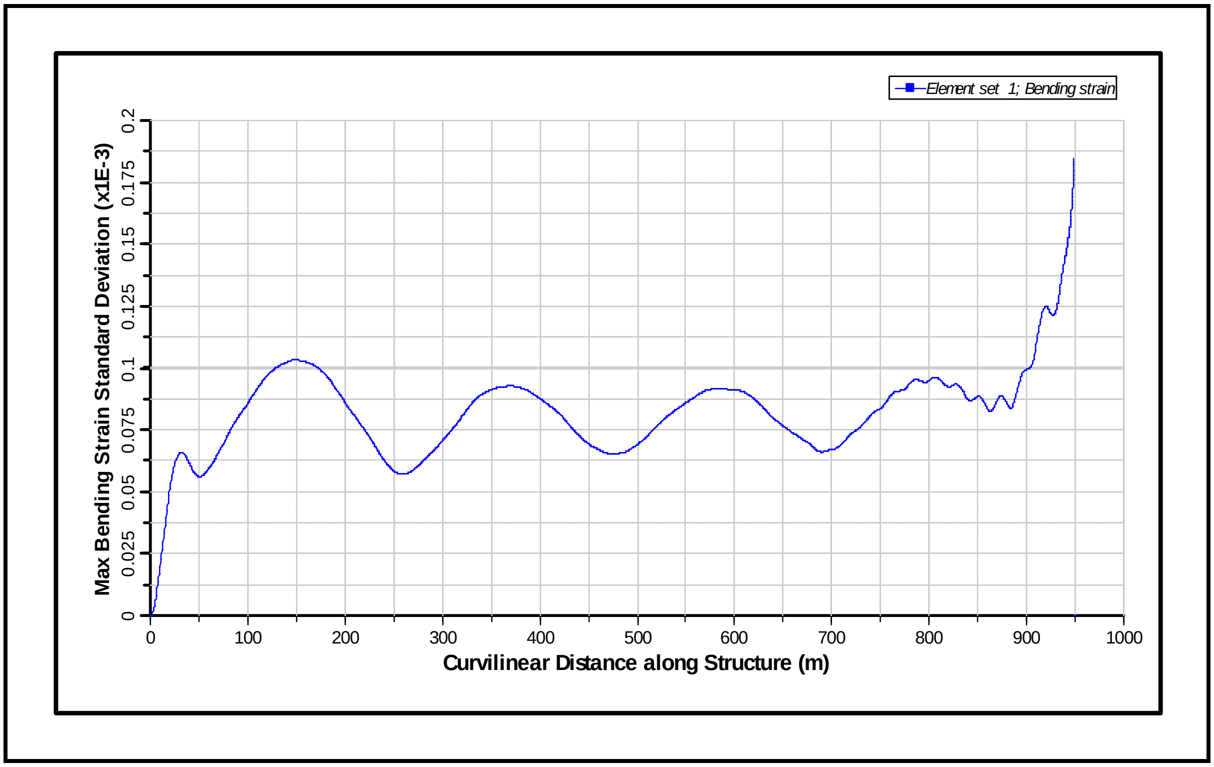


Figure 126: Standard Deviation of Bending Strain for 1000 m CWP for Bin 6 (from Bottom to Top)

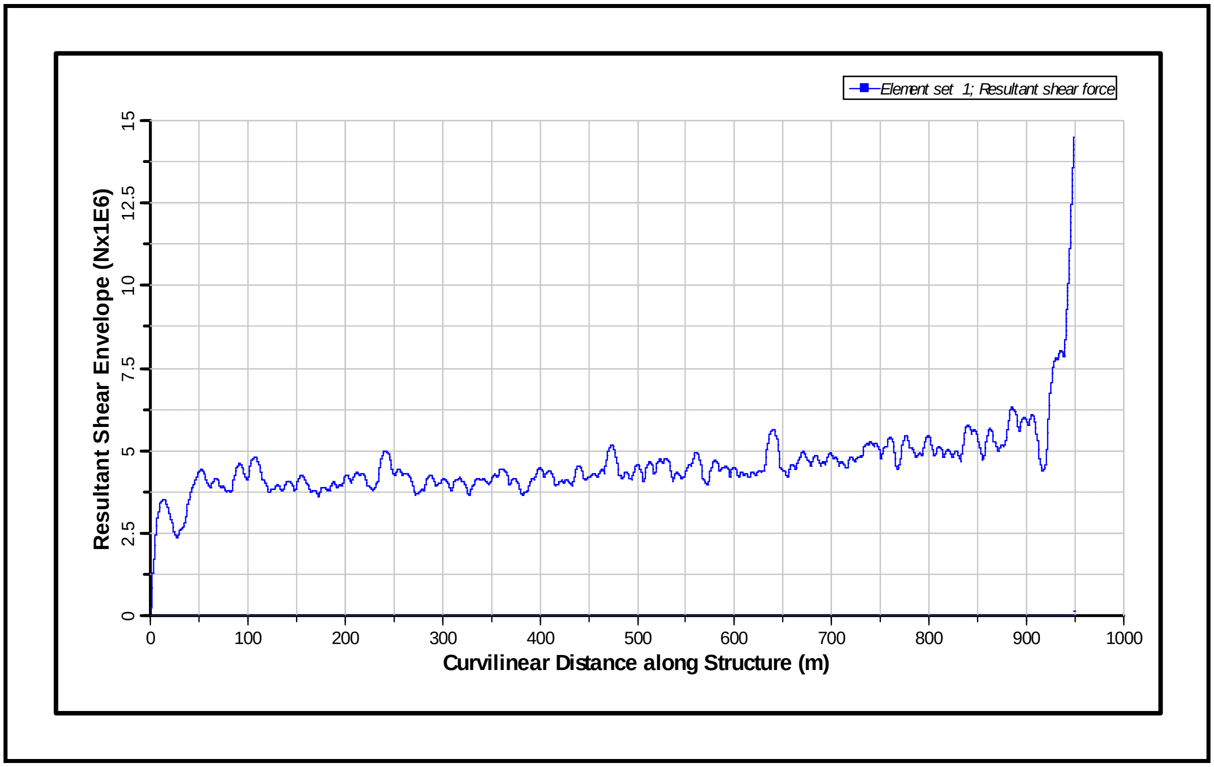


Figure 127: Shear Force Envelope for 1000 m CWP for Bin 6 (from Bottom to Top)

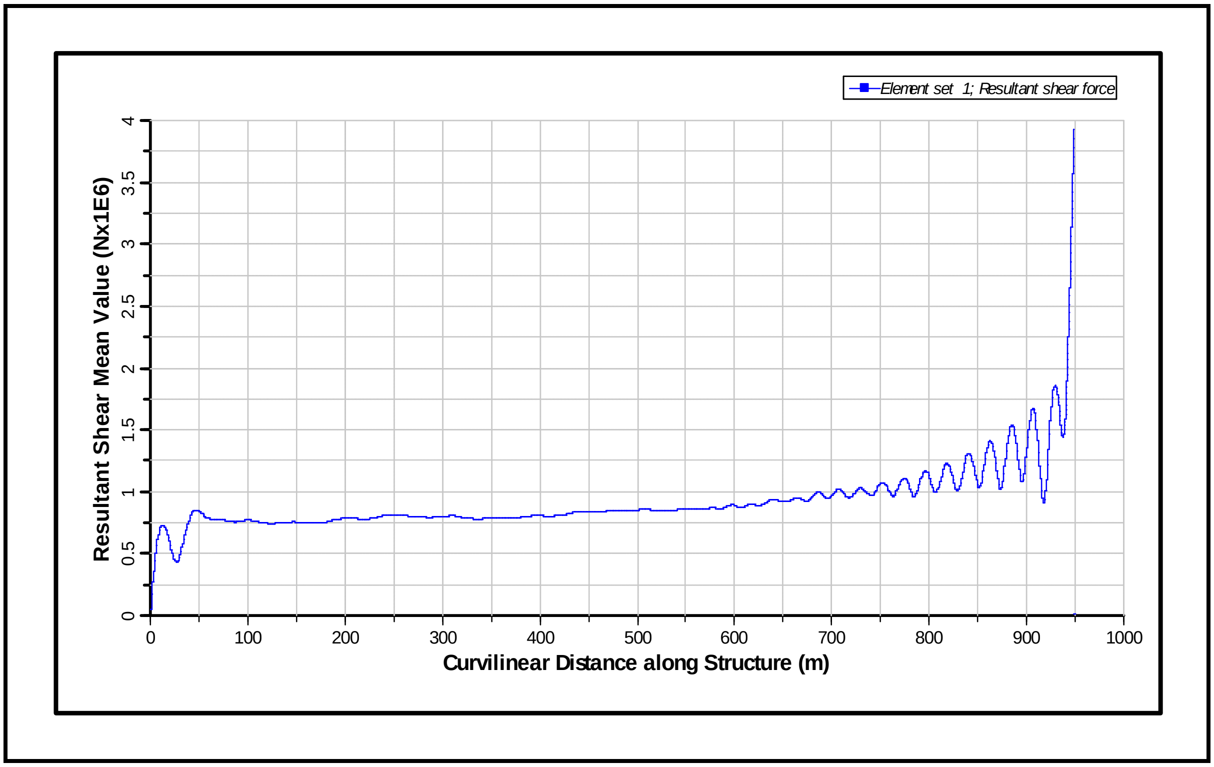


Figure 128: Mean Shear Force for 1000 m CWP for Bin 6 (from Bottom to Top)

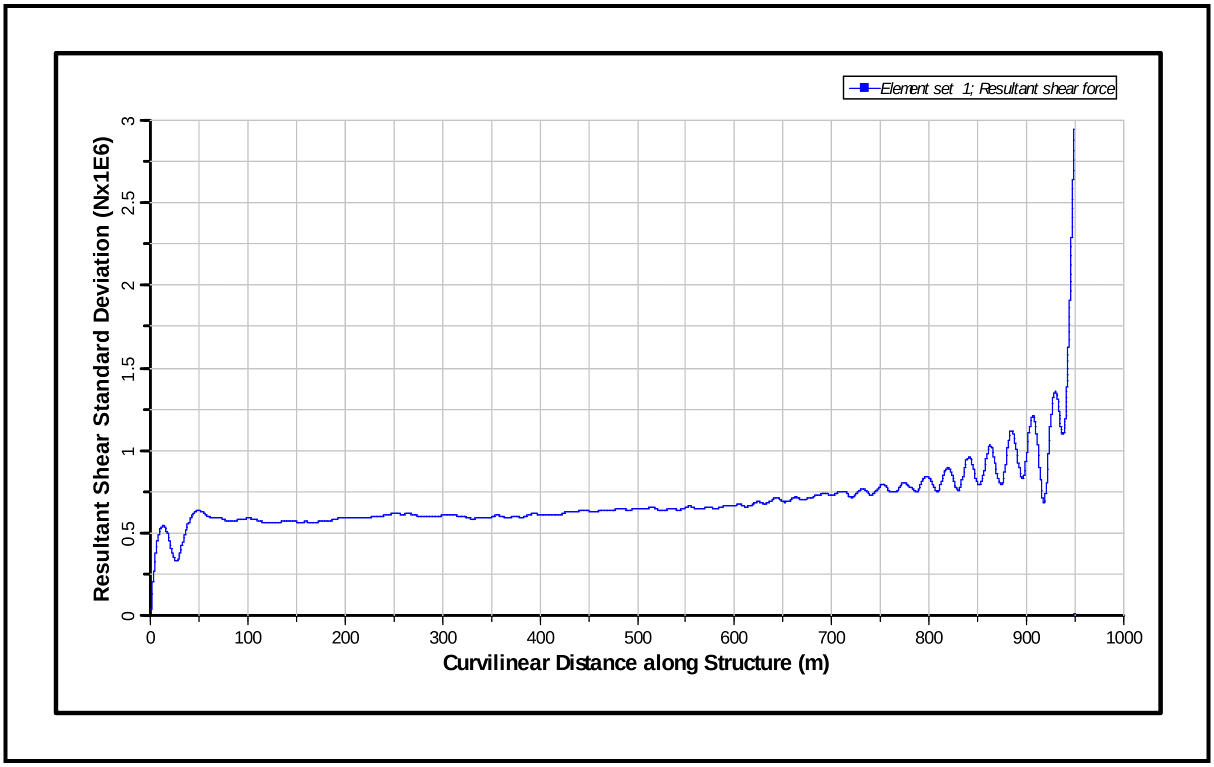


Figure 129: Standard Deviation of Shear Force for 1000 m CWP for Bin 6 (from Bottom to Top)

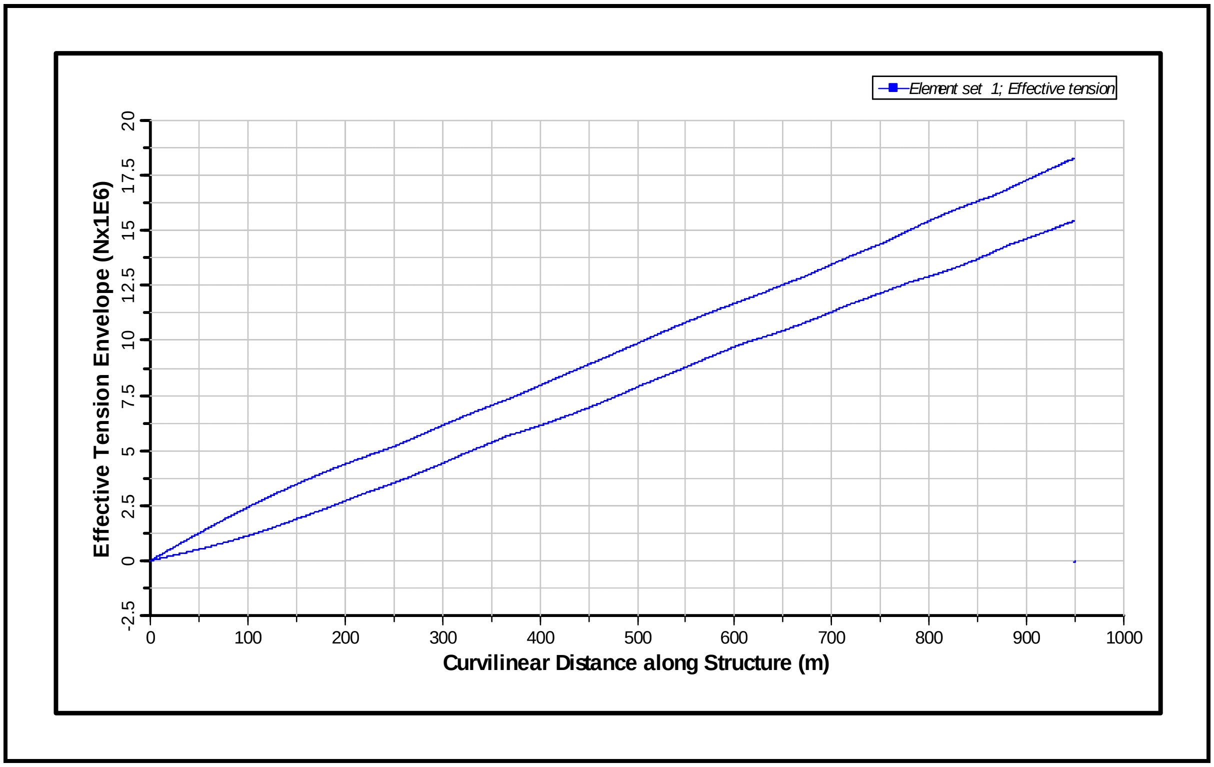


Figure 130: Axial Tension Envelope for 1000 m CWP for Bin 6 (from Bottom to Top)

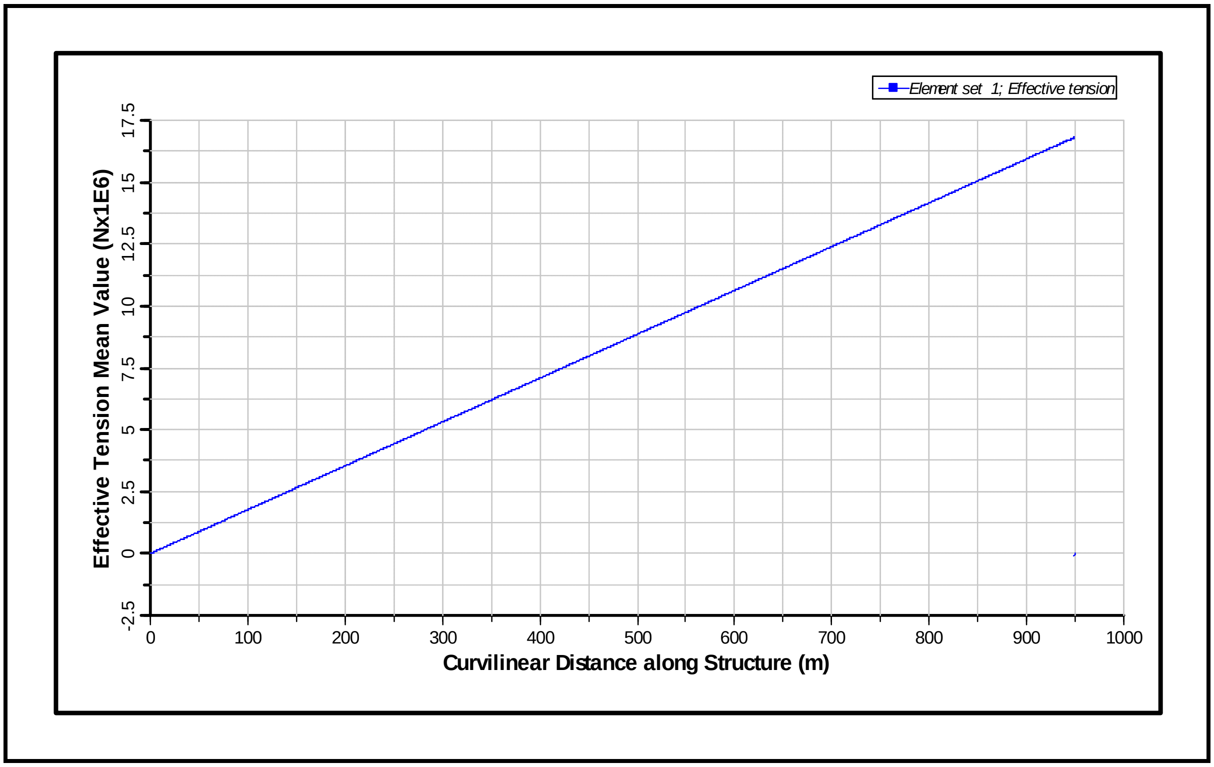


Figure 131: Mean Axial Tension for 1000 m CWP for Bin 6 (from Bottom to Top)

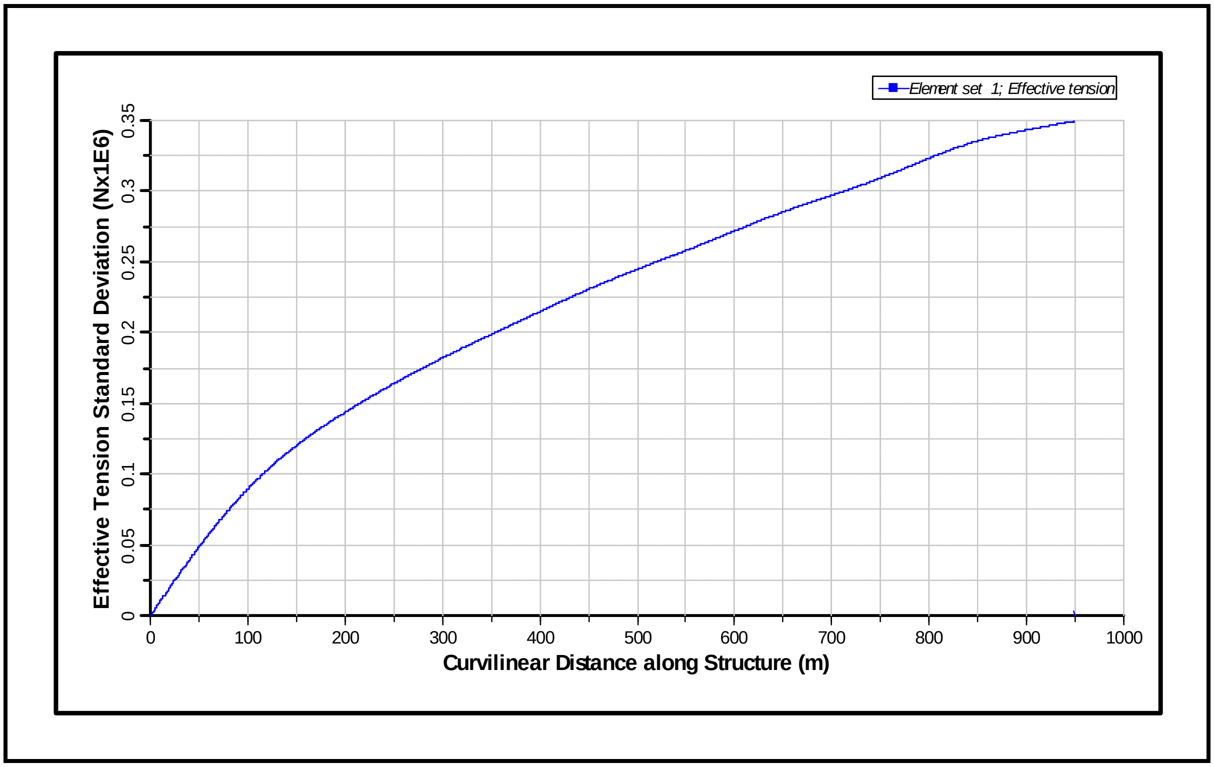


Figure 132: Standard Deviation of Axial Tension for 1000 m CWP for Bin 6 (from Bottom to Top)

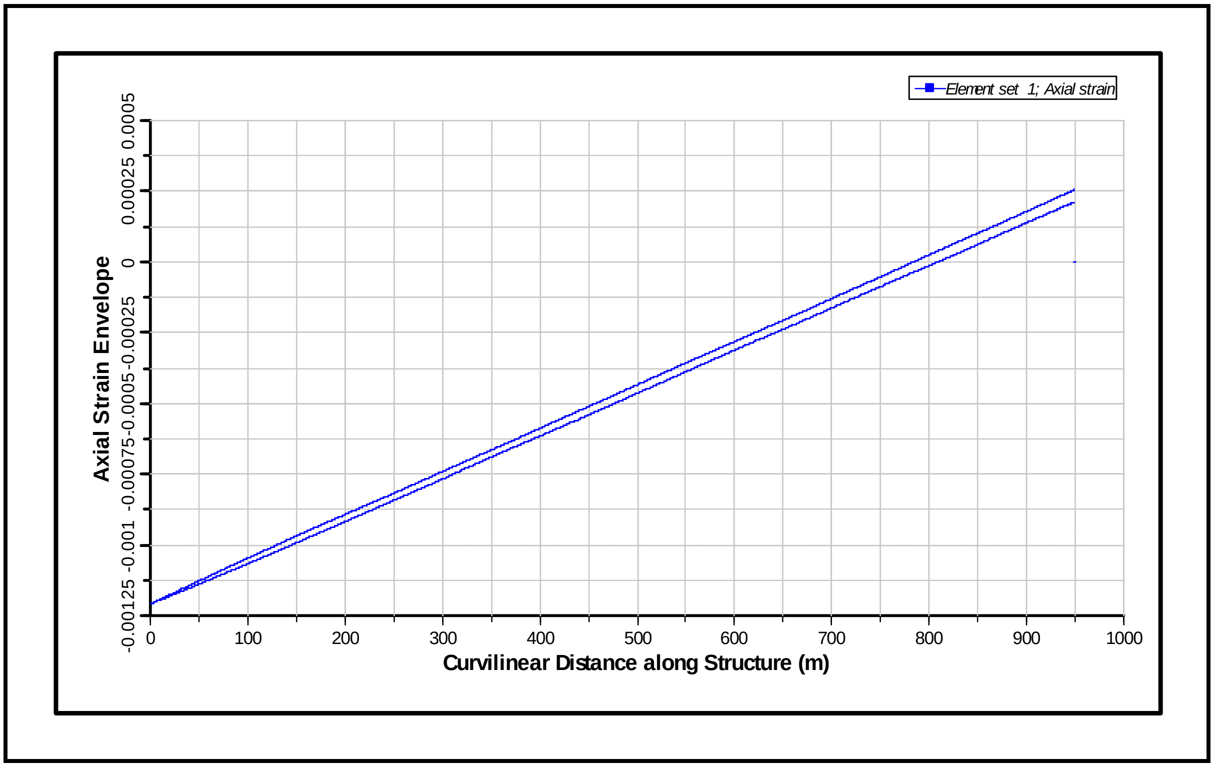


Figure 133: Axial Strain Envelope for 1000 m CWP for Bin 6 (from Bottom to Top)

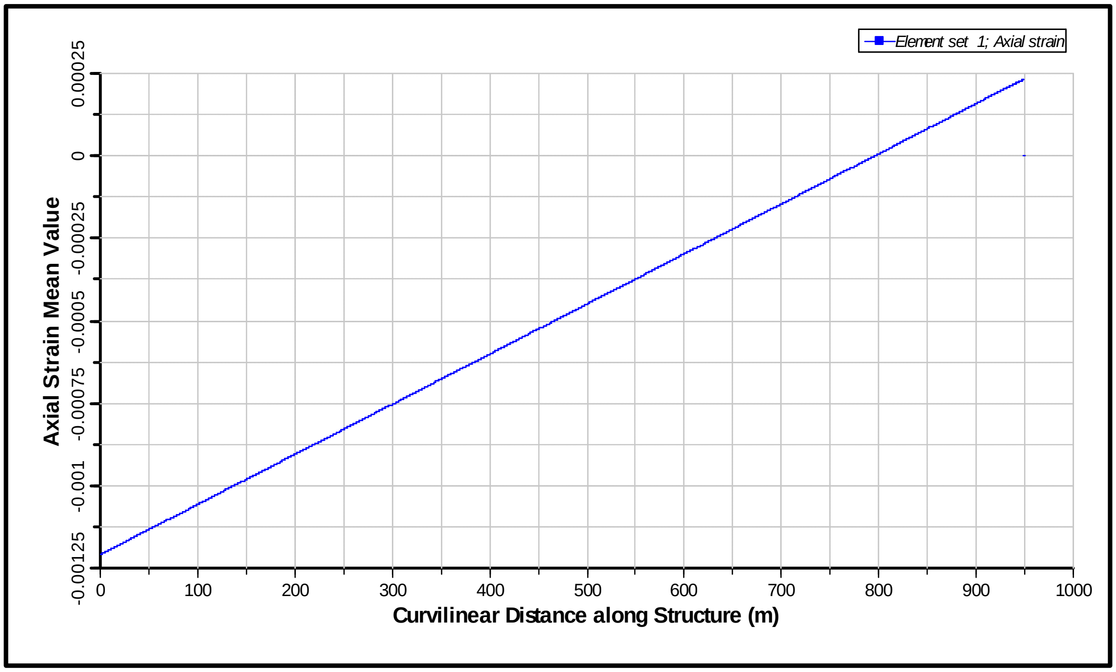


Figure 134: Mean Axial Strain for 1000 m CWP for Bin 6 (from Bottom to Top)

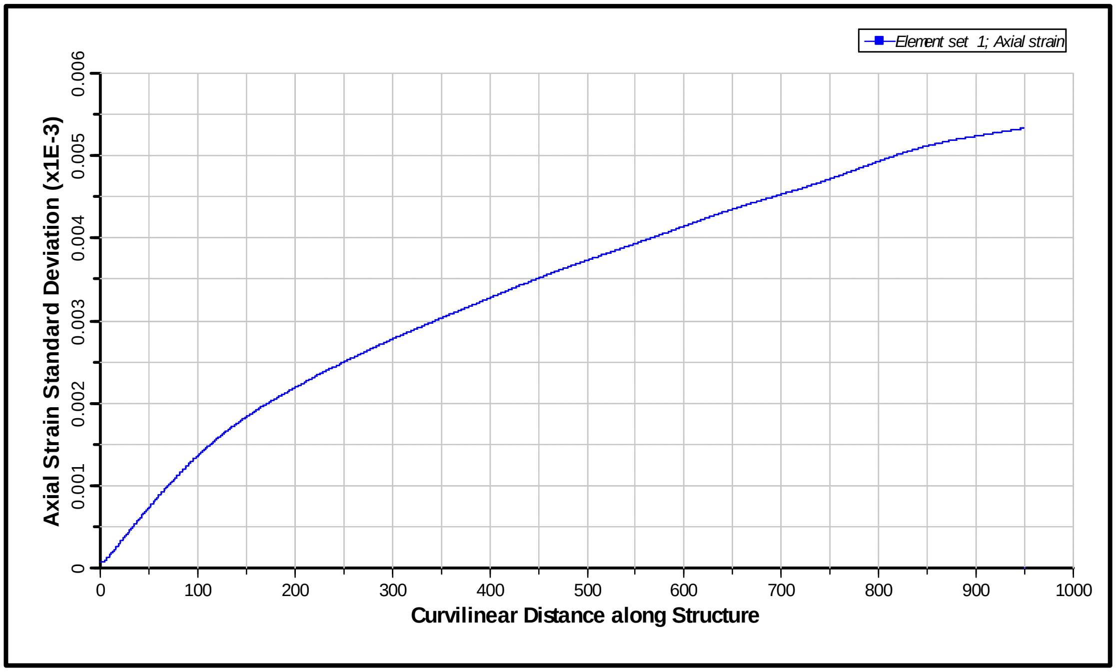


Figure 135: Standard Deviation of Axial Strain for 1000 m CWP for Bin 6 (from Bottom to Top)

6.7 Bin 7

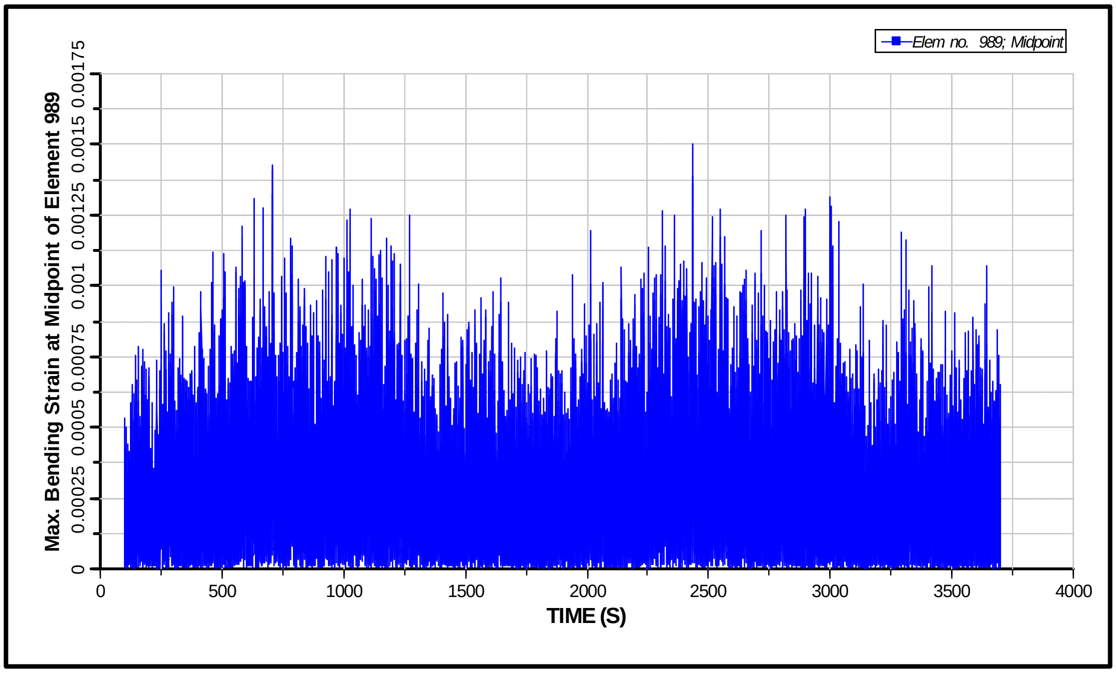


Figure 136: Maximum Bending Strain Time History at Top of CWP for Bin 7

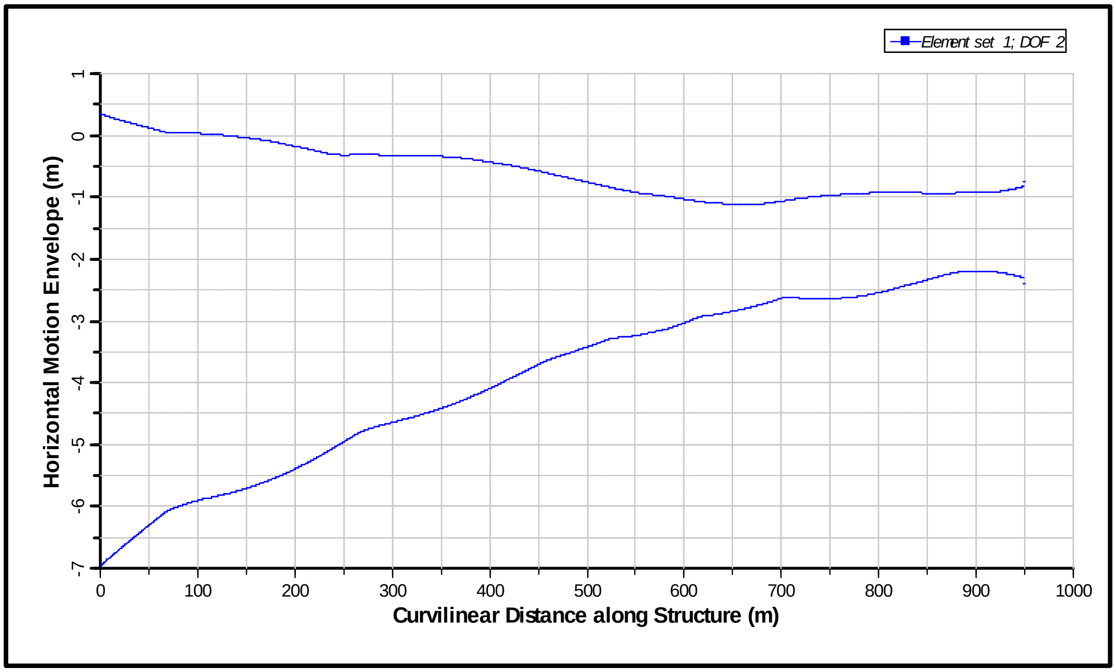


Figure 137: Motion Envelope for 1000 m CWP for Bin 7 (from Bottom to Top)

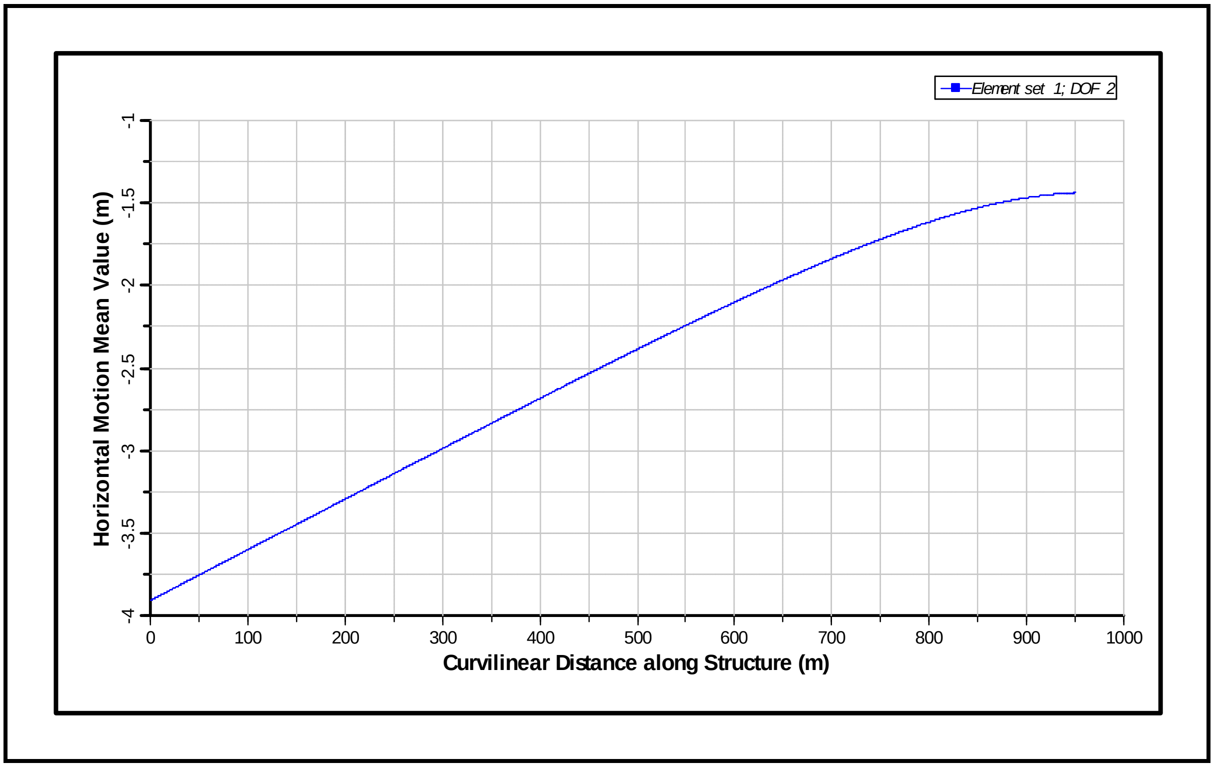


Figure 138: Mean Motion for 1000 m CWP for Bin 7 (from Bottom to Top)

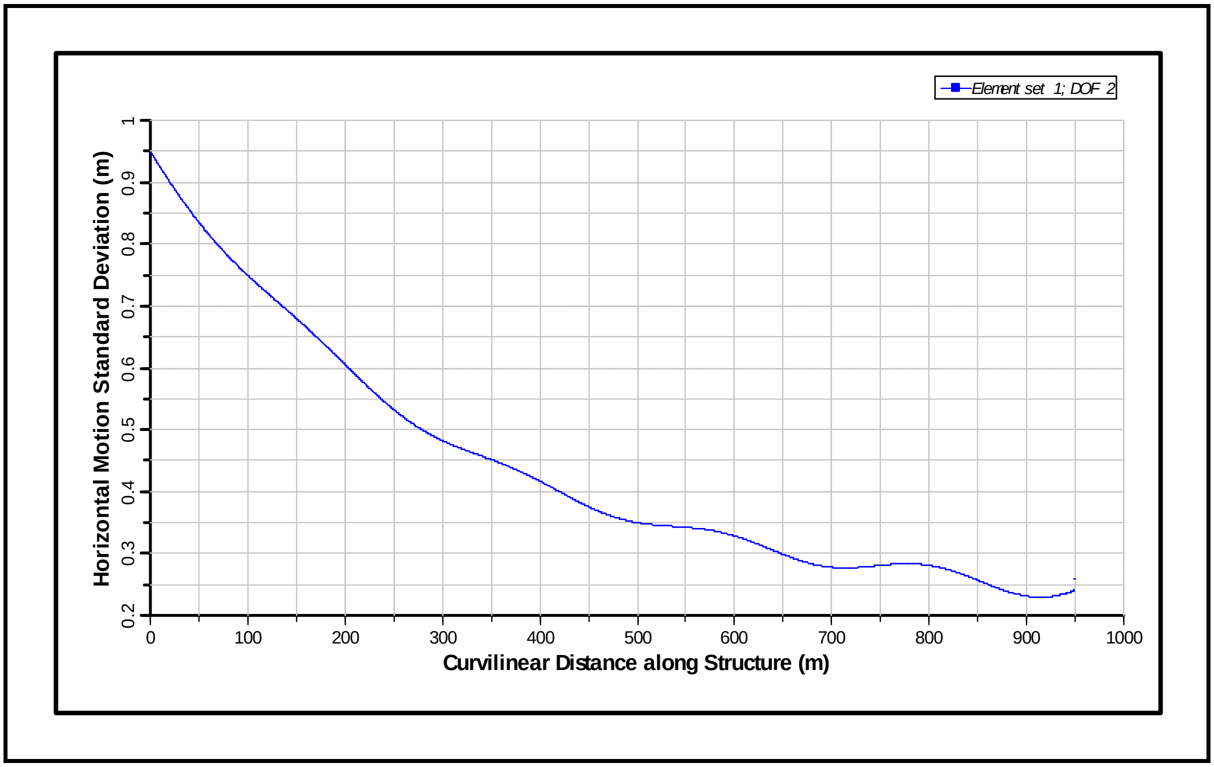


Figure 139: Standard Deviation of Motion for 1000 m CWP for Bin 7 (from Bottom to Top)

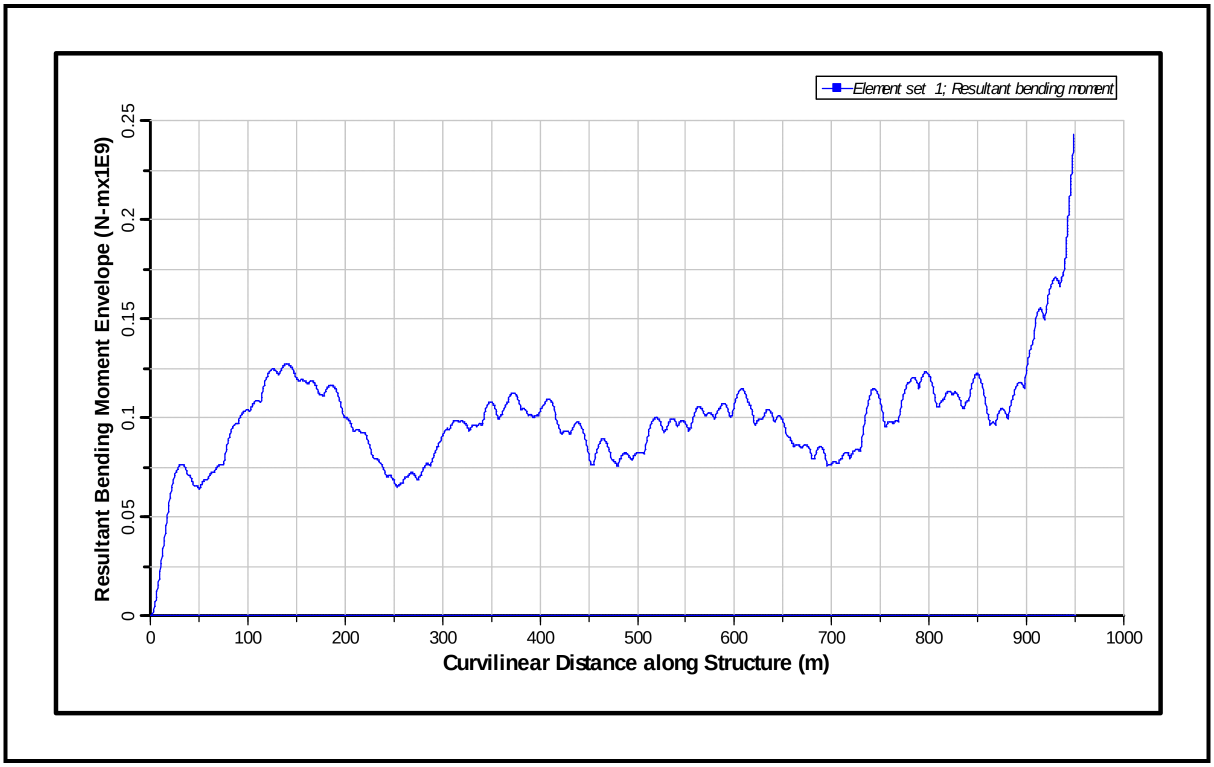


Figure 140: Bending Moment Envelope for 1000 m CWP for Bin 7 (from Bottom to Top)

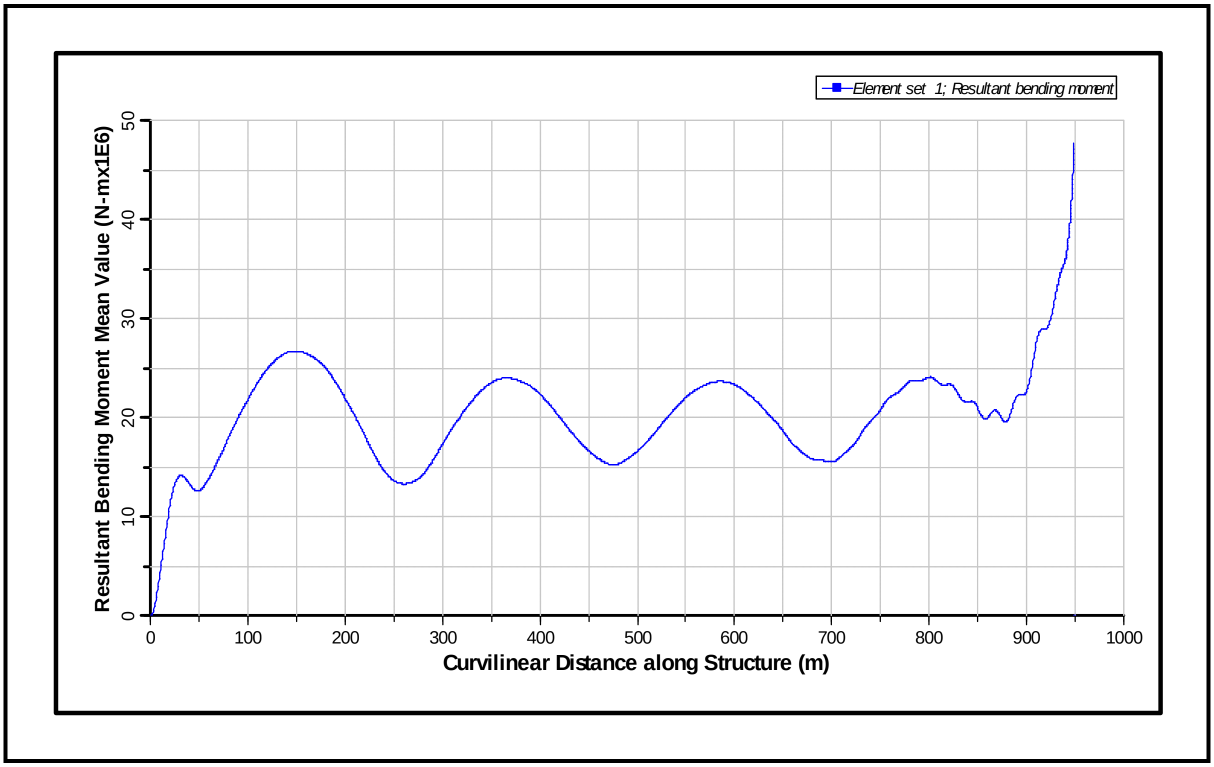


Figure 141: Mean Bending Moment for 1000 m CWP for Bin 7 (from Bottom to Top)

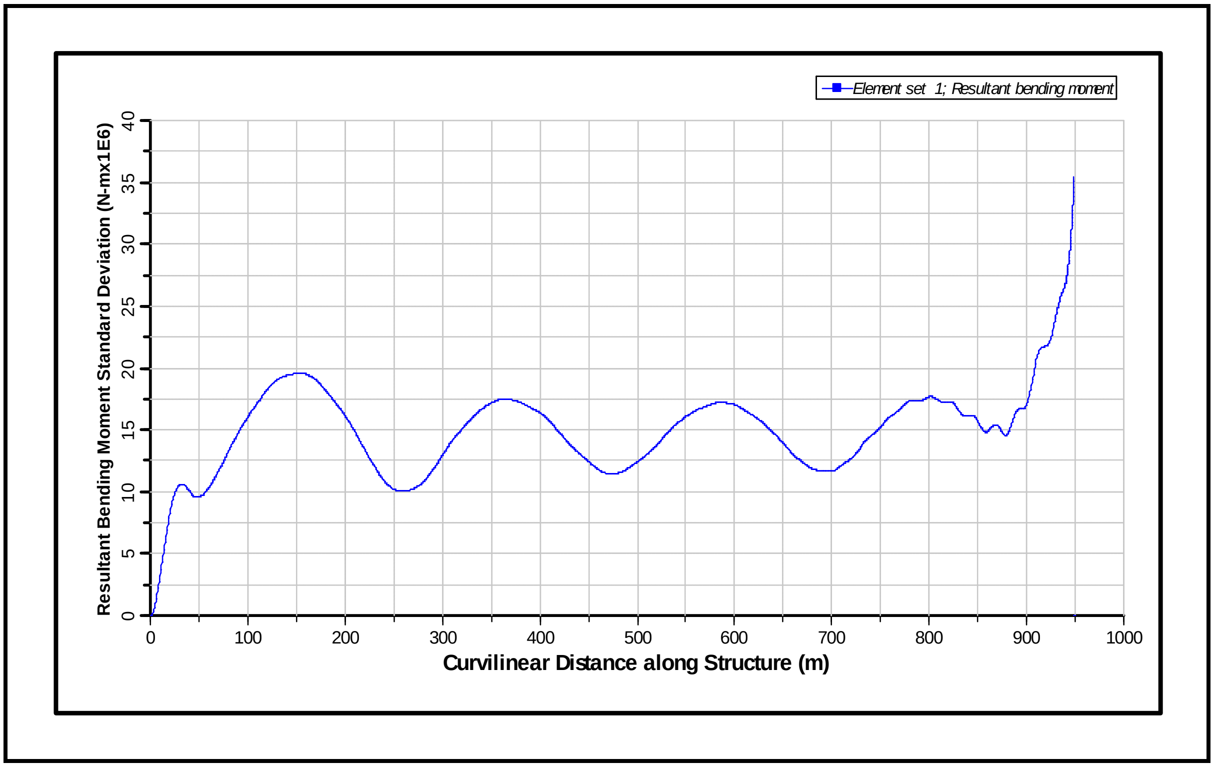


Figure 142: Standard Deviation of Bending Moment for 1000 m CWP for Bin 7 (from Bottom to Top)

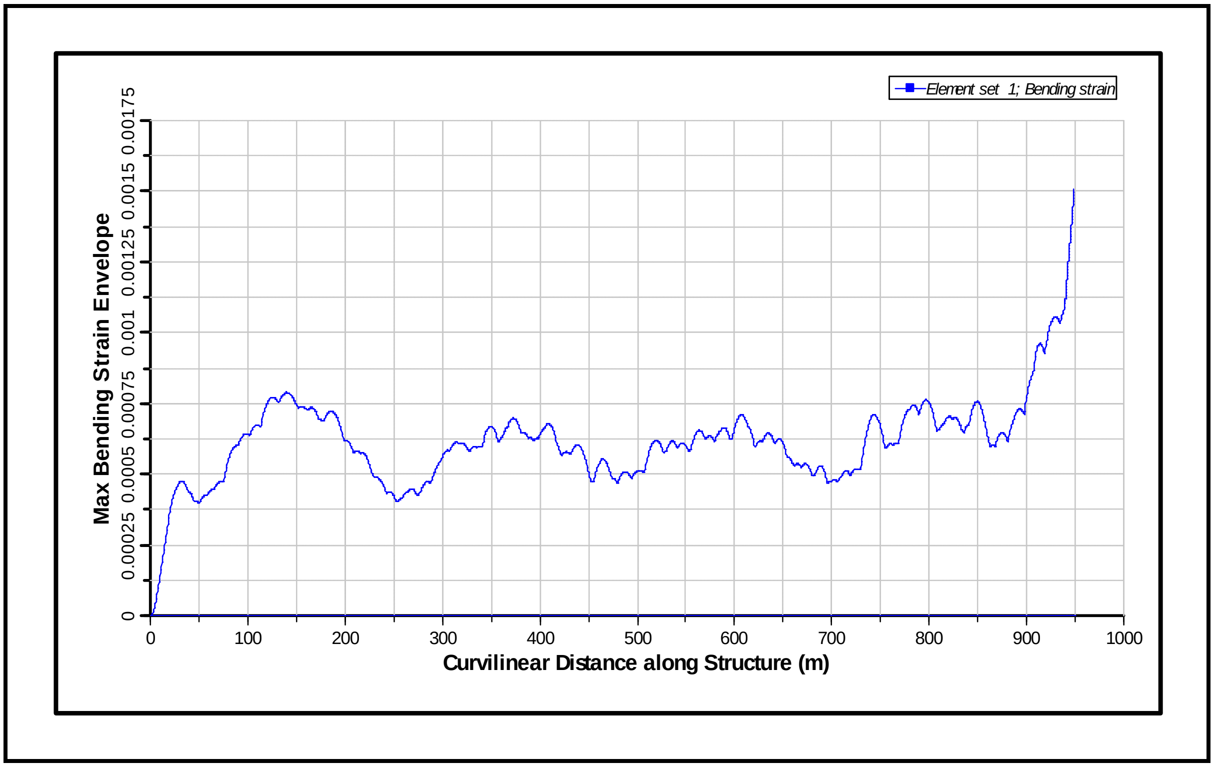


Figure 143: Bending Strain Envelope for 1000 m CWP for Bin 7 (from Bottom to Top)

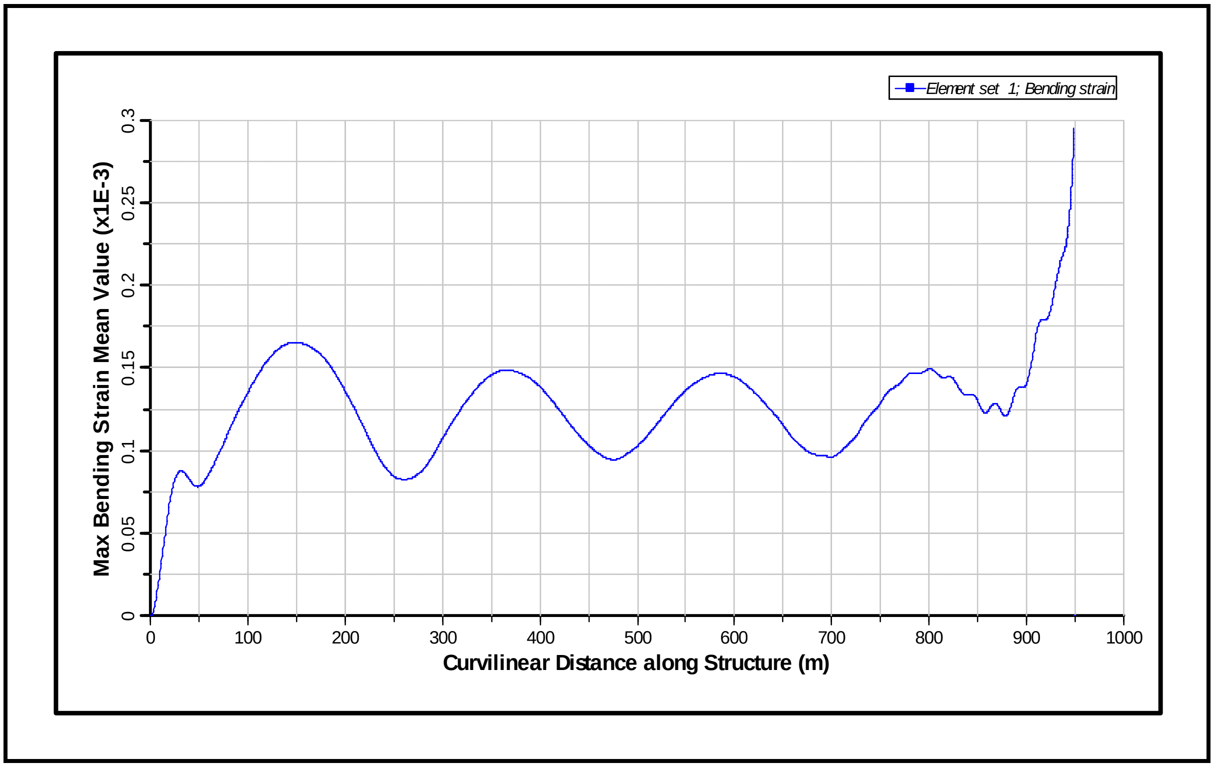


Figure 144: Mean Bending Strain for 1000 m CWP for Bin 7 (from Bottom to Top)

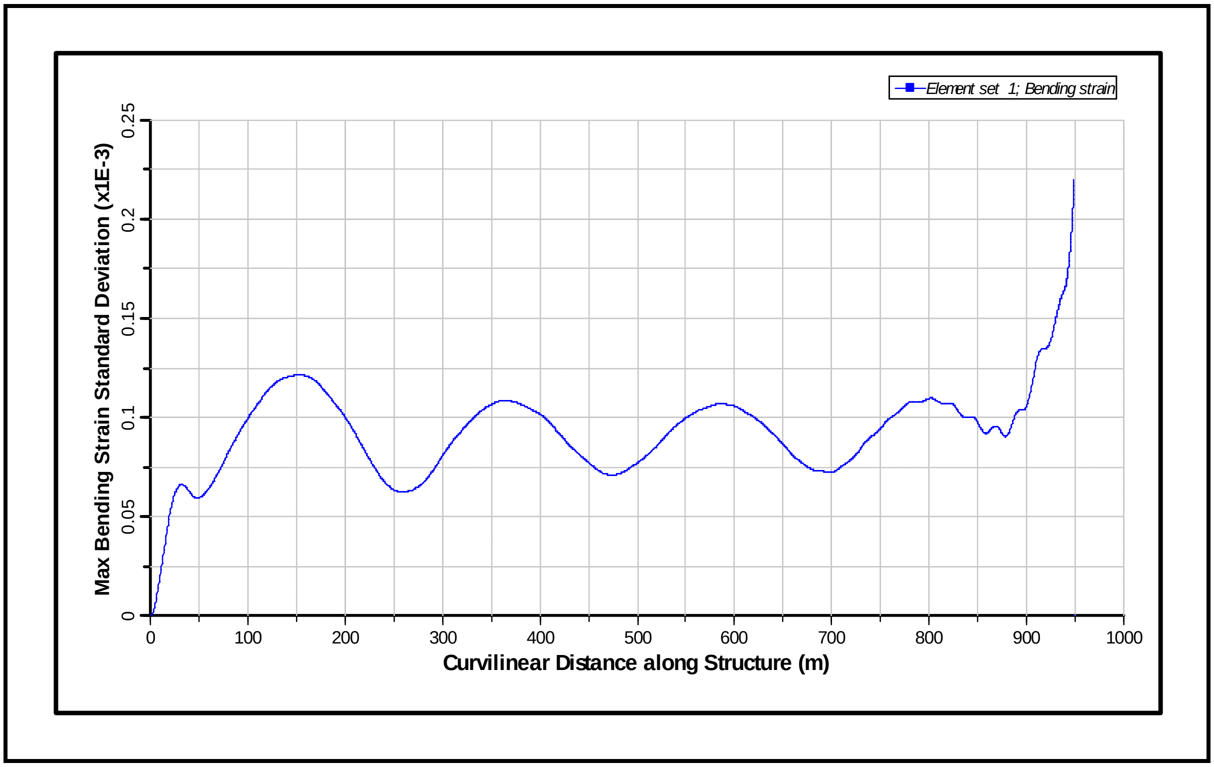


Figure 145: Standard Deviation of Bending Strain for 1000 m CWP for Bin 7 (from Bottom to Top)

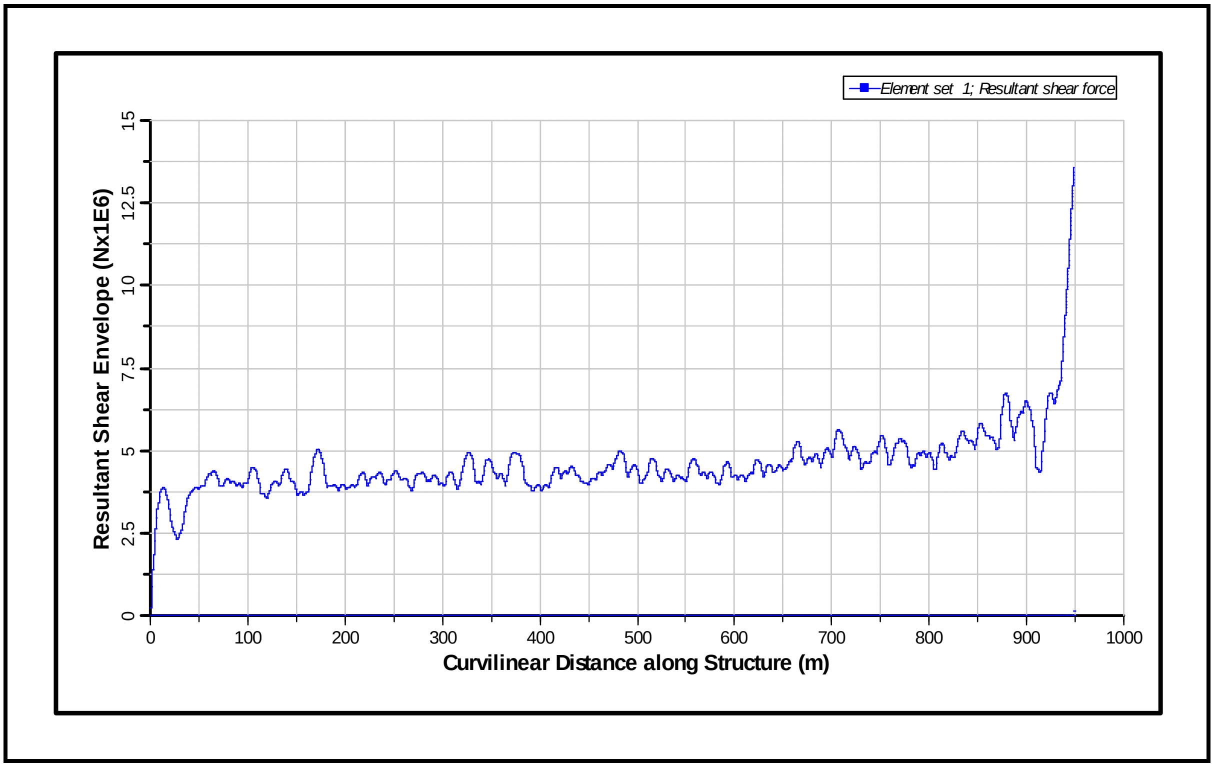


Figure 146: Shear Force Envelope for 1000 m CWP for Bin 7 (from Bottom to Top)

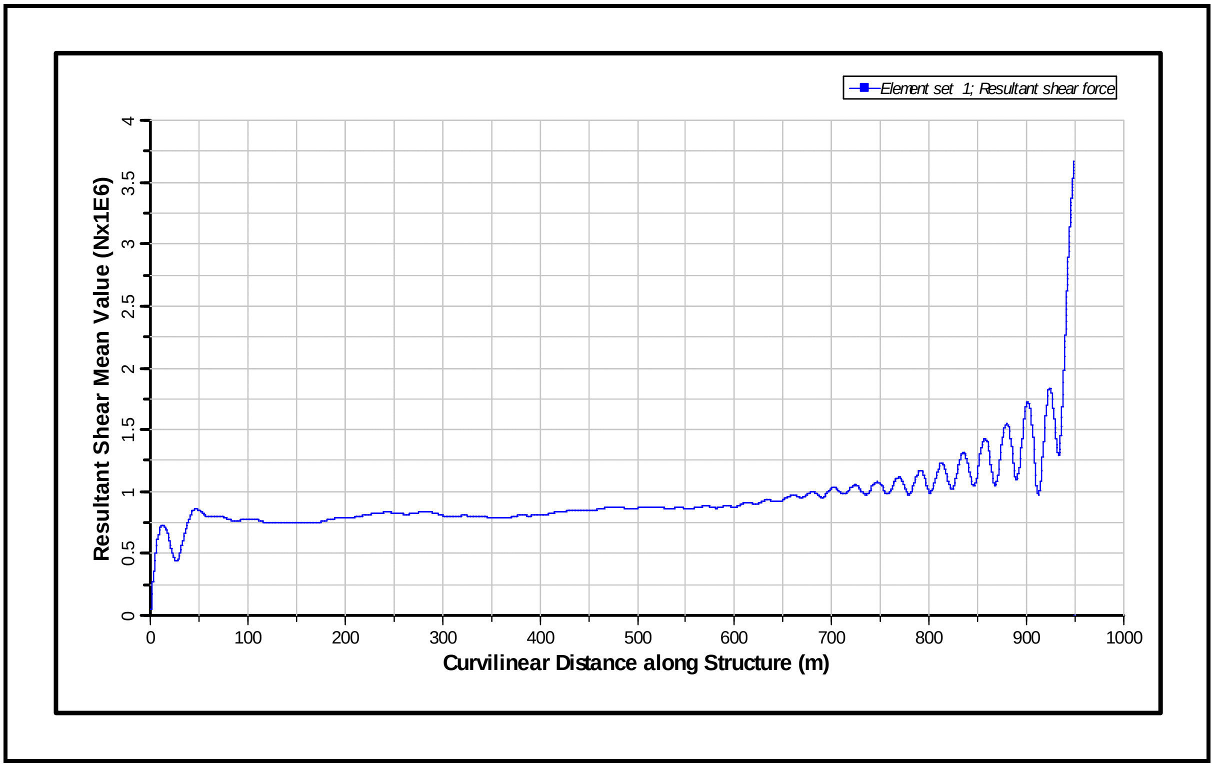


Figure 147: Mean Shear Force for 1000 m CWP for Bin 7 (from Bottom to Top)

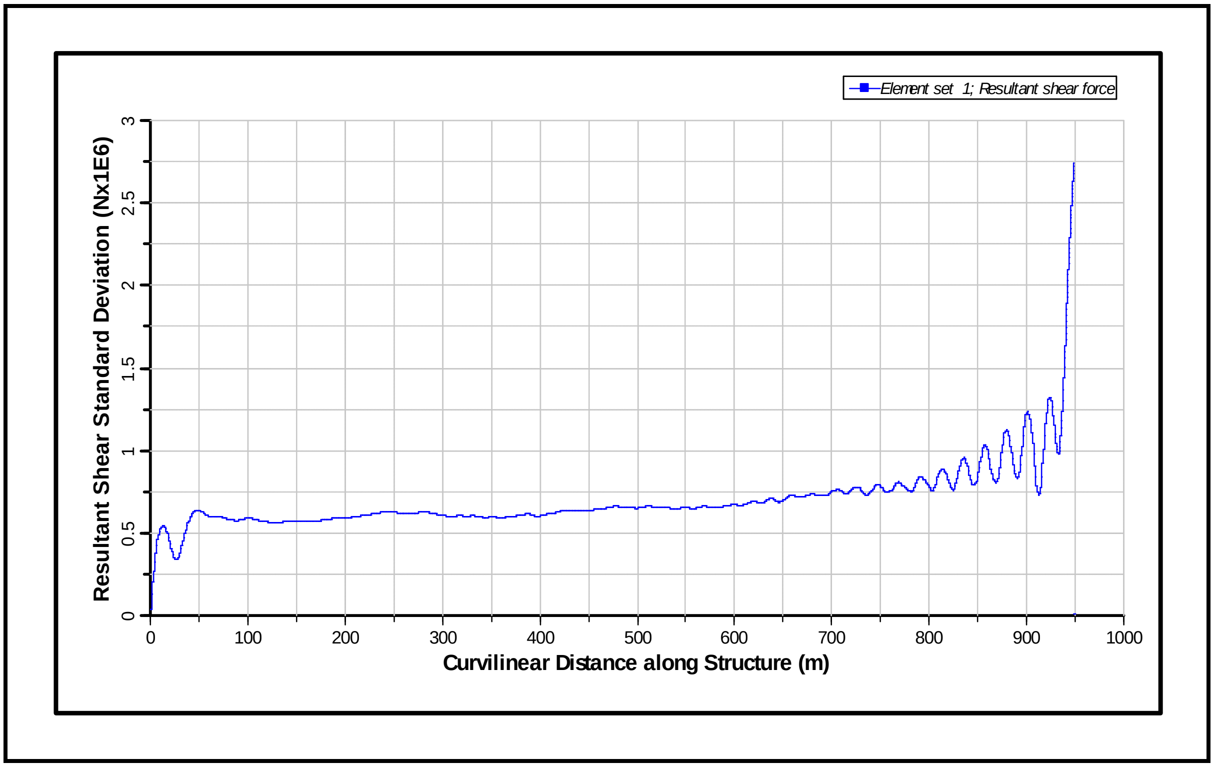


Figure 148: Standard Deviation of Shear Force for 1000 m CWP for Bin 7 (from Bottom to Top)

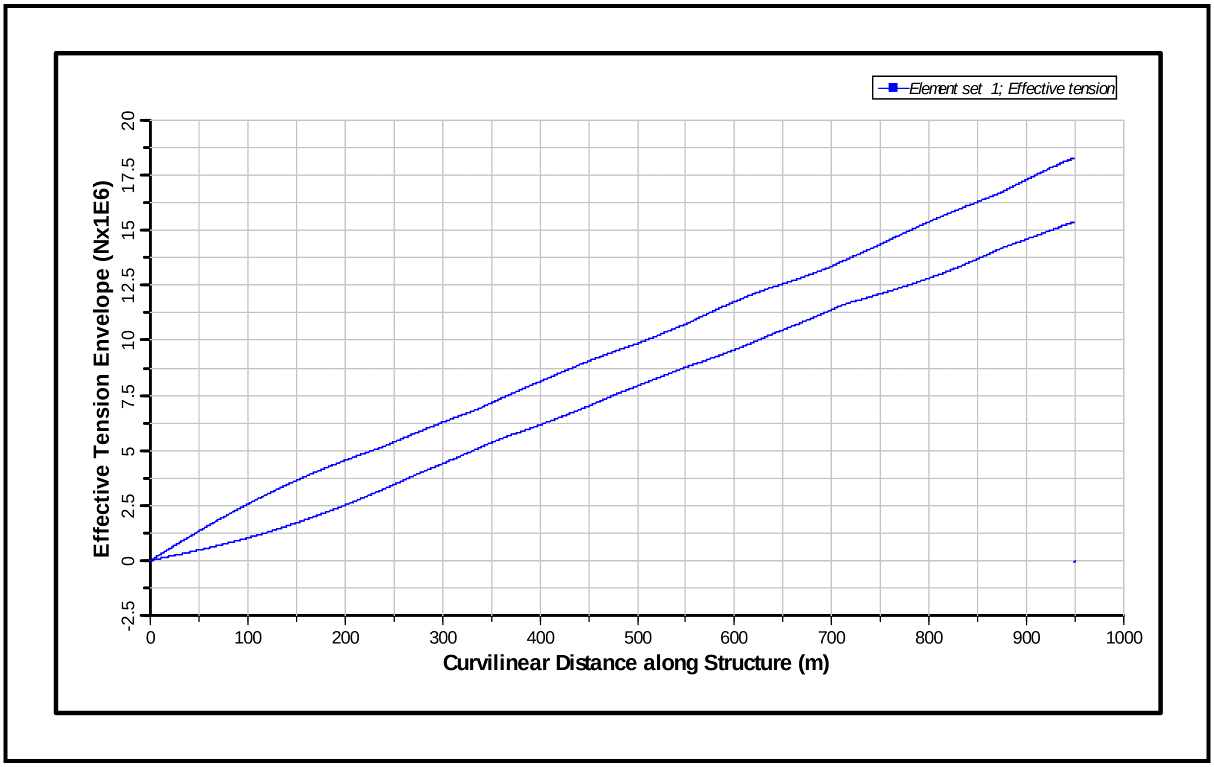


Figure 149: Axial Tension Envelope for 1000 m CWP for Bin 7 (from Bottom to Top)

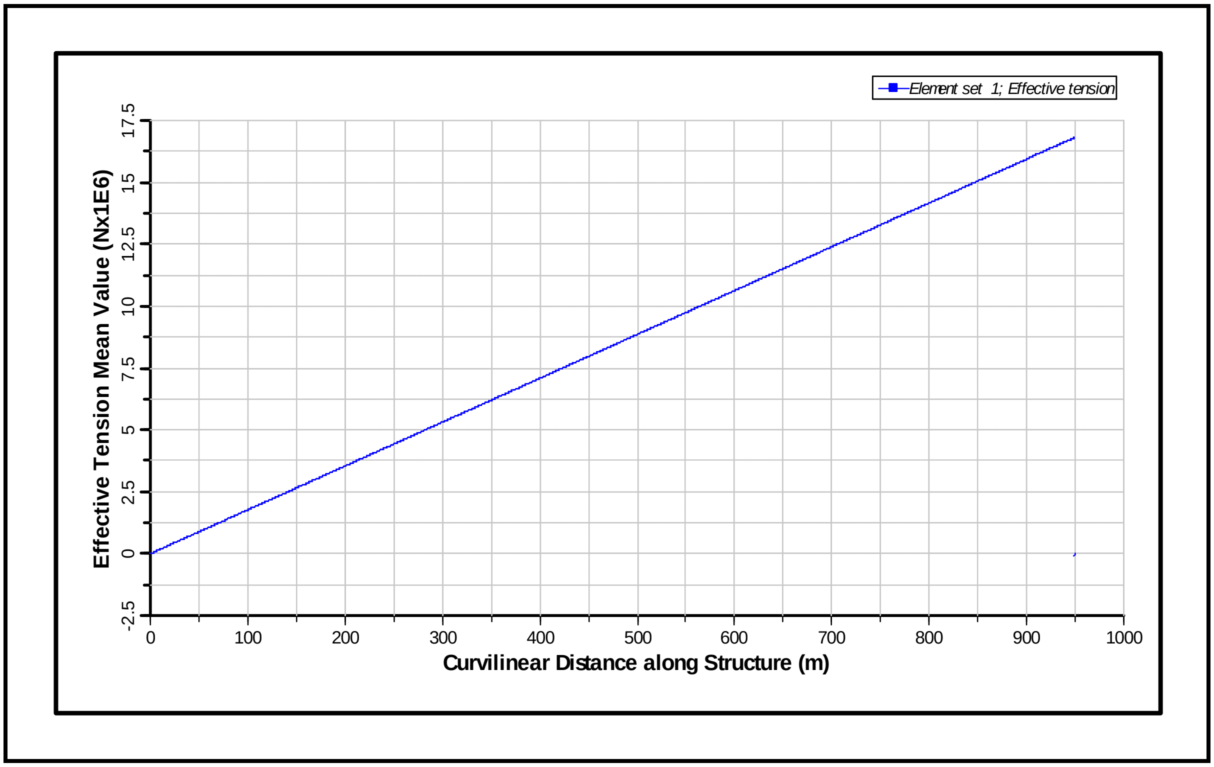


Figure 150: Mean Axial Tension for 1000 m CWP for Bin 7 (from Bottom to Top)

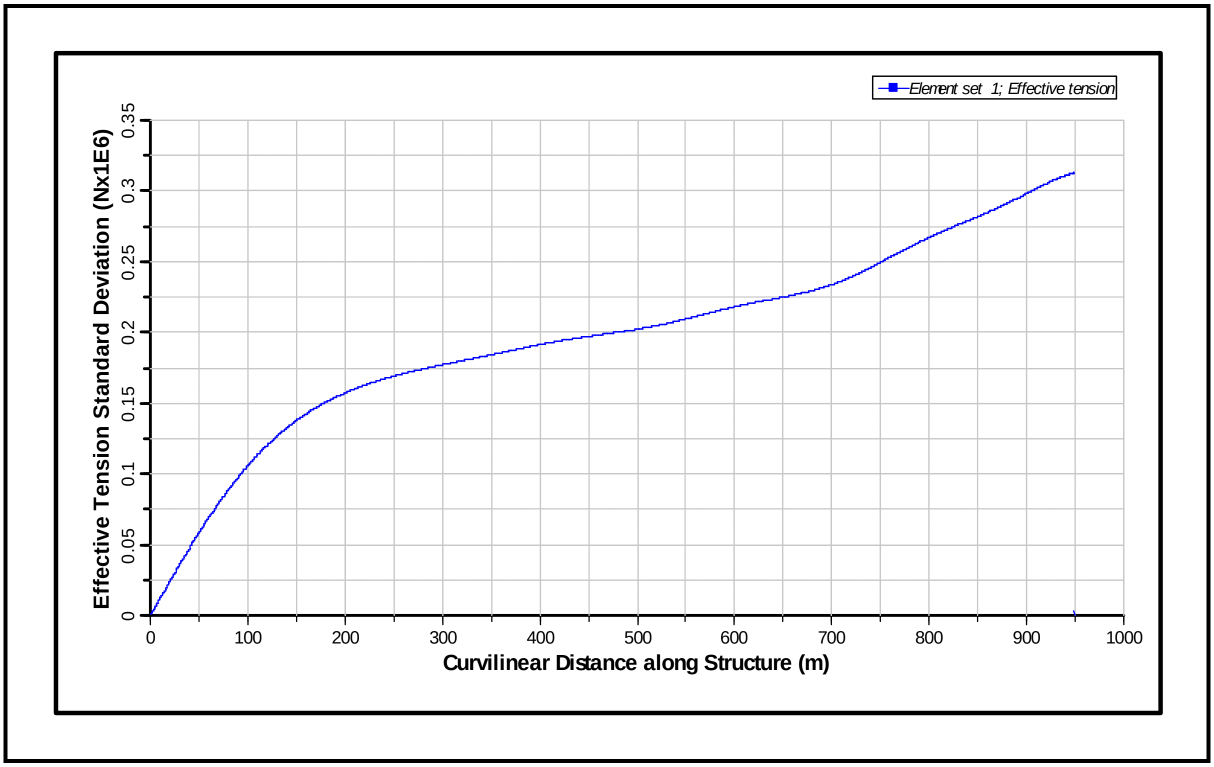


Figure 151: Standard Deviation of Axial Tension for 1000 m CWP for Bin 7 (from Bottom to Top)

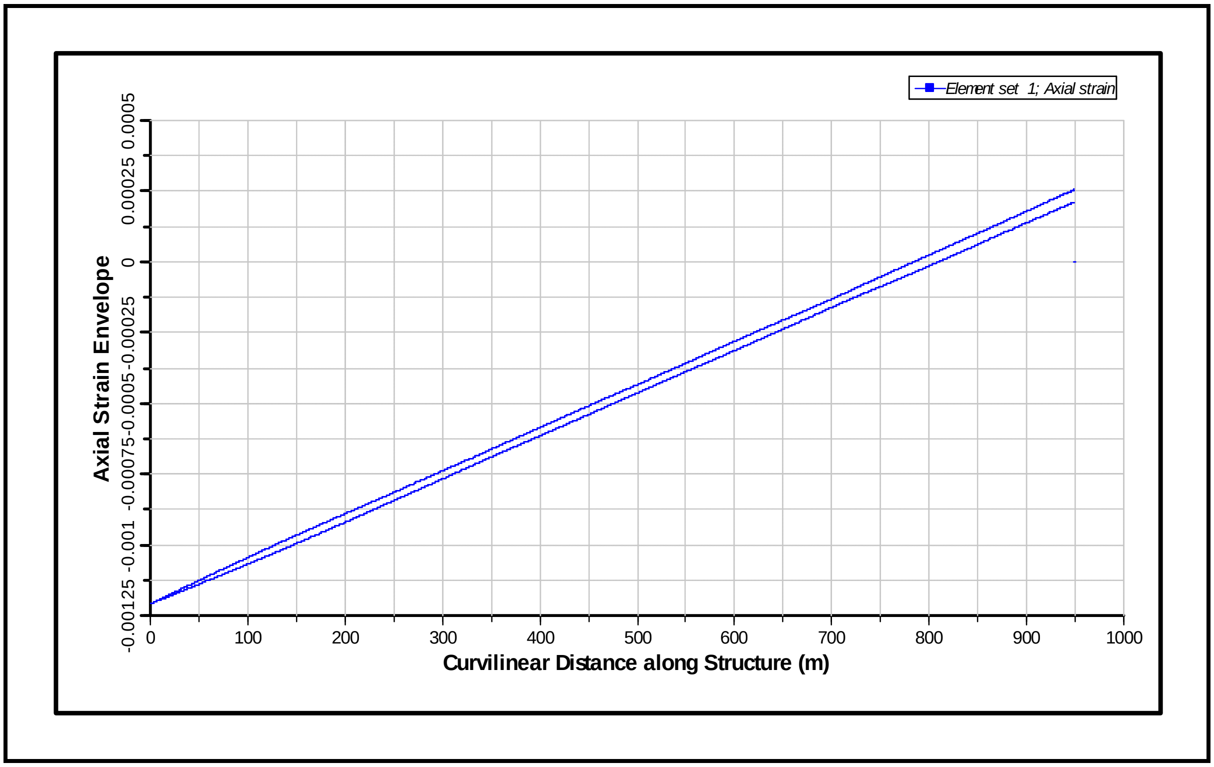


Figure 152: Axial Strain Envelope for 1000 m CWP for Bin 7 (from Bottom to Top)

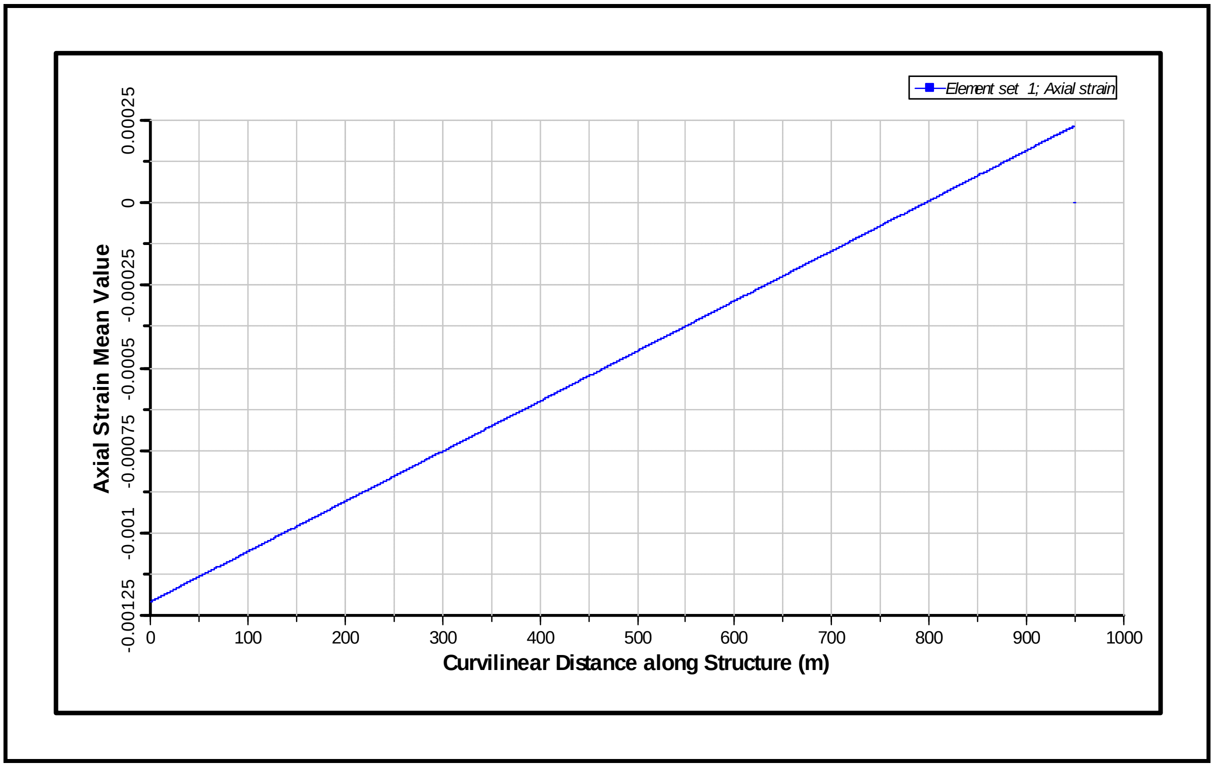


Figure 153: Mean Axial Strain for 1000 m CWP for Bin 7 (from Bottom to Top)

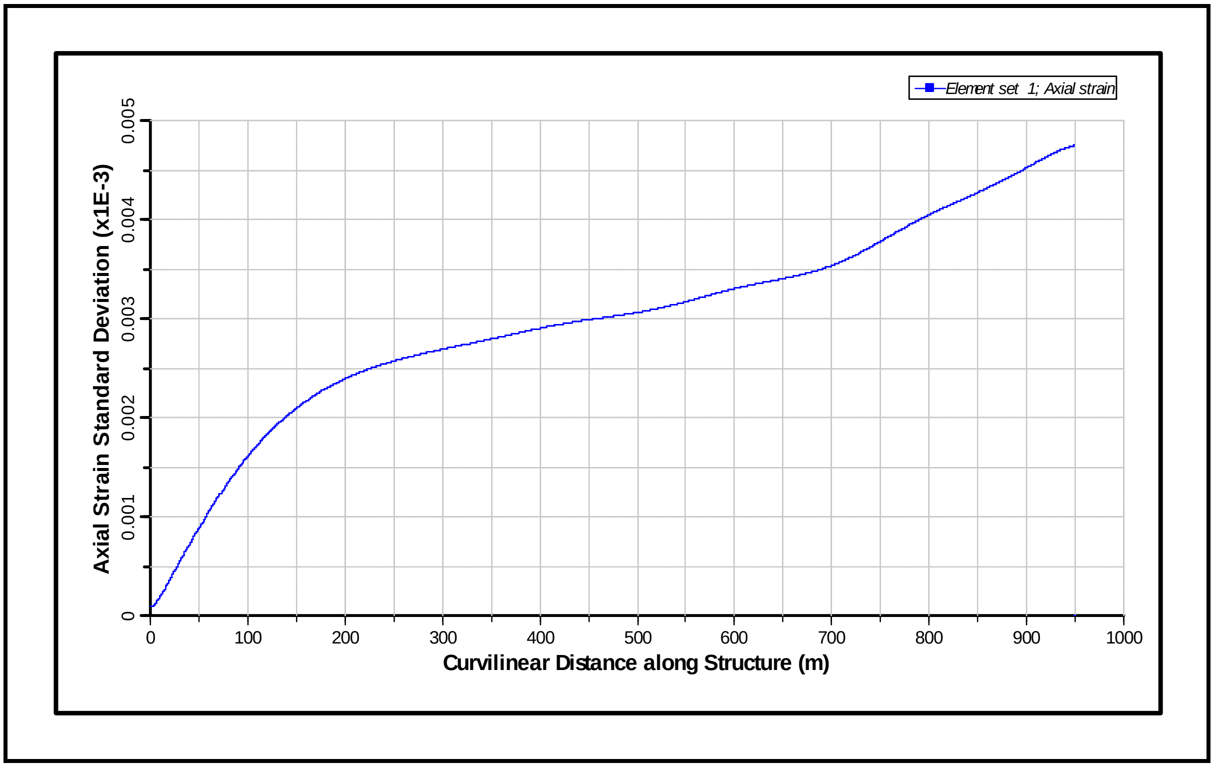


Figure 154: Standard Deviation of Axial Strain for 1000 m CWP for Bin 7 (from Bottom to Top)

6.8 Bin 8

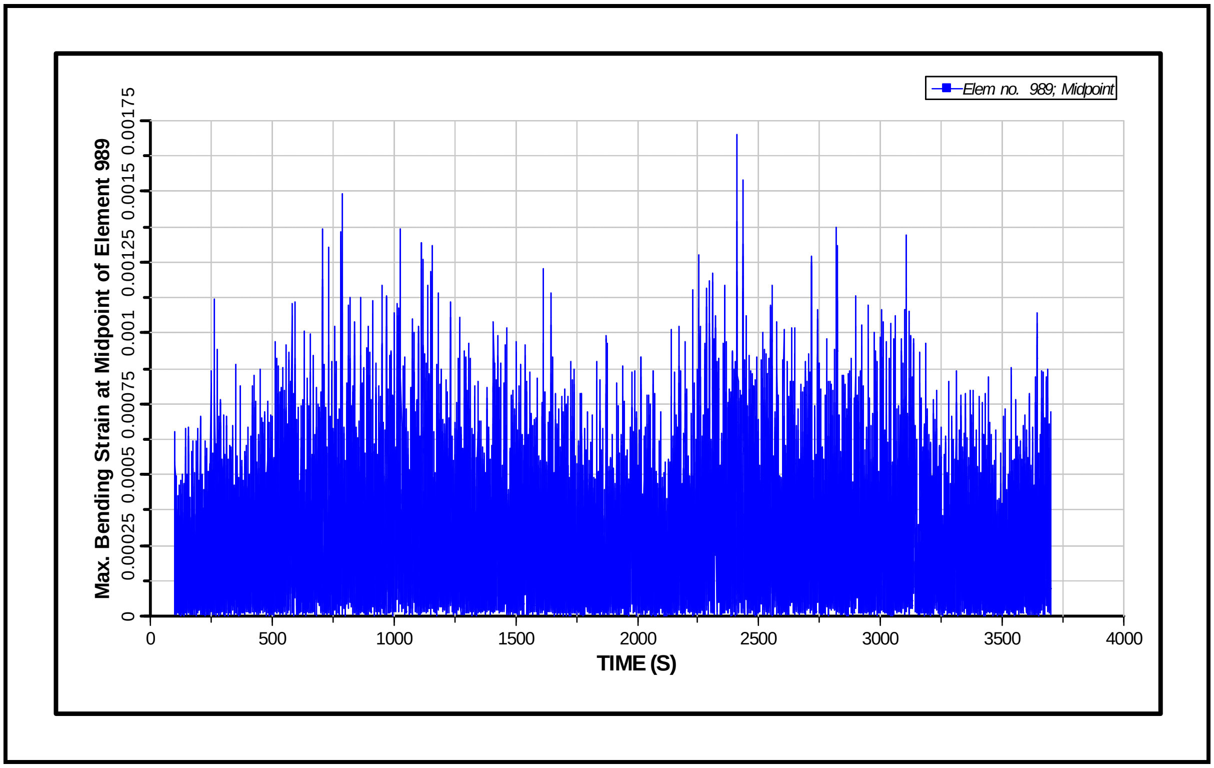


Figure 155: Maximum Bending Strain Time History at Top of CWP for Bin 8

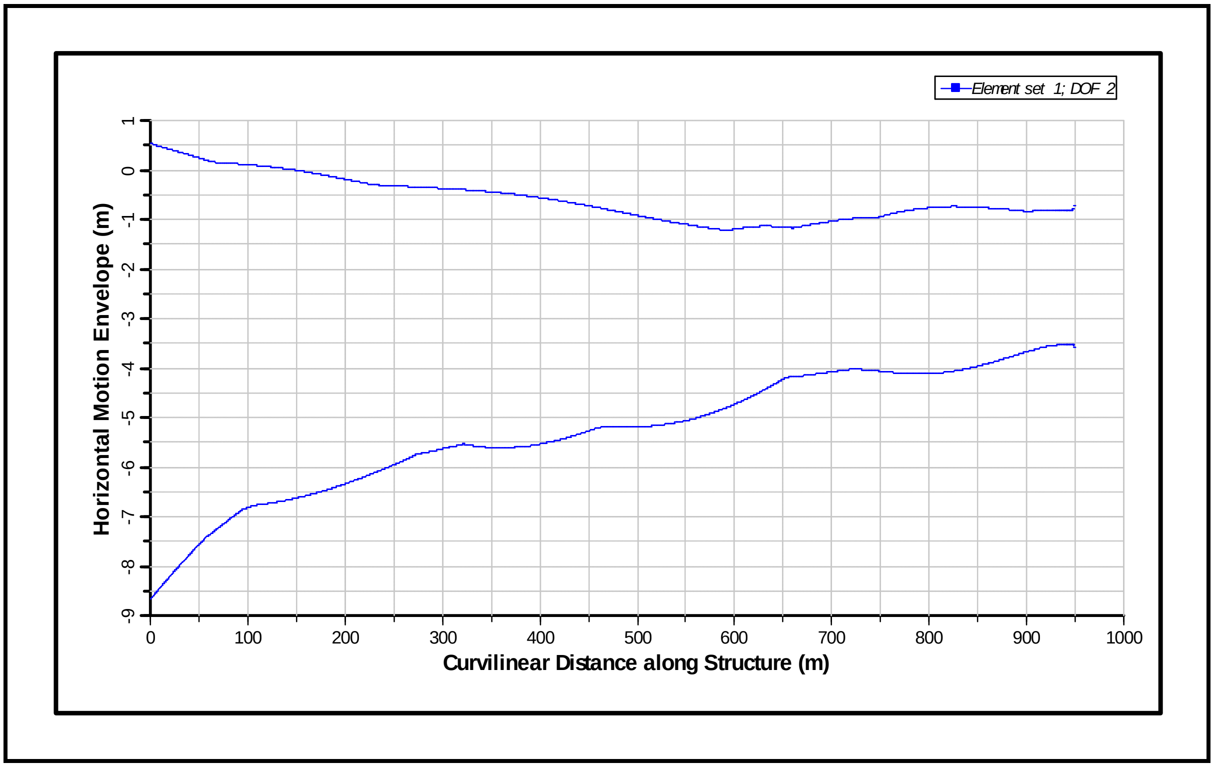


Figure 156: Motion Envelope for 1000 m CWP for Bin 8 (from Bottom to Top)

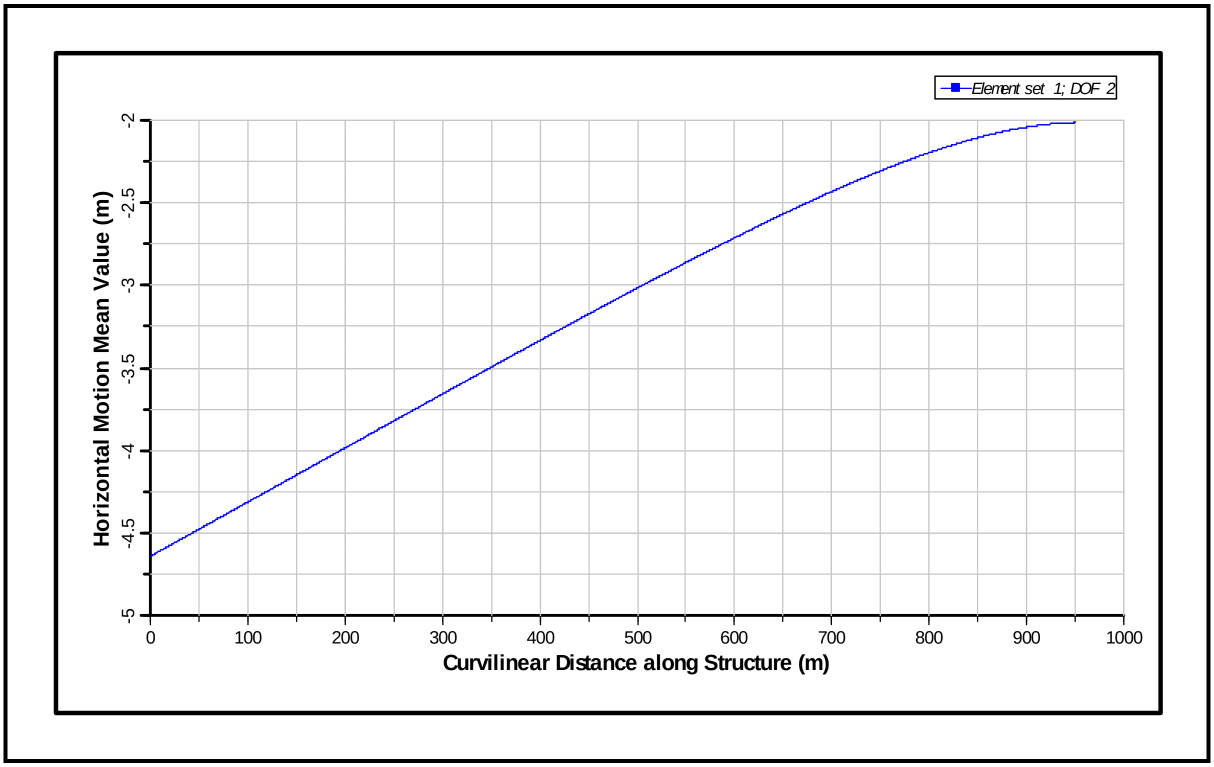


Figure 157: Mean Motion for 1000 m CWP for Bin 8 (from Bottom to Top)

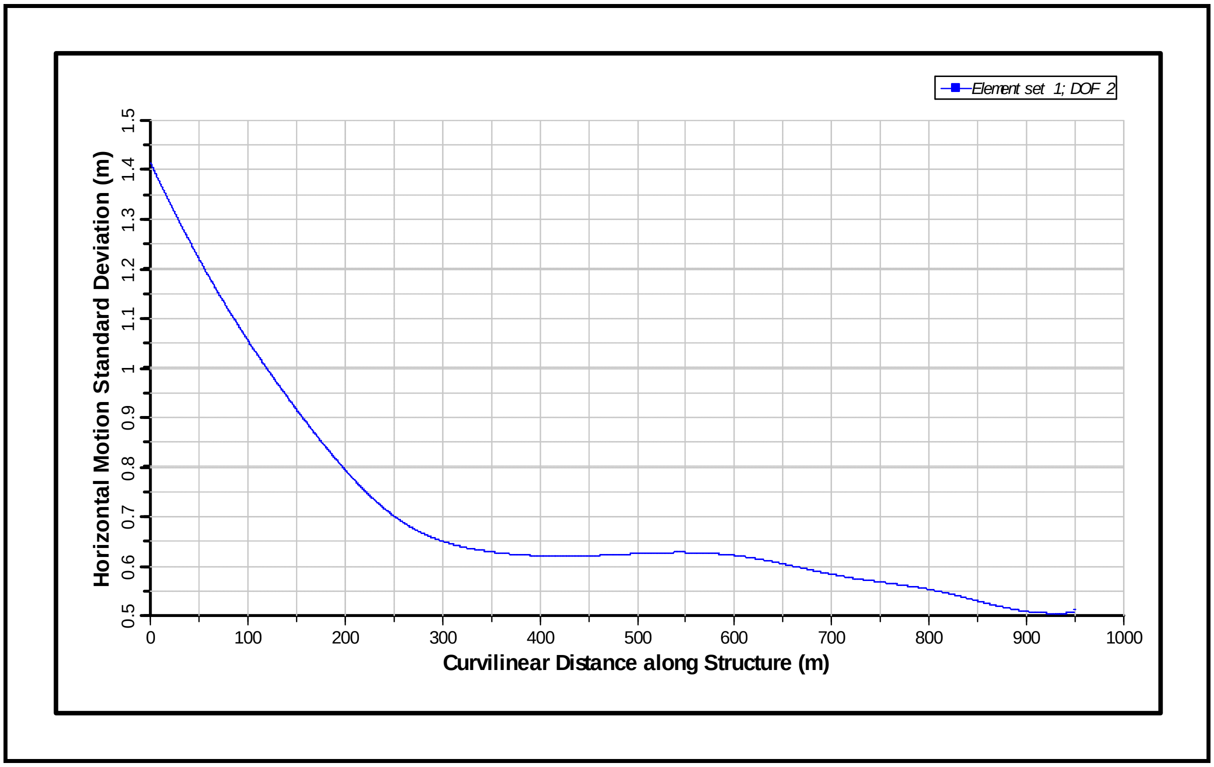


Figure 158: Standard Deviation of Motion for 1000 m CWP for Bin 8 (from Bottom to Top)

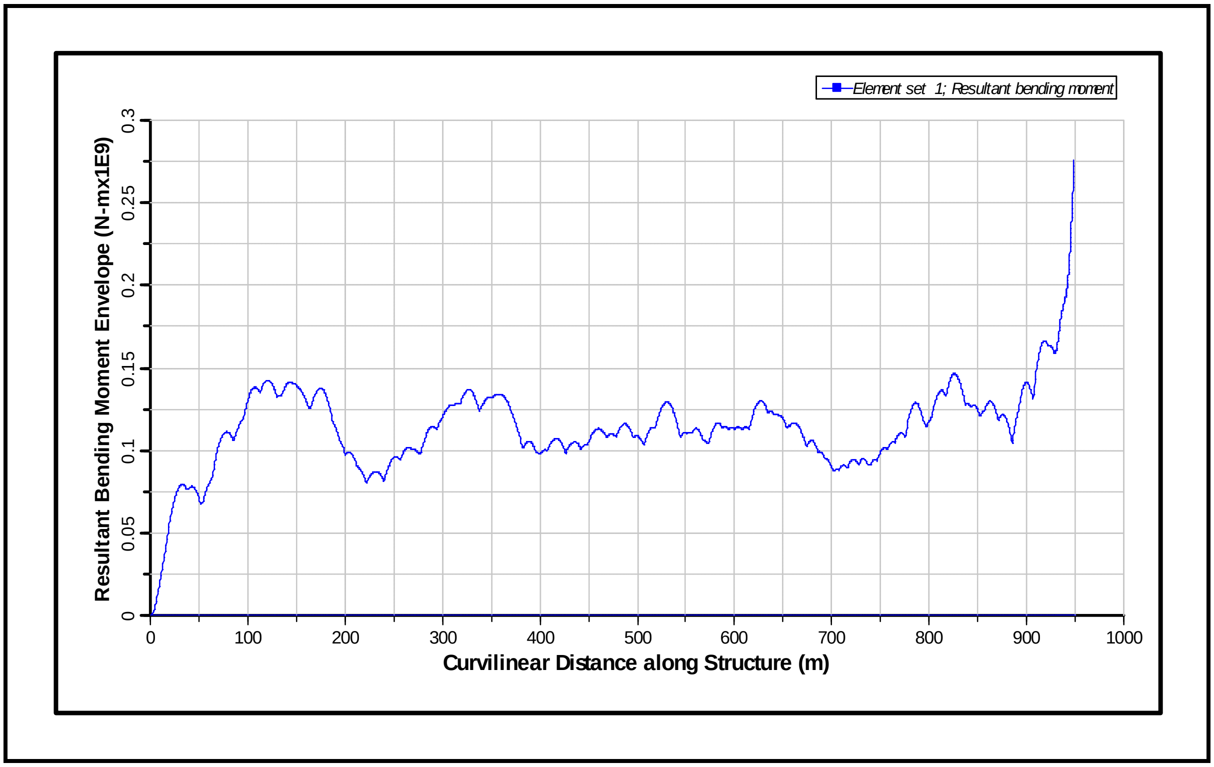


Figure 159: Bending Moment Envelope for 1000 m CWP for Bin 8 (from Bottom to Top)

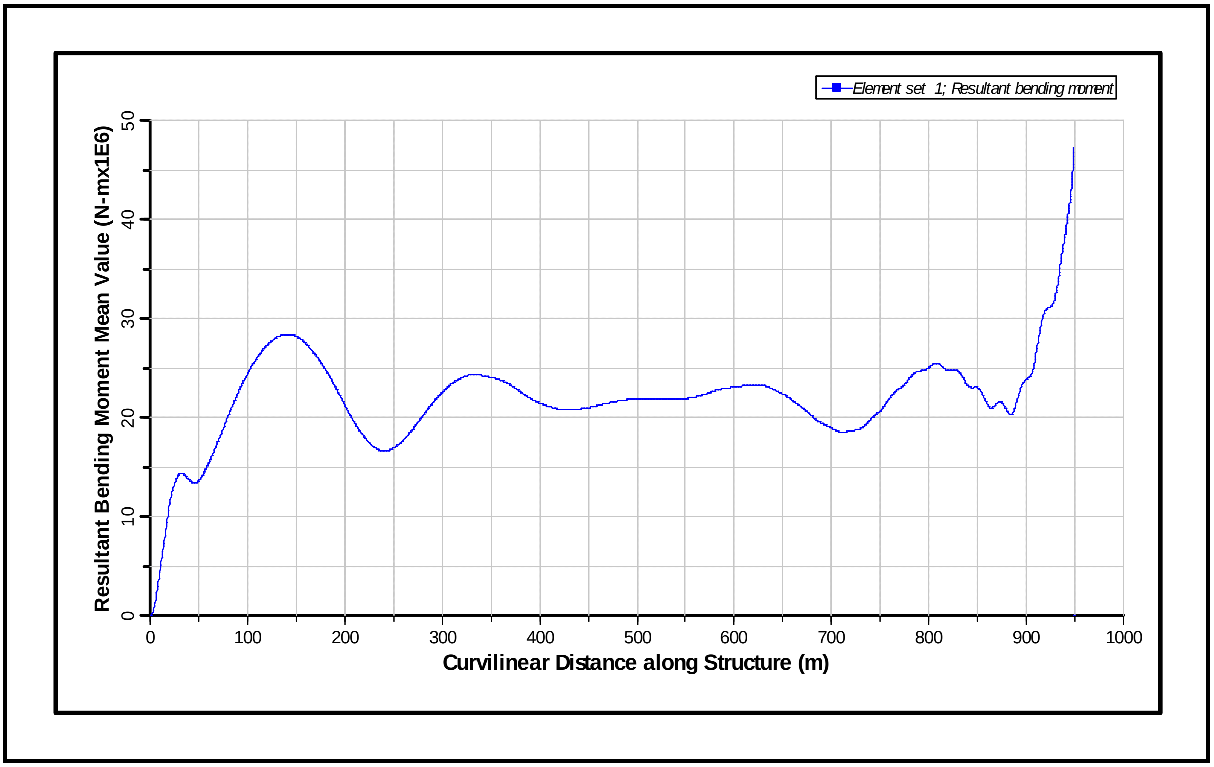


Figure 160: Mean Bending Moment for 1000 m CWP for Bin 8 (from Bottom to Top)

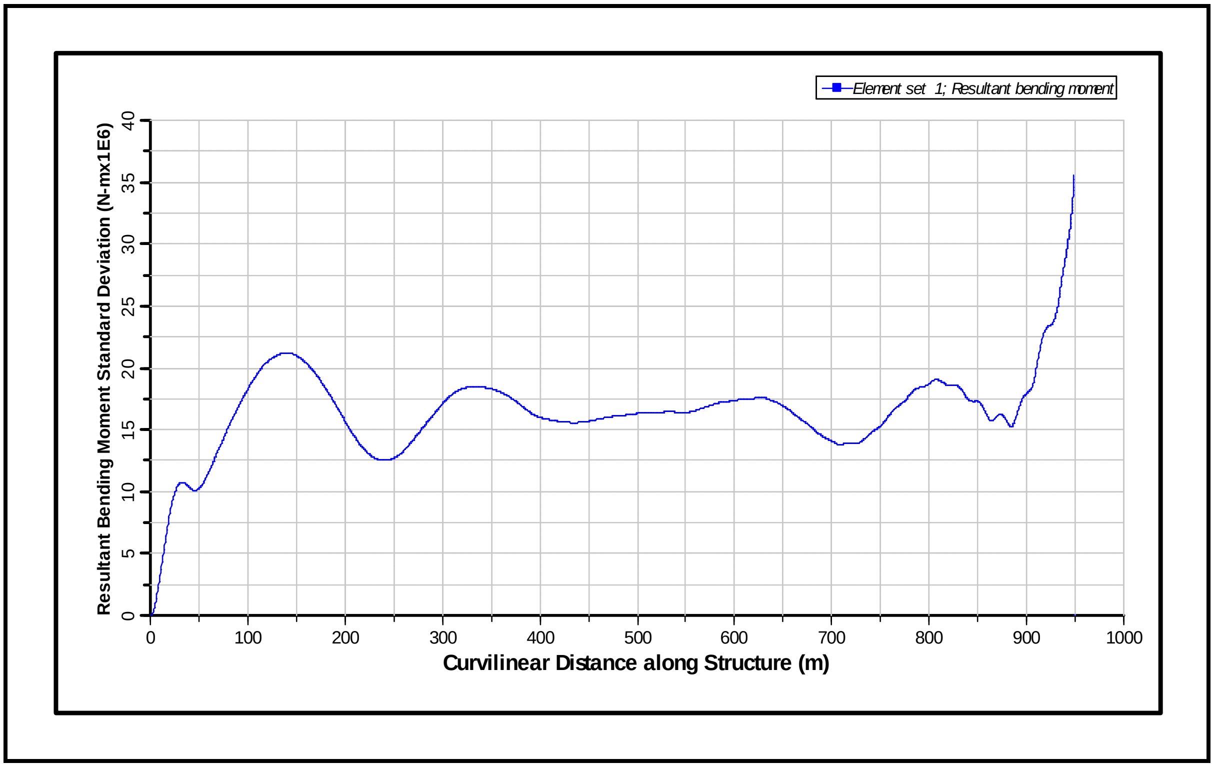


Figure 161: Standard Deviation of Bending Moment for 1000 m CWP for Bin 8 (from Bottom to Top)

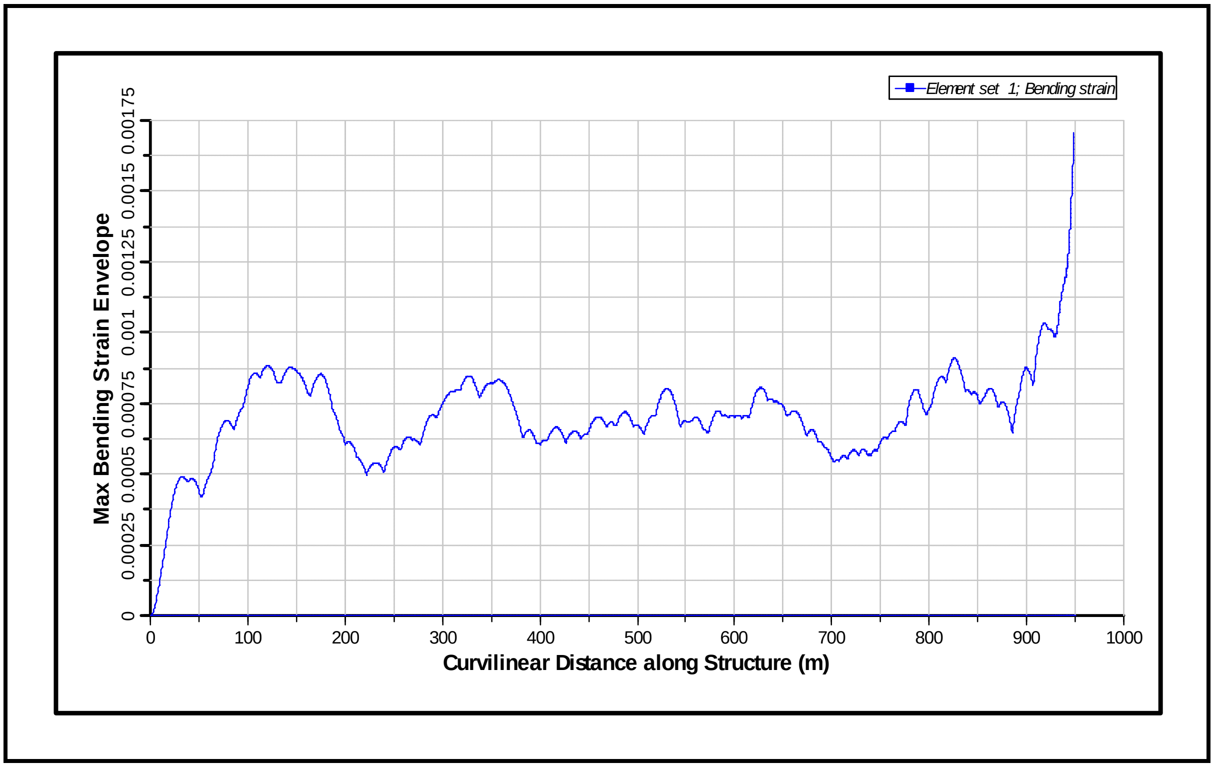


Figure 162: Bending Strain Envelope for 1000 m CWP for Bin 8 (from Bottom to Top)

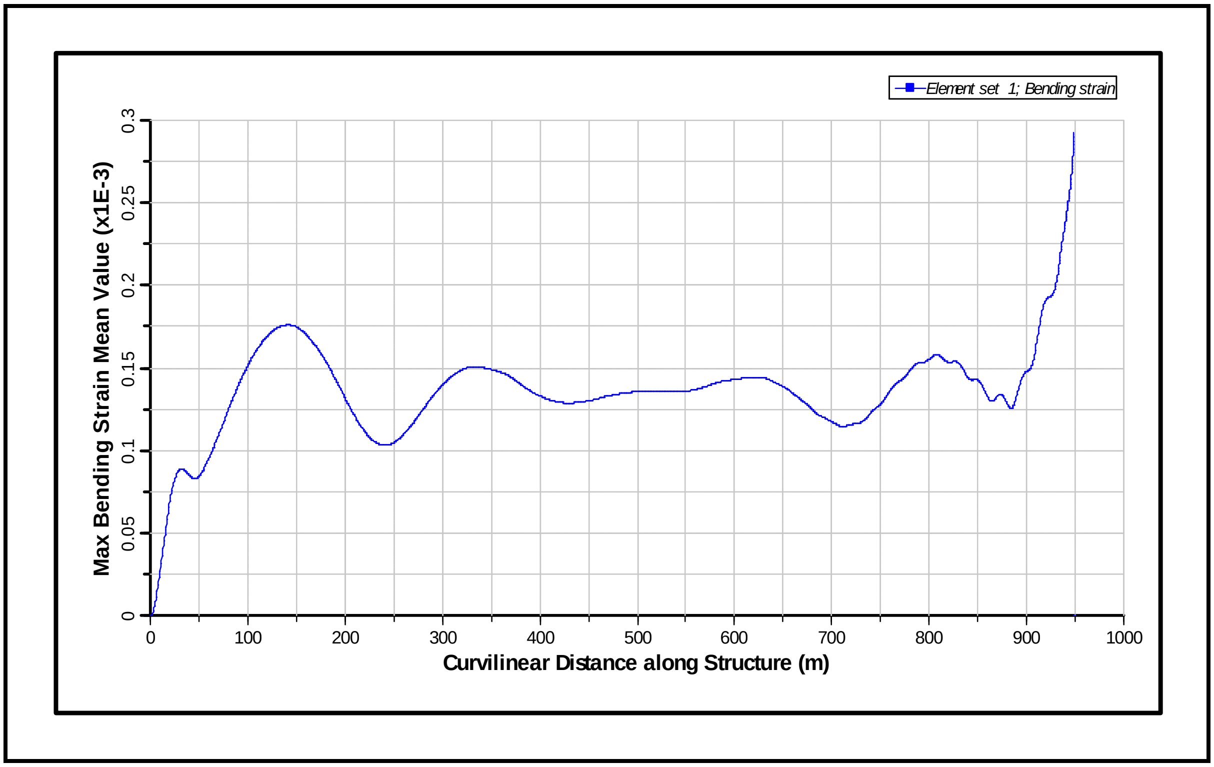


Figure 163: Mean Bending Strain for 1000 m CWP for Bin 8 (from Bottom to Top)

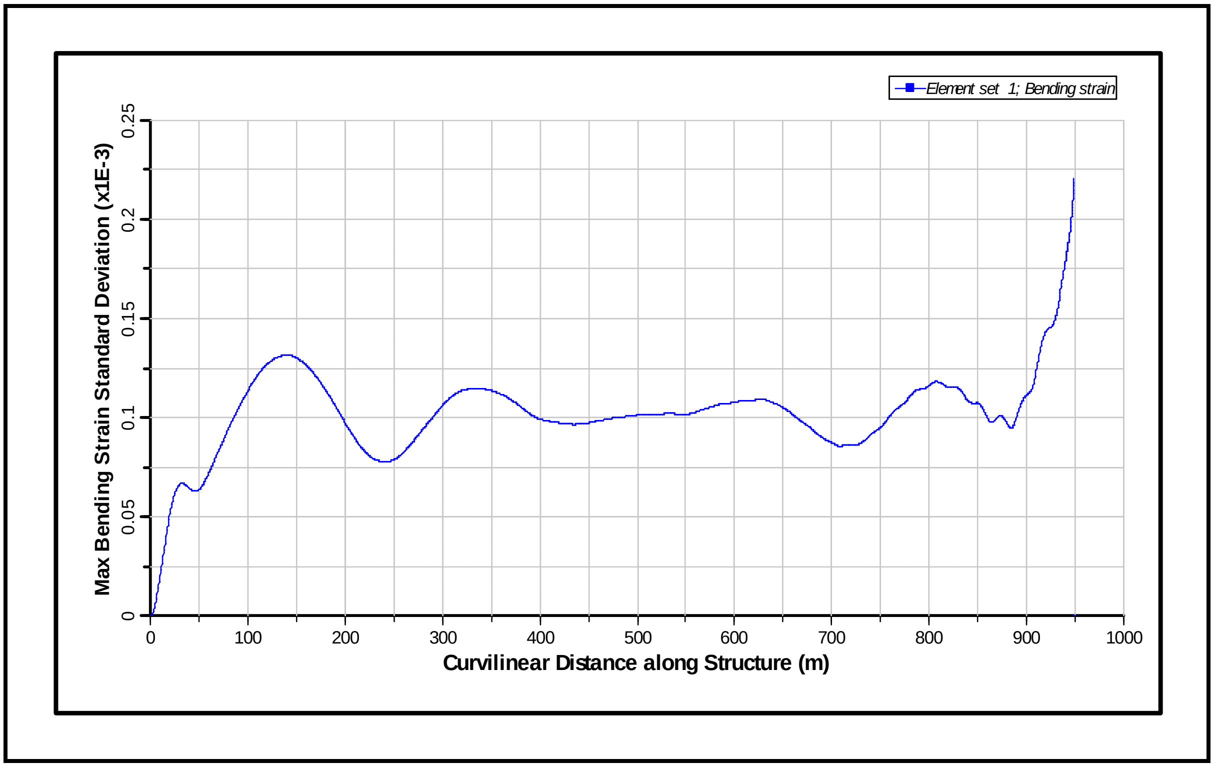


Figure 164: Standard Deviation of Bending Strain for 1000 m CWP for Bin 8 (from Bottom to Top)

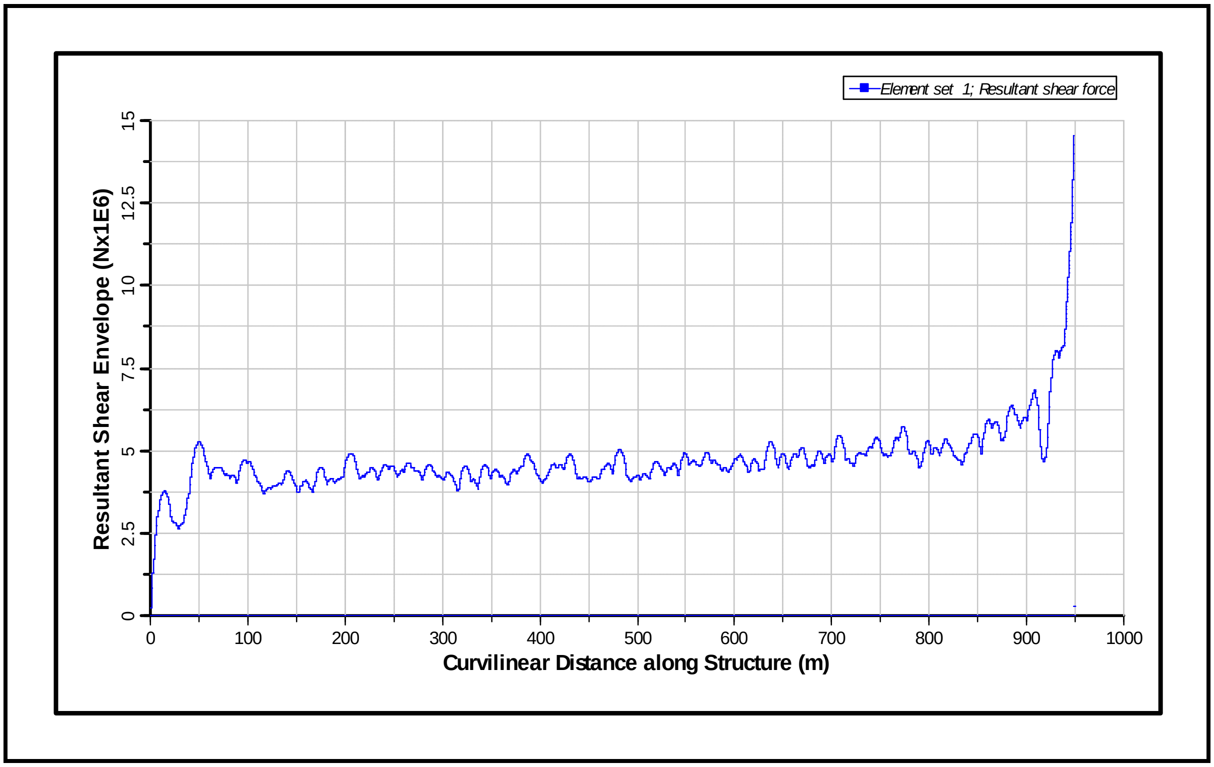


Figure 165: Shear Force Envelope for 1000 m CWP for Bin 8 (from Bottom to Top)

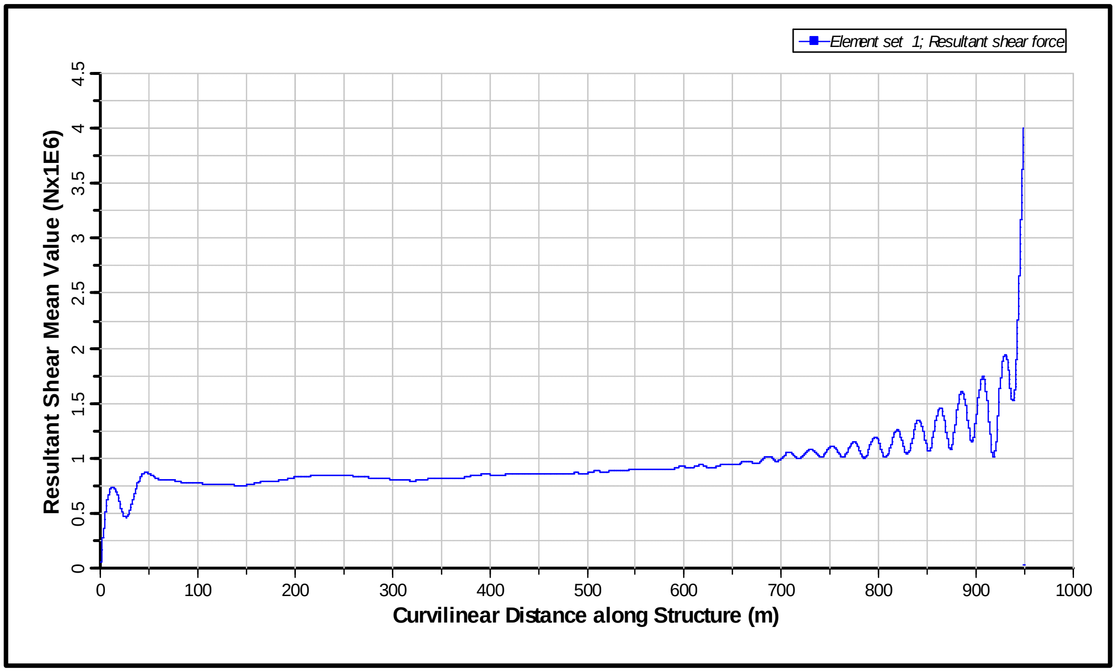


Figure 166: Mean Shear Force for 1000 m CWP for Bin 8 (from Bottom to Top)

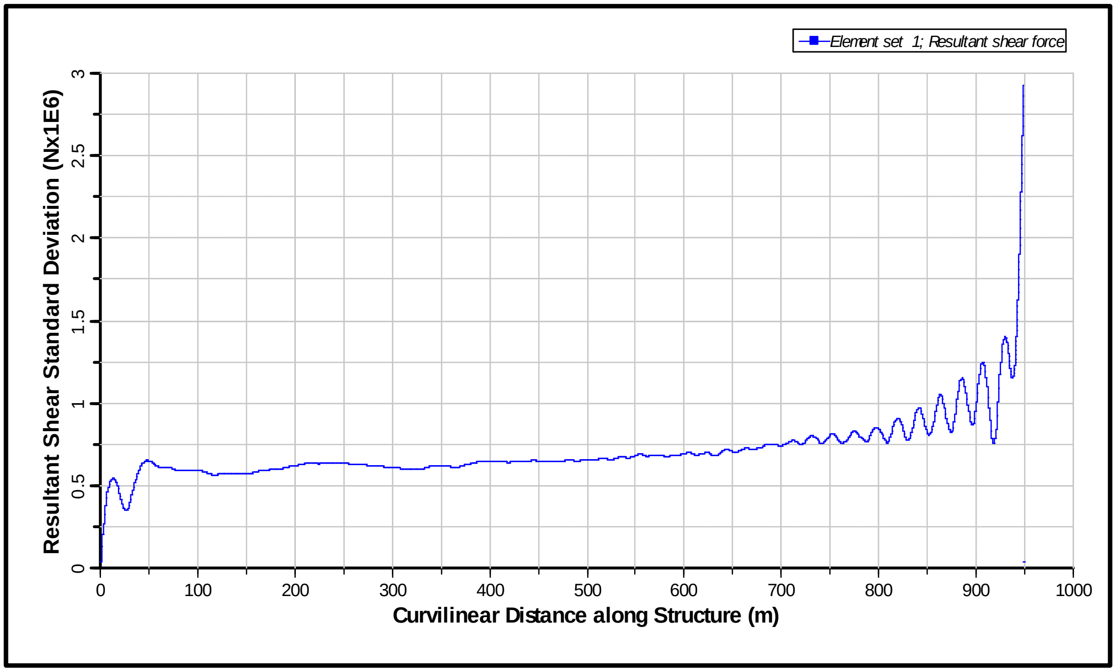


Figure 167: Standard Deviation of Shear Force for 1000 m CWP for Bin 8 (from Bottom to Top)

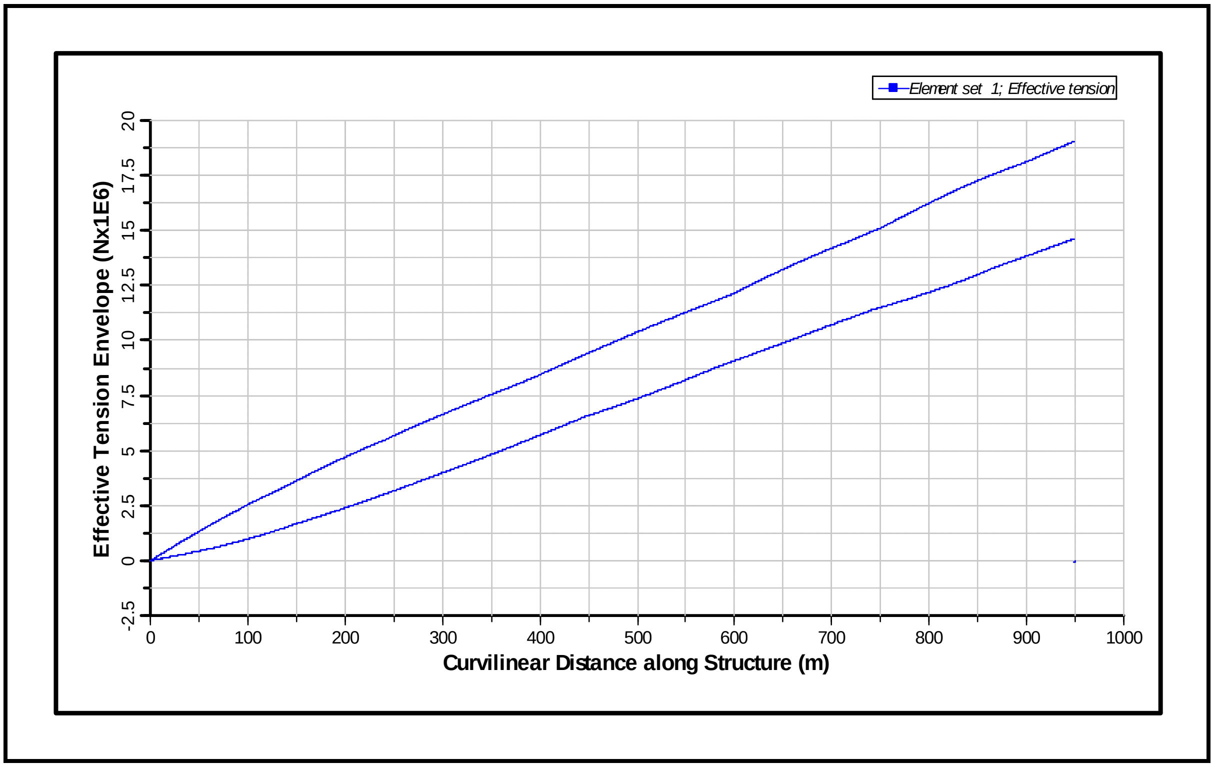


Figure 168: Axial Tension Envelope for 1000 m CWP for Bin 8 (from Bottom to Top)

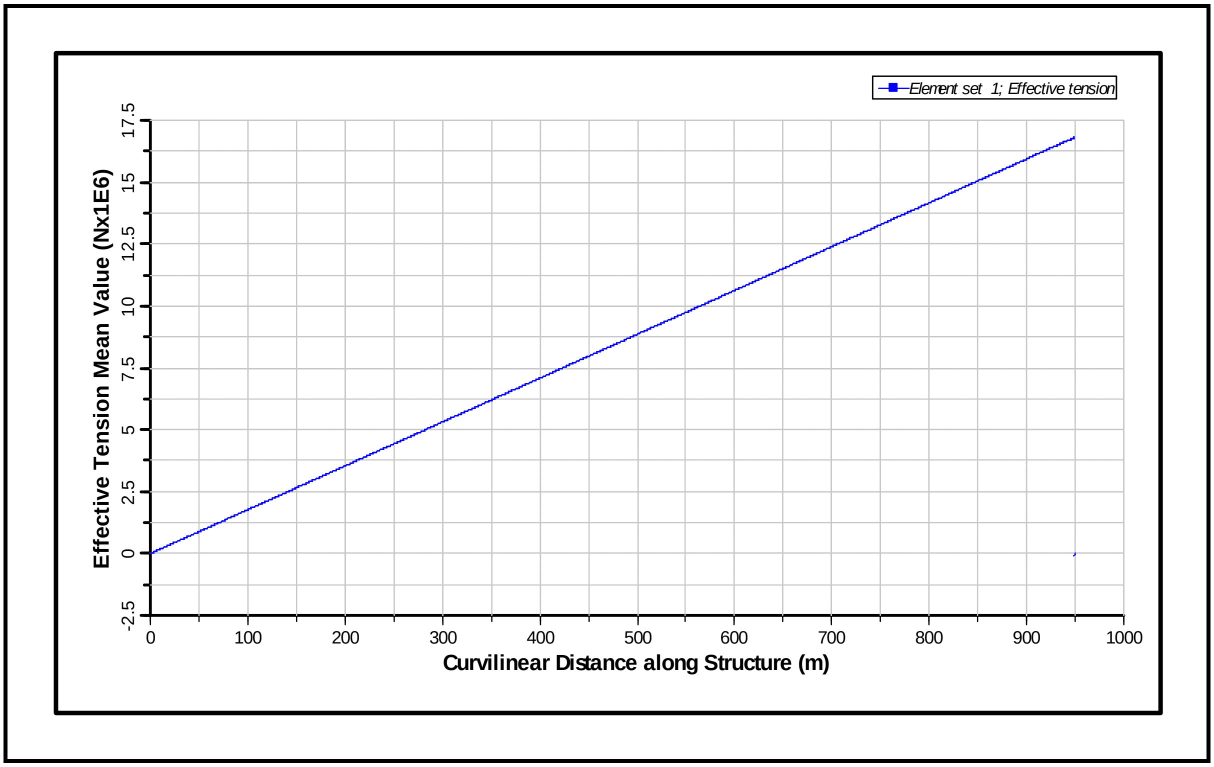


Figure 169: Mean Axial Tension for 1000 m CWP (for Bin 8 from Bottom to Top)

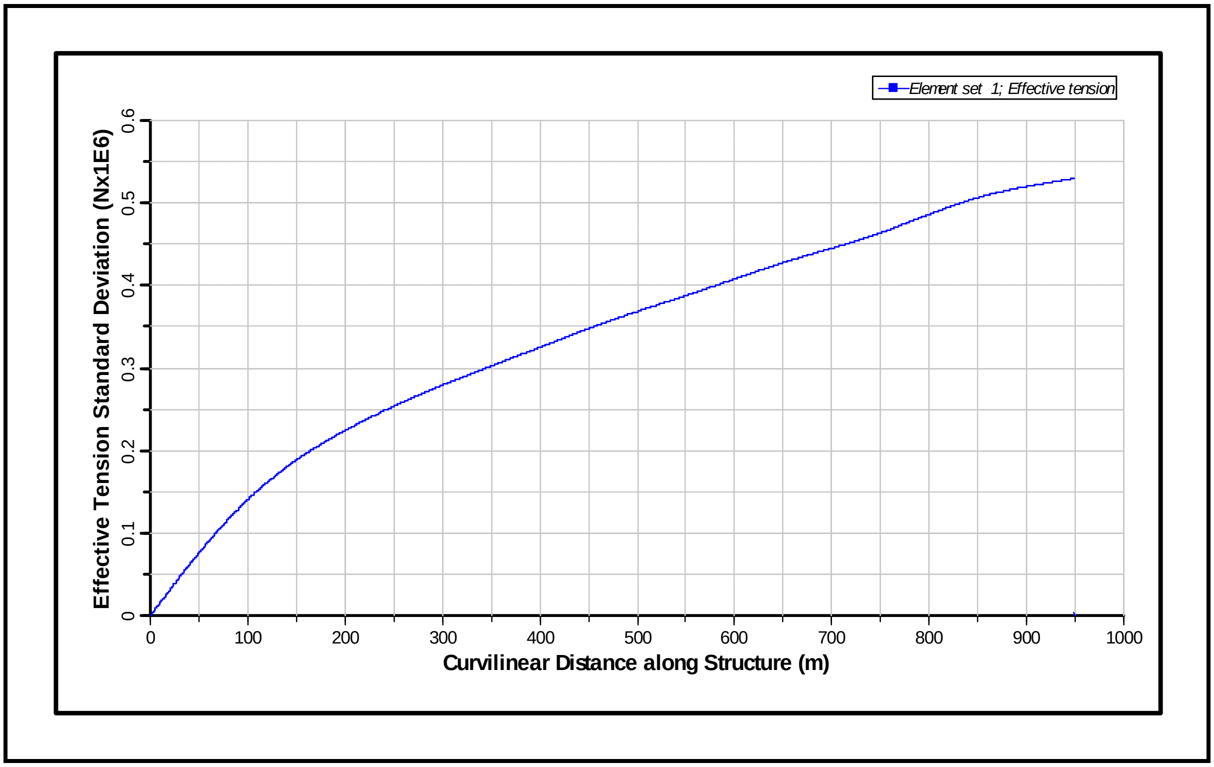


Figure 170: Standard Deviation of Axial Tension for 1000 m CWP for Bin 8 (from Bottom to Top)

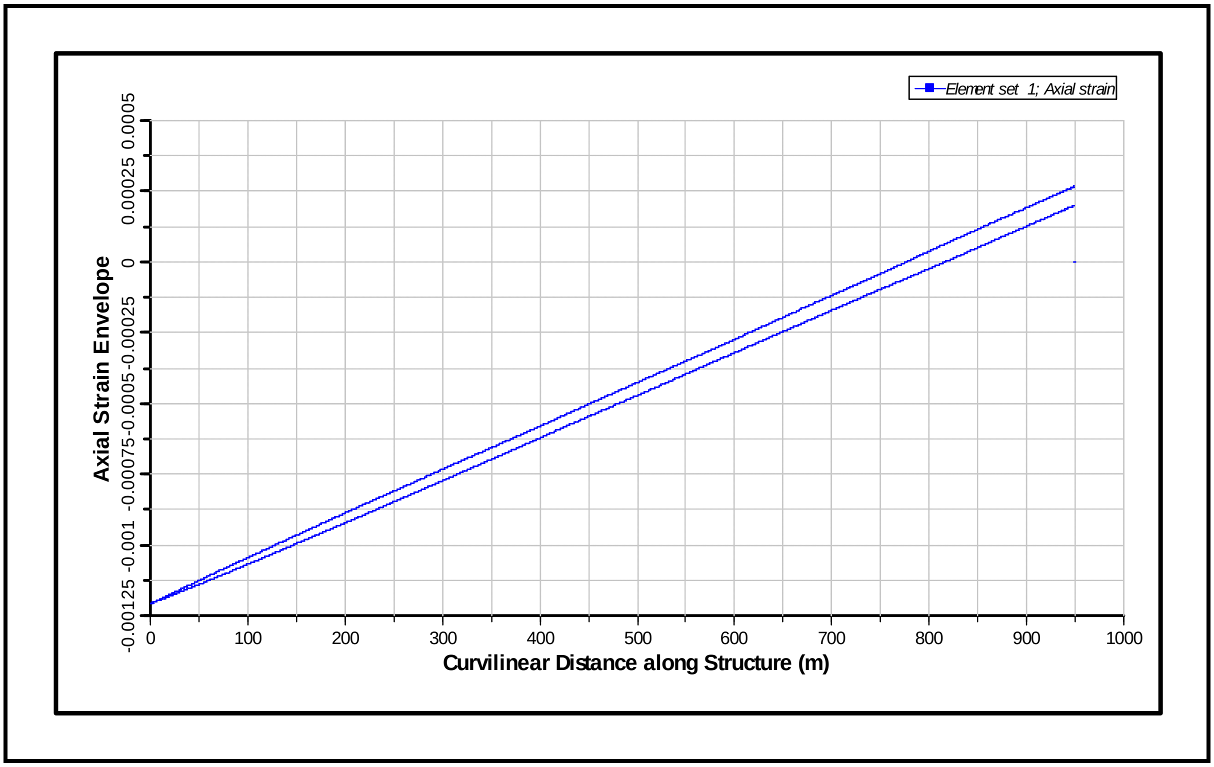


Figure 171: Axial Strain Envelope for 1000 m CWP for Bin 8 (from Bottom to Top)

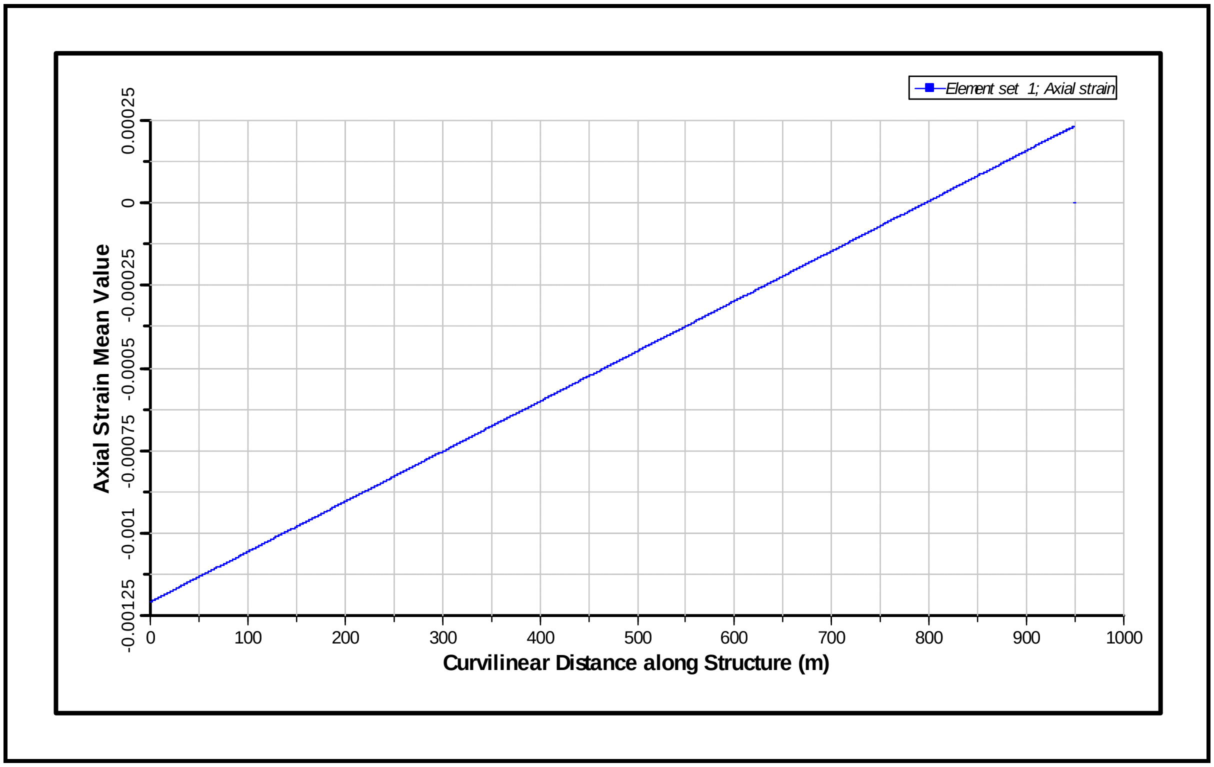


Figure 172: Mean Axial Strain for 1000 m CWP for Bin 8 (from Bottom to Top)

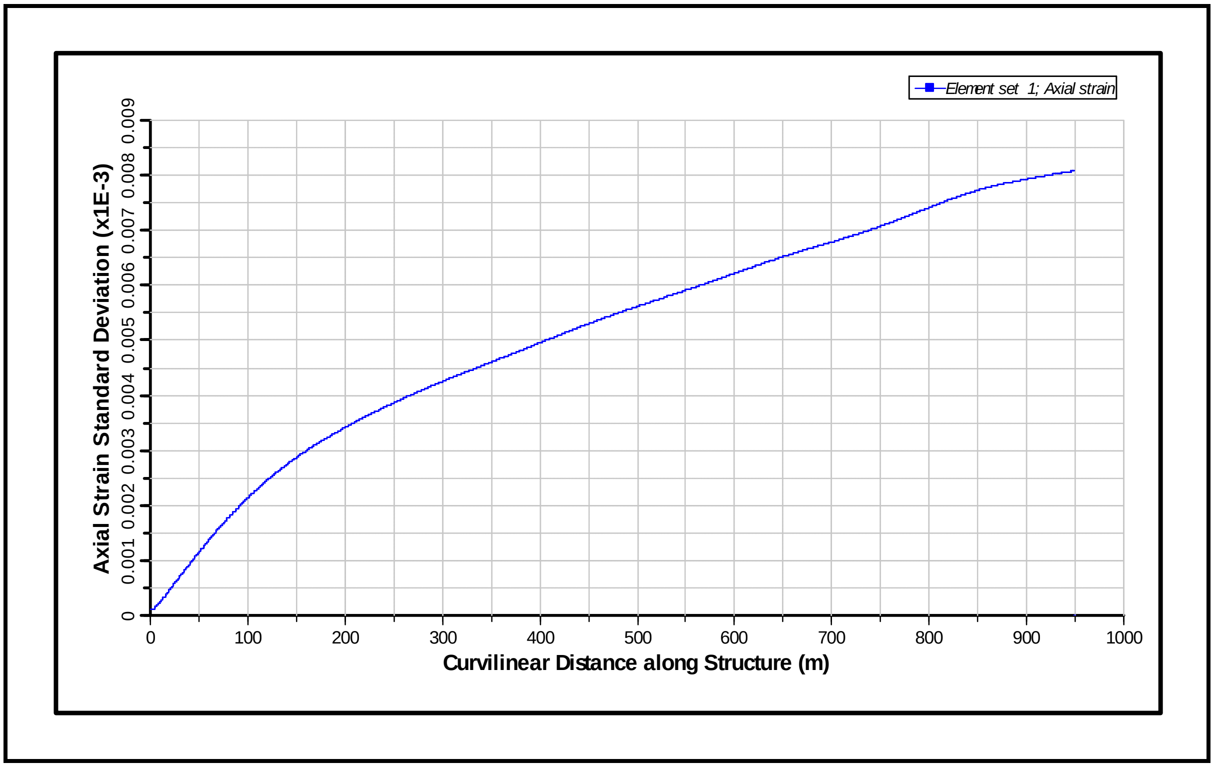


Figure 173: Standard Deviation of Axial Strain for 1000 m CWP for Bin 8 (from Bottom to Top)

6.9 Bin 9

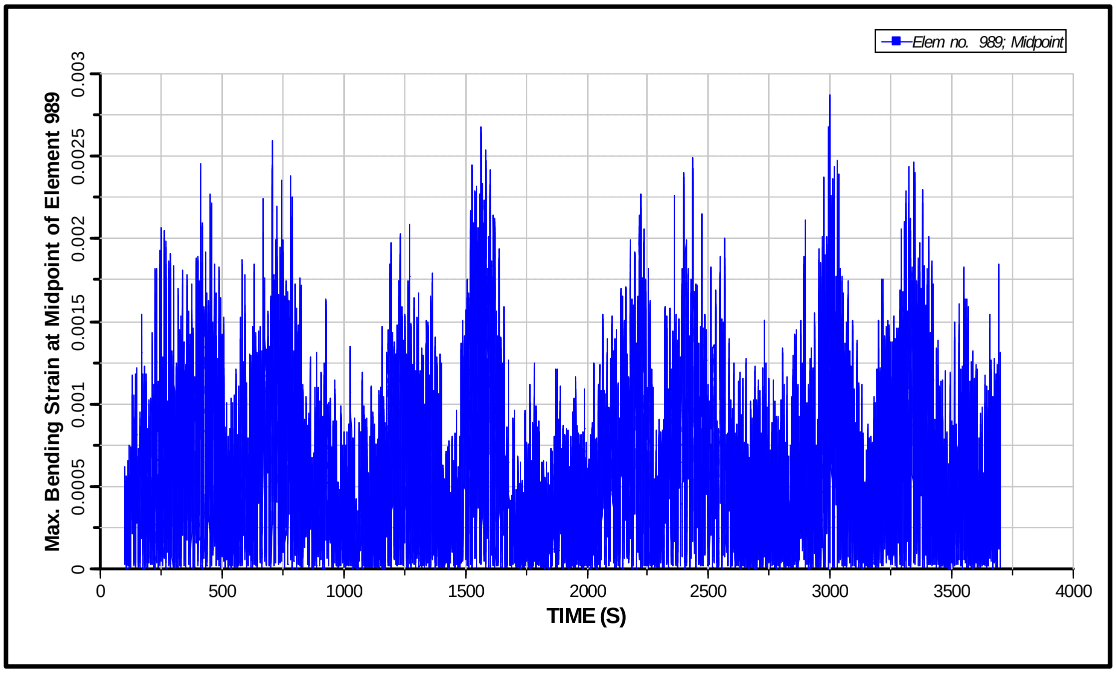


Figure 174: Maximum Bending Strain Time History at Top of CWP for Bin 9

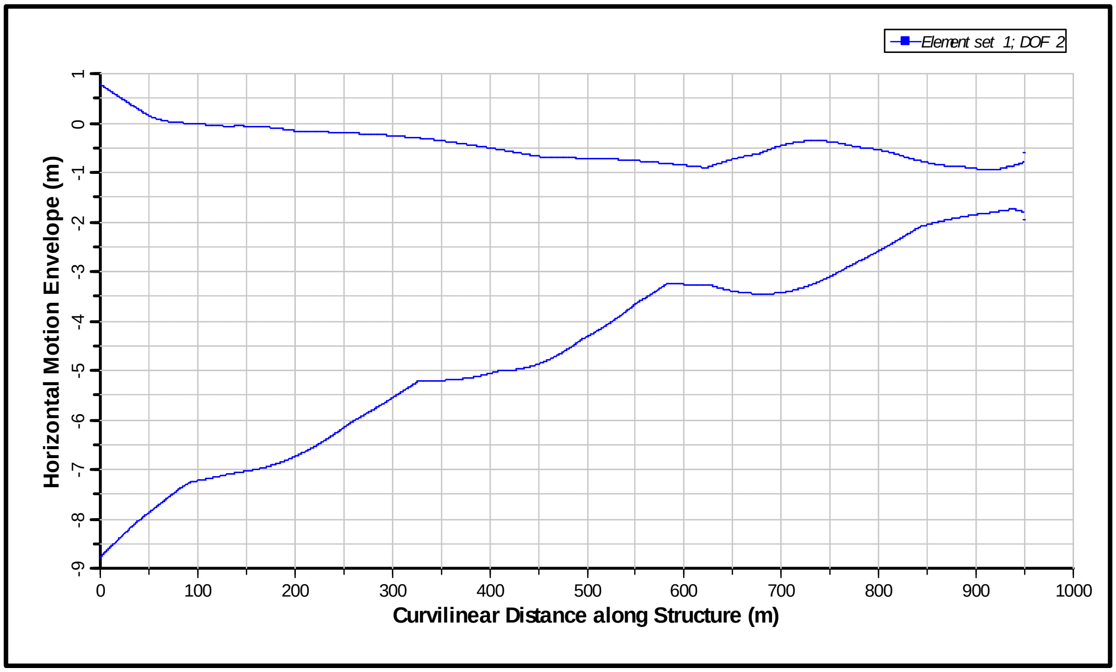


Figure 175: Motion Envelope for 1000 m CWP for Bin 9 (from Bottom to Top)

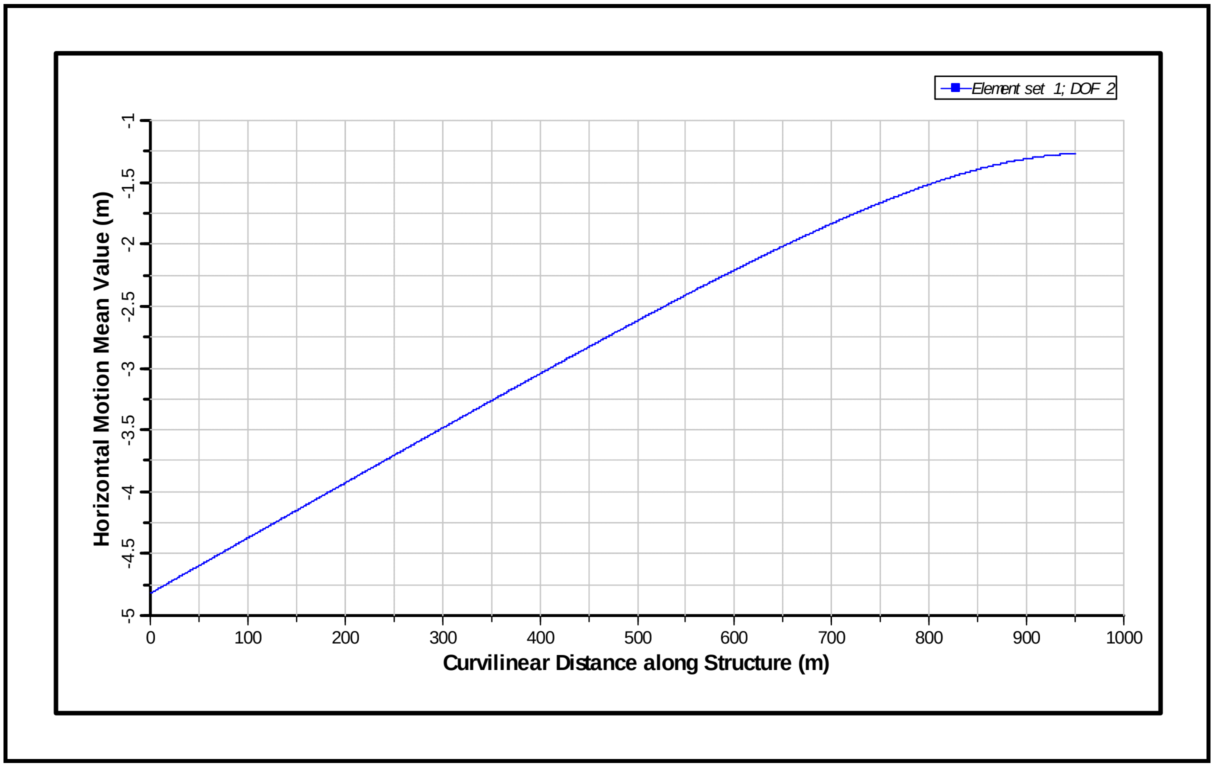


Figure 176: Mean Motion for 1000 m CWP for Bin 9 (from Bottom to Top)

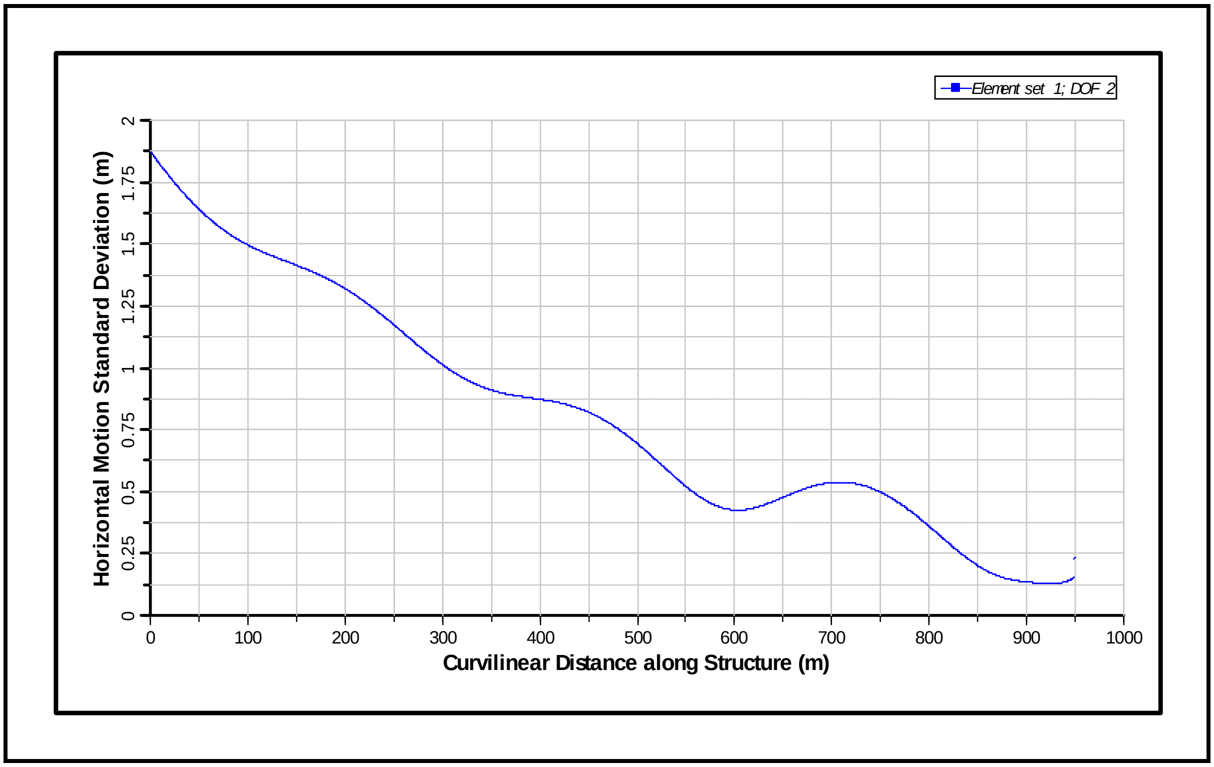


Figure 177: Standard Deviation of Motion for 1000 m CWP for Bin 9 (from Bottom to Top)

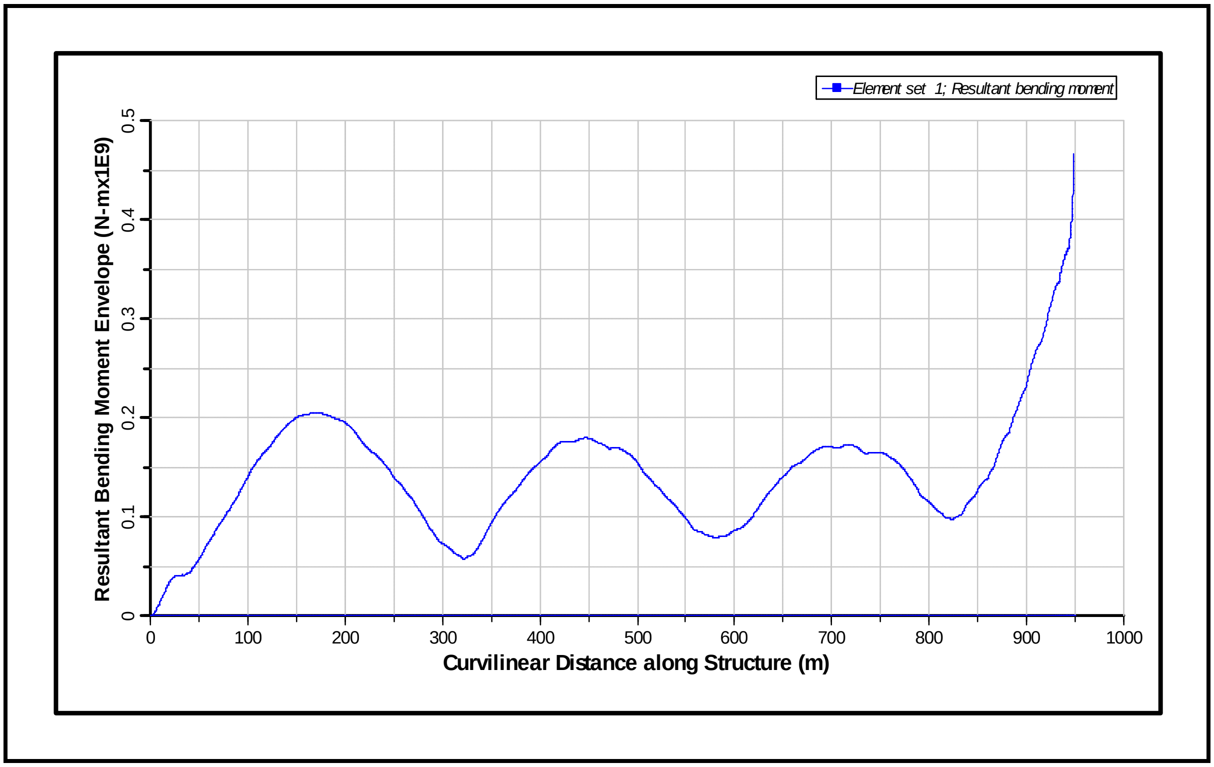


Figure 178: Bending Moment Envelope for 1000 m CWP for Bin 9 (from Bottom to Top)

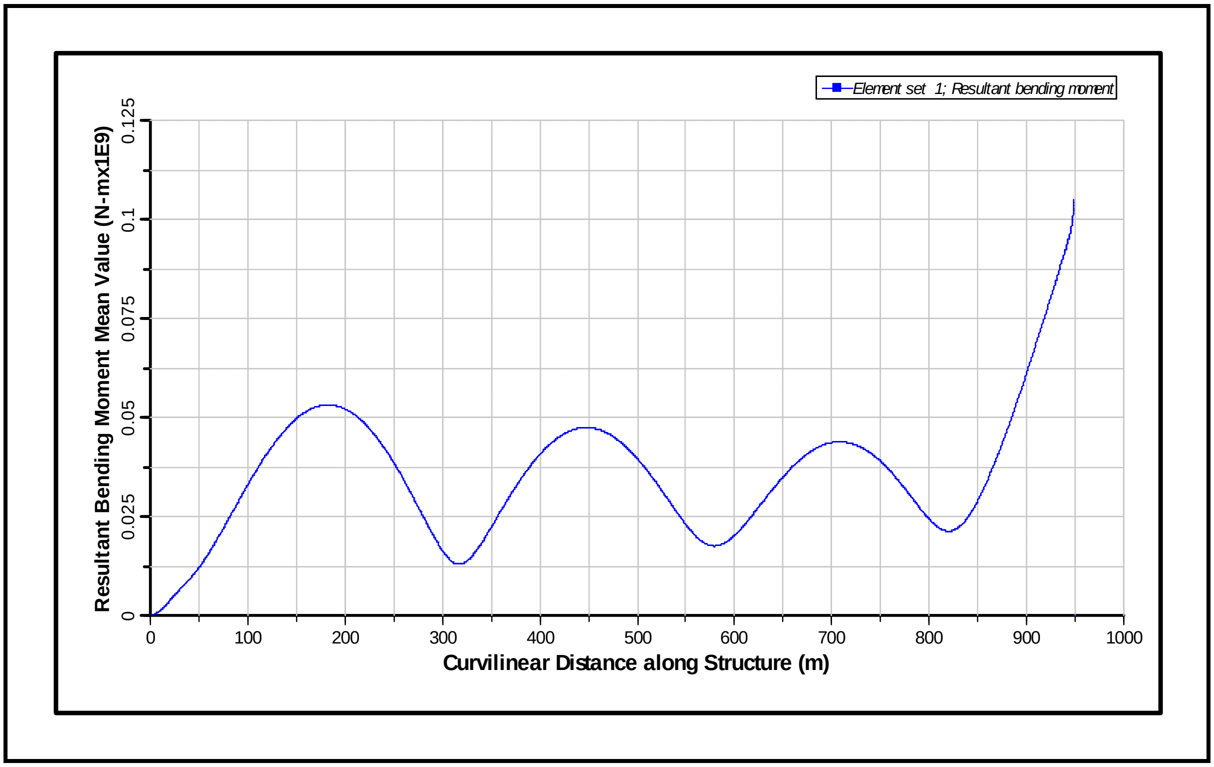


Figure 179: Mean Bending Moment for 1000 m CWP for Bin 9 (from Bottom to Top)

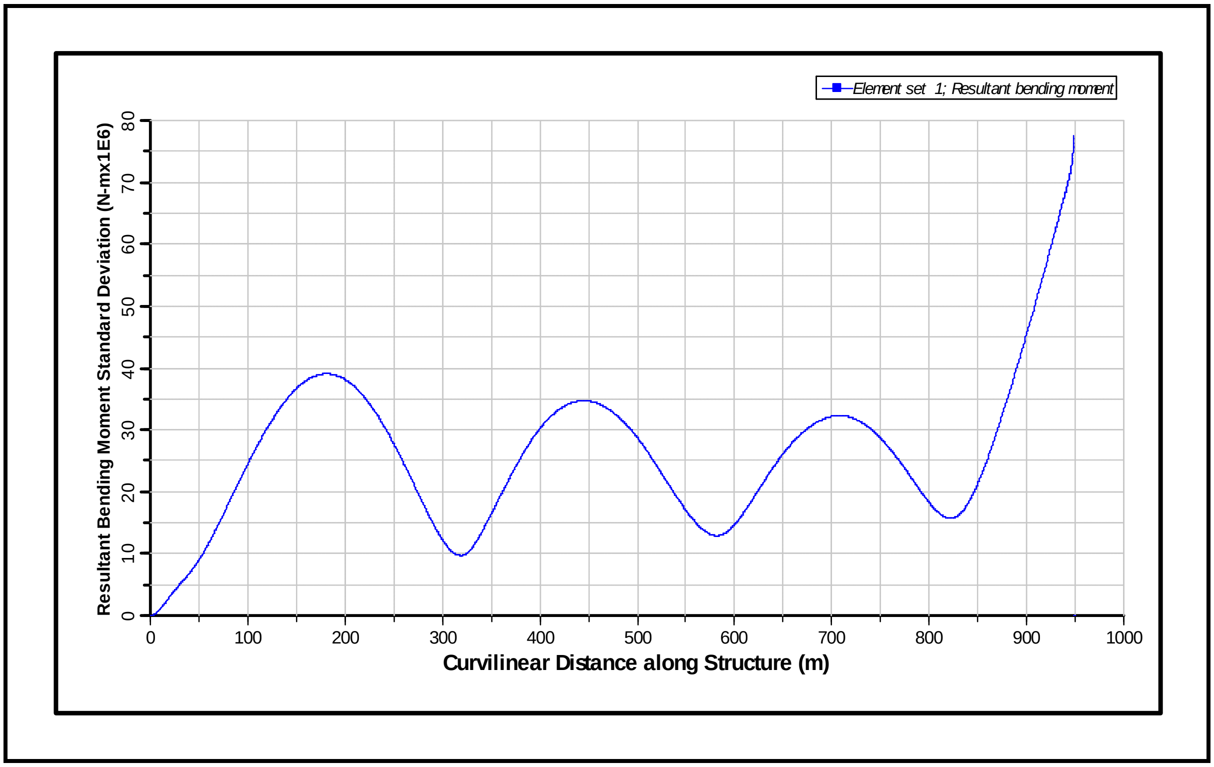


Figure 180: Standard Deviation of Bending Moment for 1000 m CWP for Bin 9 (from Bottom to Top)

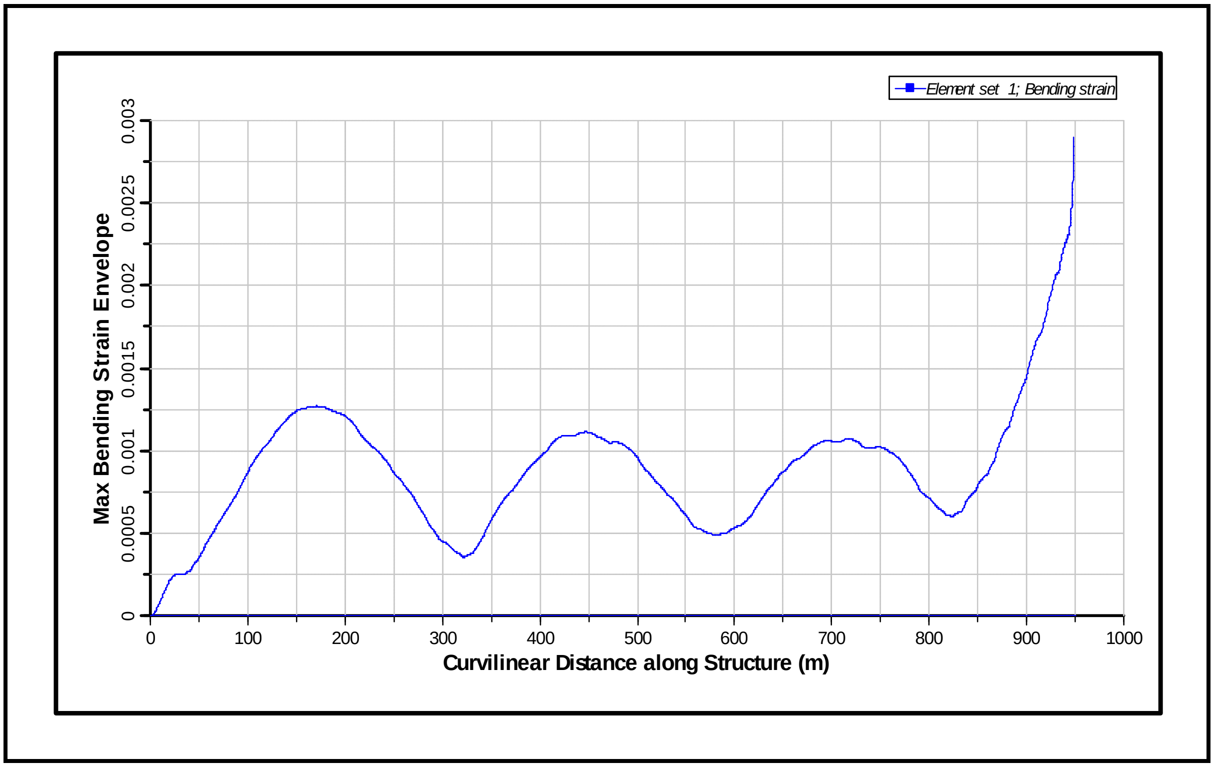


Figure 181: Bending Strain Envelope for 1000 m CWP for Bin 9 (from Bottom to Top)

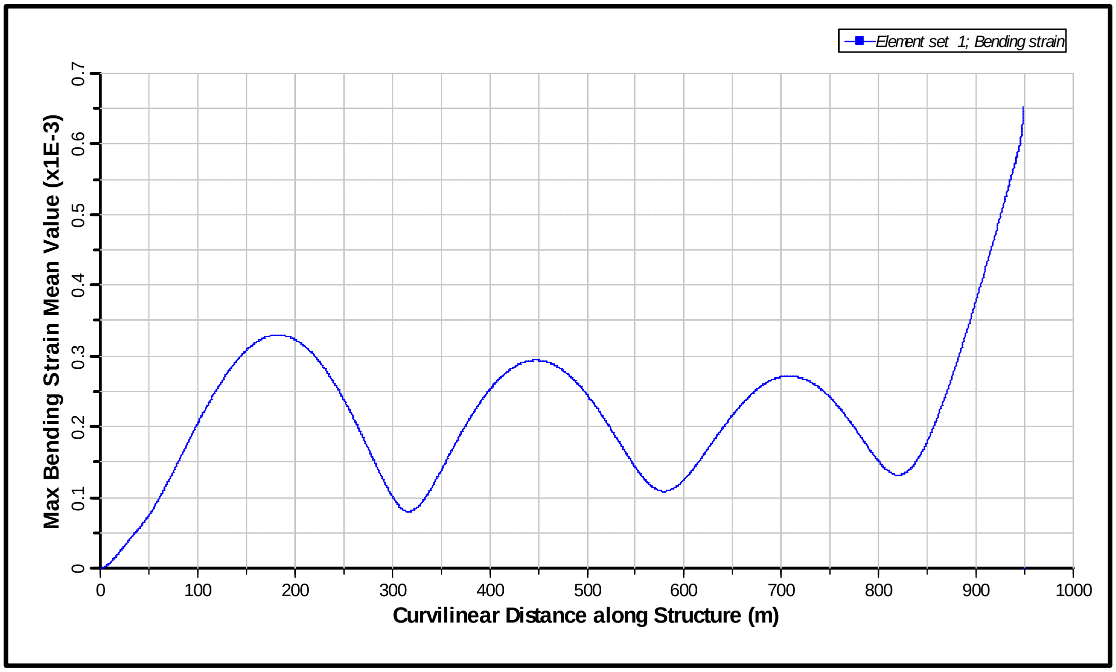


Figure 182: Mean Bending Strain for 1000 m CWP for Bin 9 (from Bottom to Top)

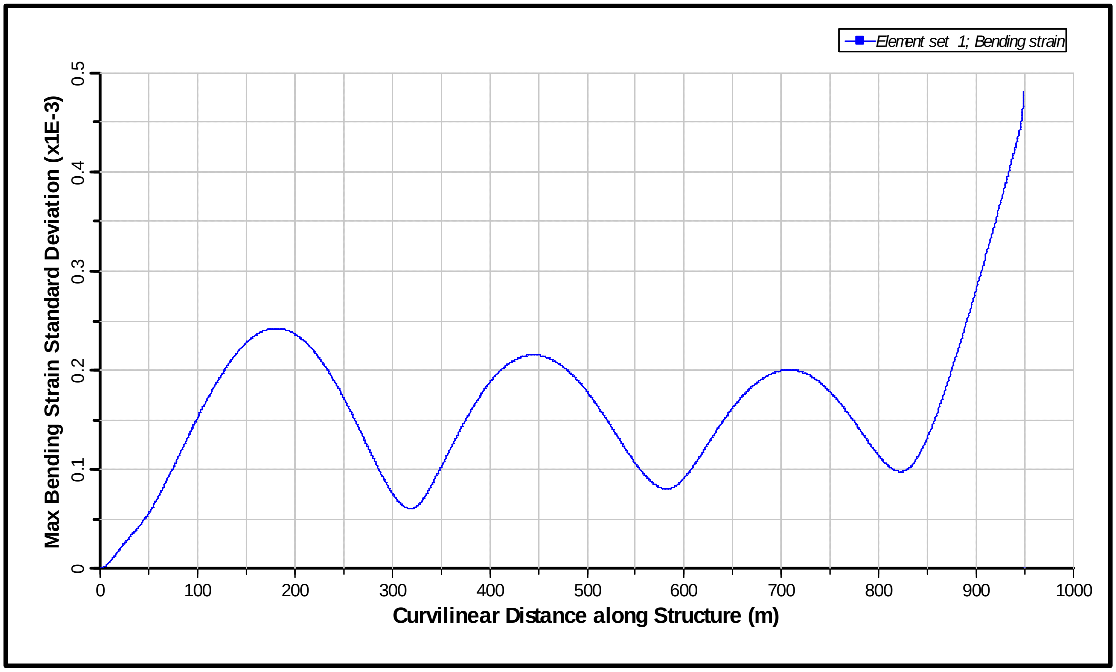


Figure 183: Standard Deviation of Bending Strain for 1000 m CWP for Bin 9 (from Bottom to Top)

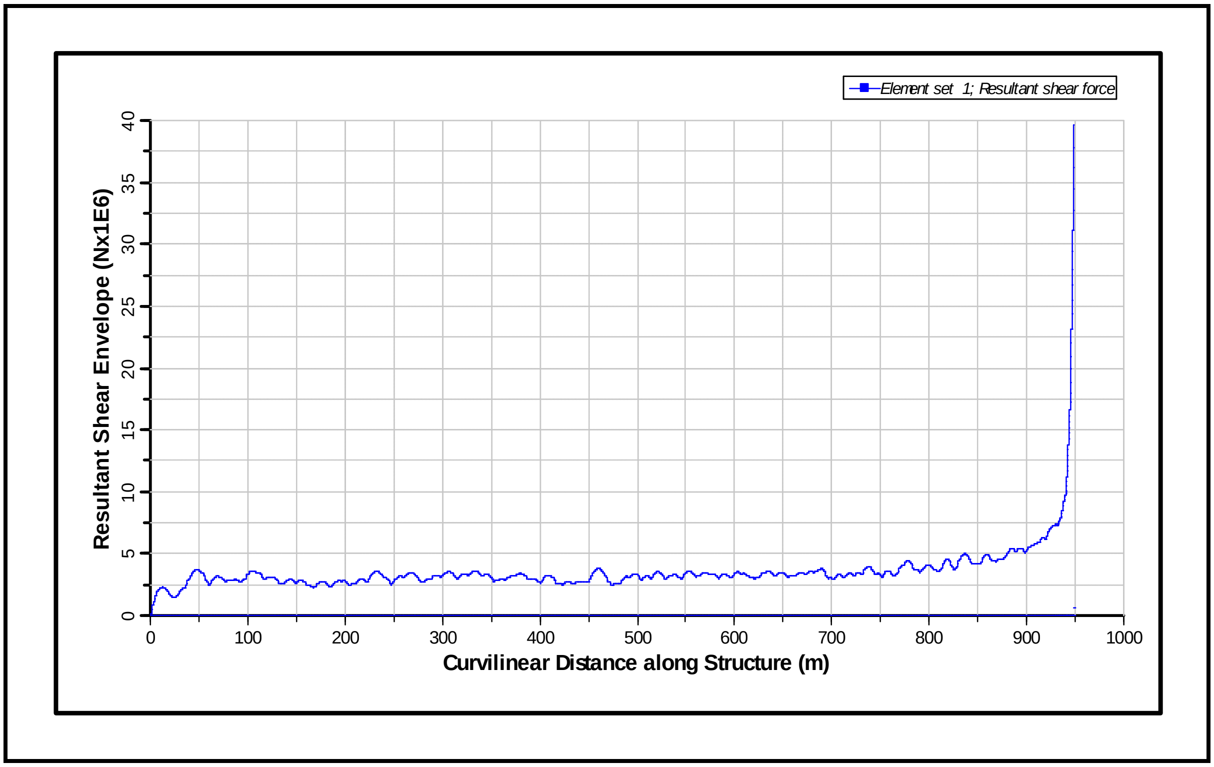


Figure 184: Shear Force Envelope for 1000 m CWP for Bin 9 (from Bottom to Top)

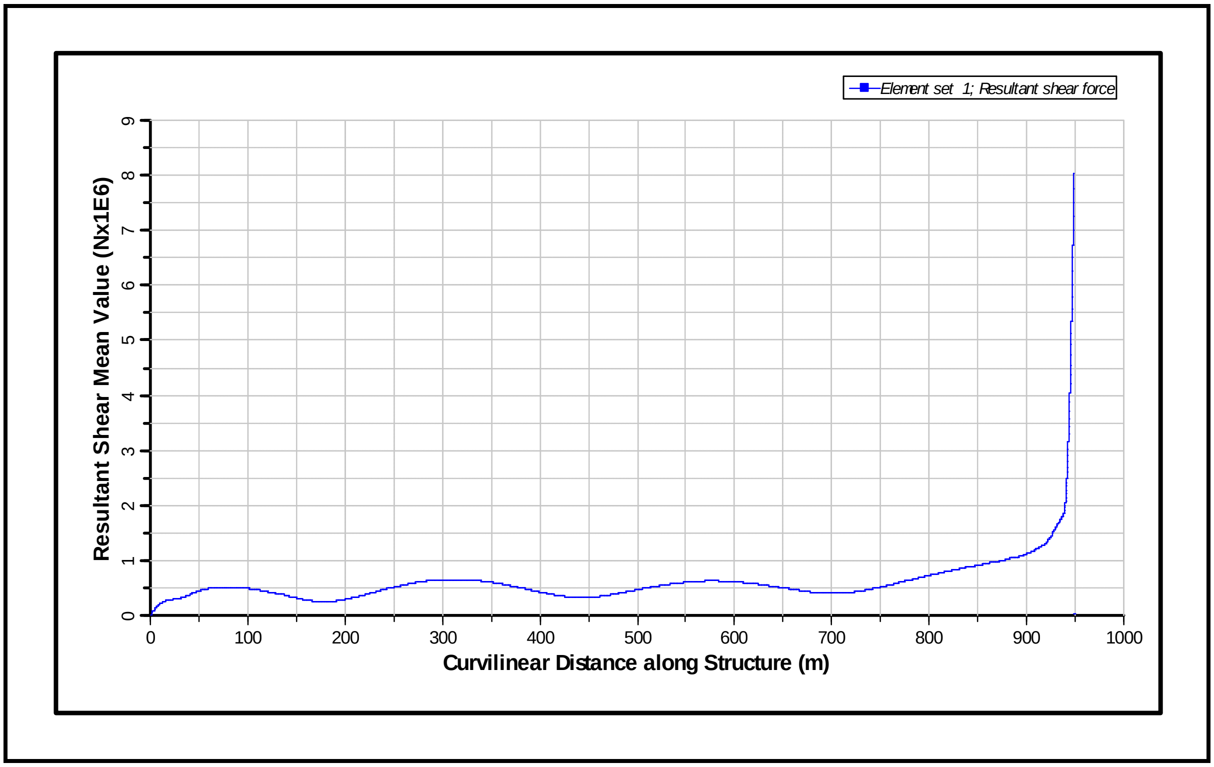


Figure 185: Mean Shear Force for 1000 m CWP for Bin 9 (from Bottom to Top)

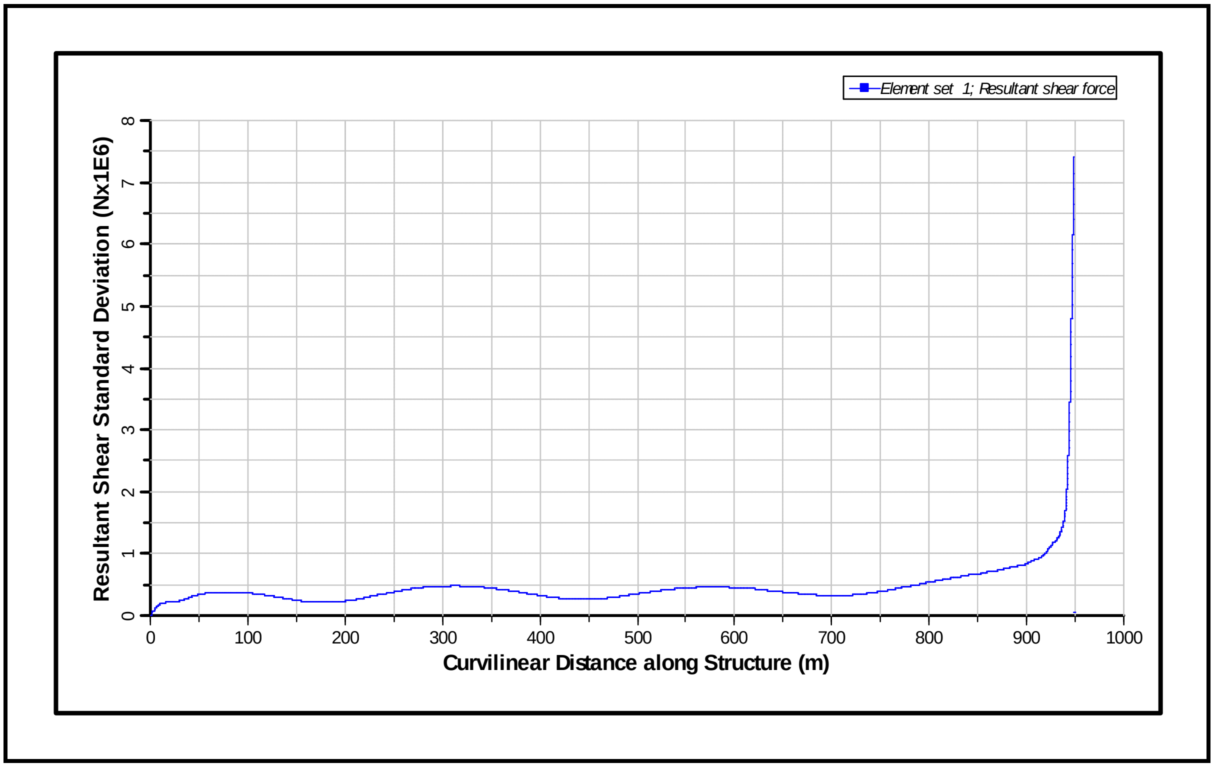


Figure 186: Standard Deviation of Shear Force for 1000 m CWP for Bin 9 (from Bottom to Top)

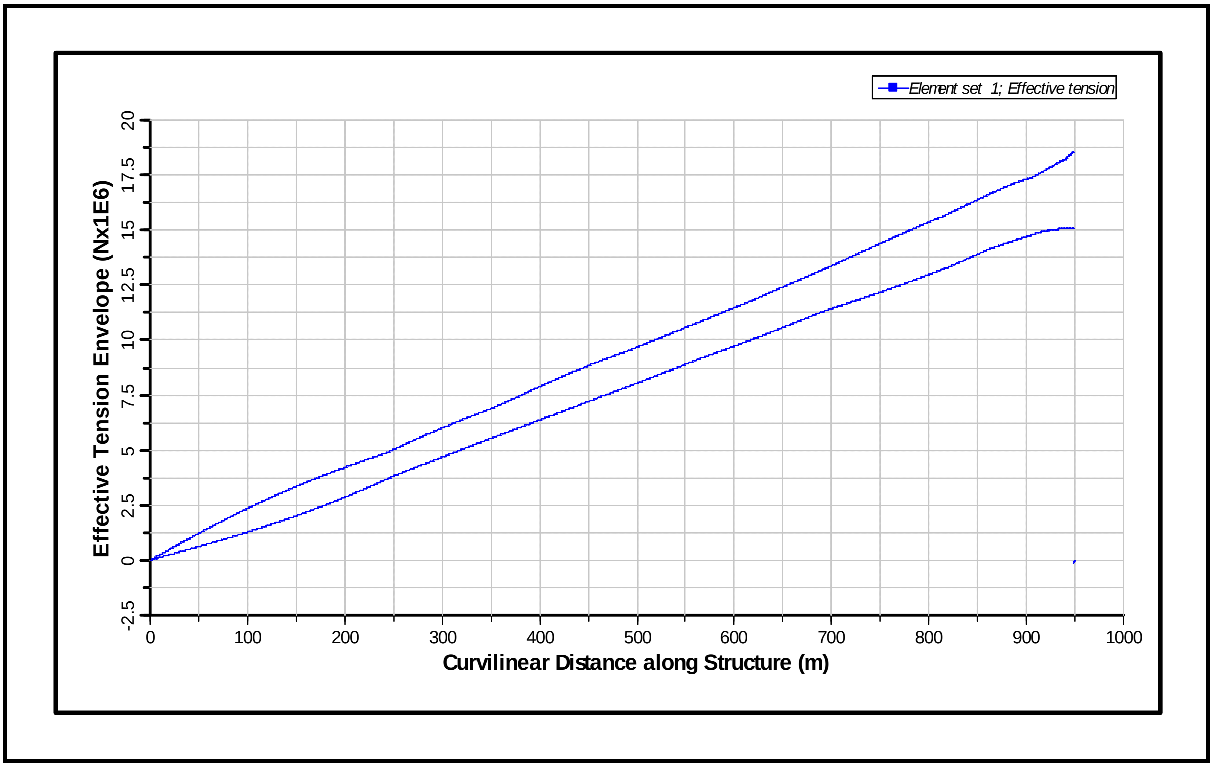


Figure 187: Axial Tension Envelope for 1000 m CWP for Bin 9 (from Bottom to Top)

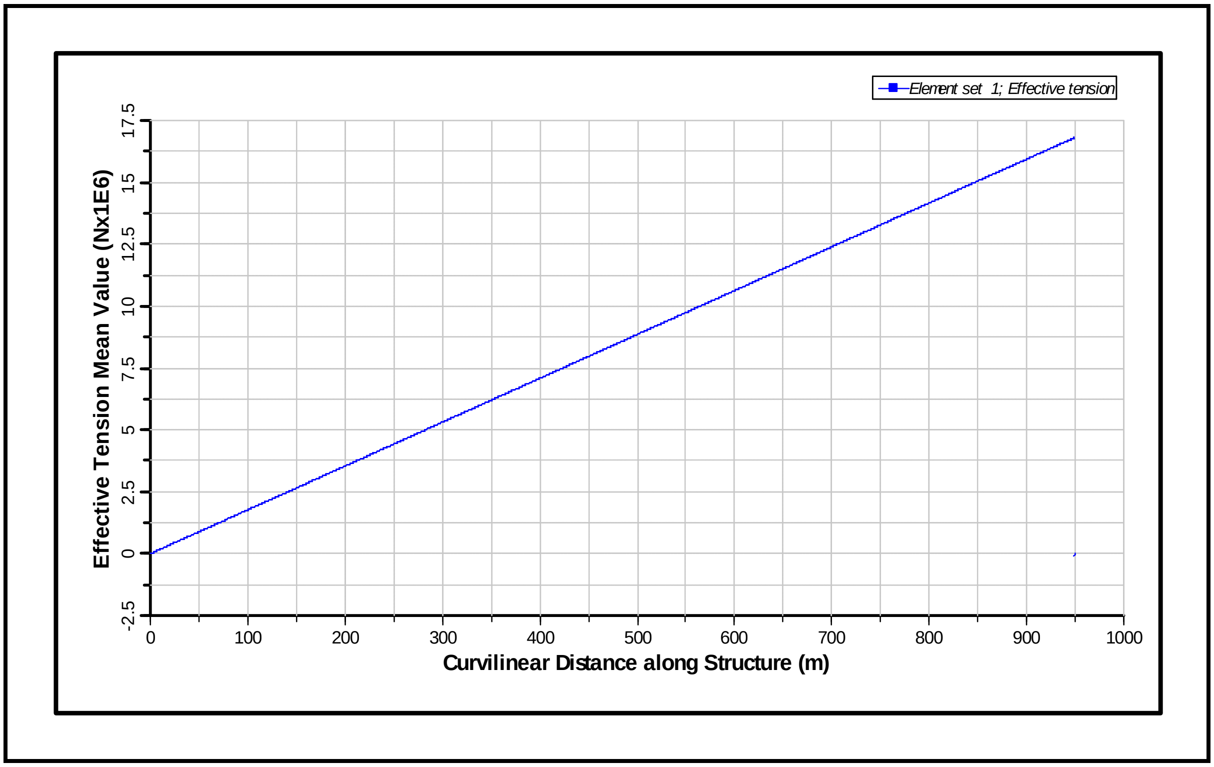


Figure 188: Mean Axial Tension for 1000 m CWP for Bin 9 (from Bottom to Top)

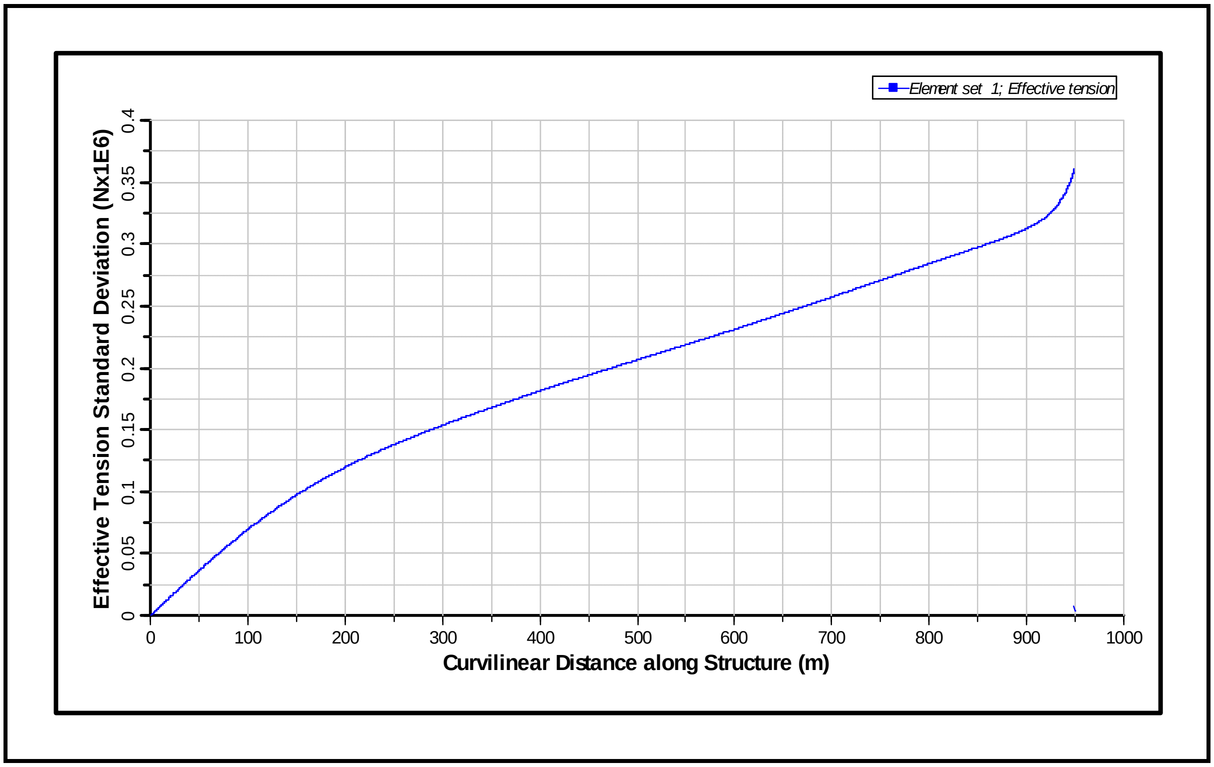


Figure 189: Standard Deviation of Axial Tension for 1000 m CWP for Bin 9 (from Bottom to Top)

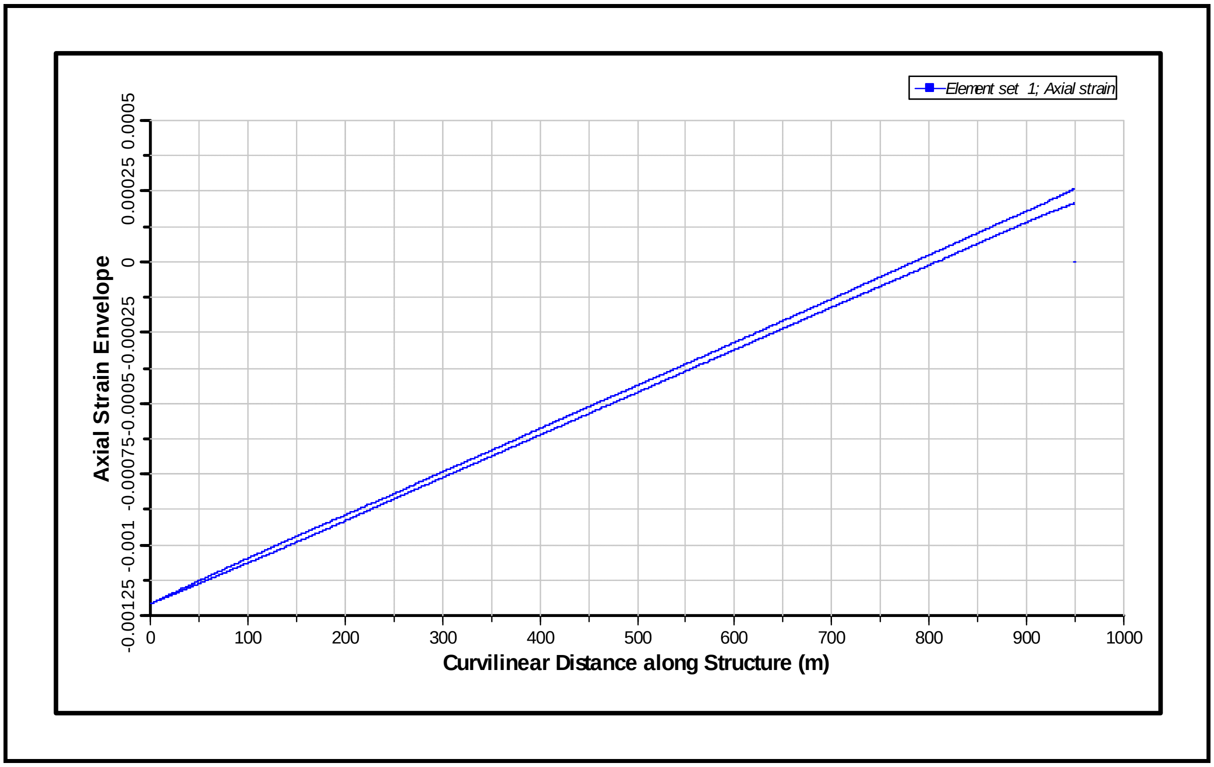


Figure 190: Axial Strain Envelope for 1000 m CWP for Bin 9 (from Bottom to Top)

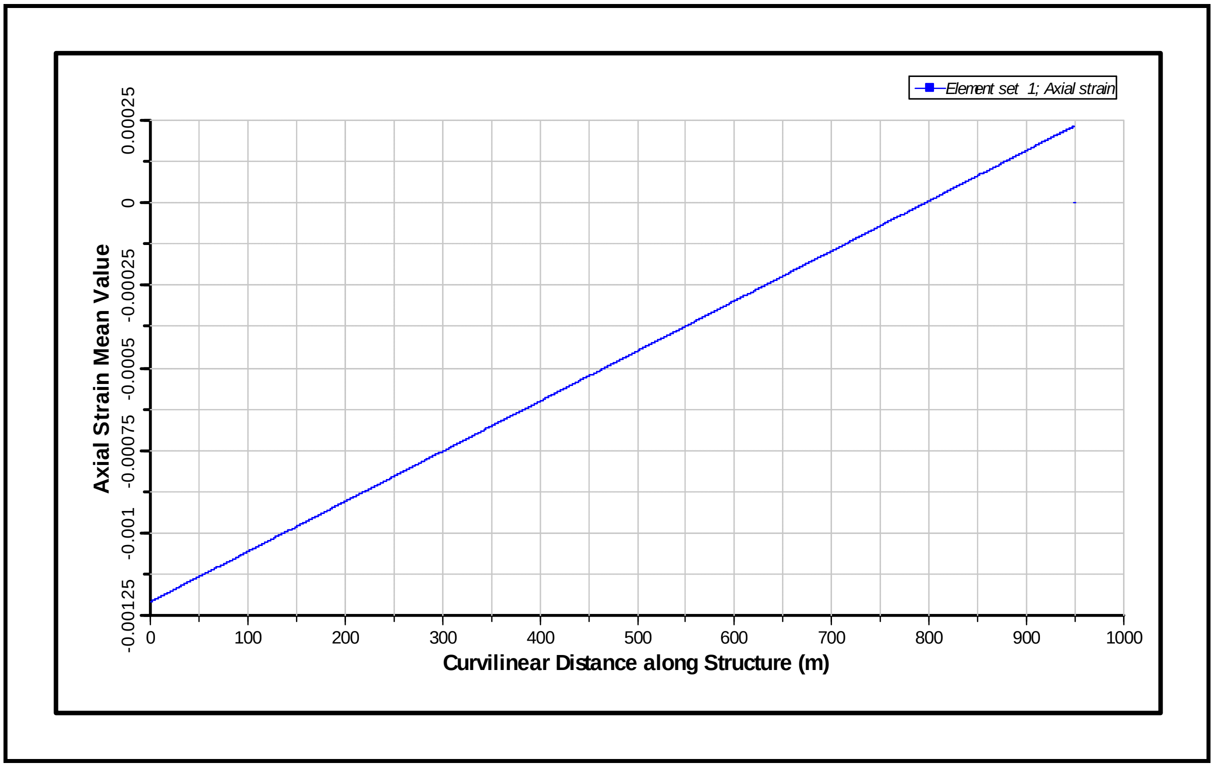


Figure 191: Mean Axial Strain for 1000 m CWP for Bin 9 (from Bottom to Top)

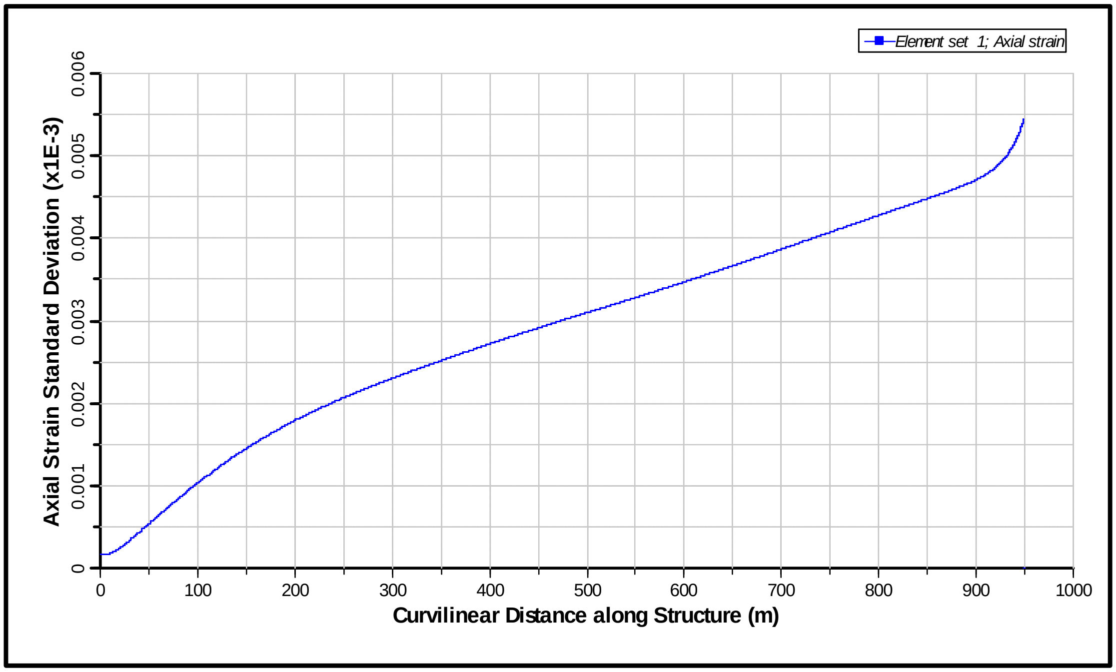


Figure 192: Standard Deviation of Axial Strain for 1000 m CWP for Bin 9 (from Bottom to Top)

6.10 Bin 10

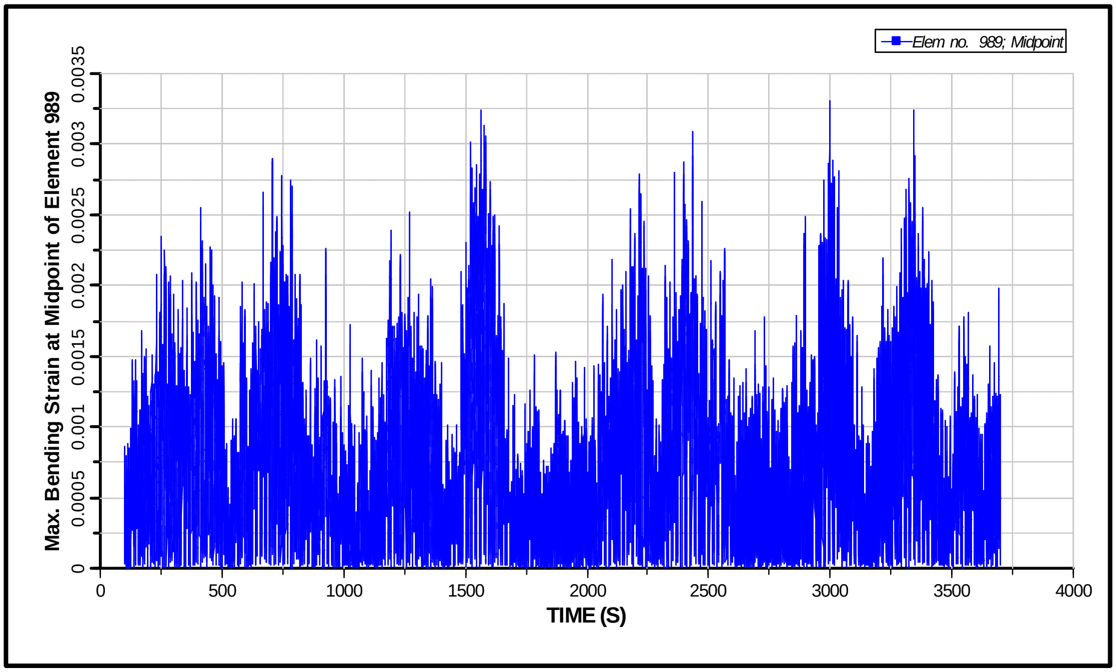


Figure 193: Maximum Bending Strain Time History at Top of CWP for Bin 10

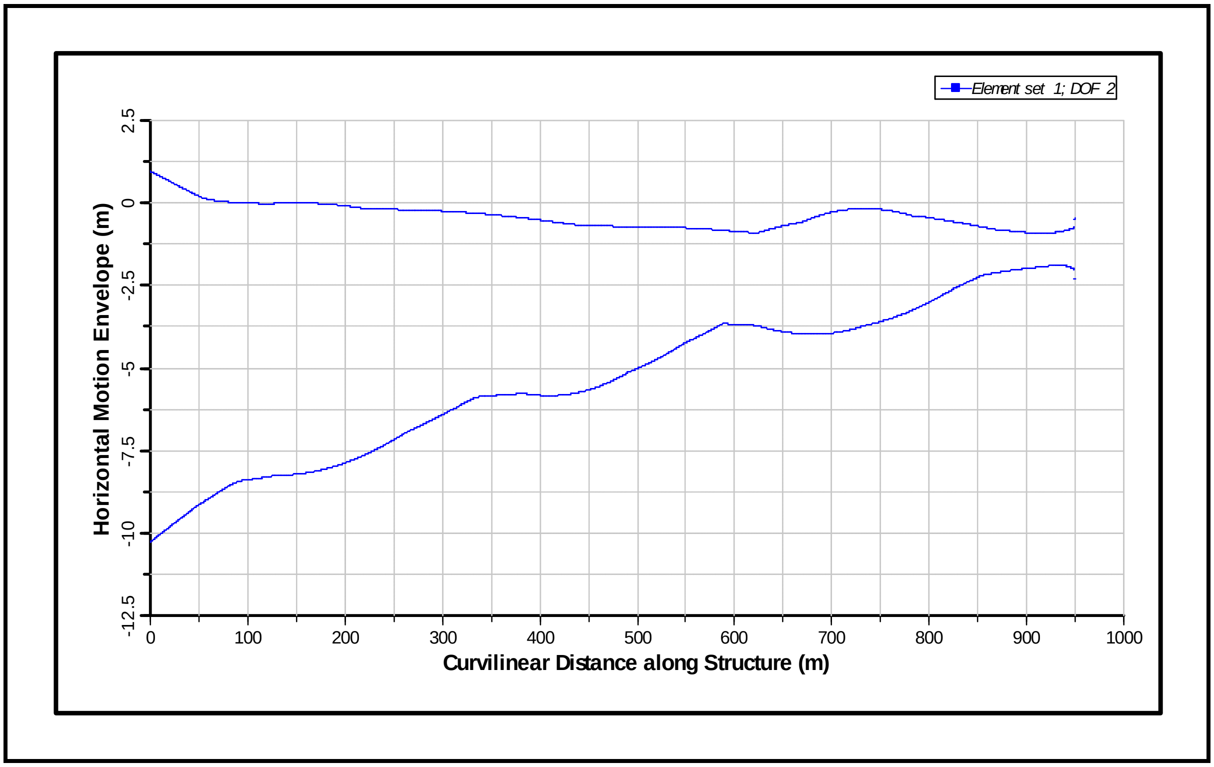


Figure 194: Motion Envelope for 1000 m CWP for Bin 10 (from Bottom to Top)

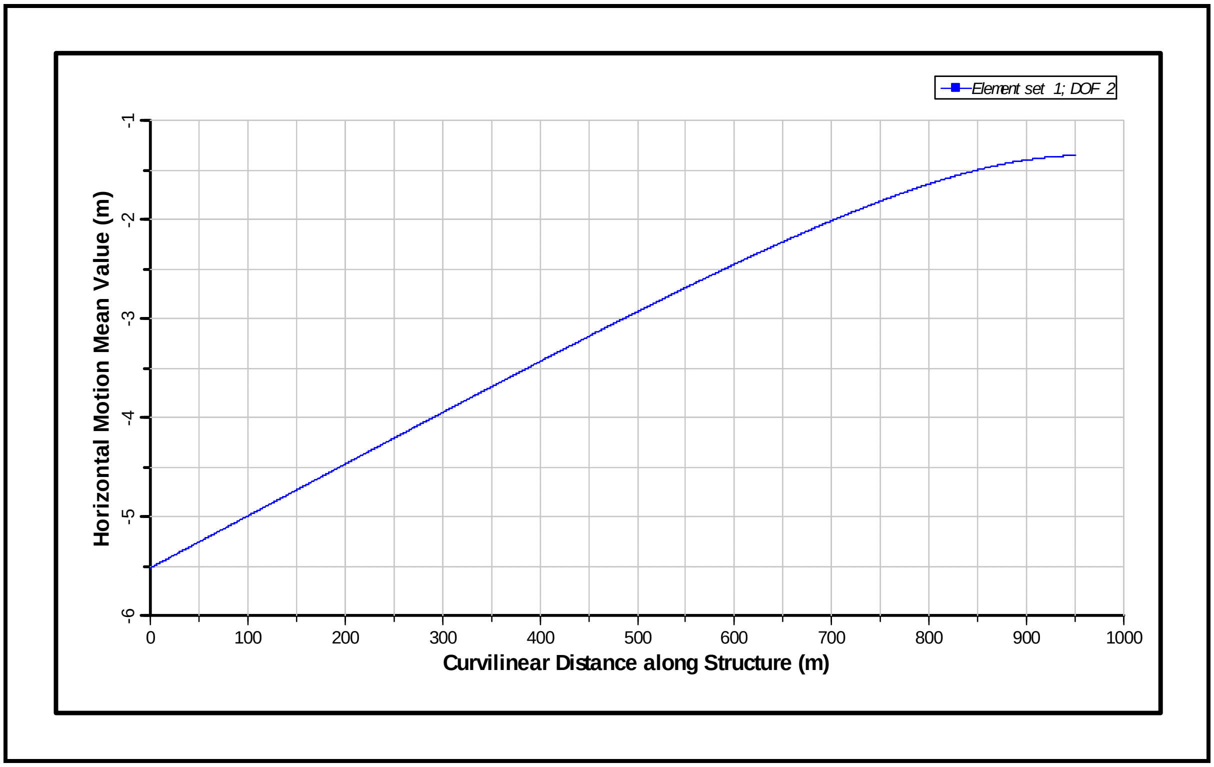


Figure 195: Mean Motion for 1000 m CWP for Bin 10 (from Bottom to Top)

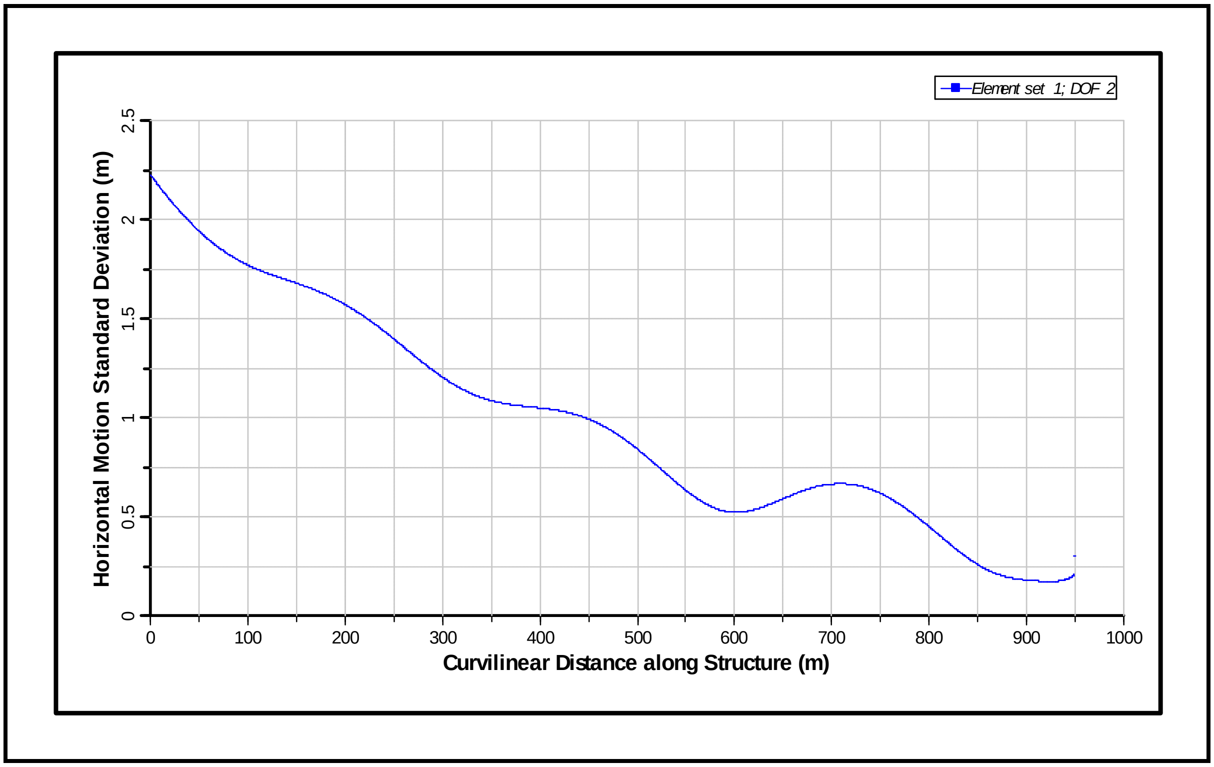


Figure 196: Standard Deviation of Motion for 1000 m CWP for Bin 10 (from Bottom to Top)

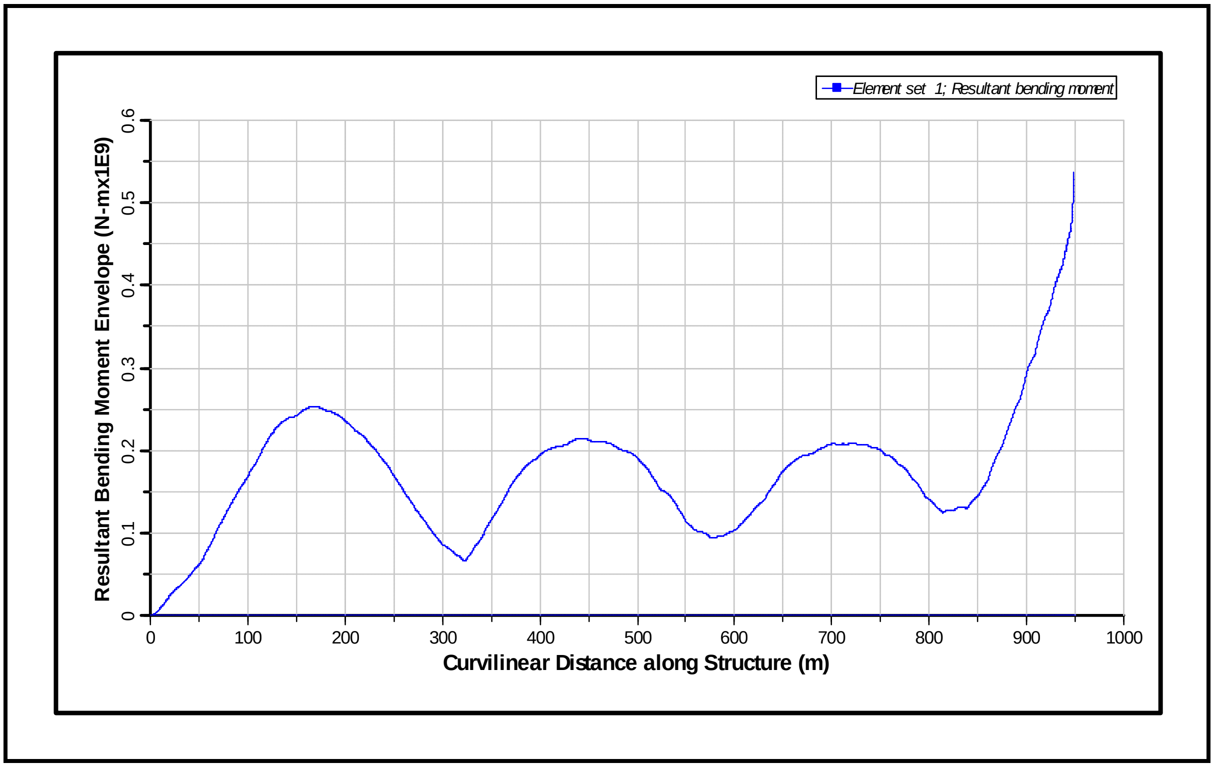


Figure 197: Bending Moment Envelope for 1000 m CWP for Bin 10 (from Bottom to Top)

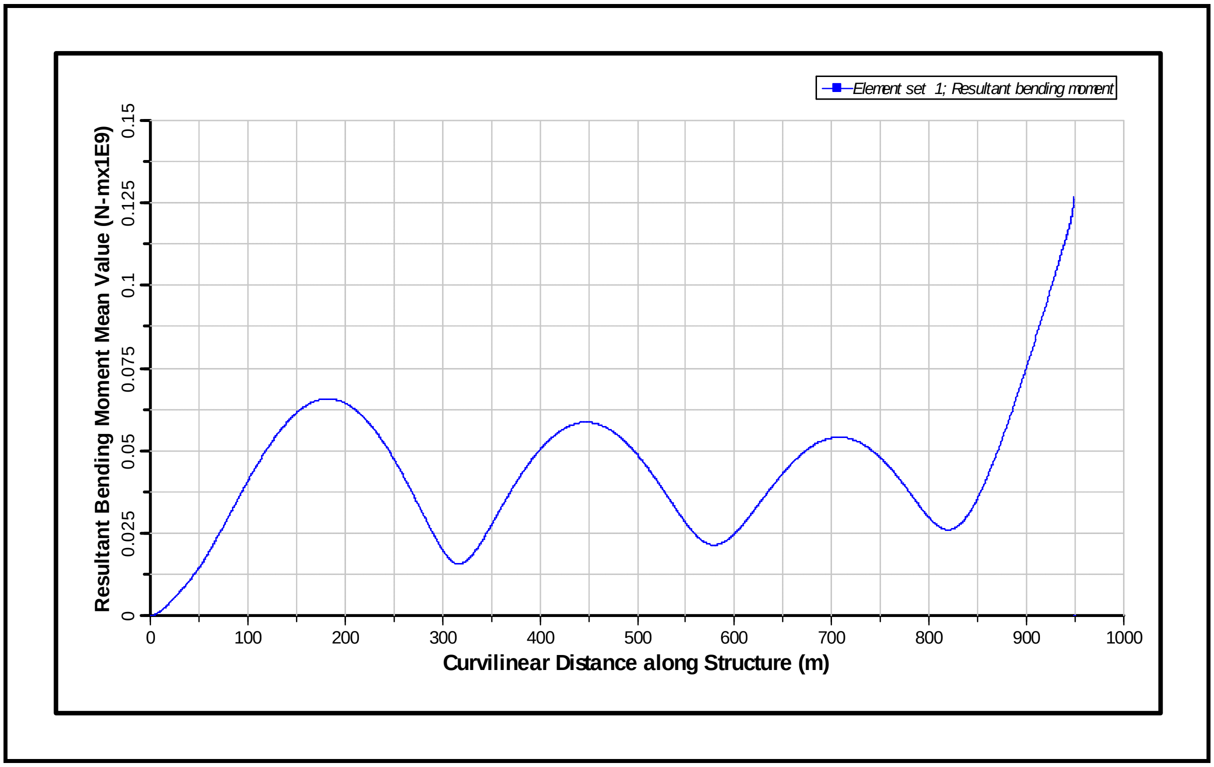


Figure 198: Mean Bending Moment for 1000 m CWP for Bin 10 (from Bottom to Top)

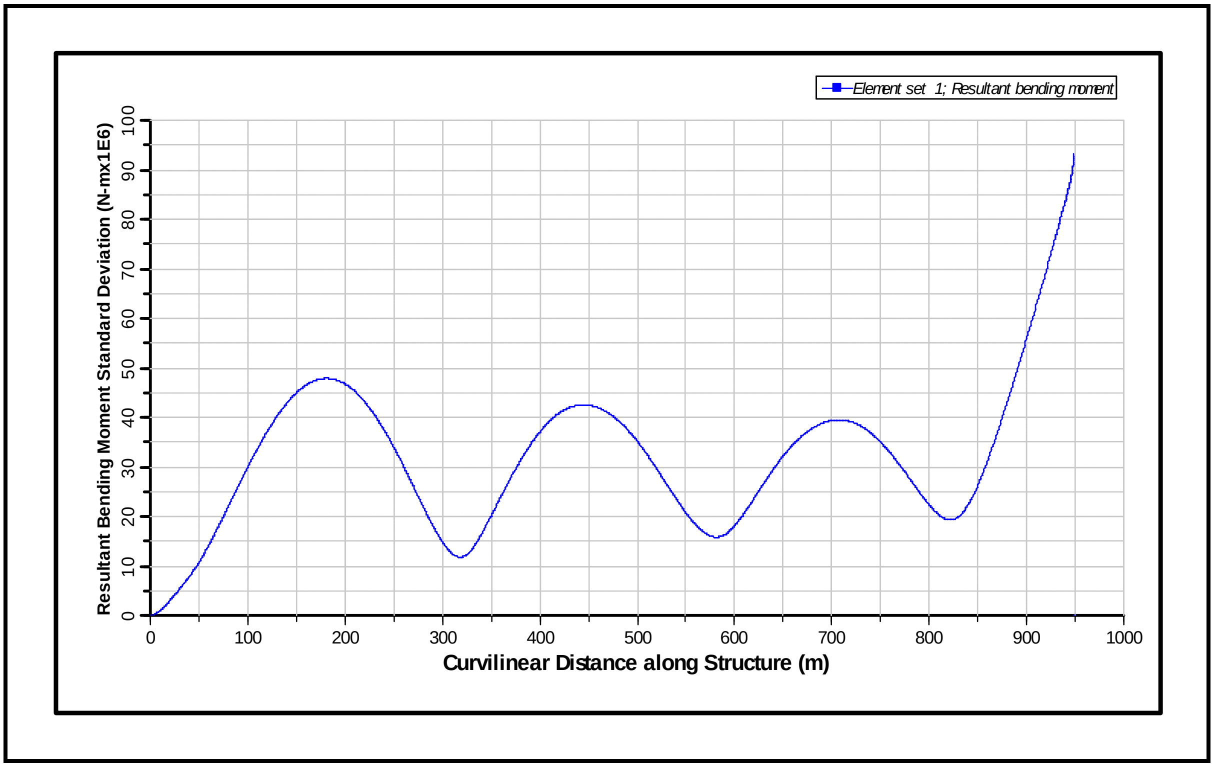


Figure 199: Standard Deviation of Bending Moment for 1000 m CWP for Bin 10 (from Bottom to Top)

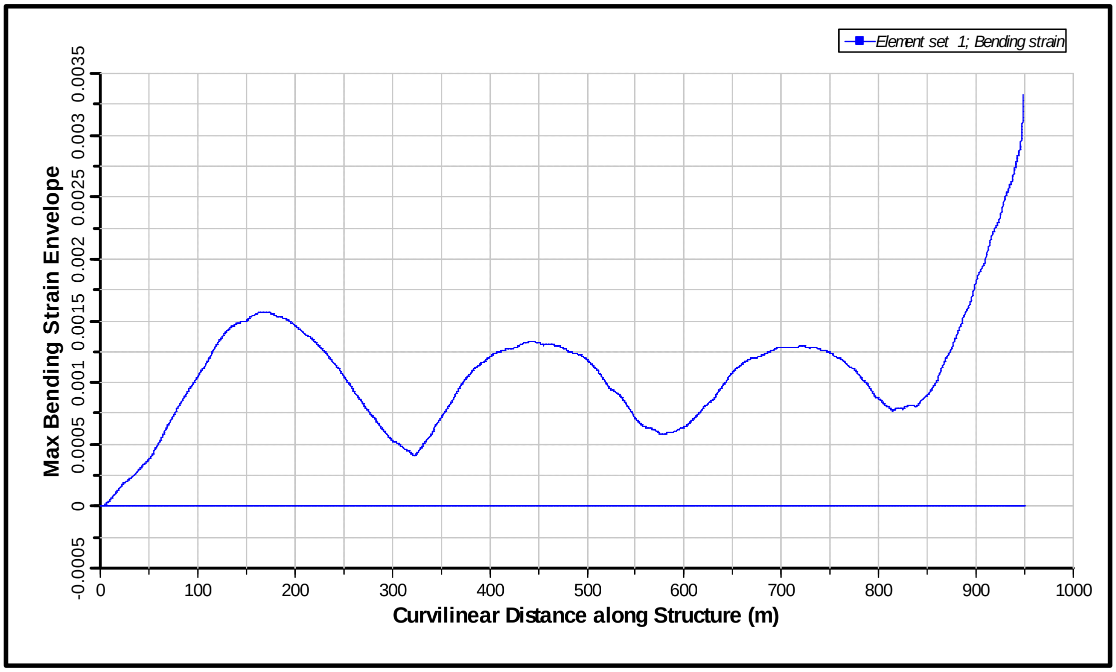


Figure 200: Bending Strain Envelope for 1000 m CWP for Bin 10 (from Bottom to Top)

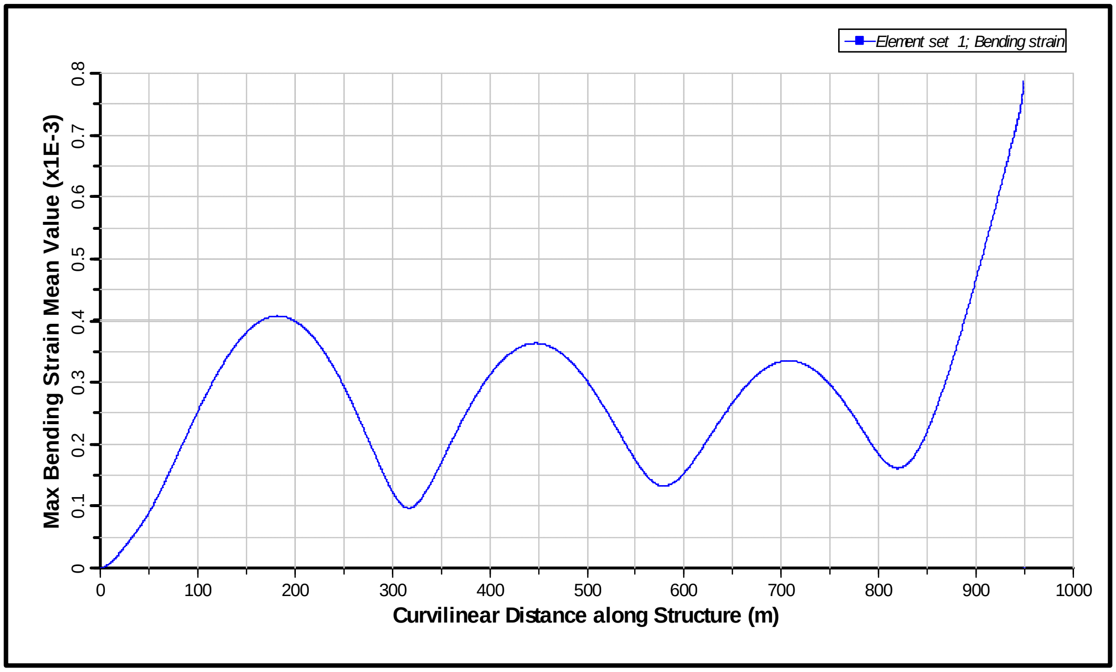


Figure 201: Mean Bending Strain for 1000 m CWP for Bin 10 (from Bottom to Top)

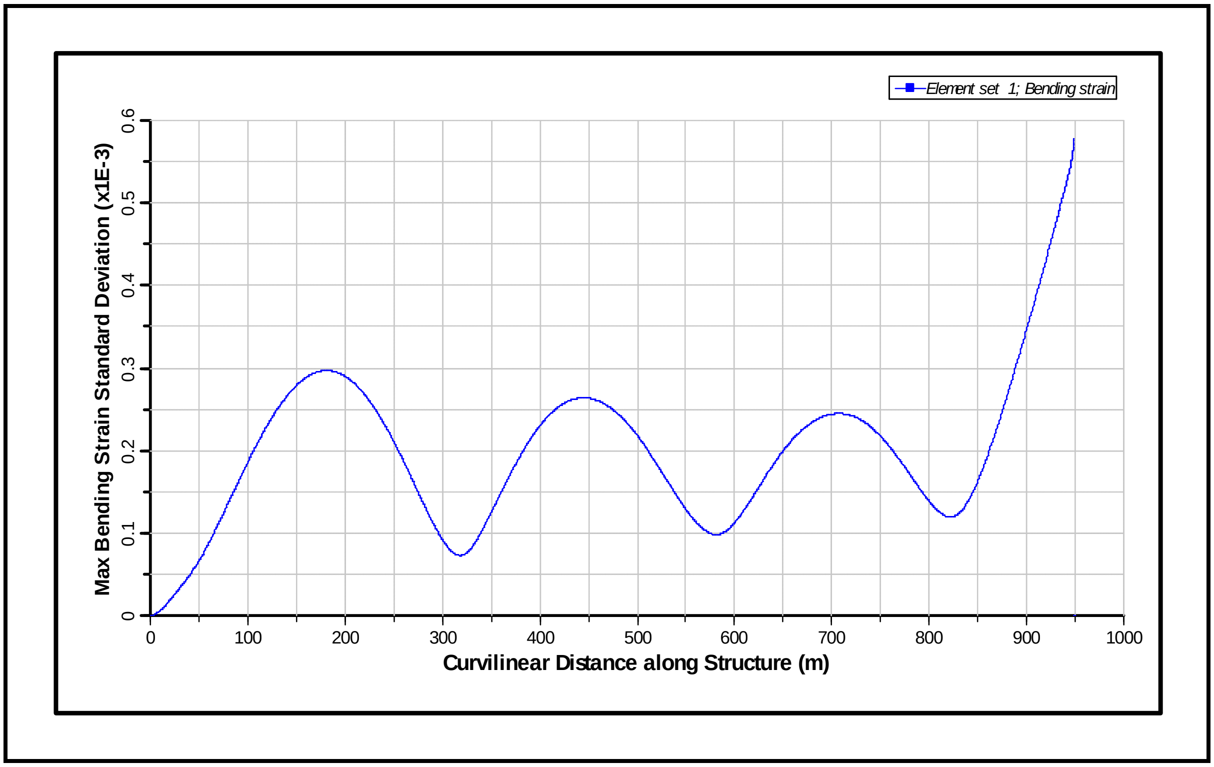


Figure 202: Standard Deviation of Bending Strain for 1000 m CWP for Bin 10 (from Bottom to Top)

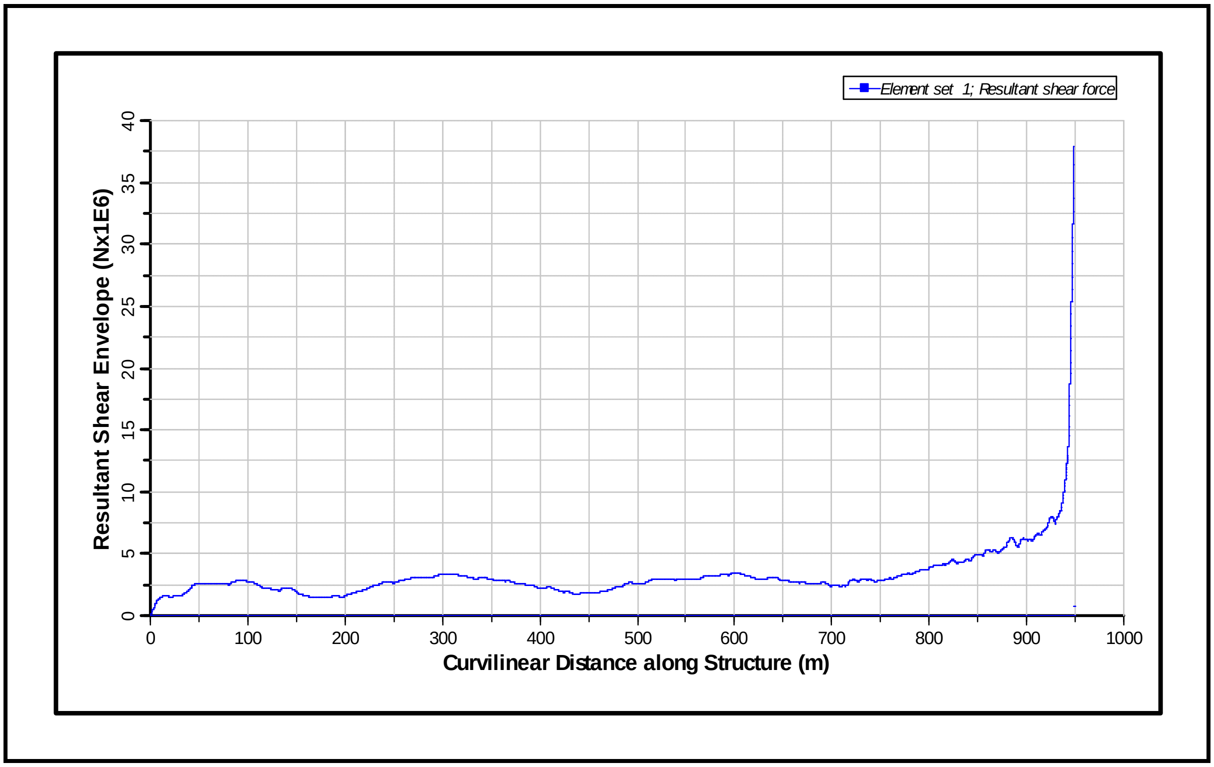


Figure 203: Shear Force Envelope for 1000 m CWP for Bin 10 (from Bottom to Top)

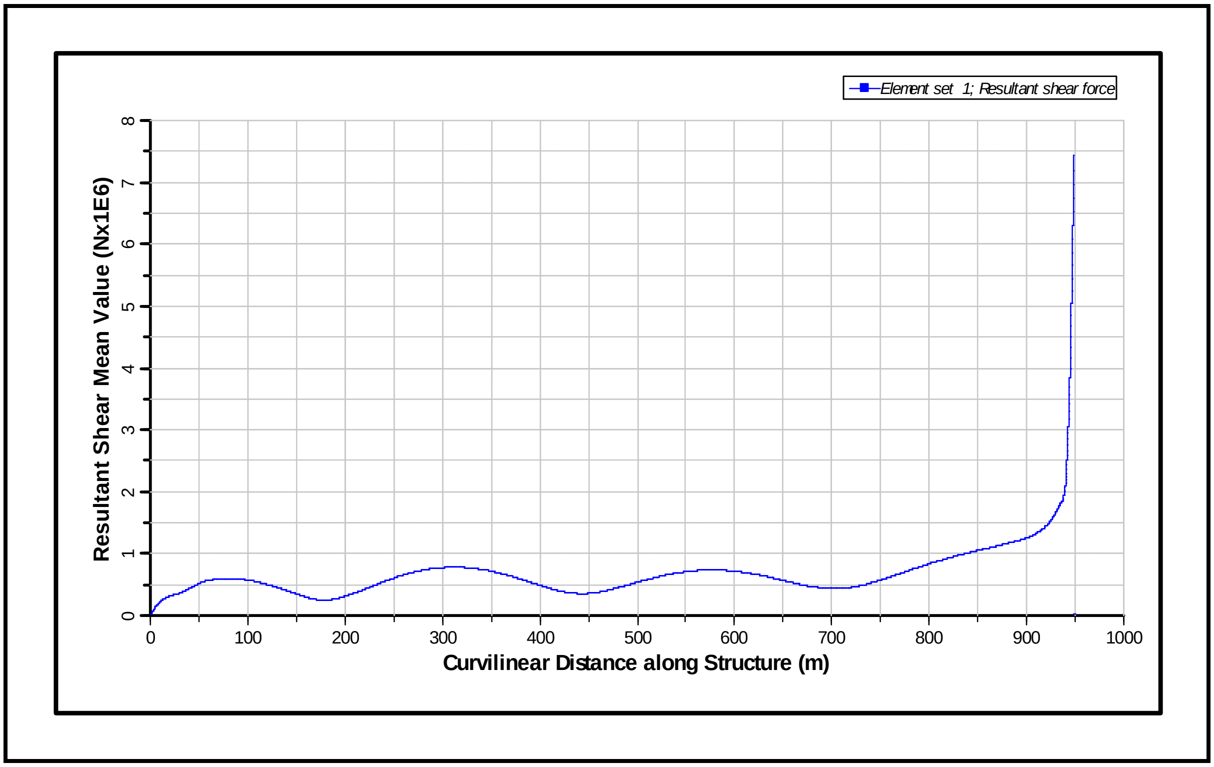


Figure 204: Mean Shear Force for 1000 m CWP for Bin 10 (from Bottom to Top)

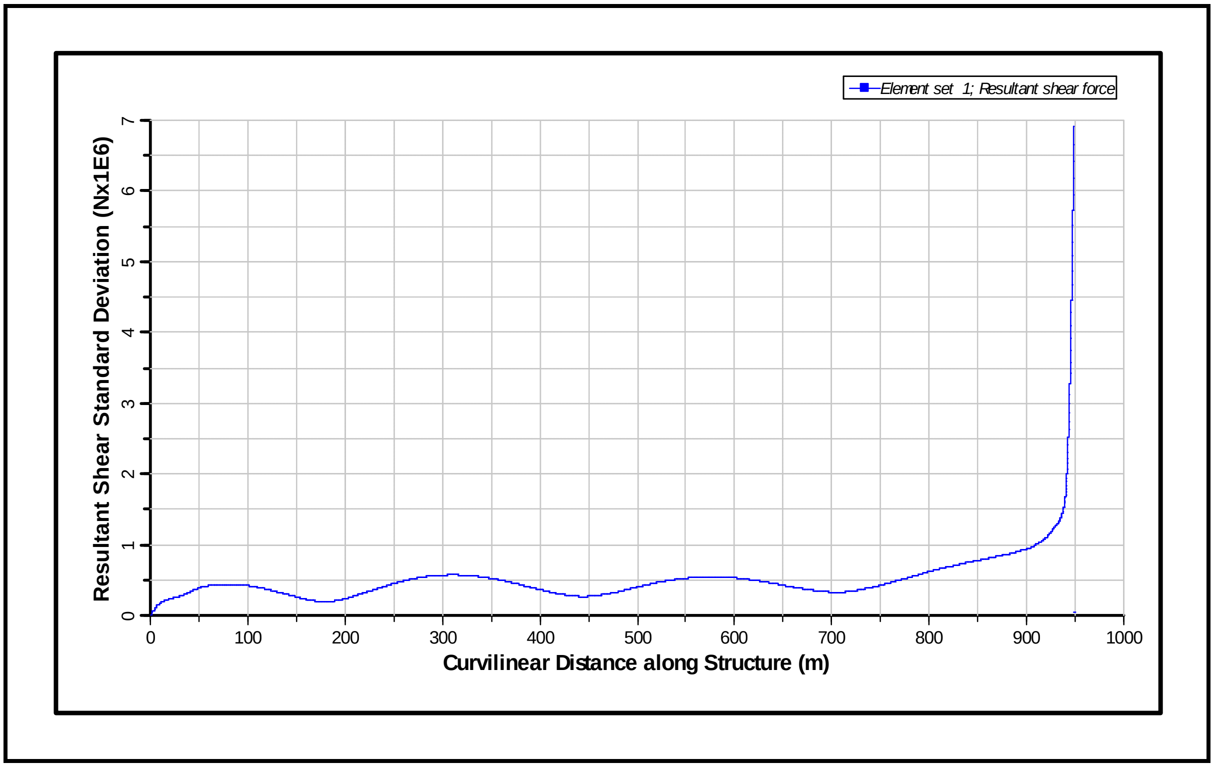


Figure 205: Standard Deviation of Shear Force for 1000 m CWP for Bin 10 (from Bottom to Top)

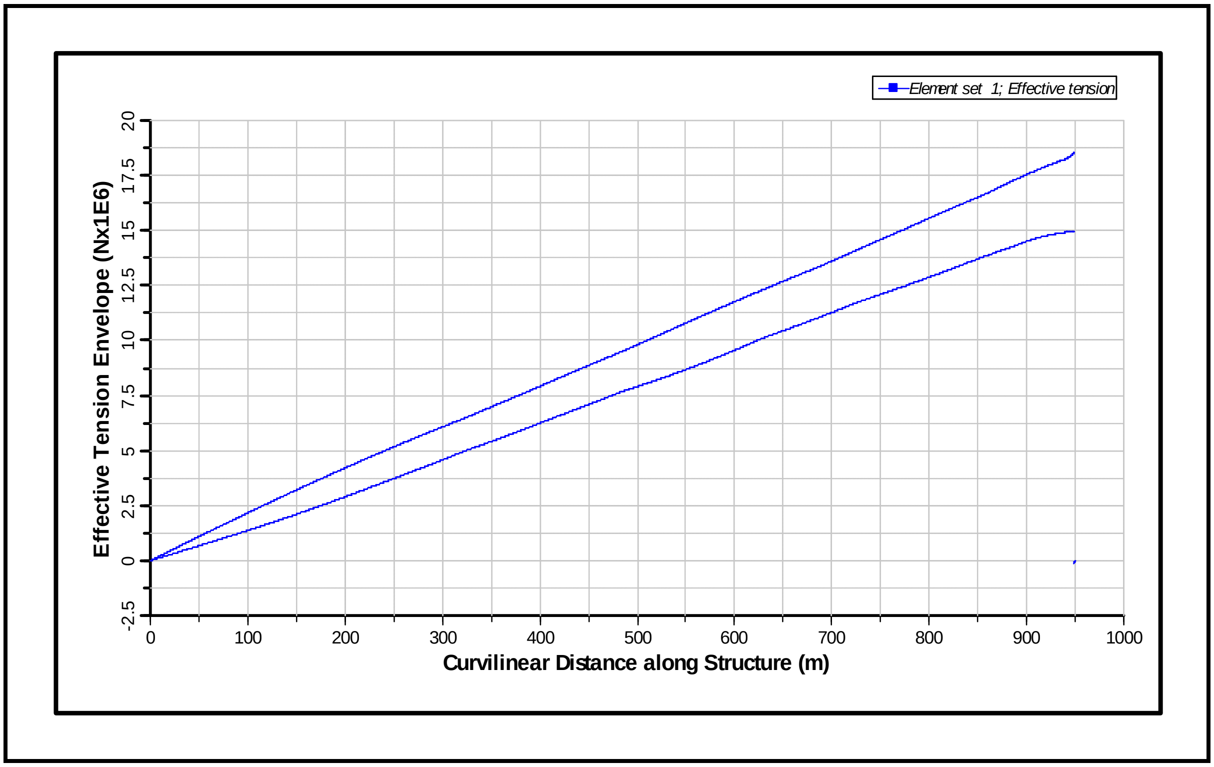


Figure 206: Axial Tension Envelope for 1000 m CWP for Bin 10 (from Bottom to Top)

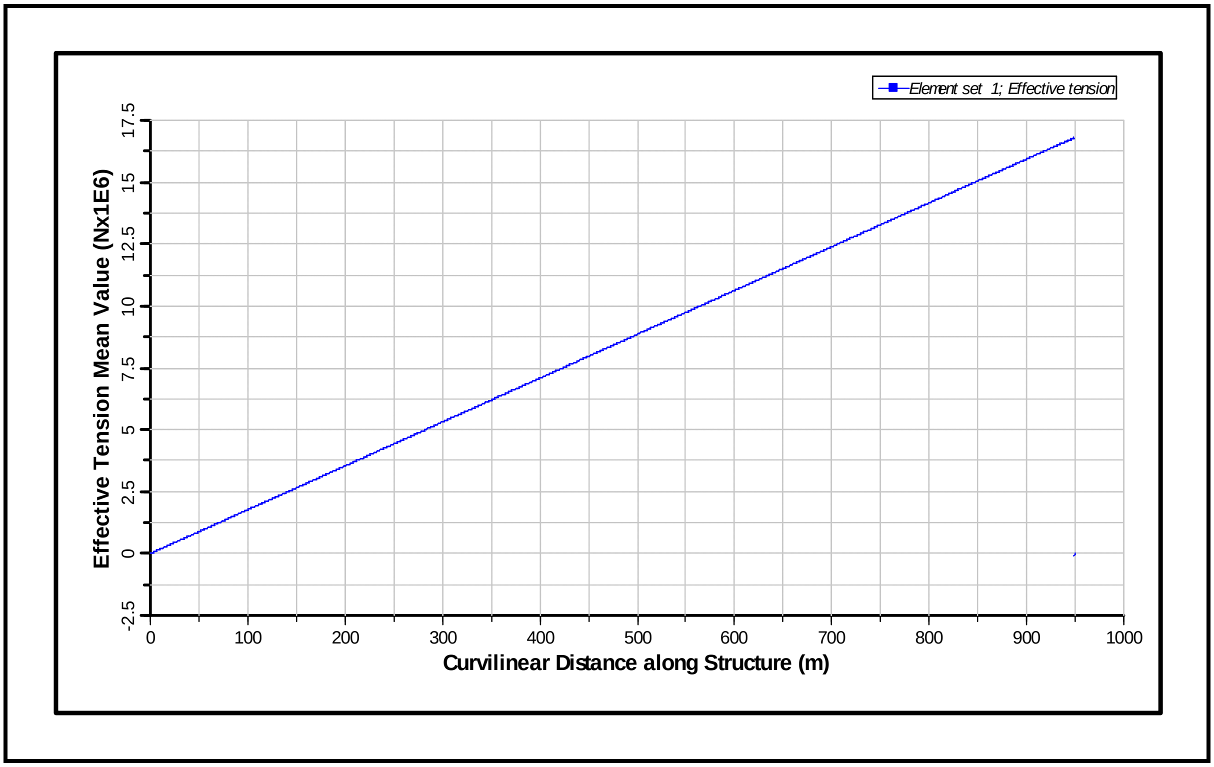


Figure 207: Mean Axial Tension for 1000 m CWP for Bin 10 (from Bottom to Top)

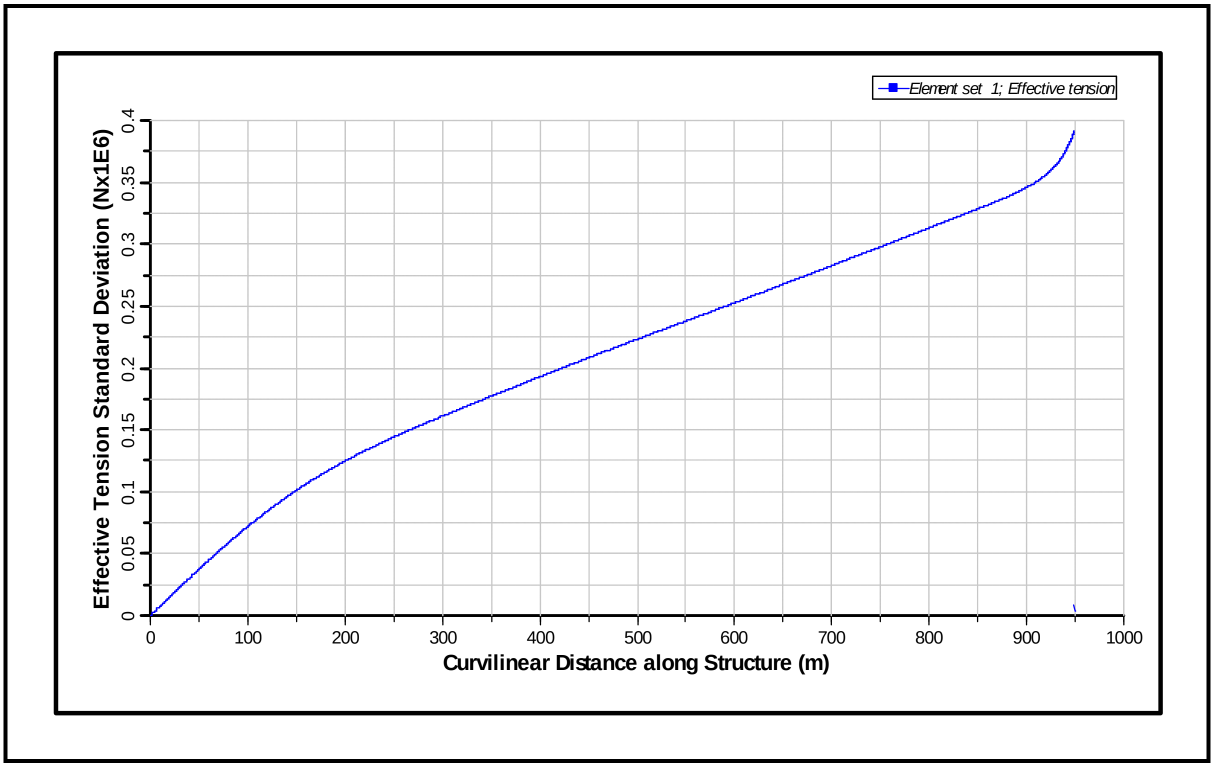


Figure 208: Standard Deviation of Axial Tension for 1000 m CWP for Bin 10 (from Bottom to Top)

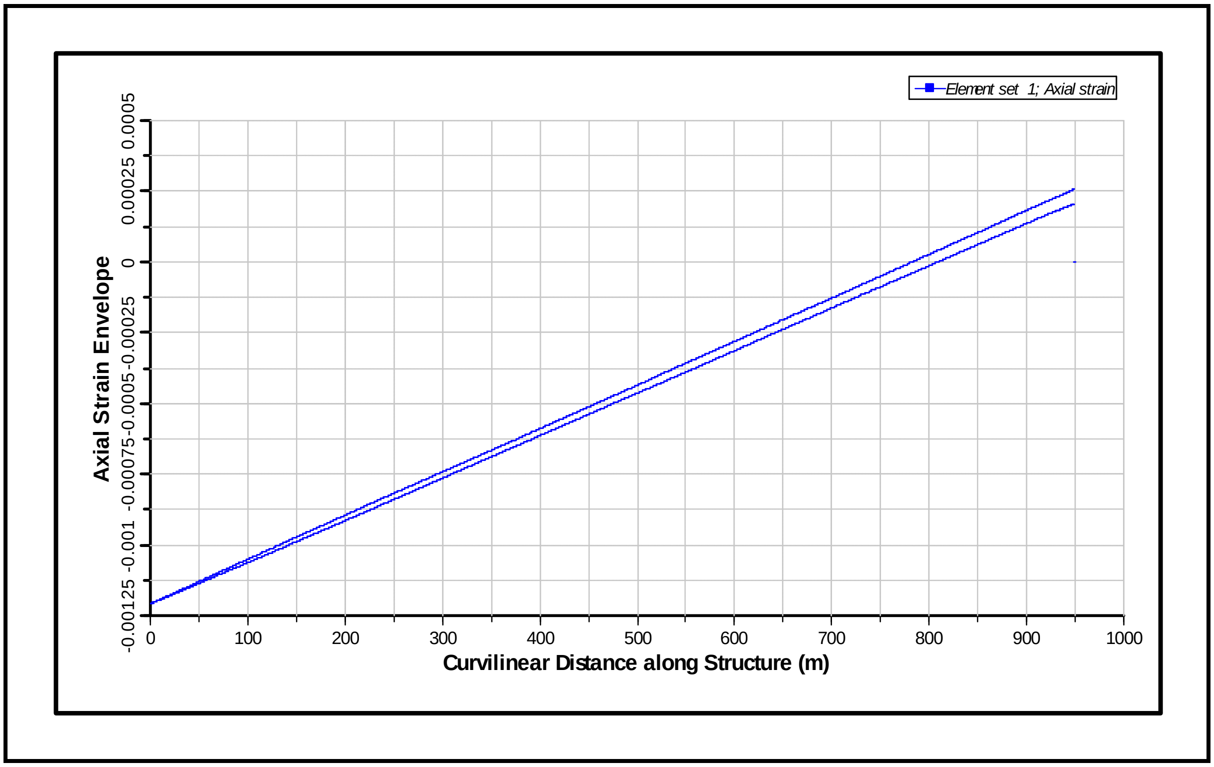


Figure 209: Axial Strain Envelope for 1000 m CWP for Bin 10 (from Bottom to Top)

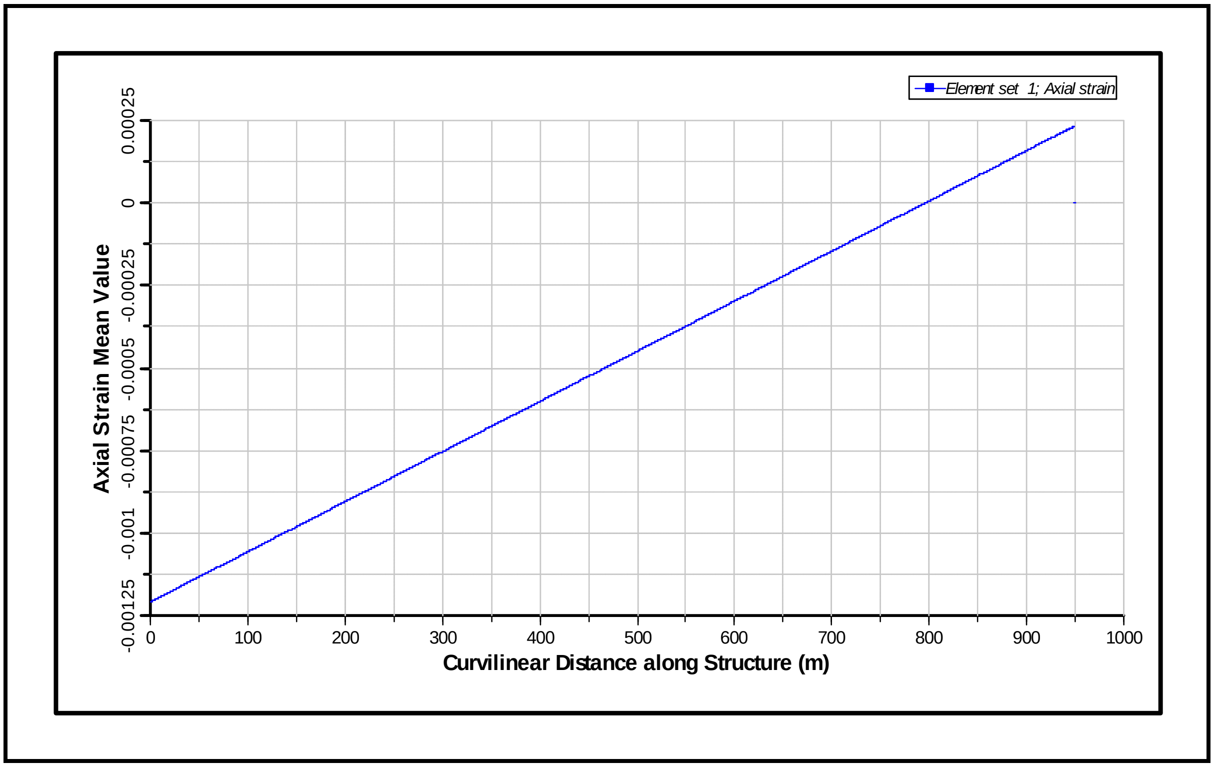


Figure 210: Mean Axial Strain for 1000 m CWP for Bin 10 (from Bottom to Top)

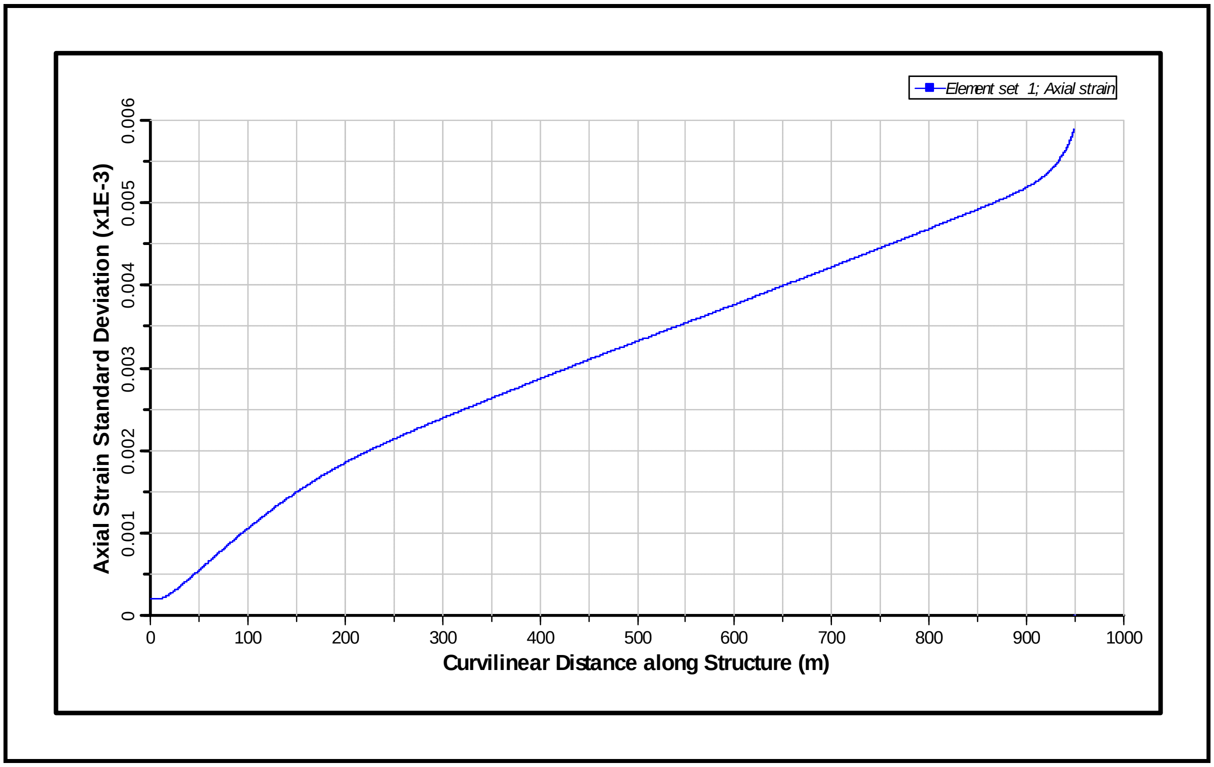


Figure 211: Standard Deviation of Axial Strain for 1000 m CWP for Bin 10 (from Bottom to Top)

6.11 Bin 11

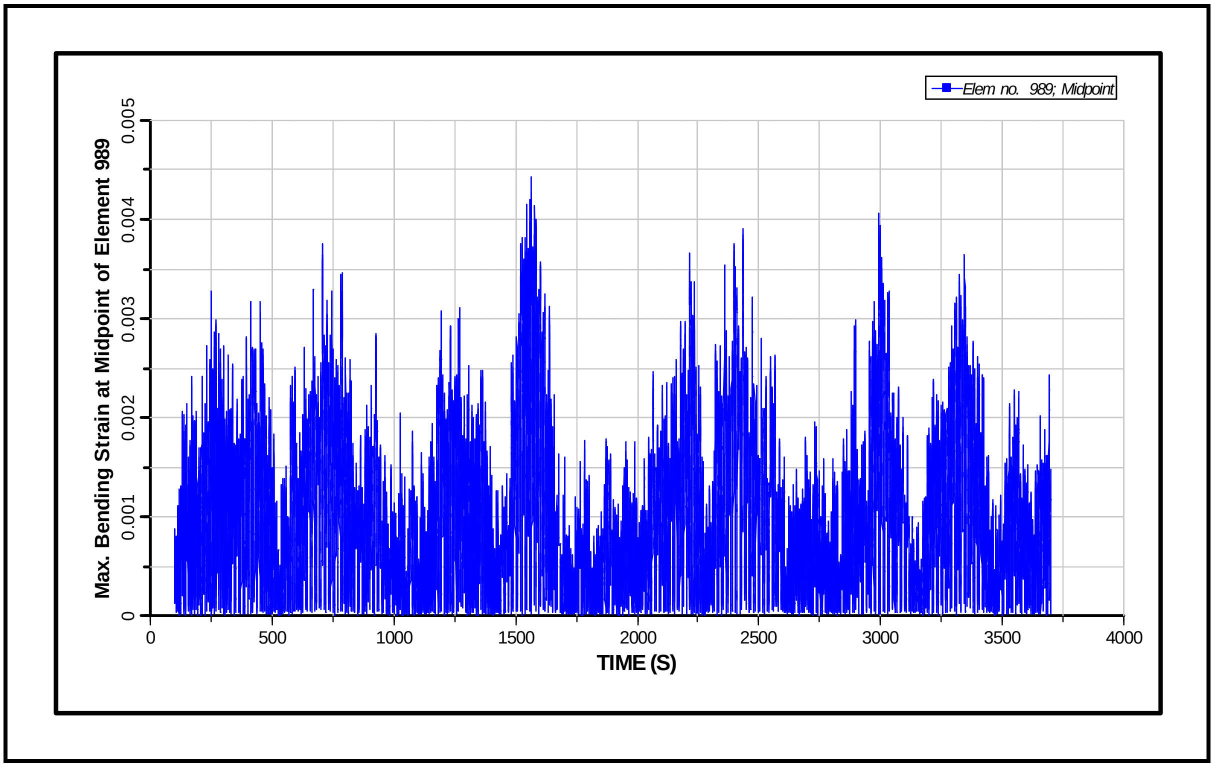


Figure 212: Maximum Bending Strain Time History at Top of CWP for Bin 11

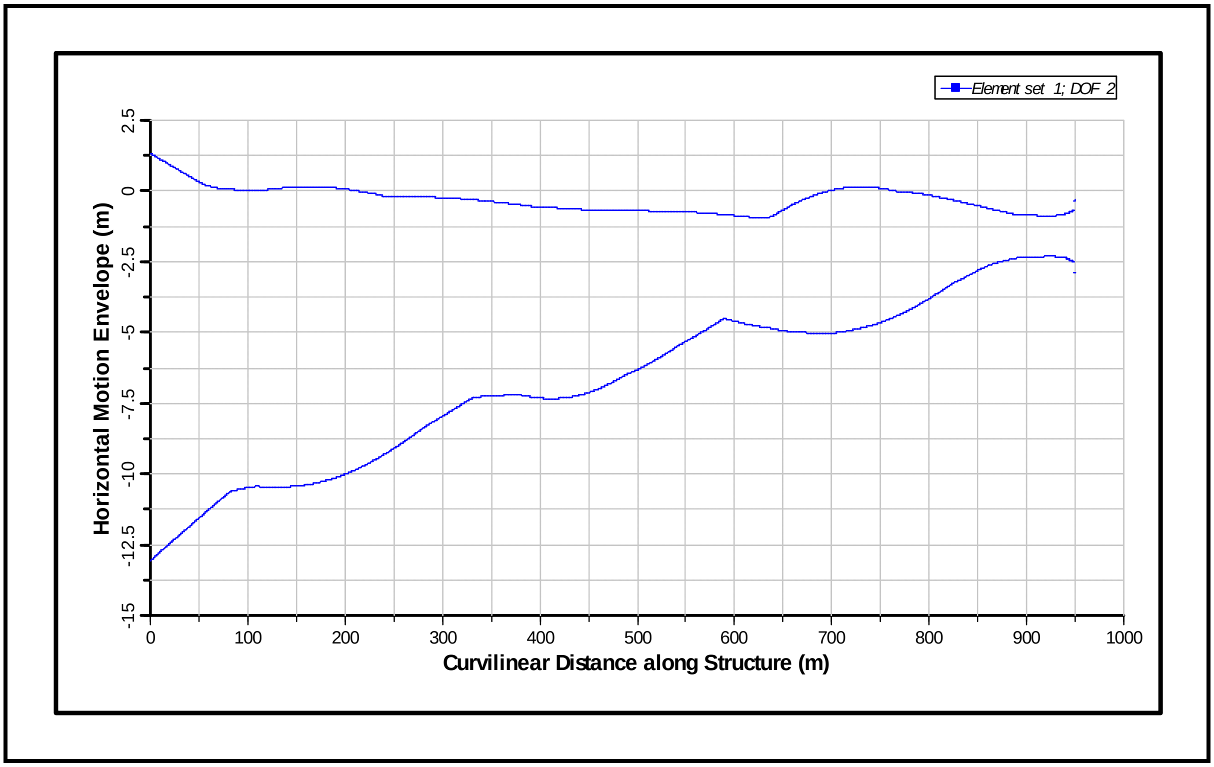


Figure 213: Motion Envelope for 1000 m CWP for Bin 11 (from Bottom to Top)

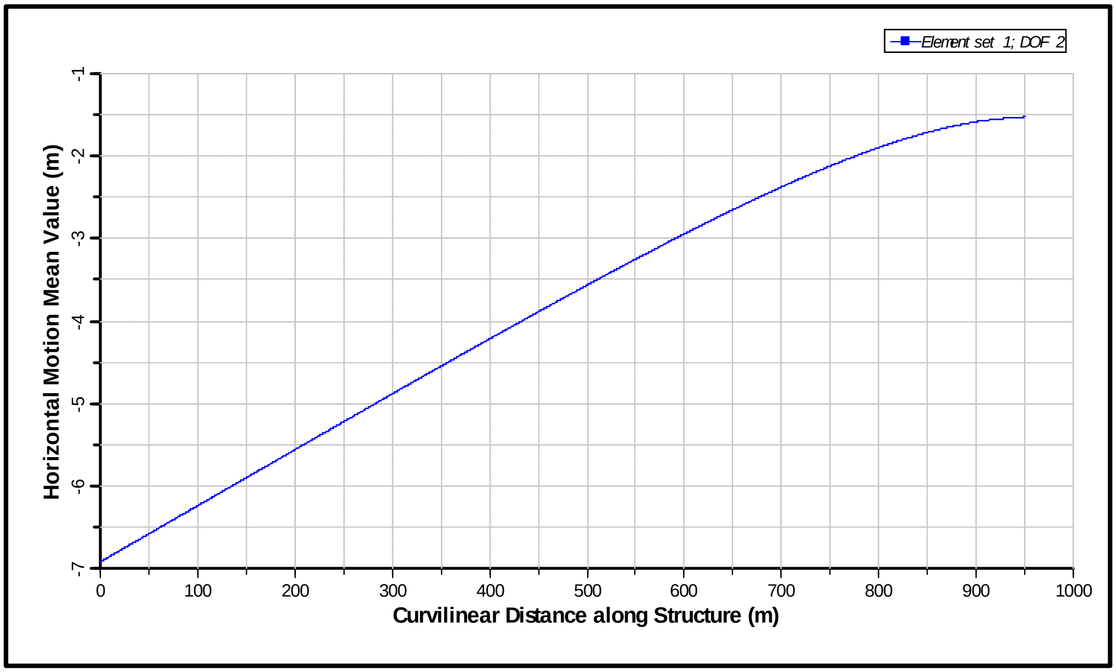


Figure 214: Mean Motion for 1000 m CWP for Bin 11 (from Bottom to Top)

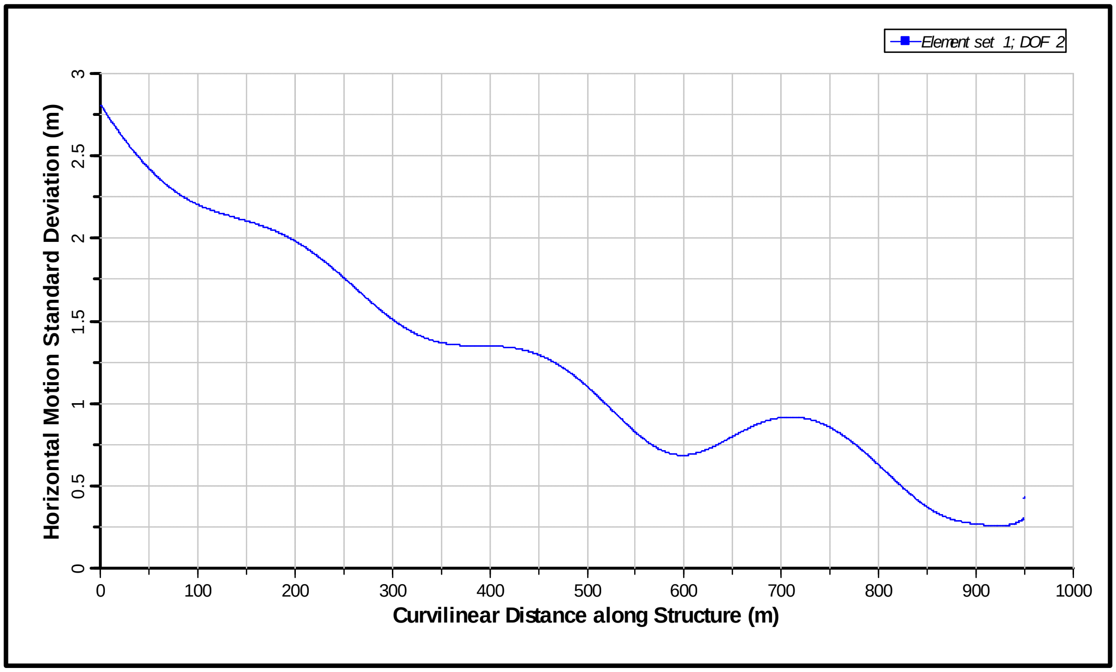


Figure 215: Standard Deviation of Motion for 1000 m CWP for Bin 11 (from Bottom to Top)

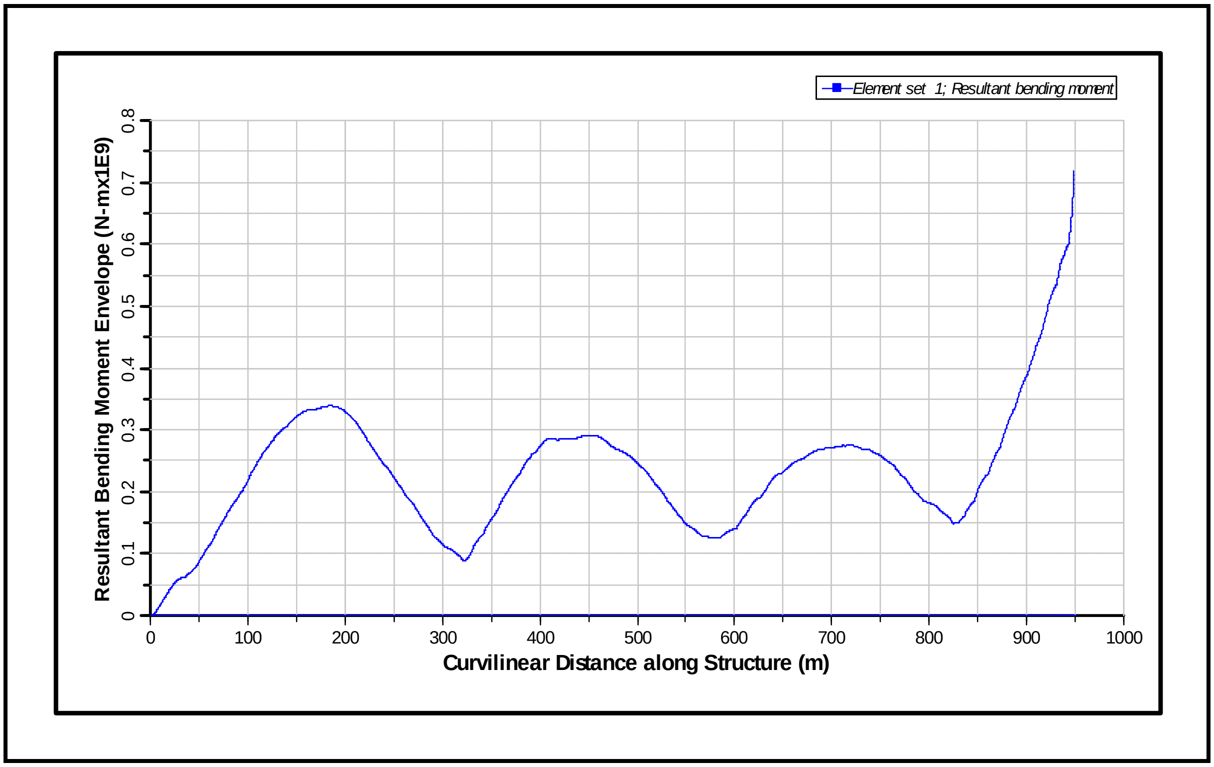


Figure 216: Bending Moment Envelope for 1000 m CWP for Bin 11 (from Bottom to Top)

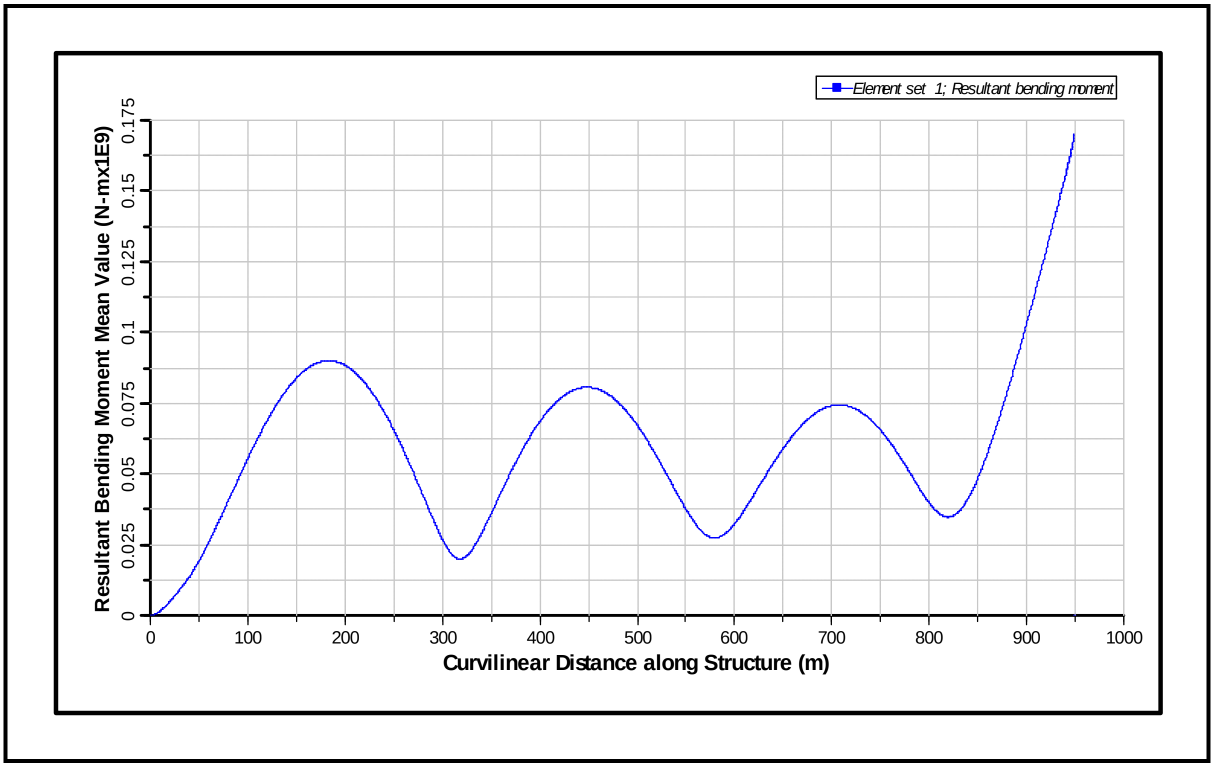


Figure 217: Mean Bending Moment for 1000 m CWP for Bin 11 (from Bottom to Top)

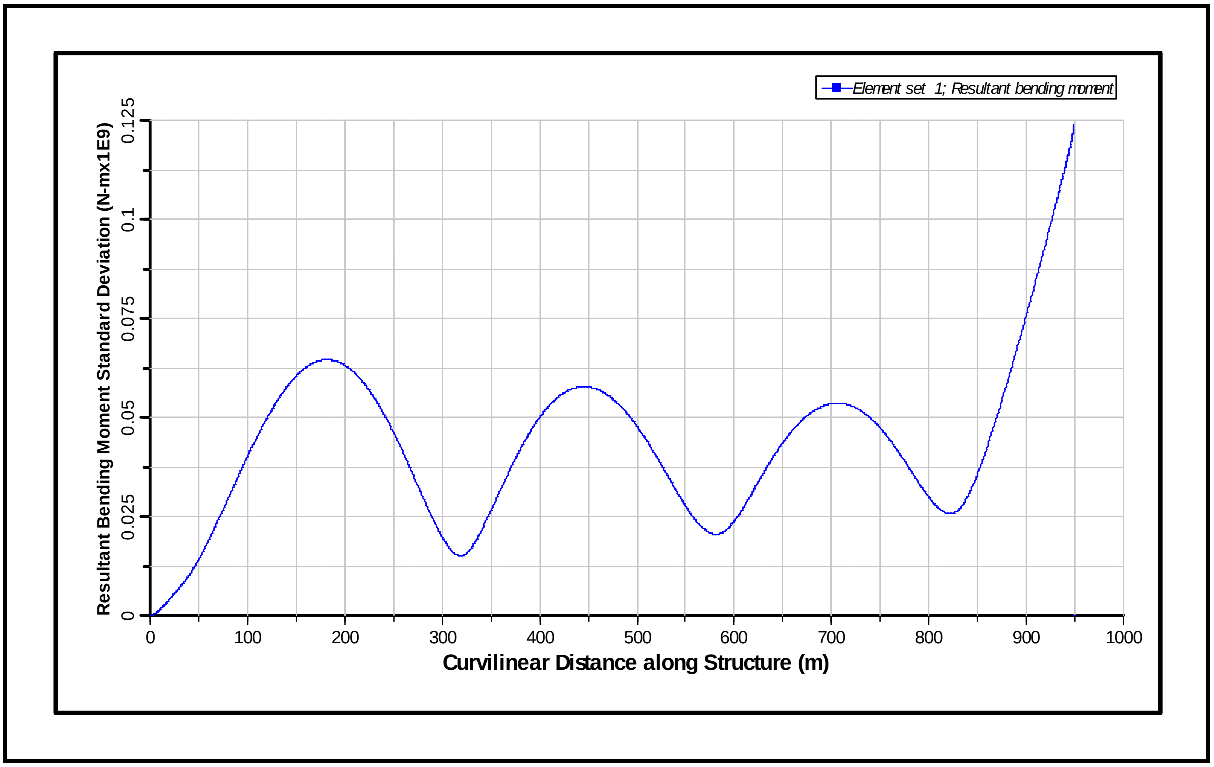


Figure 218: Standard Deviation of Bending Moment for 1000 m CWP for Bin 11 (from Bottom to Top)

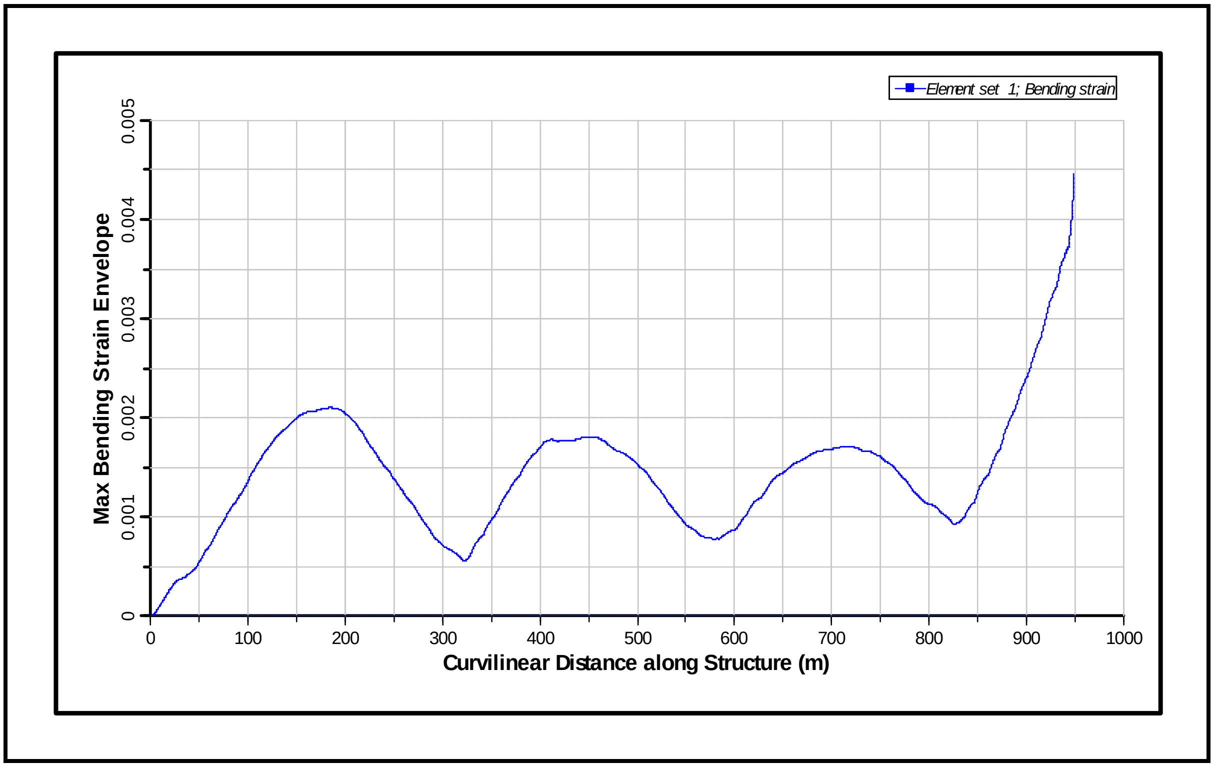


Figure 219: Bending Strain Envelope for 1000 m CWP for Bin 11 (from Bottom to Top)

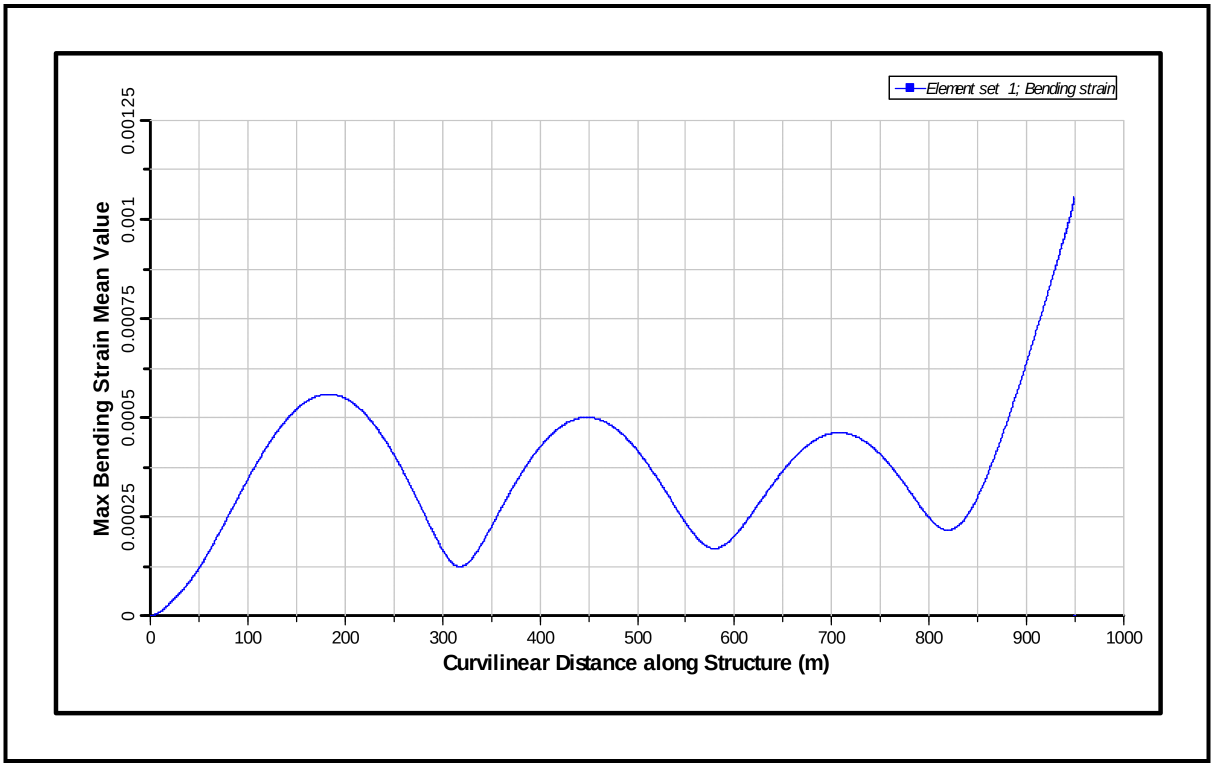


Figure 220: Mean Bending Strain for 1000 m CWP for Bin 11 (from Bottom to Top)

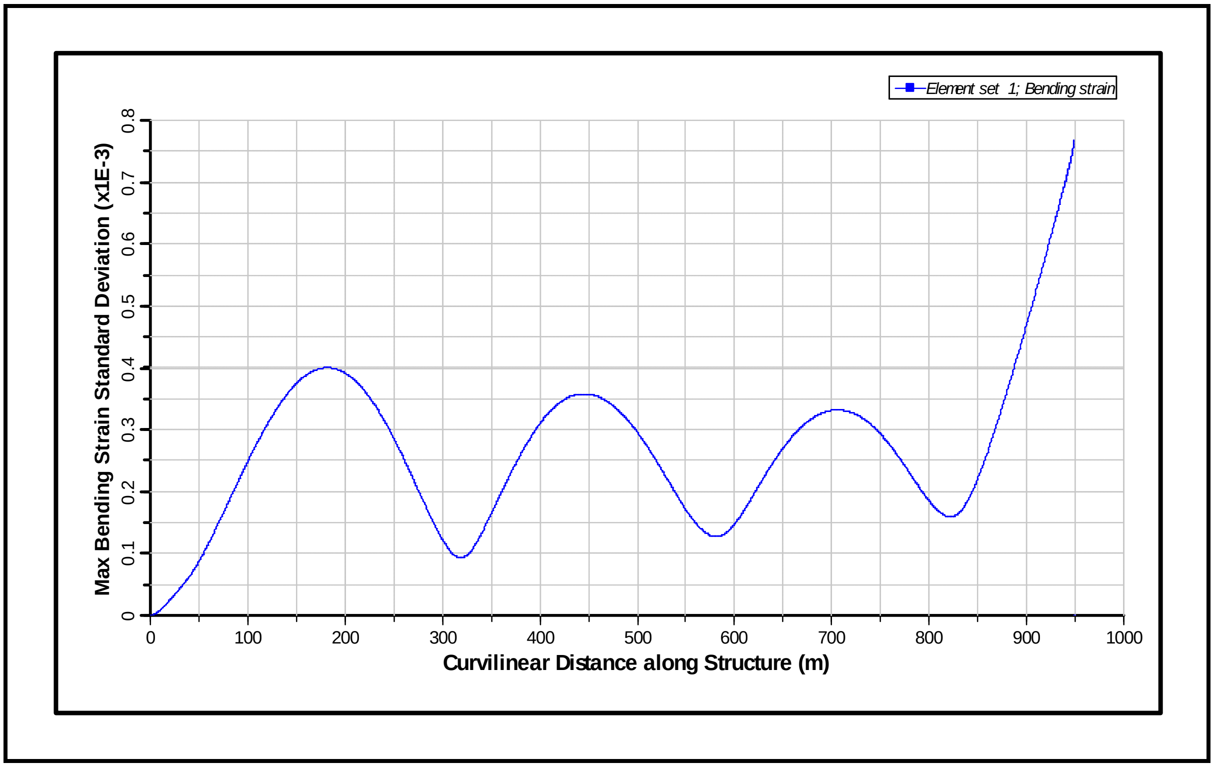


Figure 221: Standard Deviation of Bending Strain for 1000 m CWP for Bin 11 (from Bottom to Top)

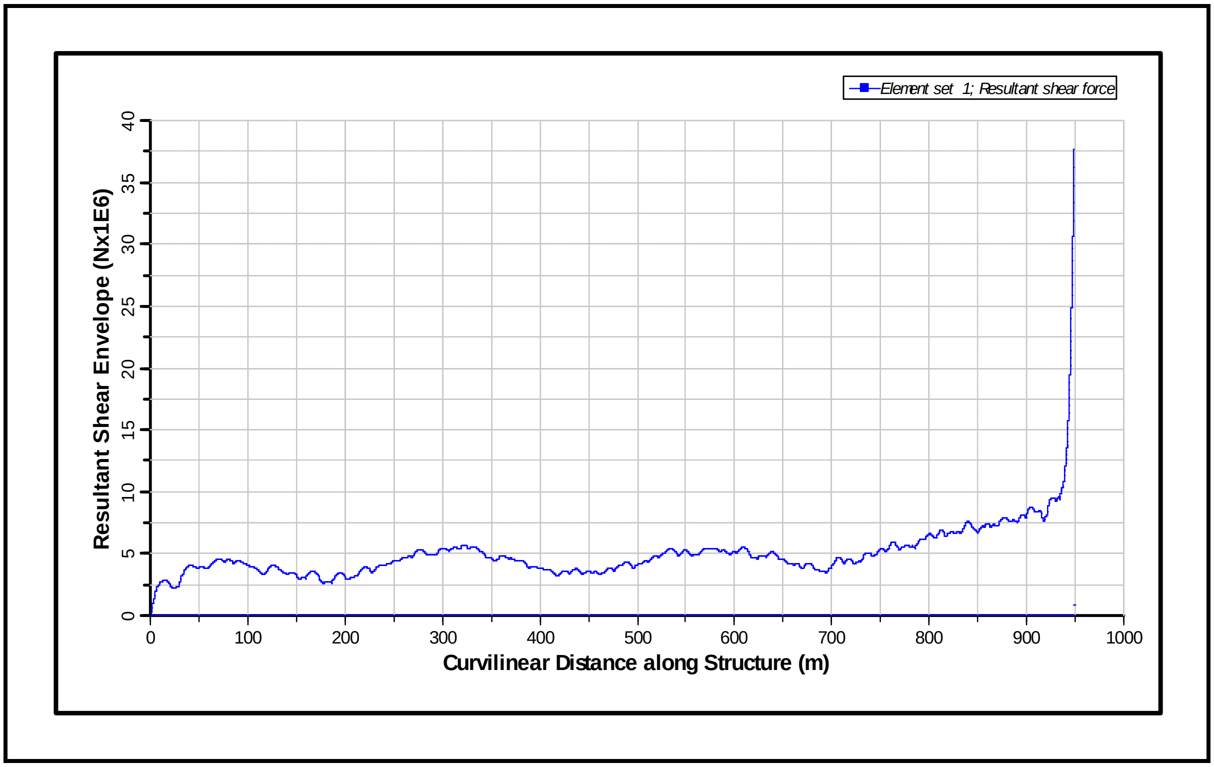


Figure 222: Shear Force Envelope for 1000 m CWP for Bin 11 (from Bottom to Top)

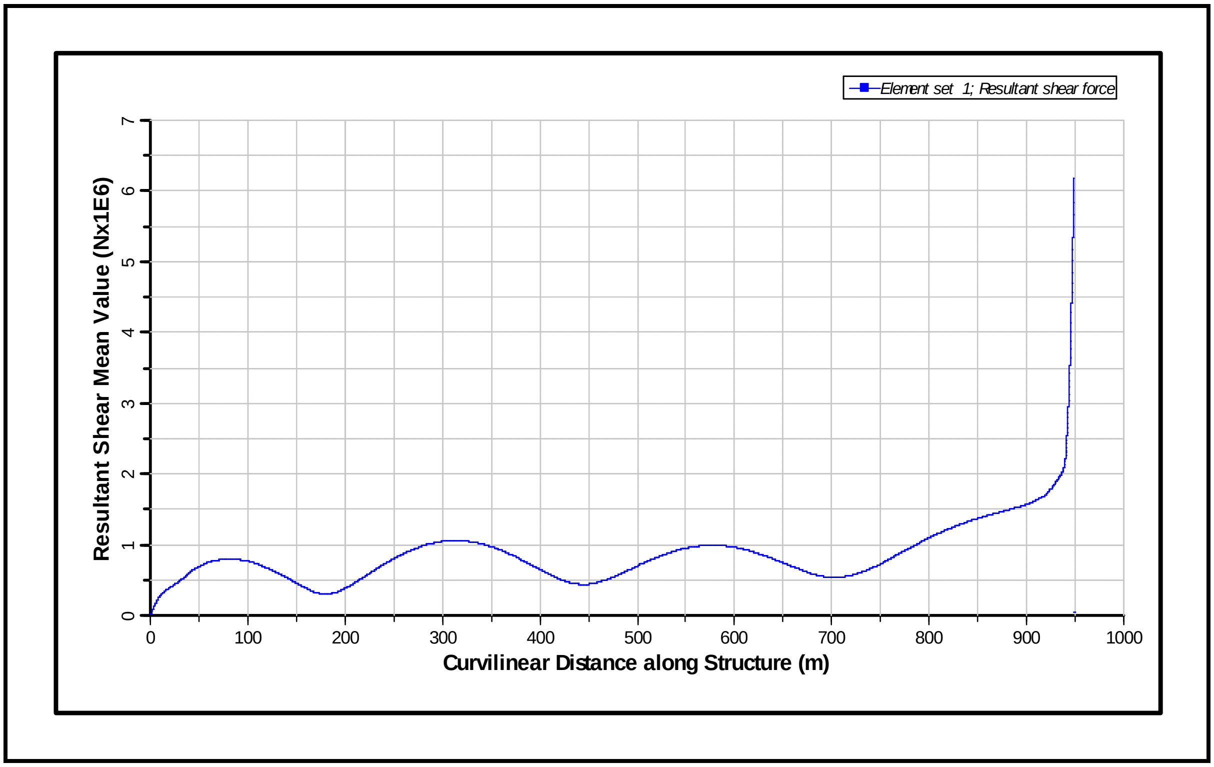


Figure 223: Mean Shear Force for 1000 m CWP for Bin 11 (from Bottom to Top)

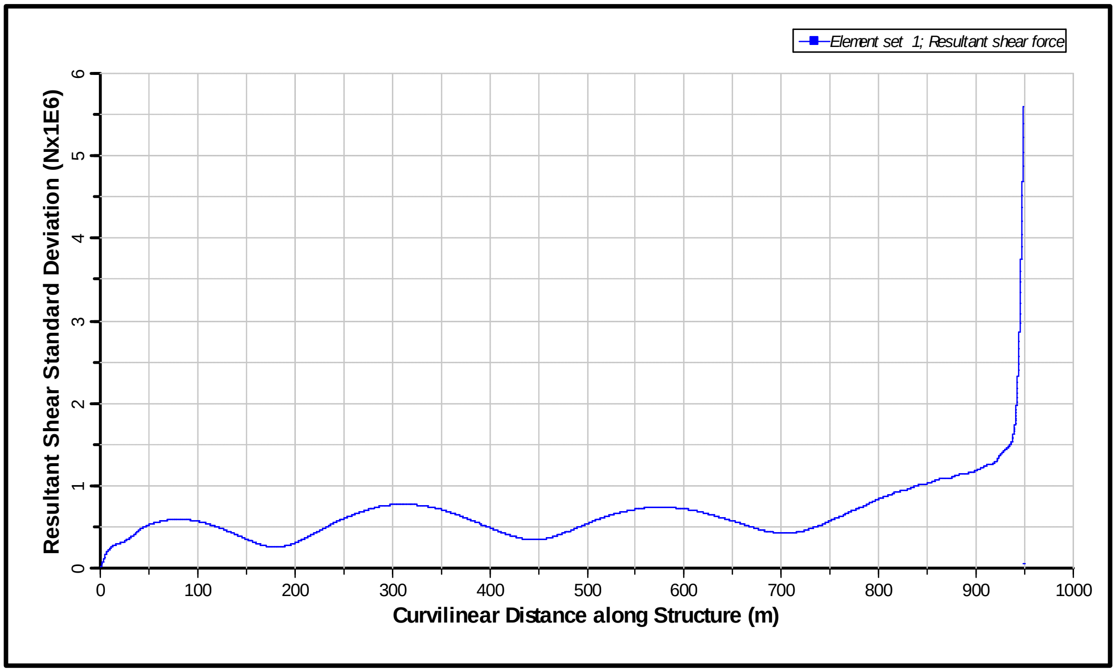


Figure 224: Standard Deviation of Shear Force for 1000 m CWP for Bin 11 (from Bottom to Top)

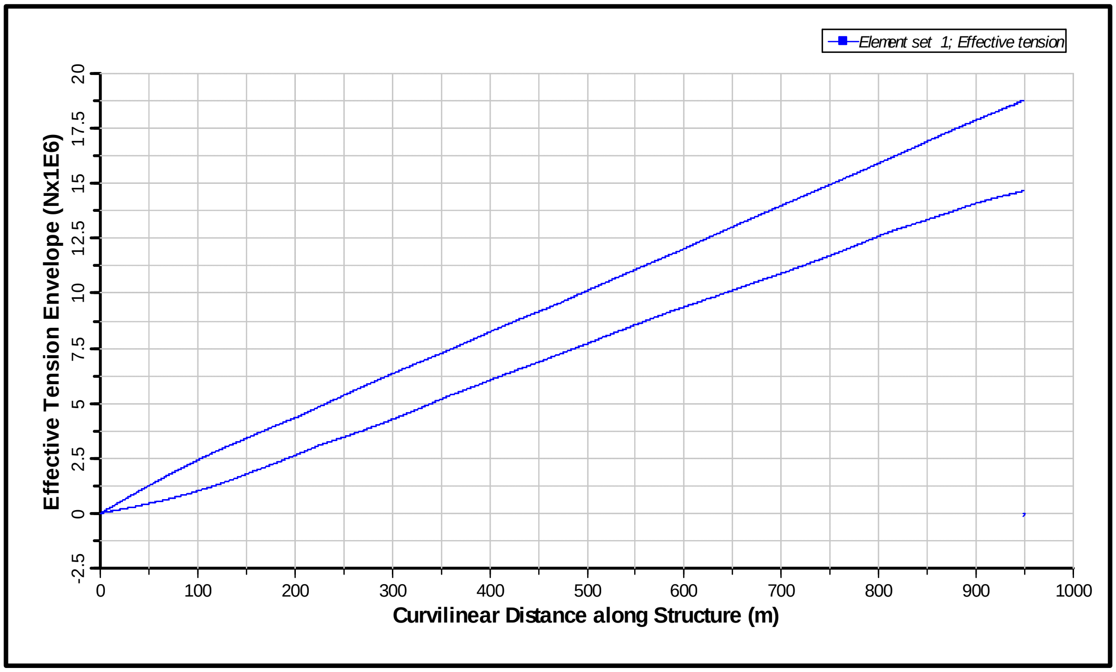


Figure 225: Axial Tension Envelope for 1000 m CWP for Bin 11 (from Bottom to Top)

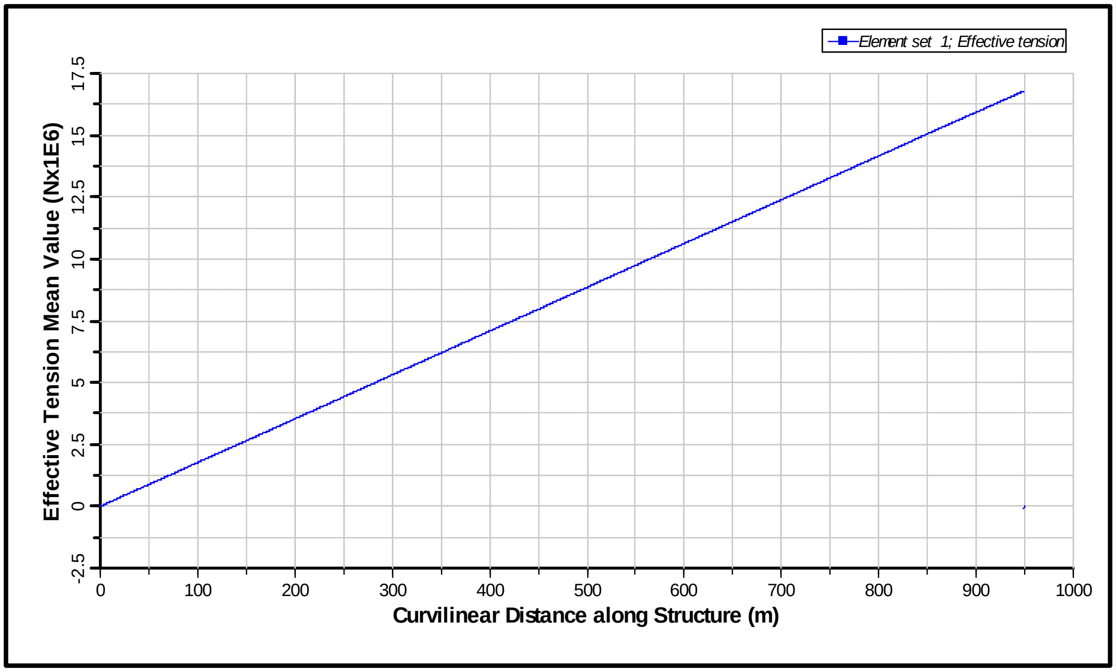


Figure 226: Mean Axial Tension for 1000 m CWP for Bin 11 (from Bottom to Top)

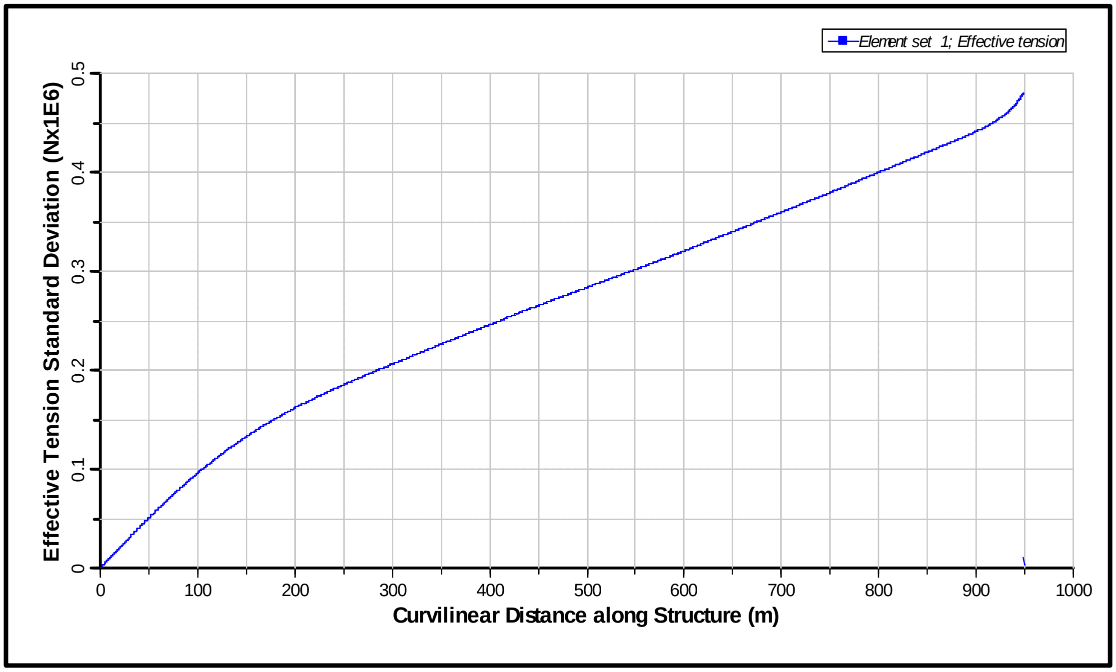


Figure 227: Standard Deviation of Axial Tension for 1000 m CWP for Bin 11 (from Bottom to Top)

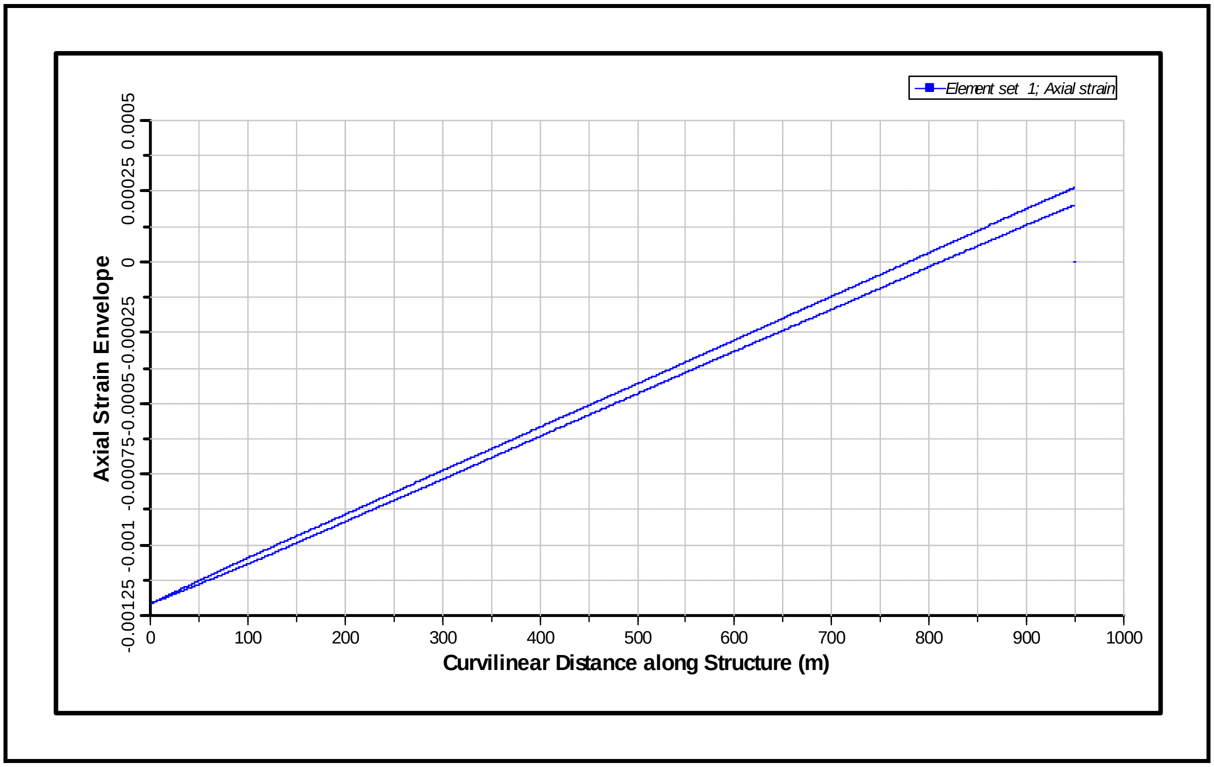


Figure 228: Axial Strain Envelope for 1000 m CWP for Bin 11 (from Bottom to Top)

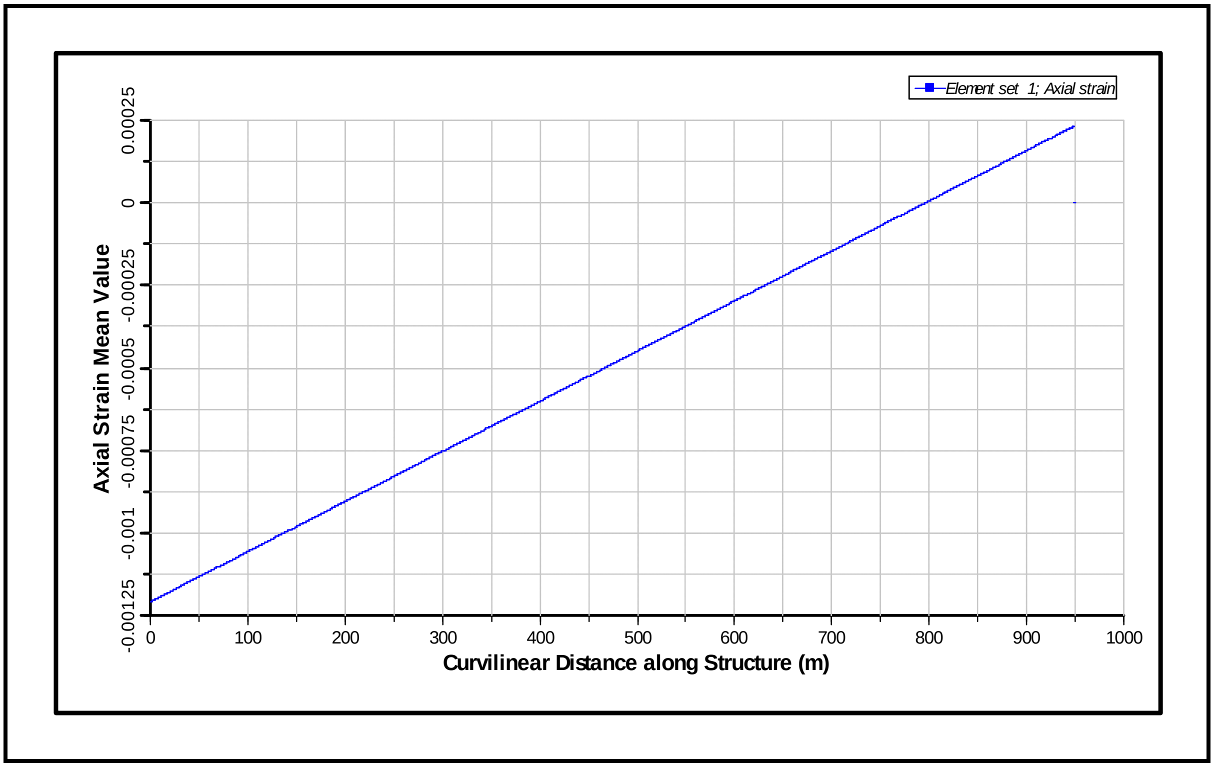


Figure 229: Mean Axial Strain for 1000 m CWP for Bin 11 (from Bottom to Top)

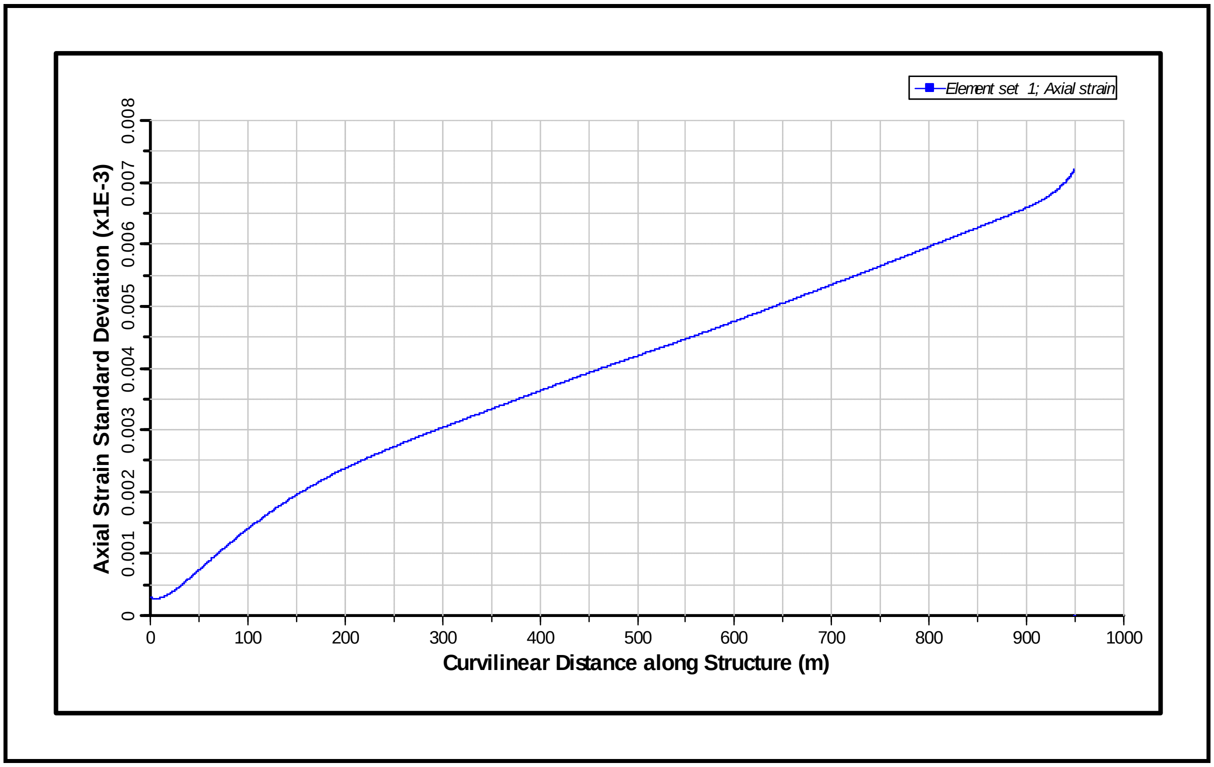


Figure 230: Standard Deviation of Axial Strain for 1000 m CWP for Bin 11 (from Bottom to Top)

6.1 Bin 12

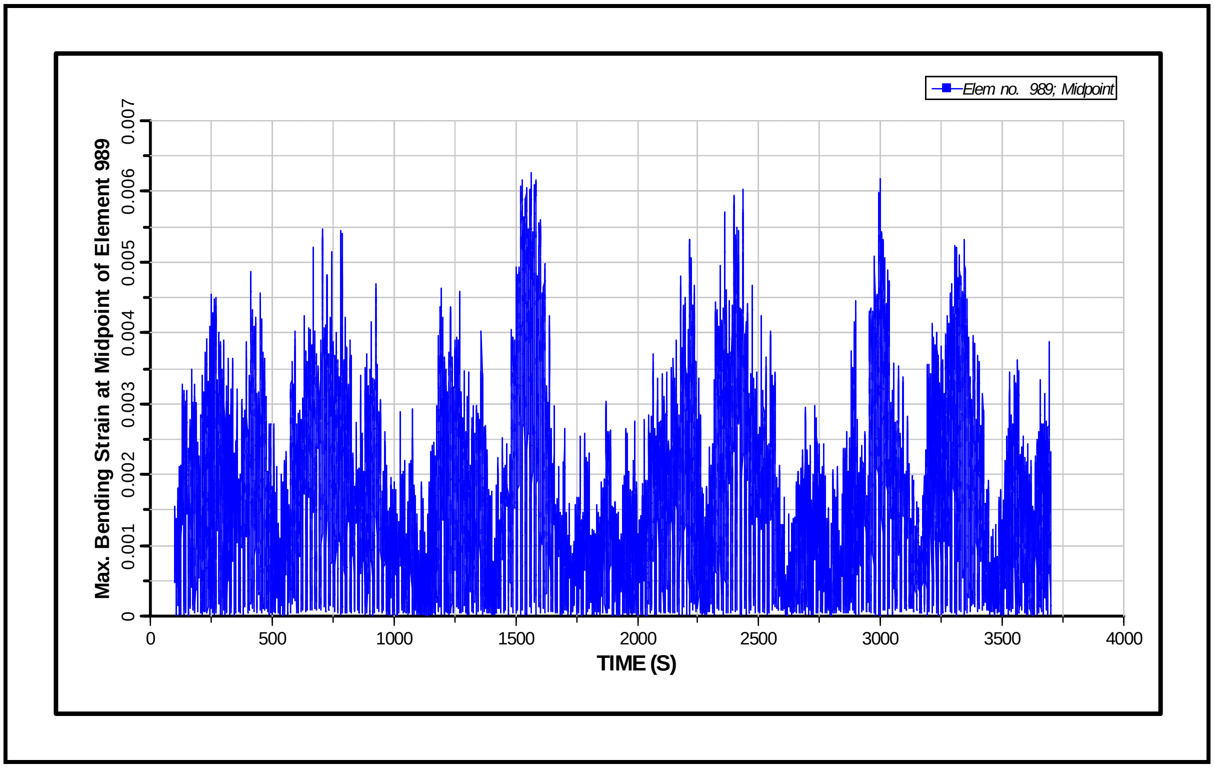


Figure 231: Maximum Bending Strain Time History at Top of CWP for Bin 12

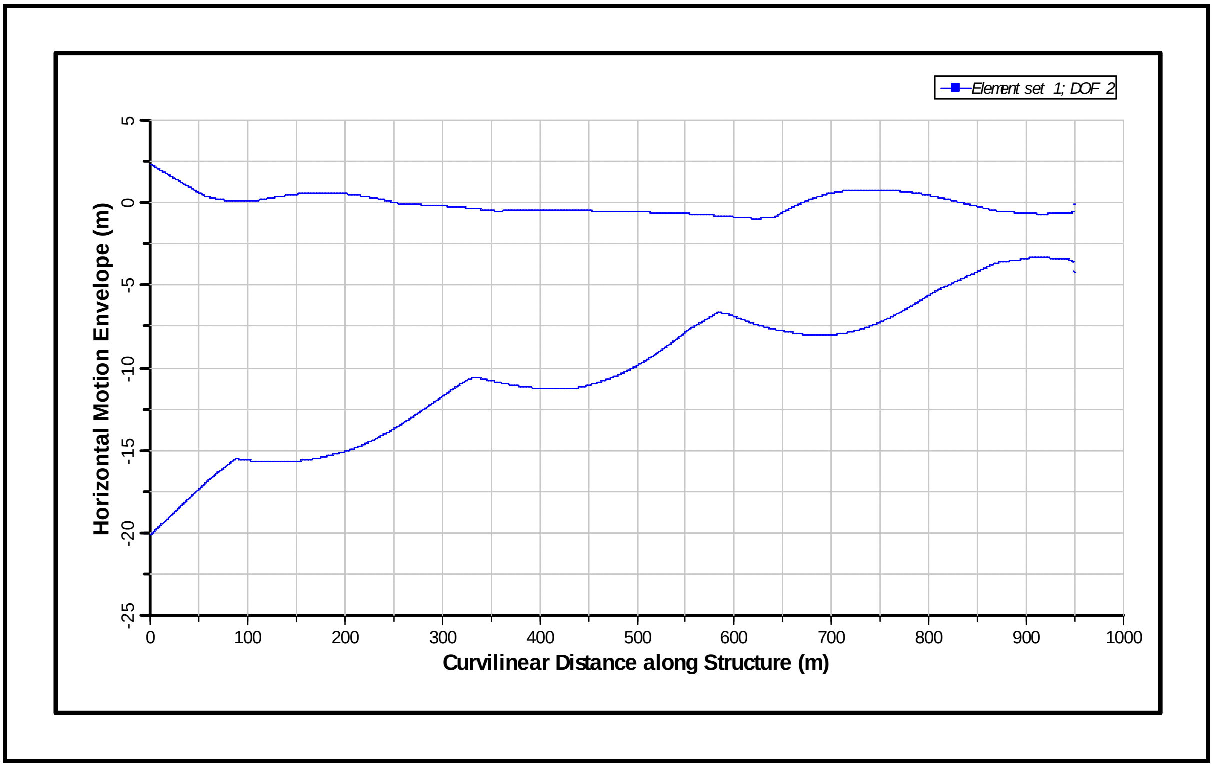


Figure 232: Motion Envelope for 1000 m CWP for Bin 12 (from Bottom to Top)

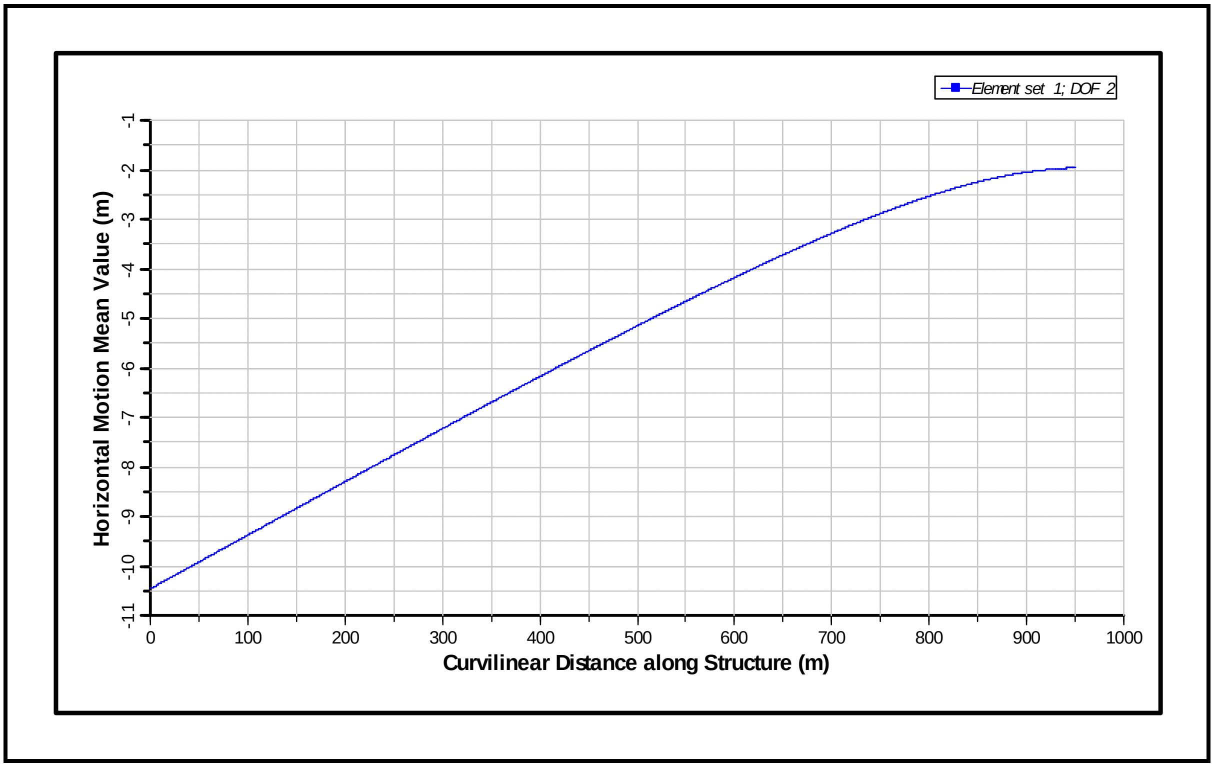


Figure 233: Mean Motion for 1000 m CWP for Bin 12 (from Bottom to Top)

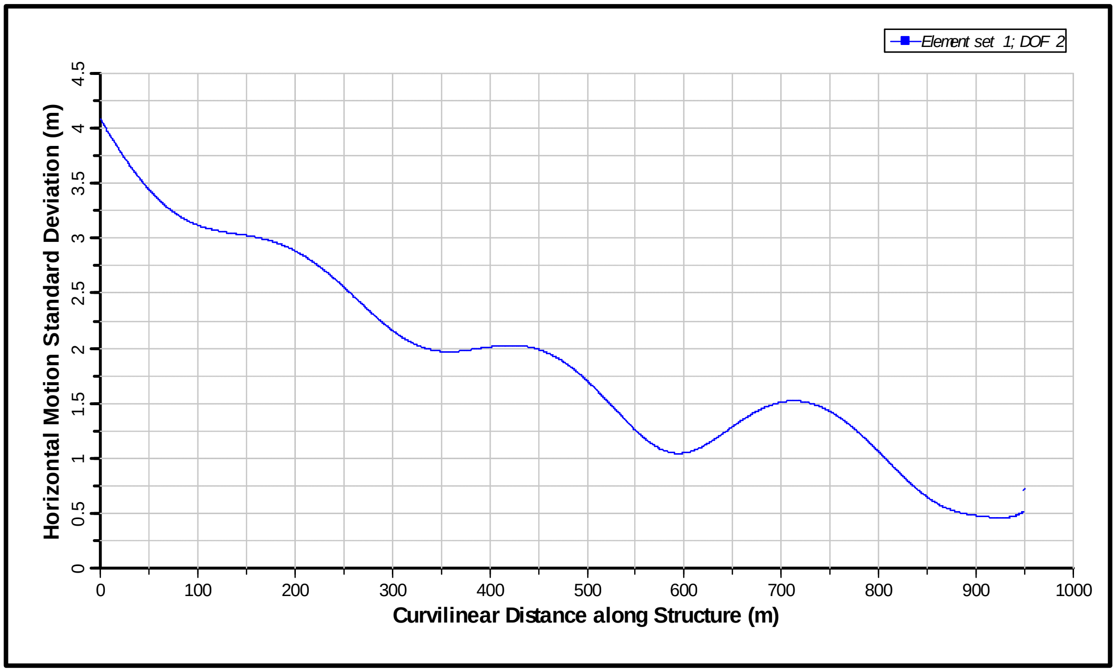


Figure 234: Standard Deviation of Motion for 1000 m CWP for Bin 12 (from Bottom to Top)

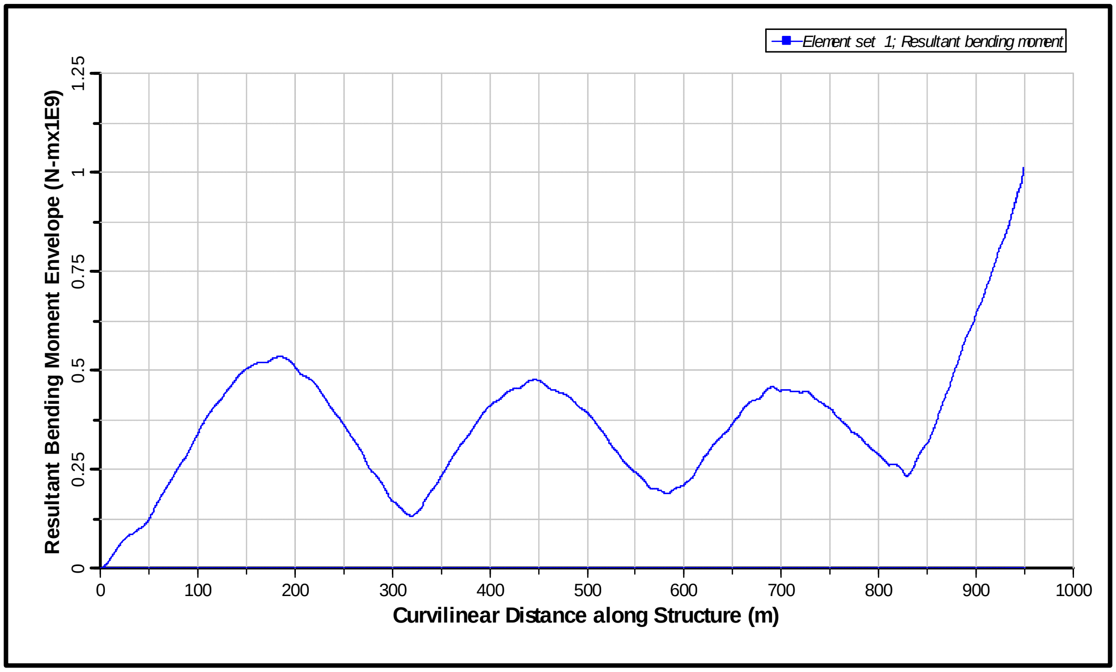


Figure 235: Bending Moment Envelope for 1000 m CWP for Bin 12 (from Bottom to Top)

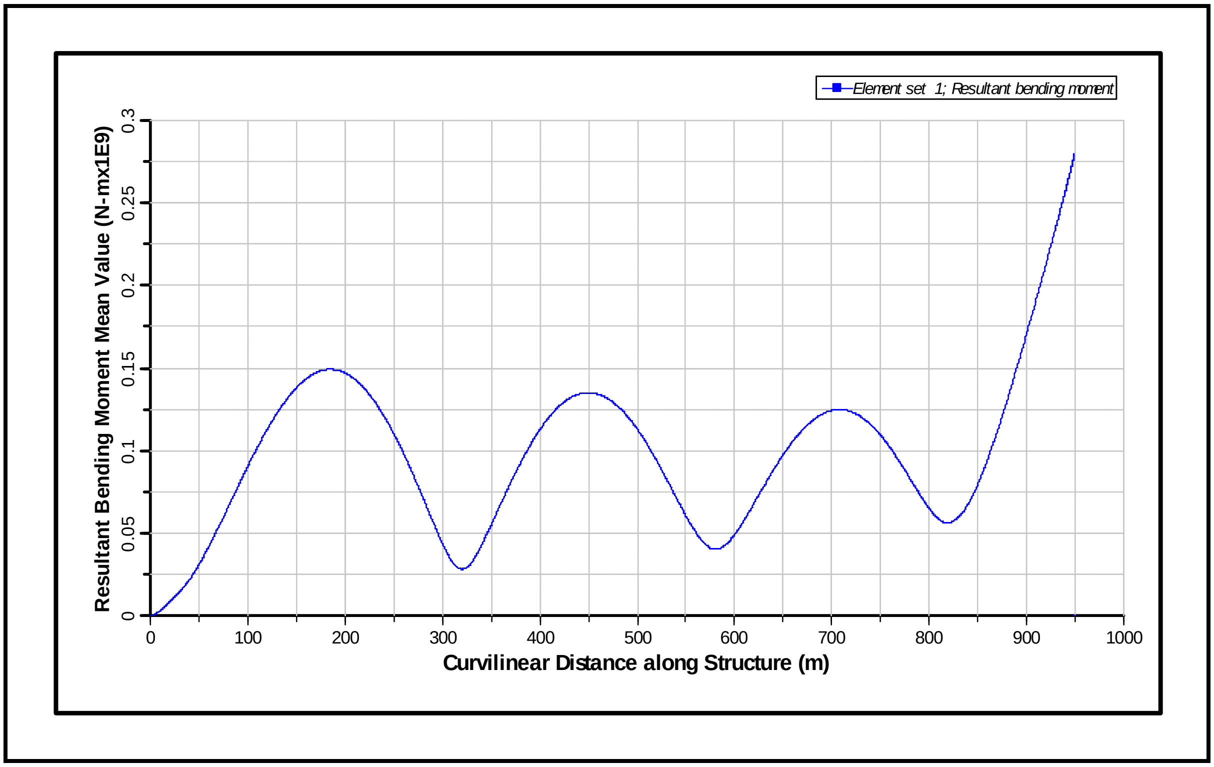


Figure 236: Mean Bending Moment for 1000 m CWP for Bin 12 (from Bottom to Top)

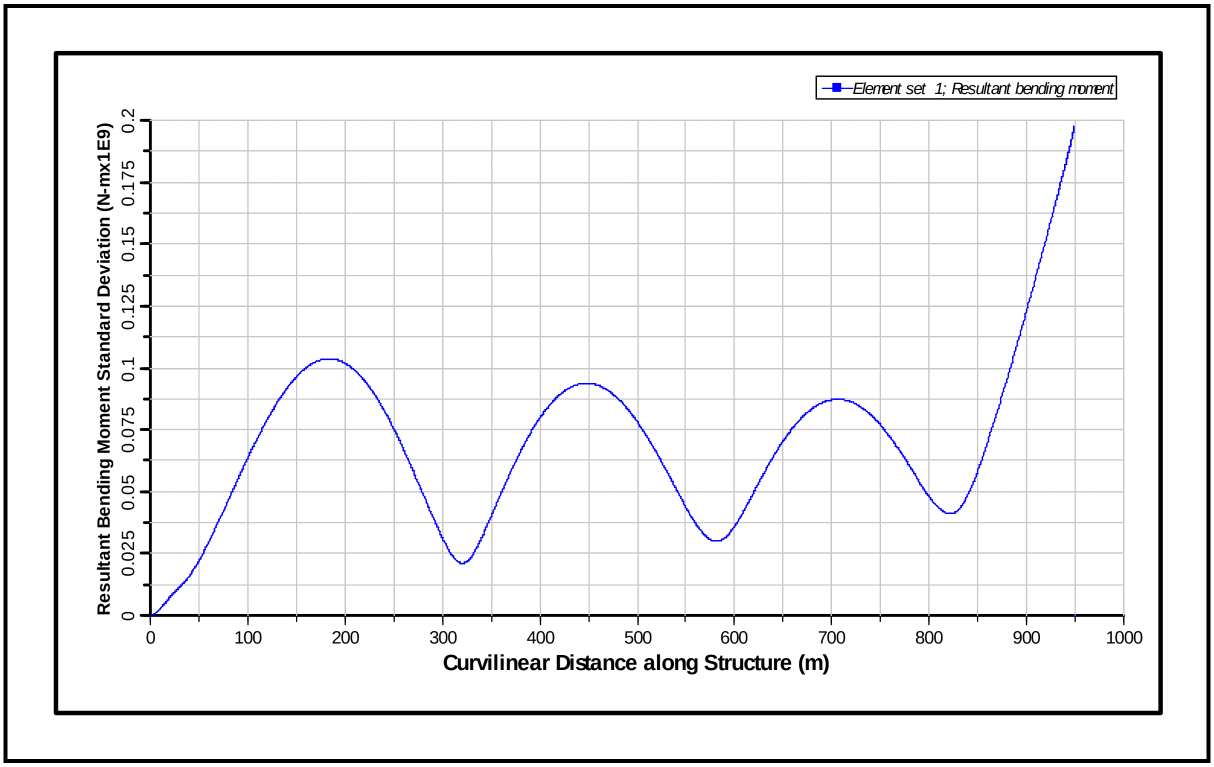


Figure 237: Standard Deviation of Bending Moment for 1000 m CWP for Bin 12 (from Bottom to Top)

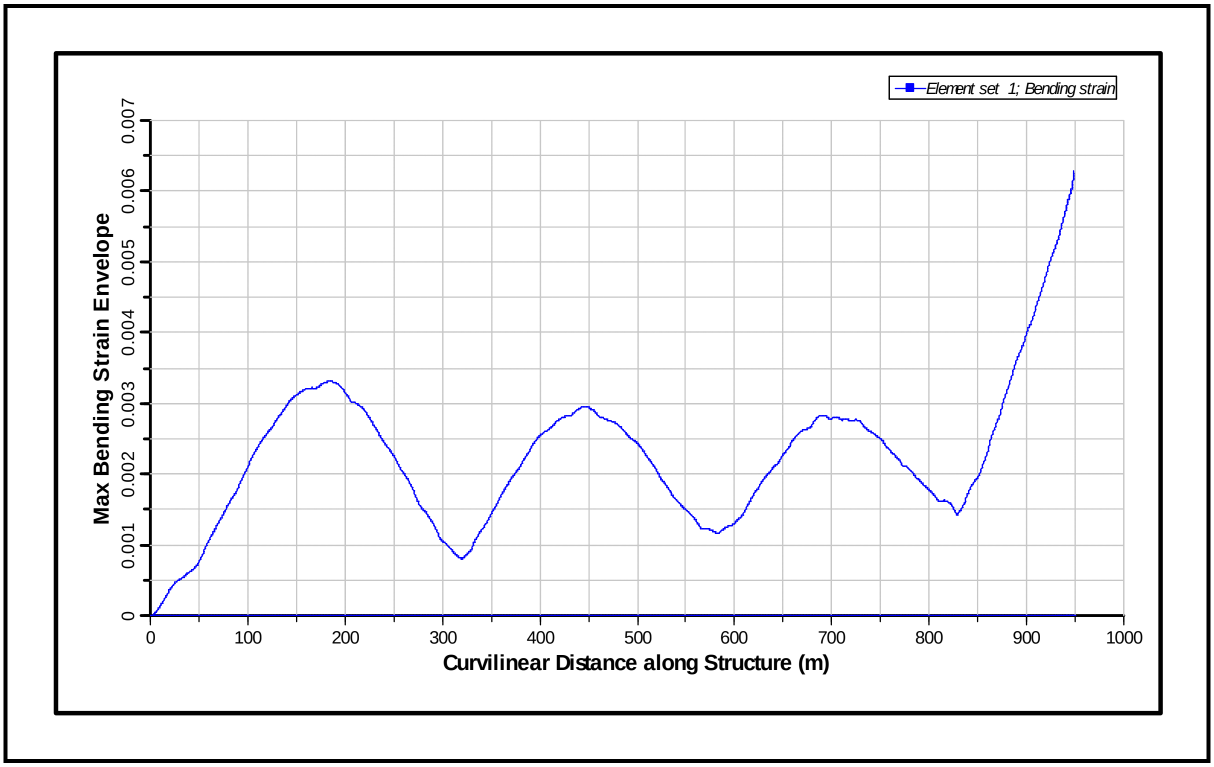


Figure 238: Bending Strain Envelope for 1000 m CWP for Bin 12 (from Bottom to Top)

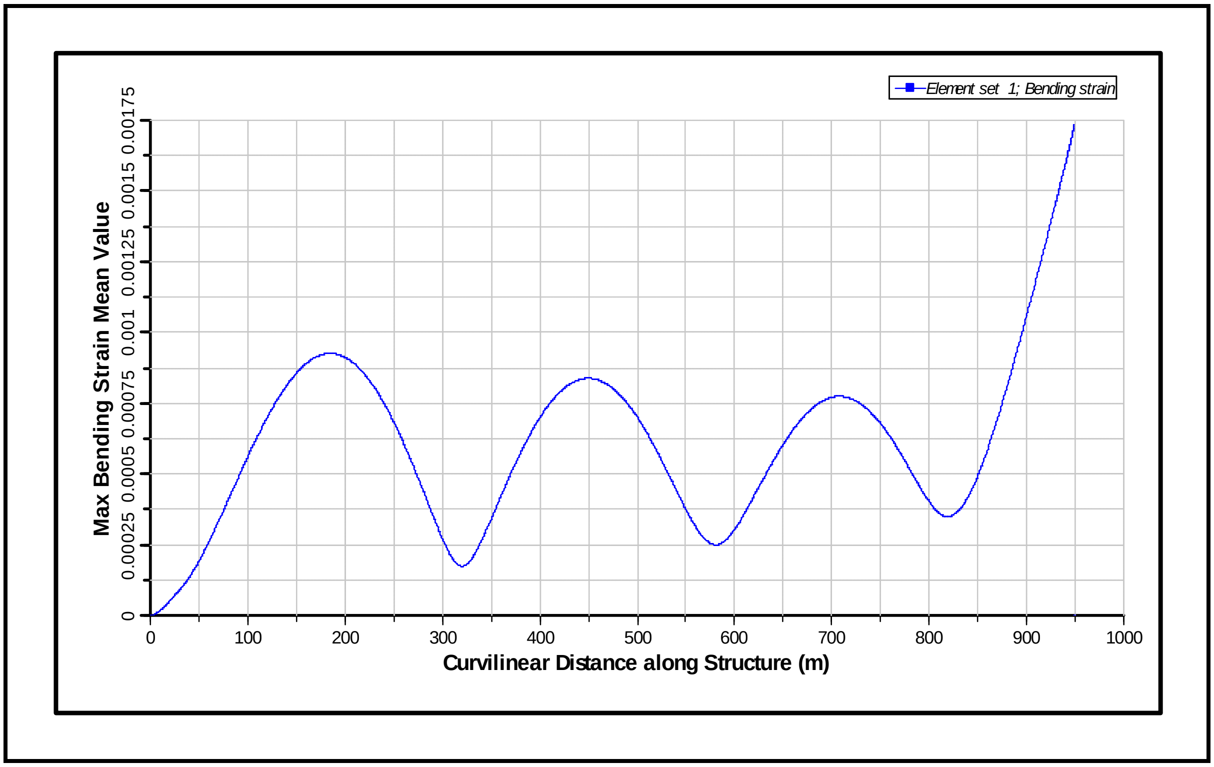


Figure 239: Mean Bending Strain for 1000 m CWP for Bin 12 (from Bottom to Top)

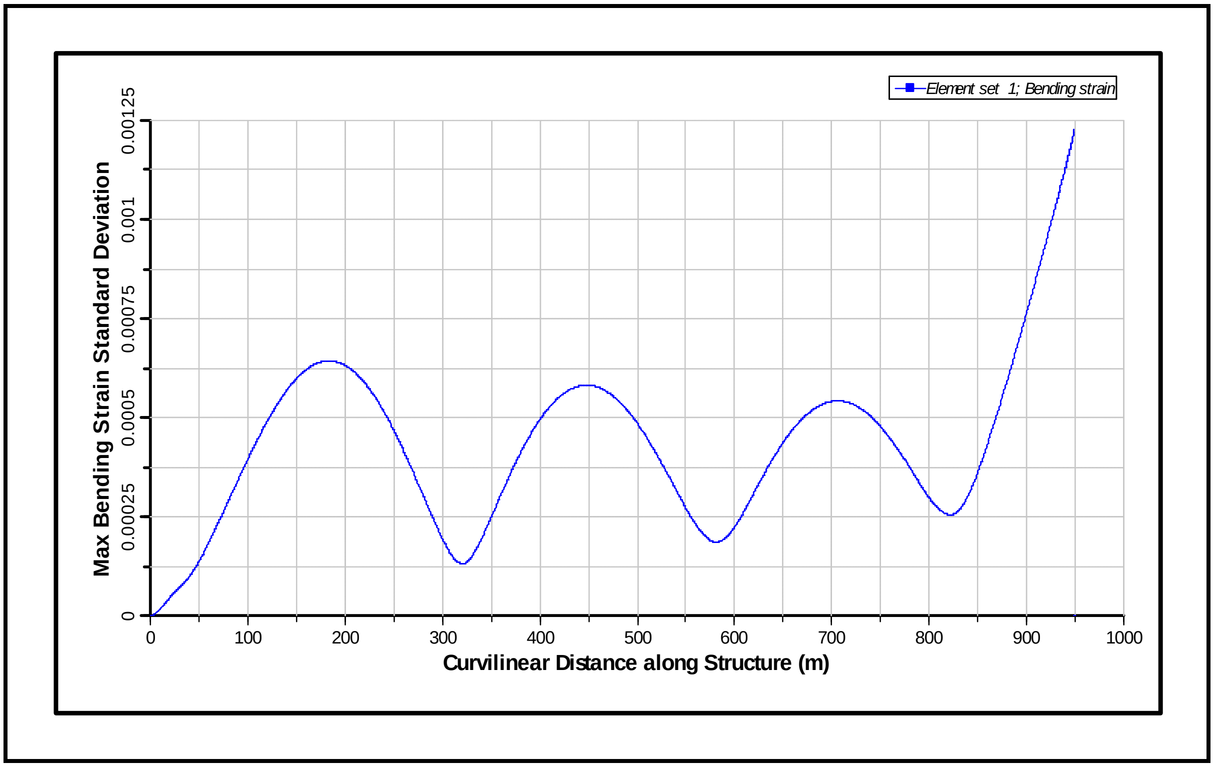


Figure 240: Standard Deviation of Bending Strain for 1000 m CWP for Bin 12 (from Bottom to Top)

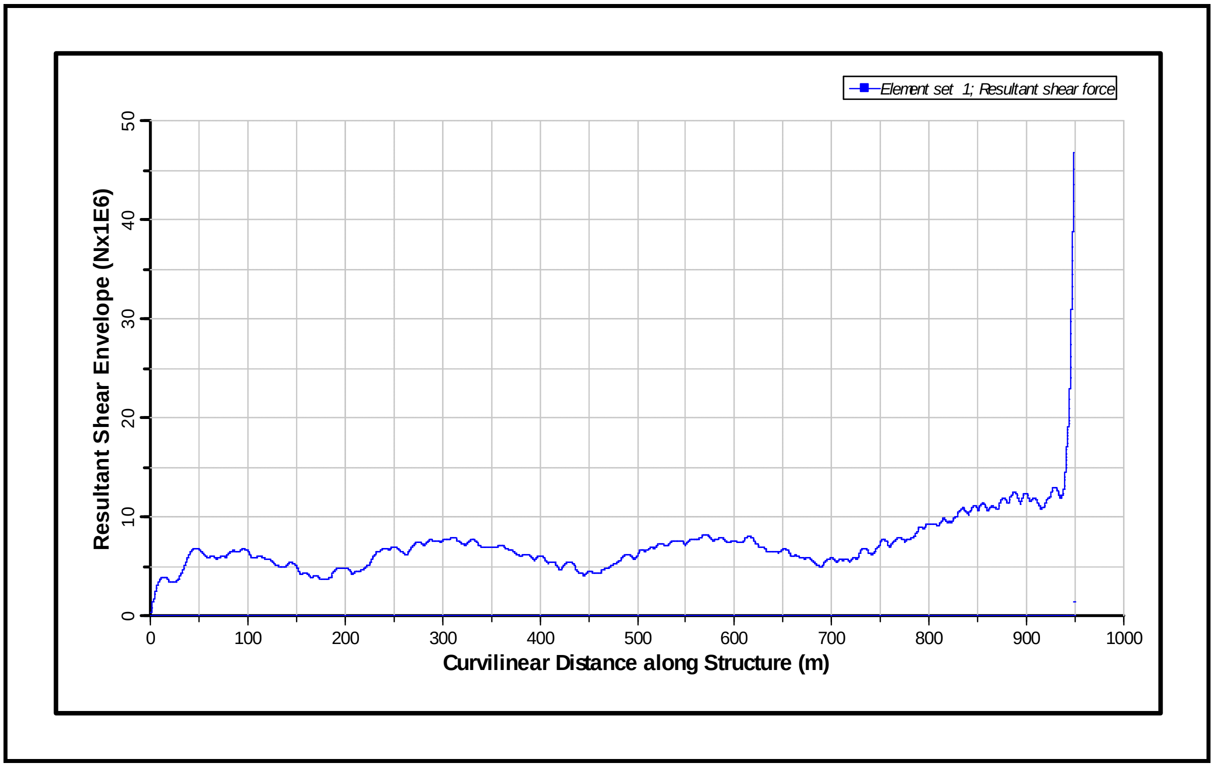


Figure 241: Shear Force Envelope for 1000 m CWP for Bin 12 (from Bottom to Top)

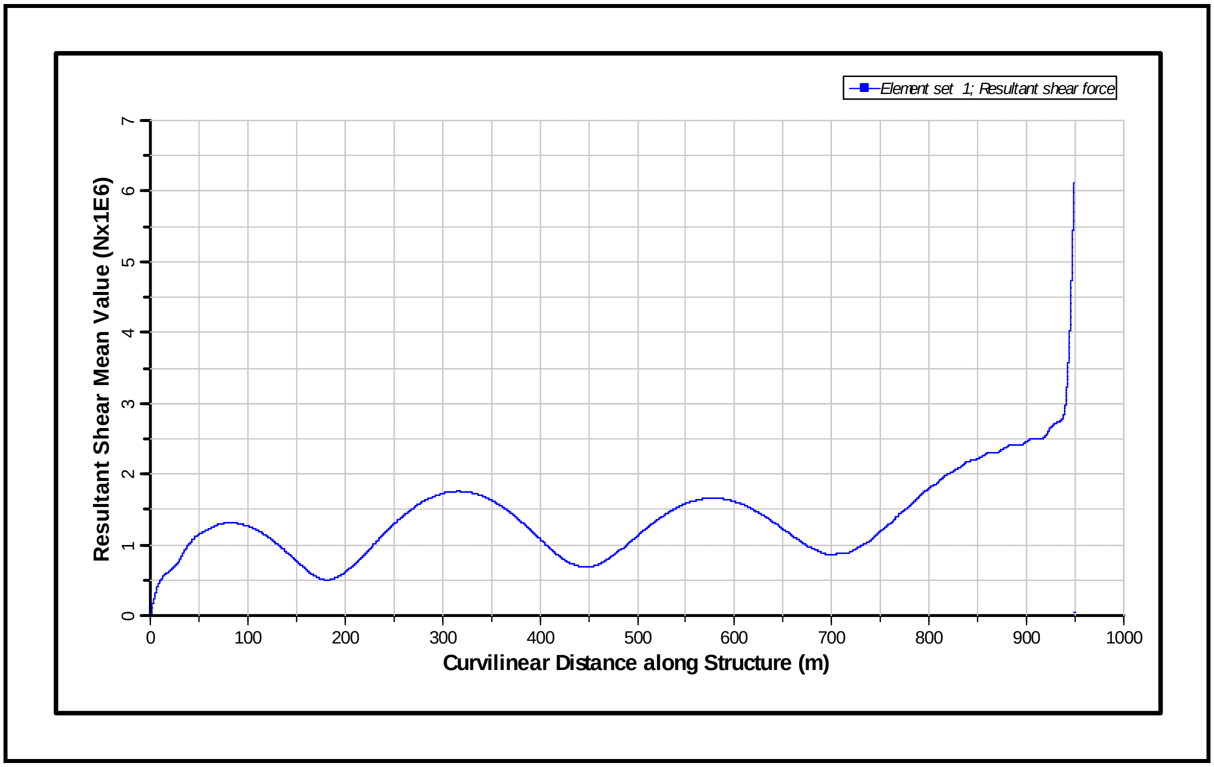


Figure 242: Mean Shear Force for 1000 m CWP for Bin 12 (from Bottom to Top)

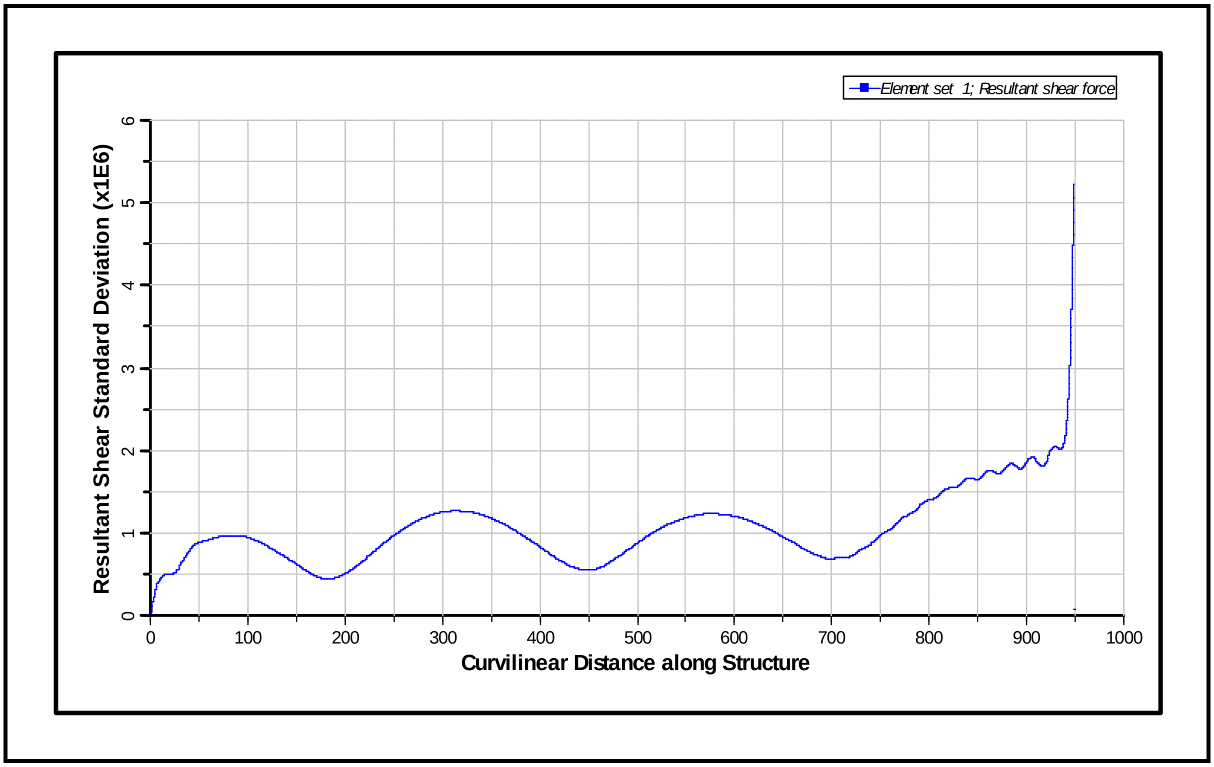


Figure 243: Standard Deviation of Shear Force for 1000 m CWP for Bin 12 (from Bottom to Top)

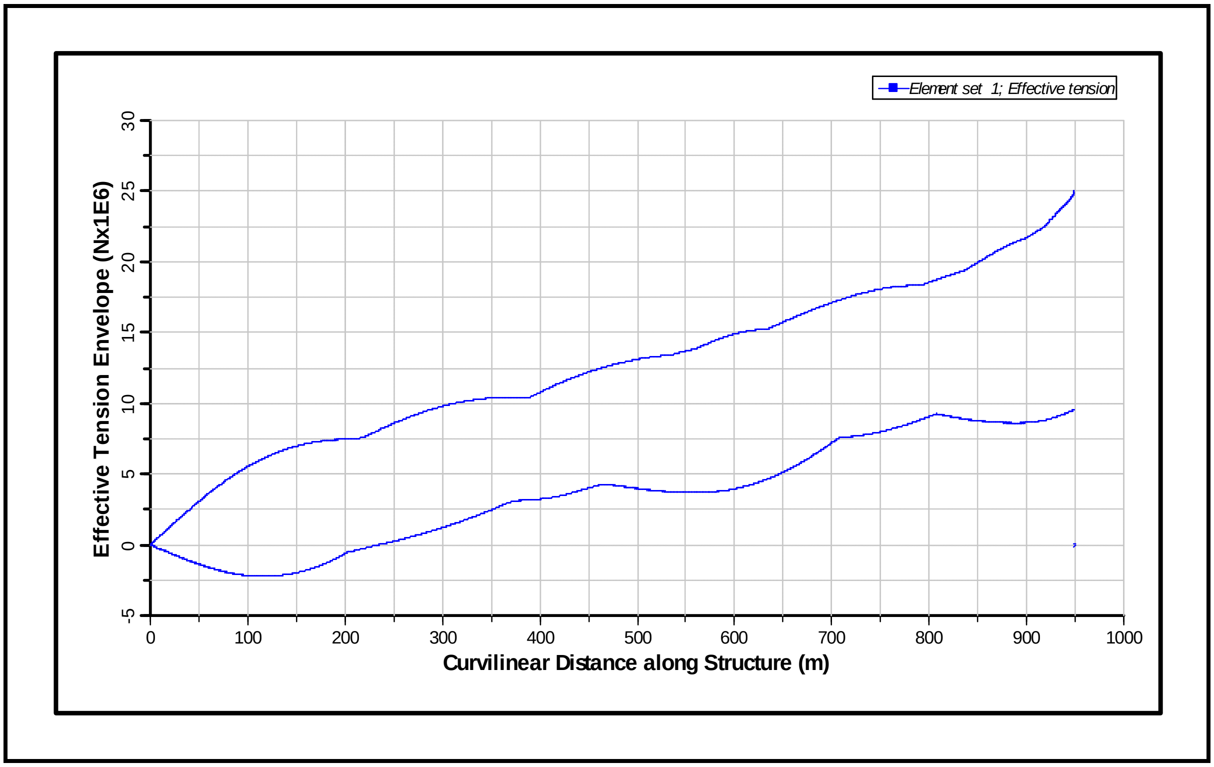


Figure 244: Axial Tension Envelope for 1000 m CWP for Bin 12 (from Bottom to Top)

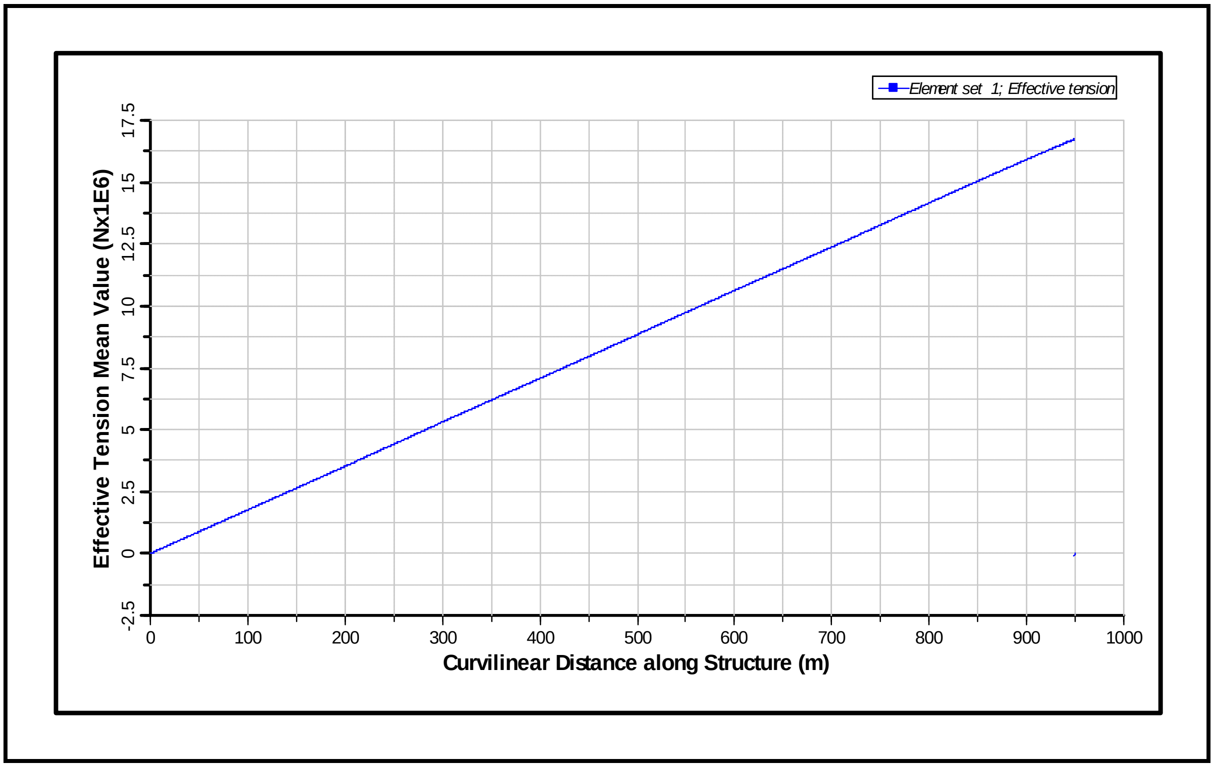


Figure 245: Mean Axial Tension for 1000 m CWP for Bin 12 (from Bottom to Top)

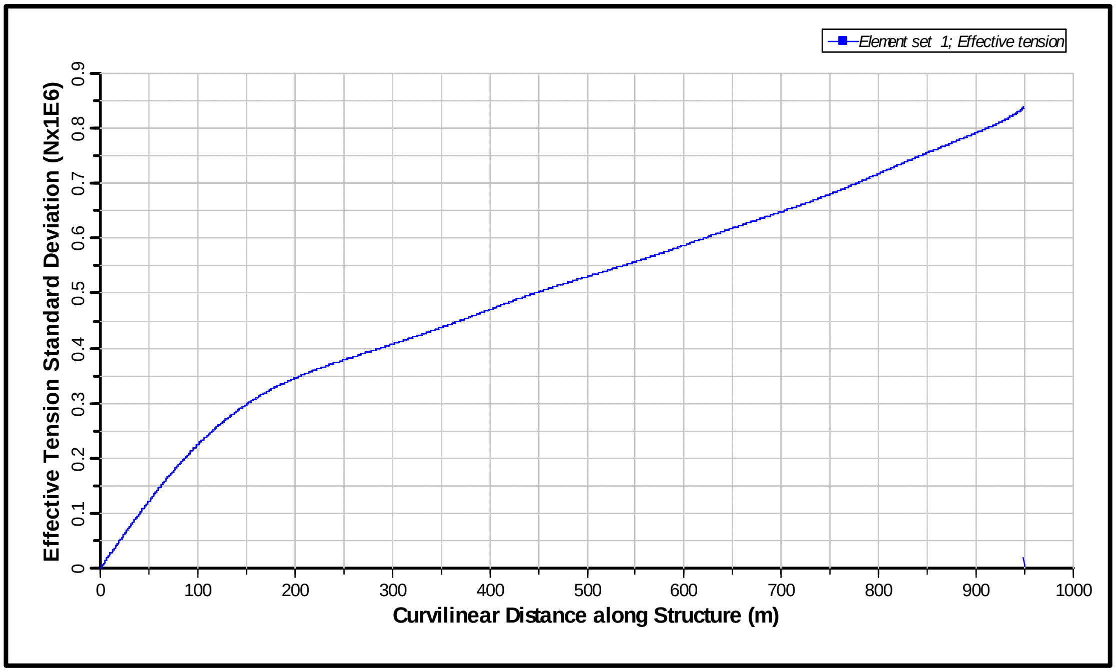


Figure 246: Standard Deviation of Axial Tension for 1000 m CWP for Bin 12 (from Bottom to Top)

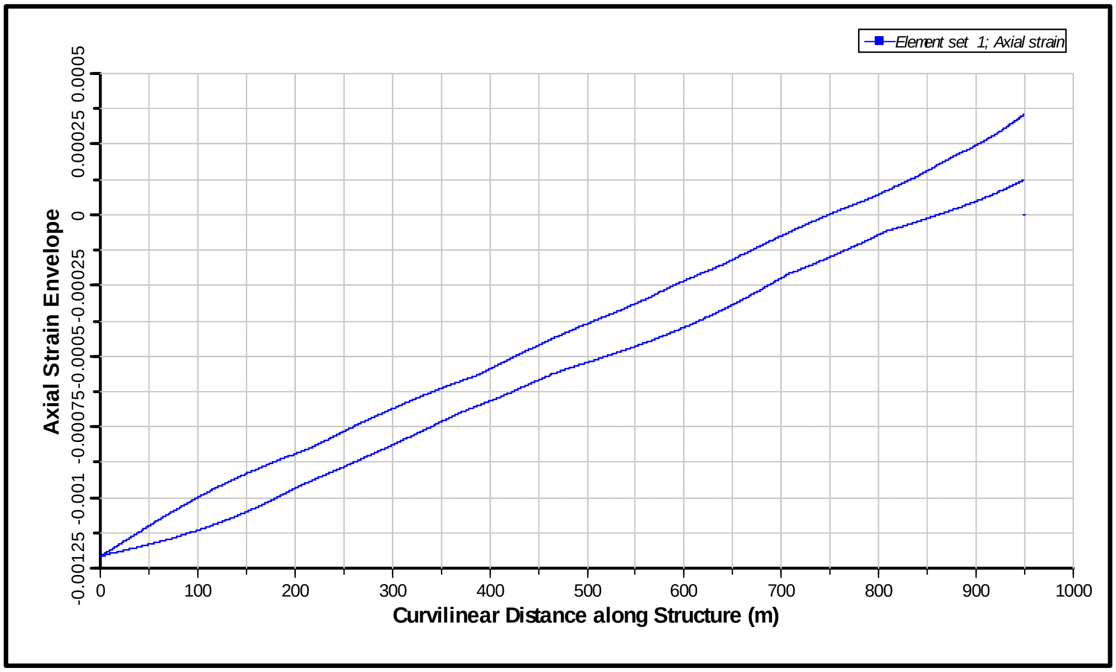


Figure 247: Axial Strain Envelope for 1000 m CWP for Bin 12 (from Bottom to Top)

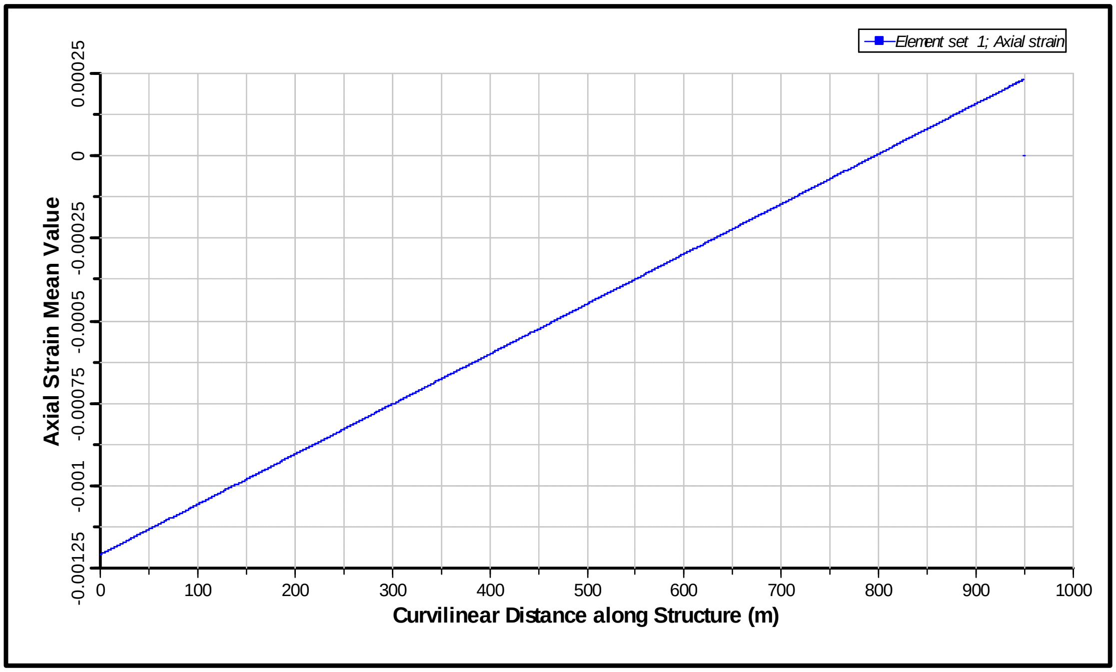


Figure 248: Mean Axial Strain for 1000 m CWP for Bin 12 (from Bottom to Top)

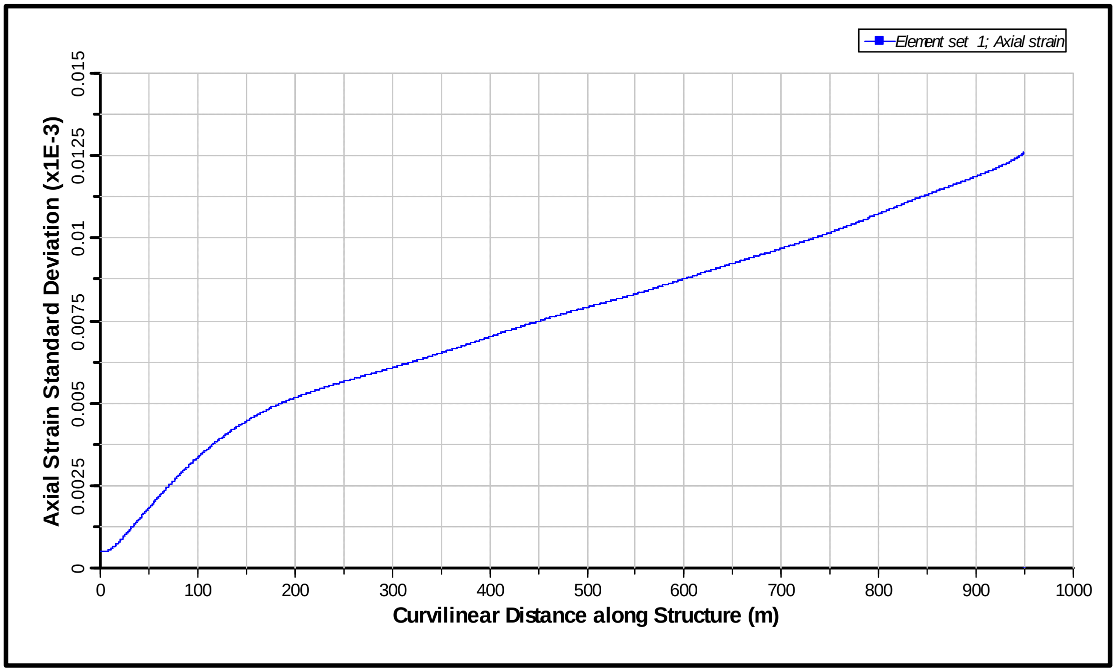


Figure 249: Standard Deviation of Axial Strain for 1000 m CWP for Bin 12 (from Bottom to Top)

6.1 Bin 13

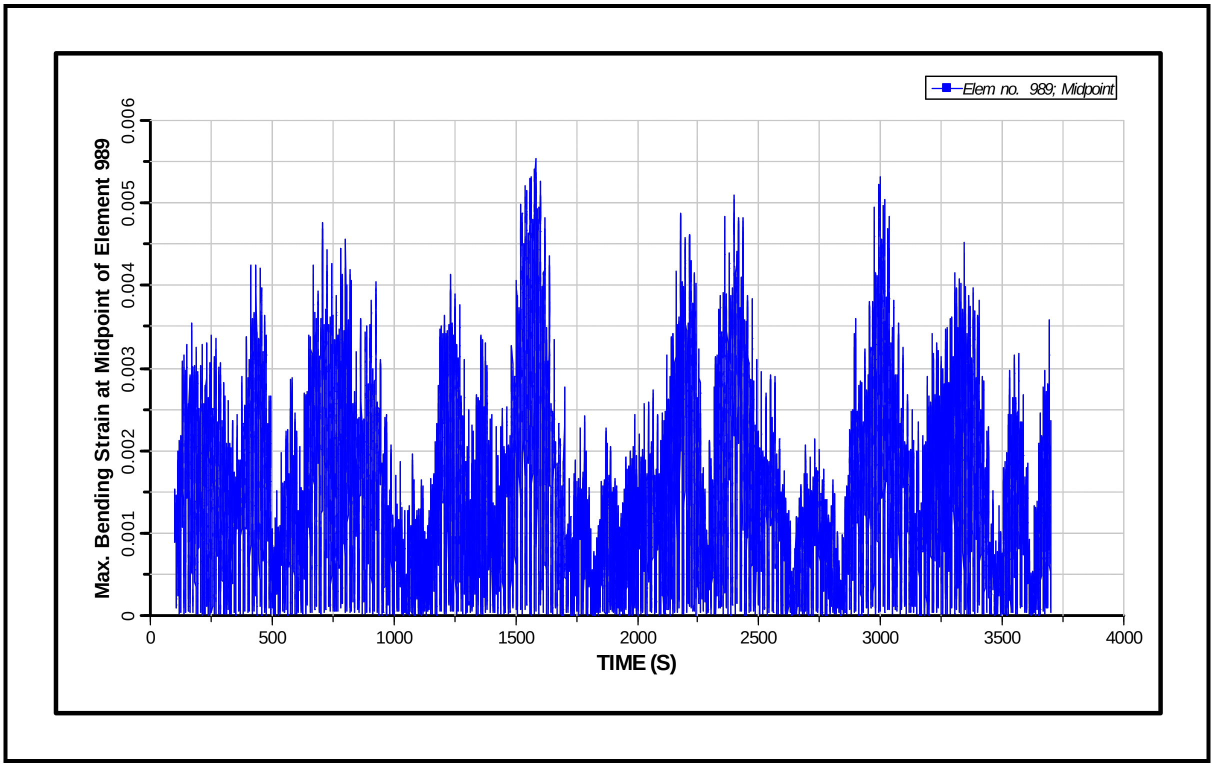


Figure 250: Maximum Bending Strain Time History at Top of CWP for Bin 13

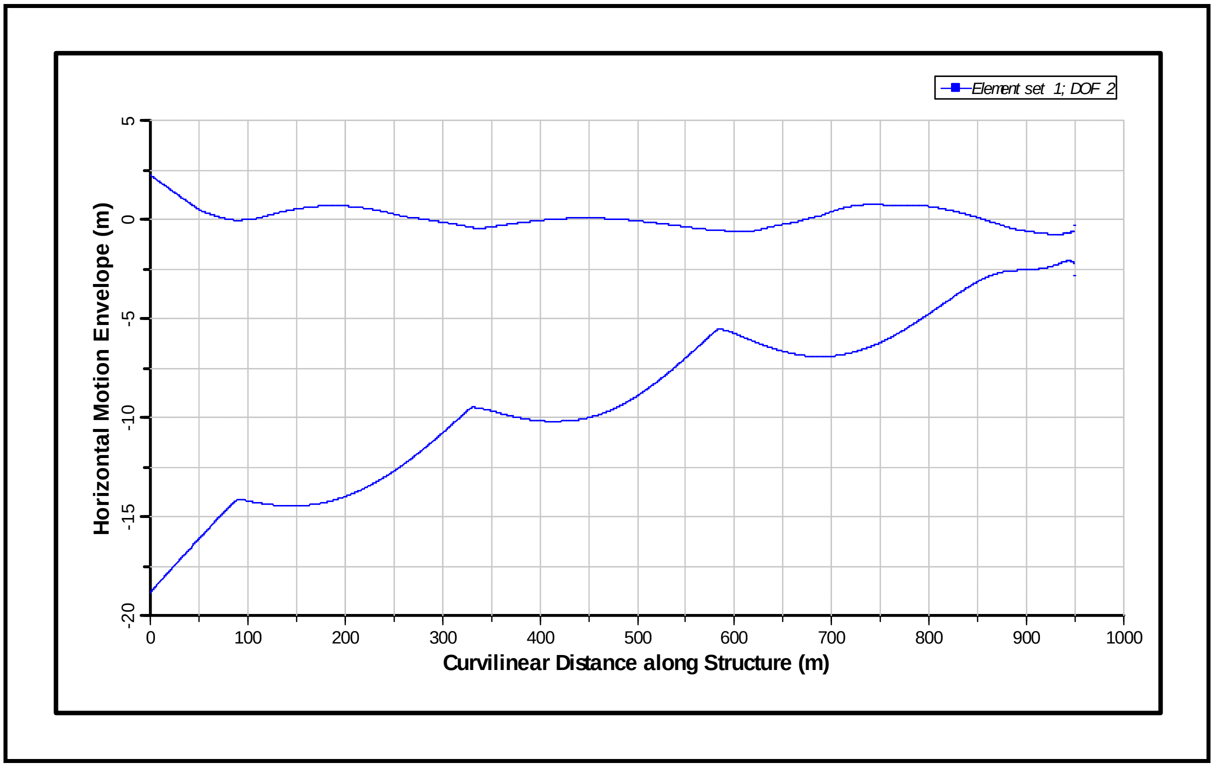


Figure 251: Motion Envelope for 1000 m CWP for Bin 13 (from Bottom to Top)

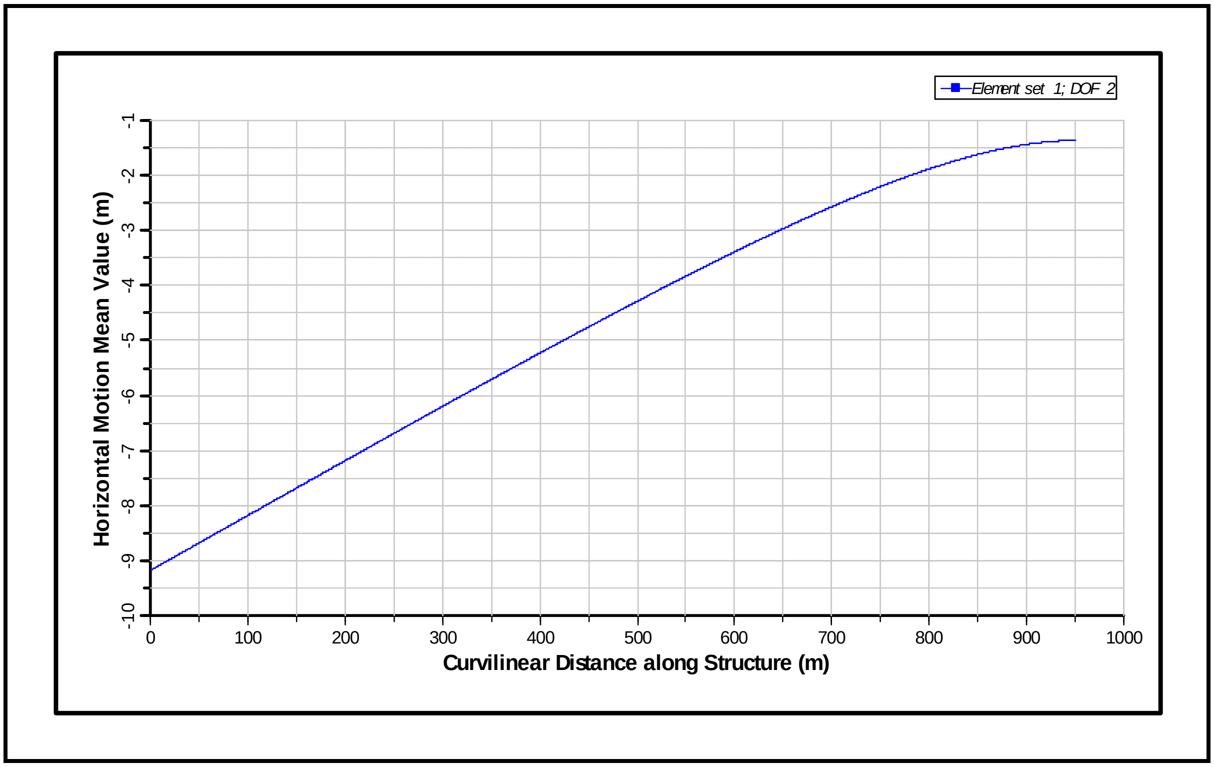


Figure 252: Mean Motion for 1000 m CWP for Bin 13 (from Bottom to Top)

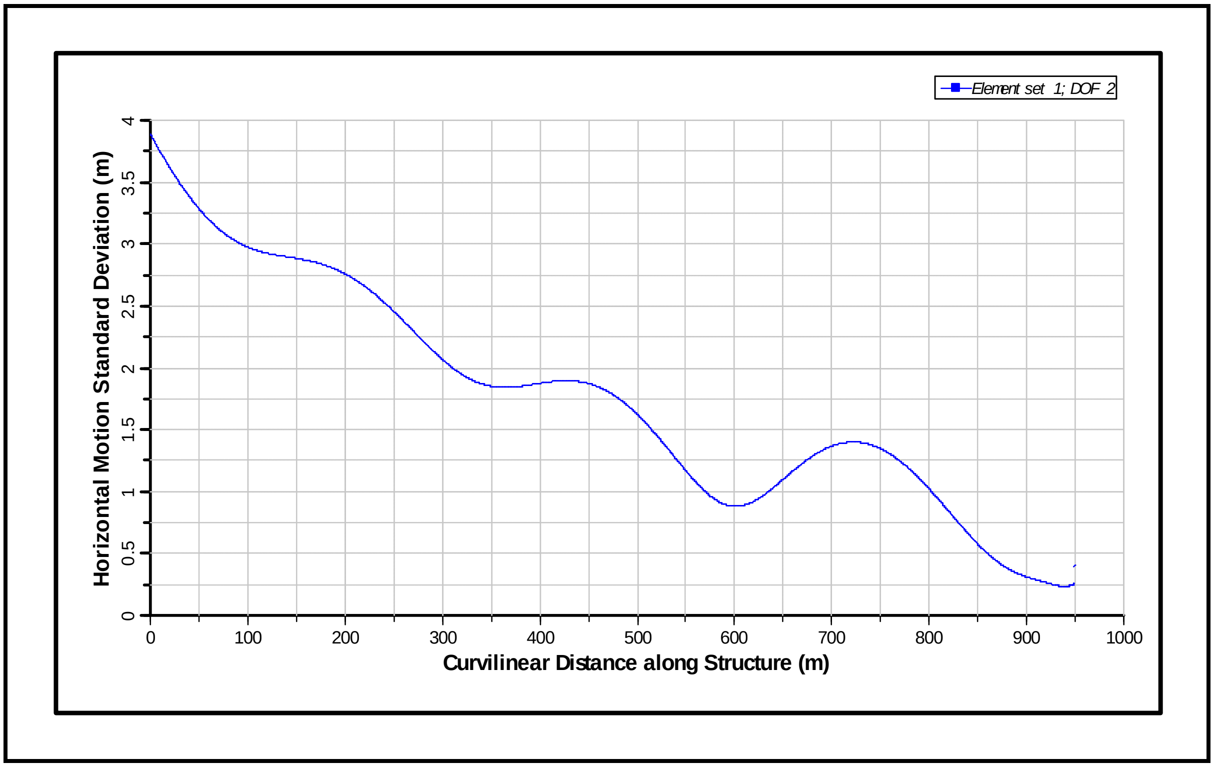


Figure 253: Standard Deviation of Motion for 1000 m CWP for Bin 13 (from Bottom to Top)

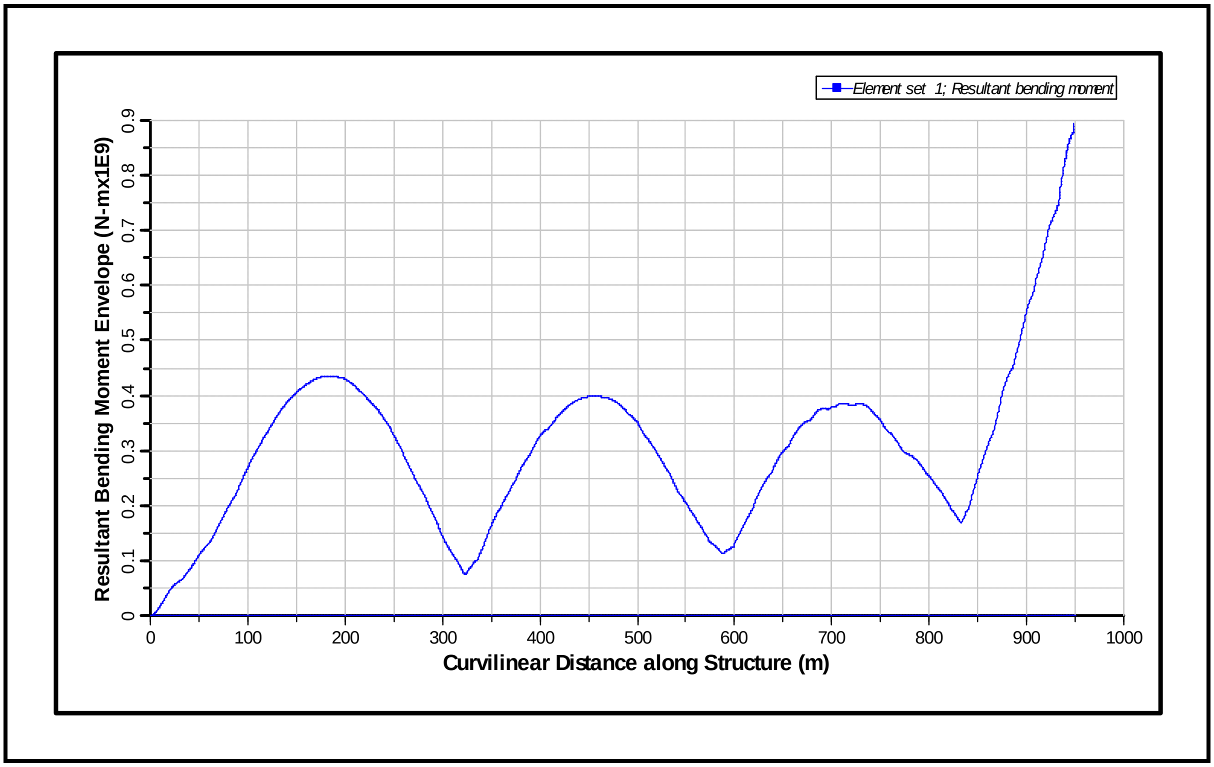


Figure 254: Bending Moment Envelope for 1000 m CWP for Bin 13 (from Bottom to Top)

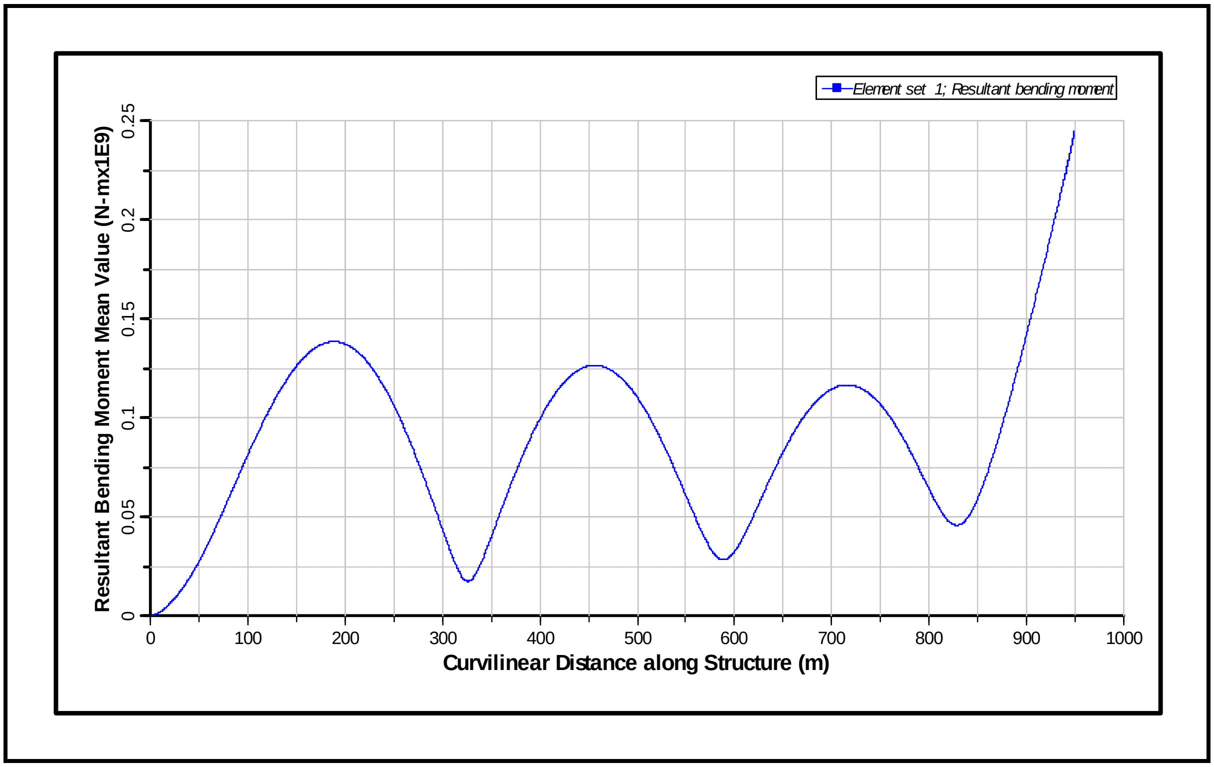


Figure 255: Mean Bending Moment for 1000 m CWP for Bin 13 (from Bottom to Top)

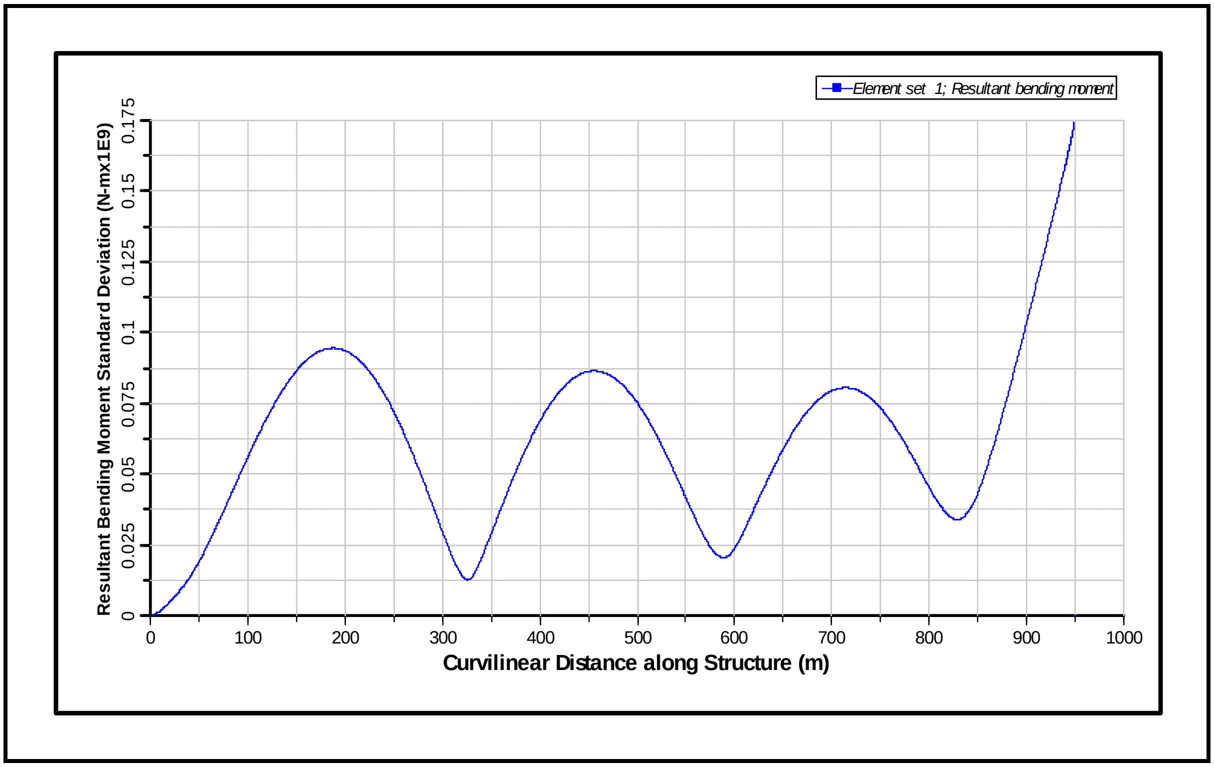


Figure 256: Standard Deviation of Bending Moment for 1000 m CWP for Bin 13 (from Bottom to Top)

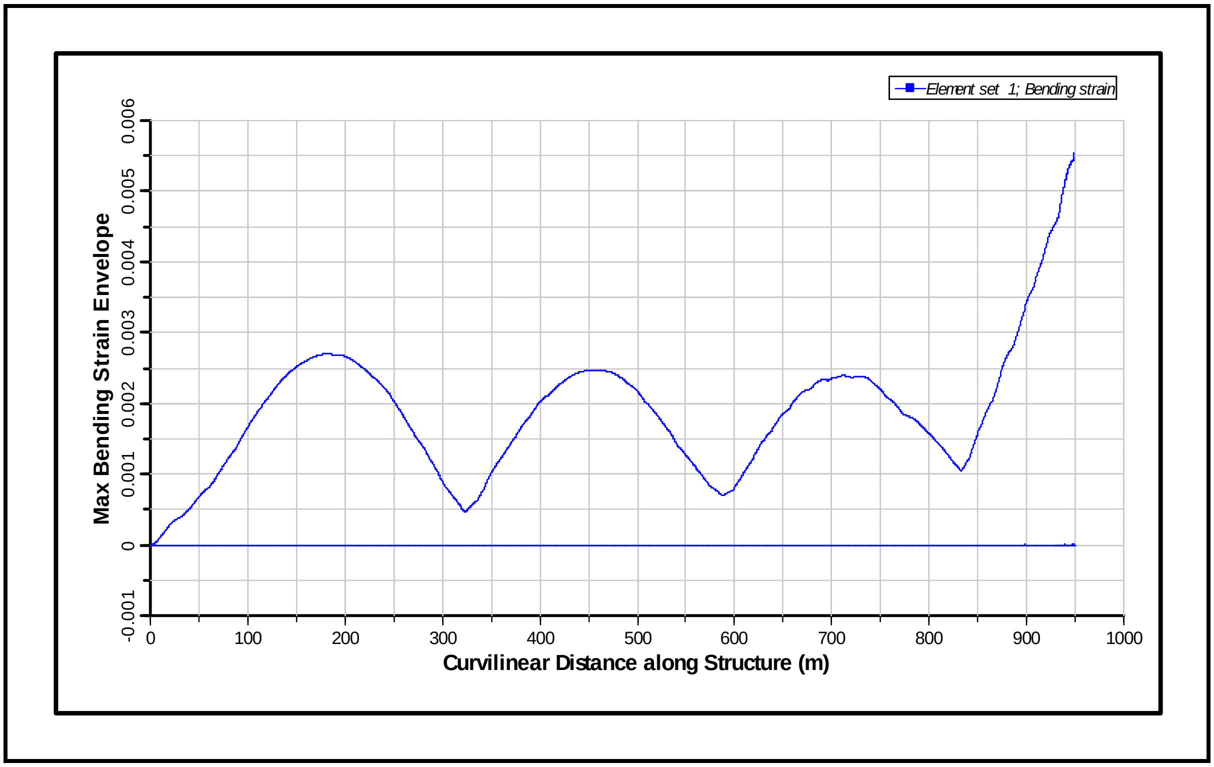


Figure 257: Bending Strain Envelope for 1000 m CWP for Bin 13 (from Bottom to Top)

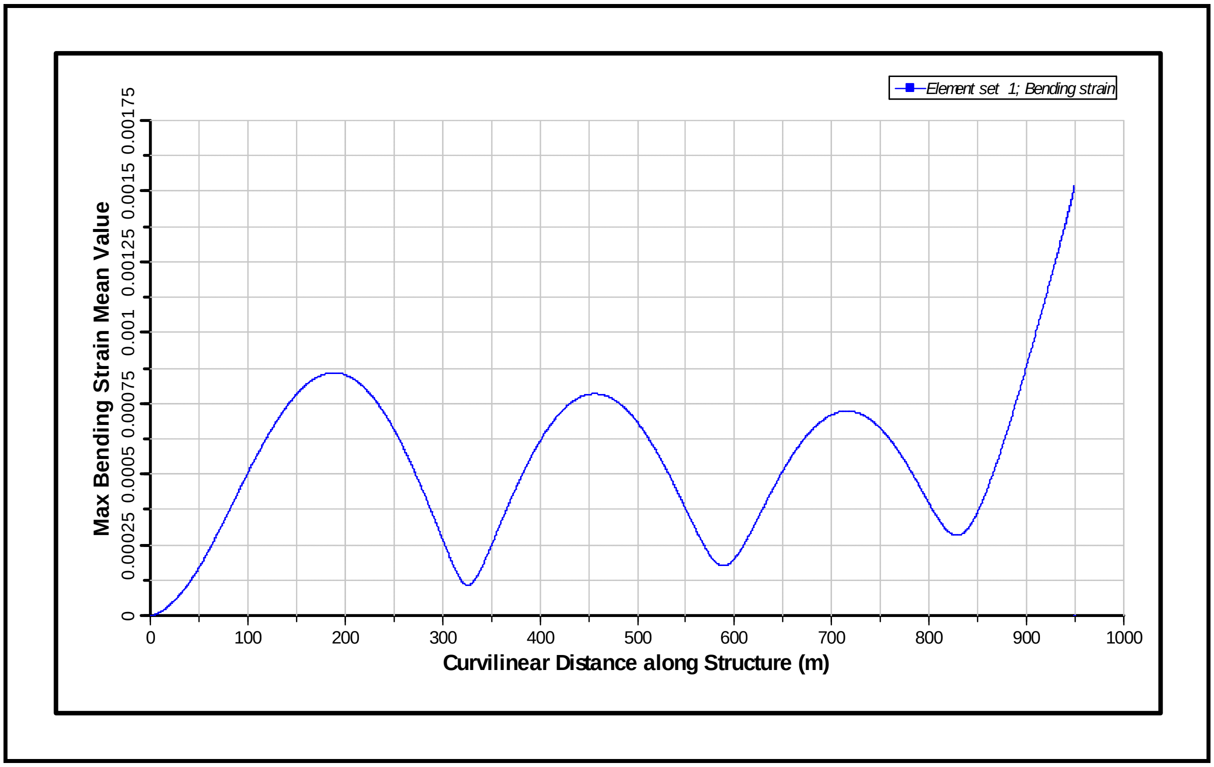


Figure 258: Mean Bending Strain for 1000 m CWP for Bin 13 (from Bottom to Top)

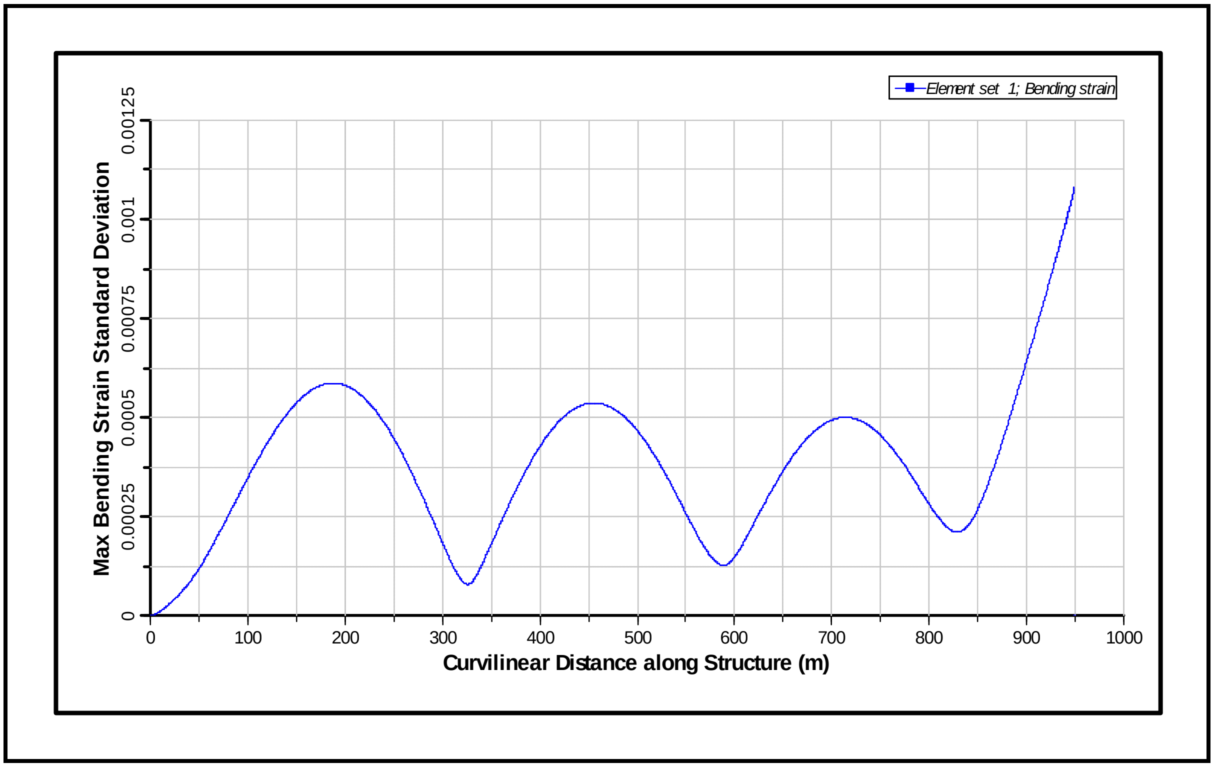


Figure 259: Standard Deviation of Bending Strain for 1000 m CWP for Bin 13 (from Bottom to Top)

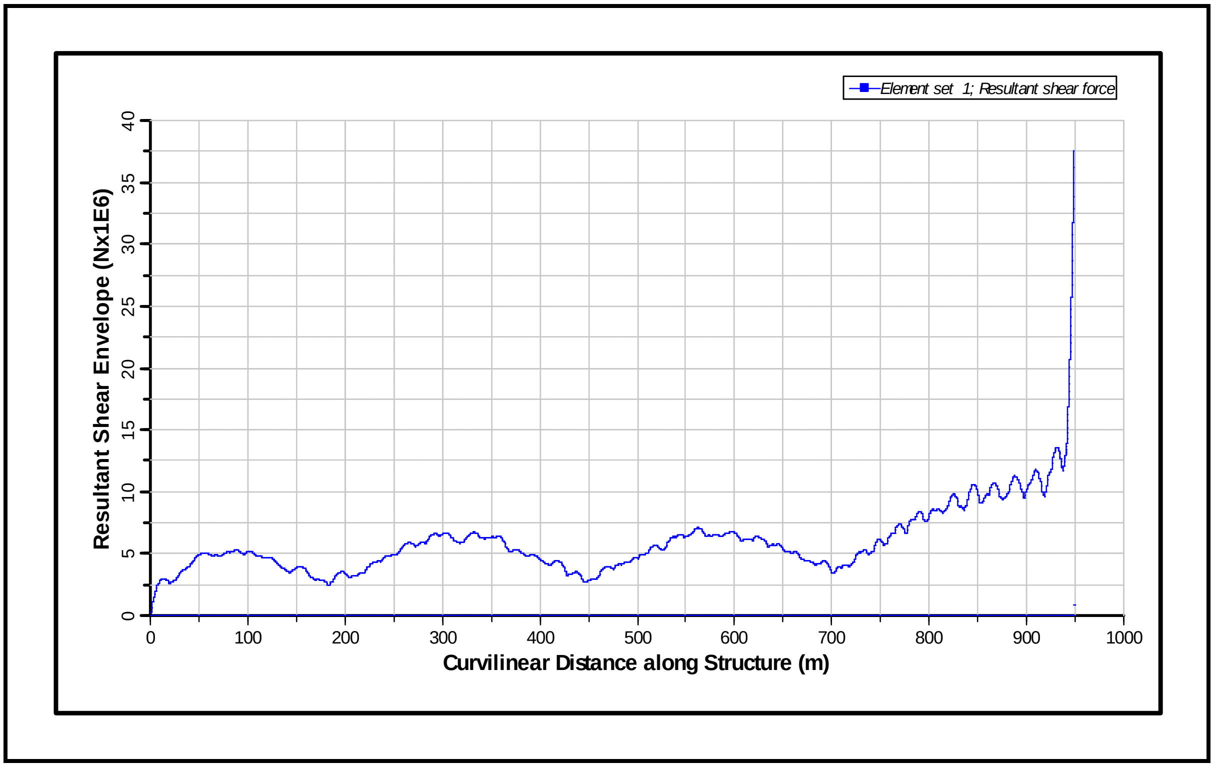


Figure 260: Shear Force Envelope for 1000 m CWP for Bin 13 (from Bottom to Top)

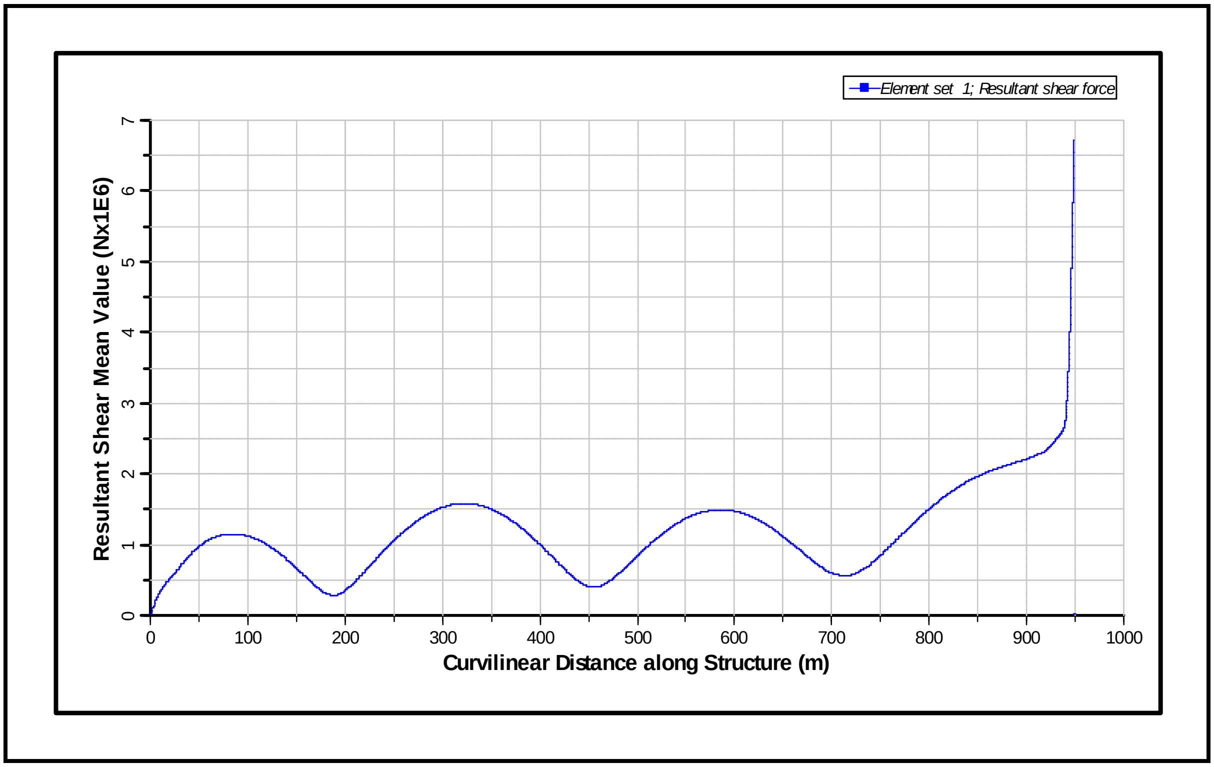


Figure 261: Mean Shear Force for 1000 m CWP for Bin 13 (from Bottom to Top)

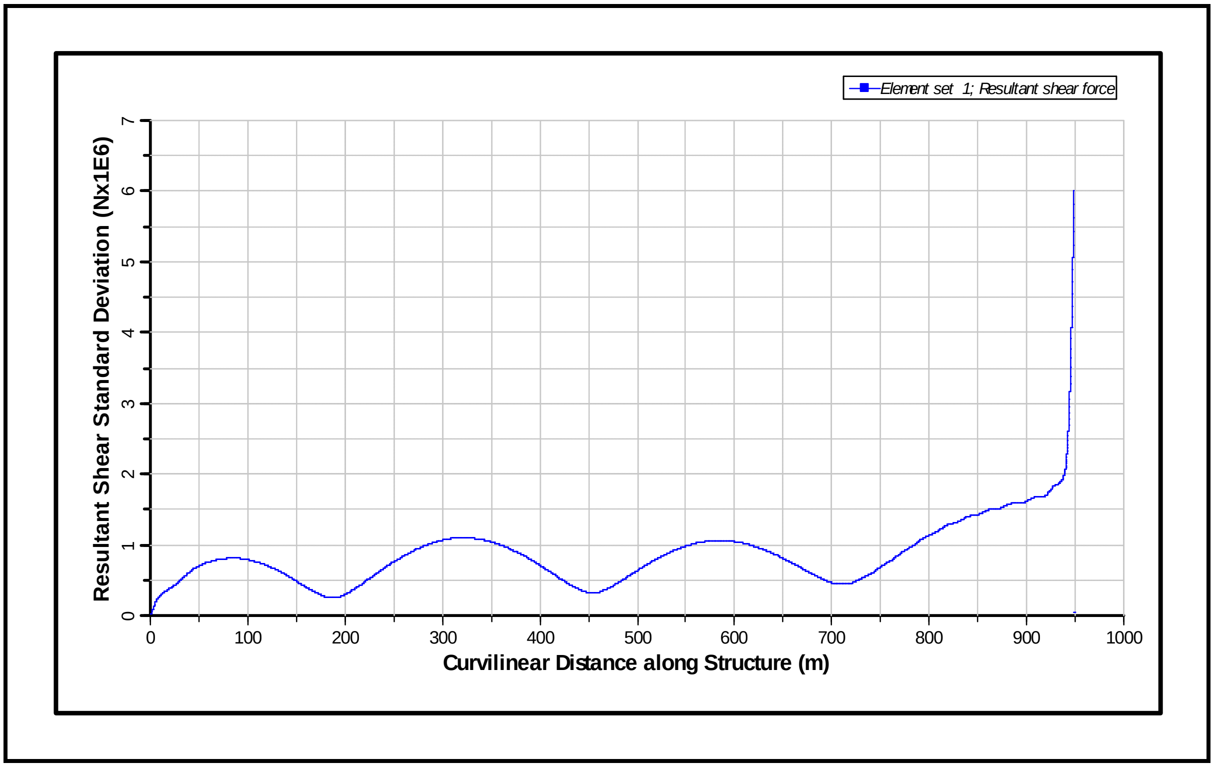


Figure 262: Standard Deviation of Shear Force for 1000 m CWP for Bin 13 (from Bottom to Top)

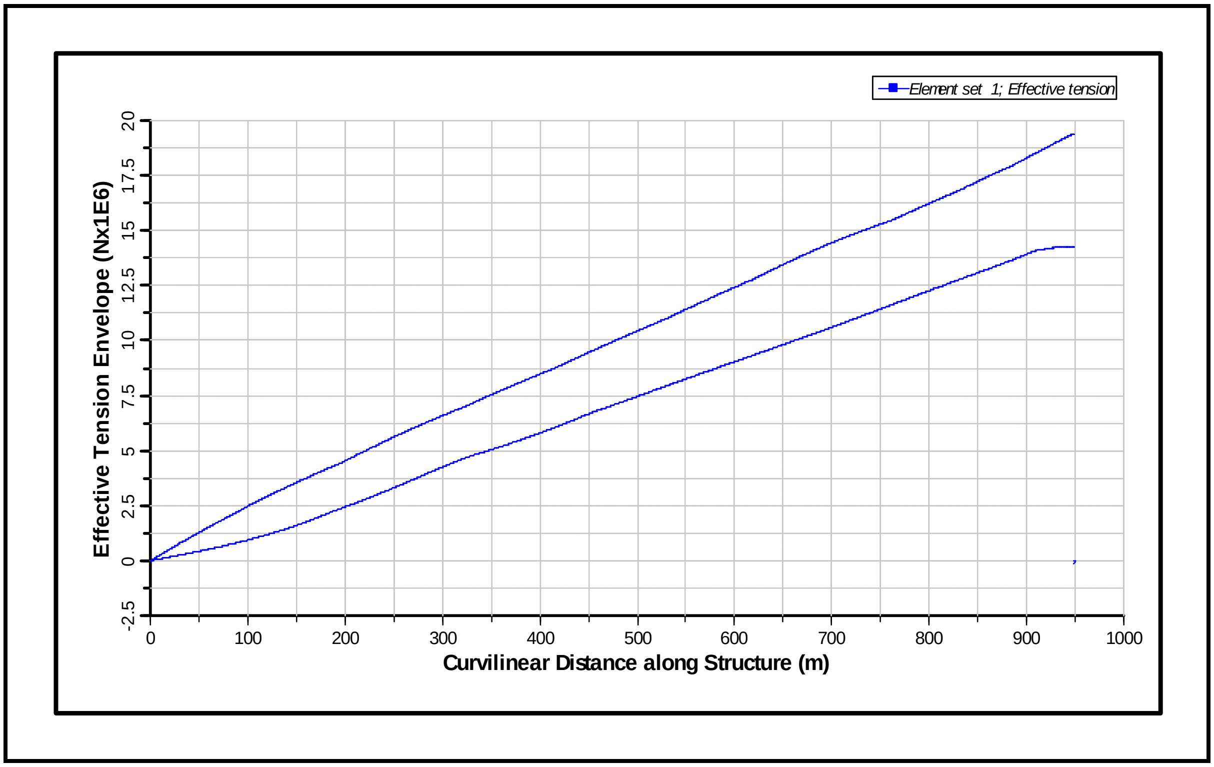


Figure 263: Axial Tension Envelope for 1000 m CWP for Bin 13 (from Bottom to Top)

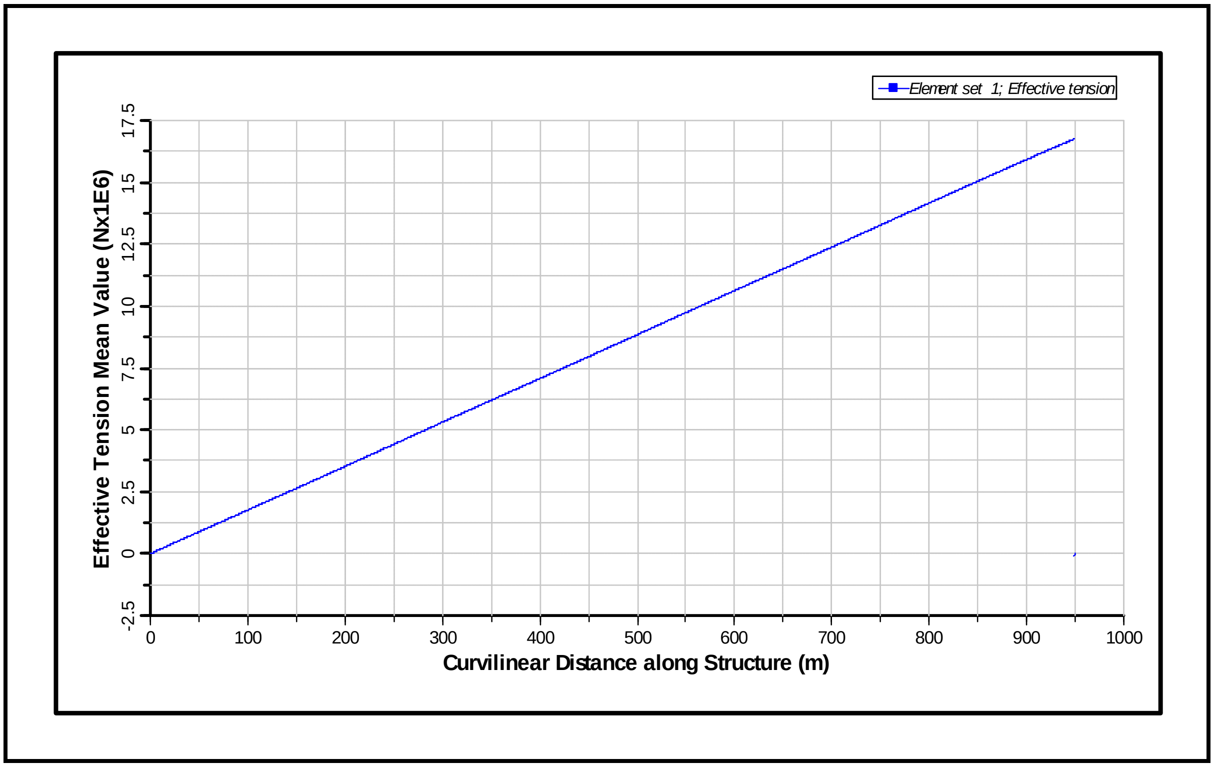


Figure 264: Mean Axial Tension for 1000 m CWP for Bin 13 (from Bottom to Top)

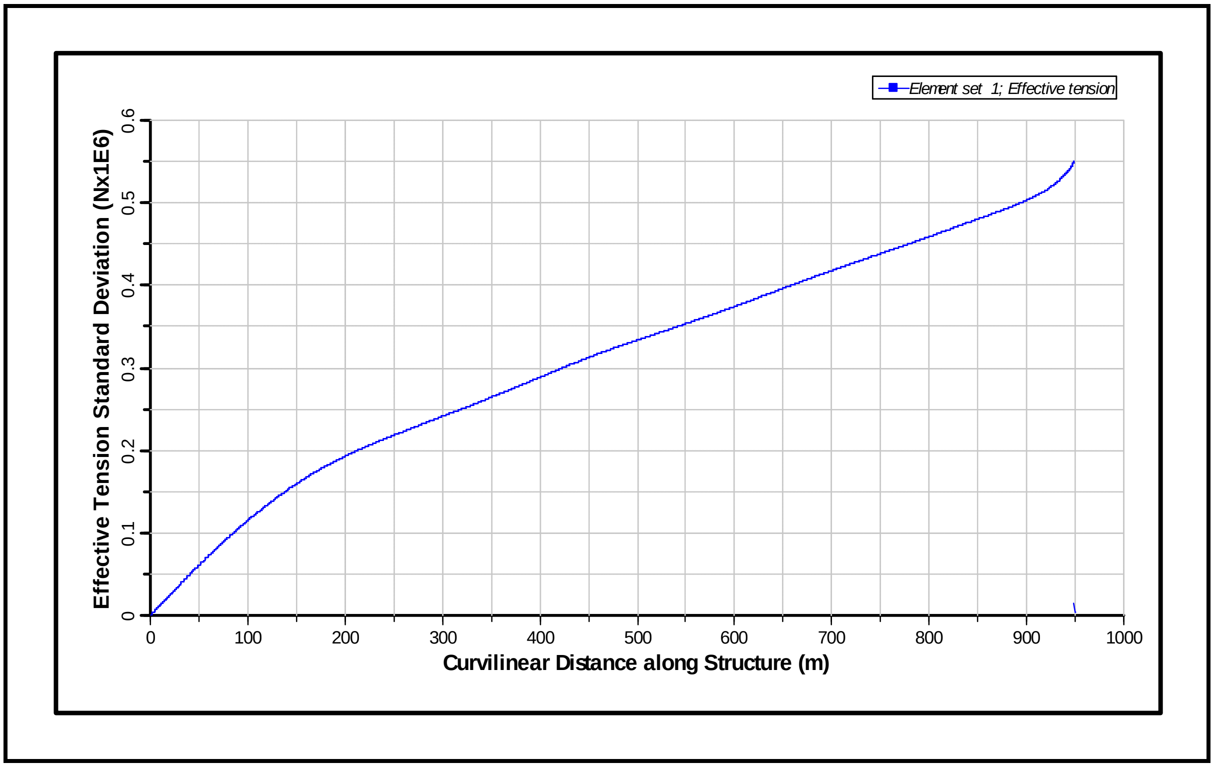


Figure 265: Standard Deviation of Axial Tension for 1000 m CWP for Bin 13 (from Bottom to Top)

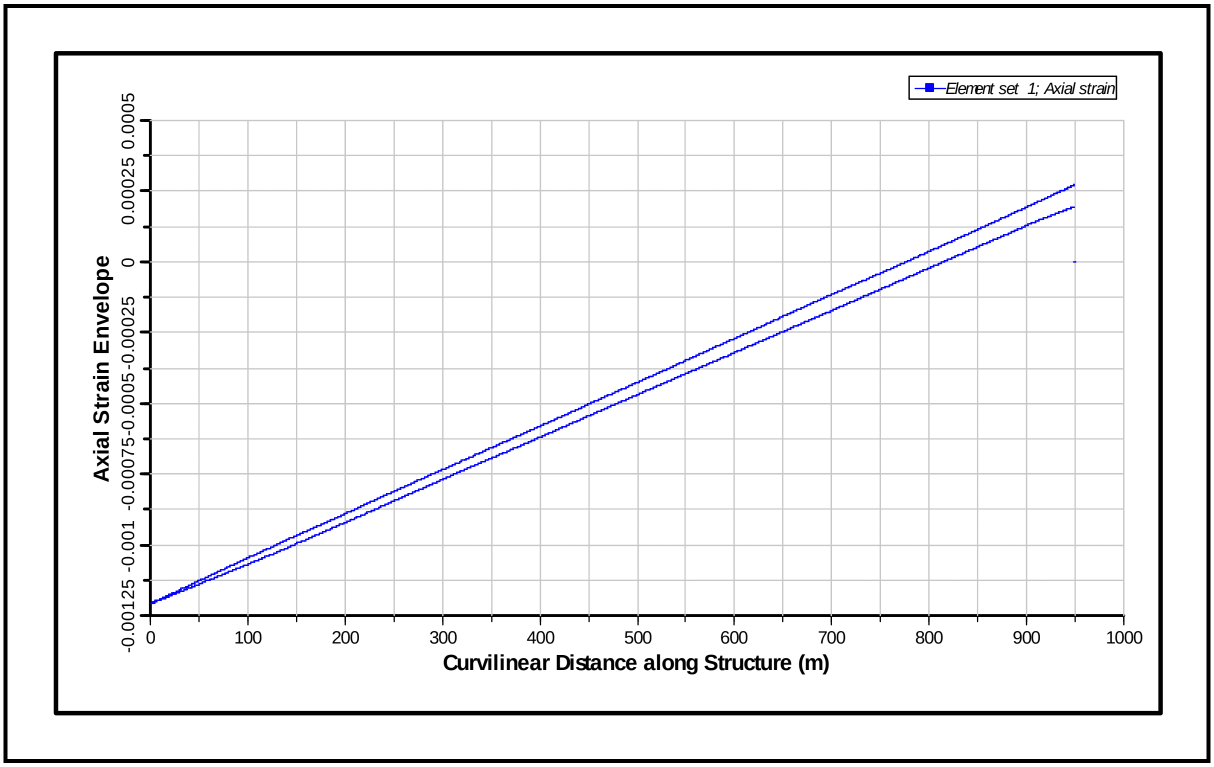


Figure 266: Axial Strain Envelope for 1000 m CWP for Bin 13 (from Bottom to Top)

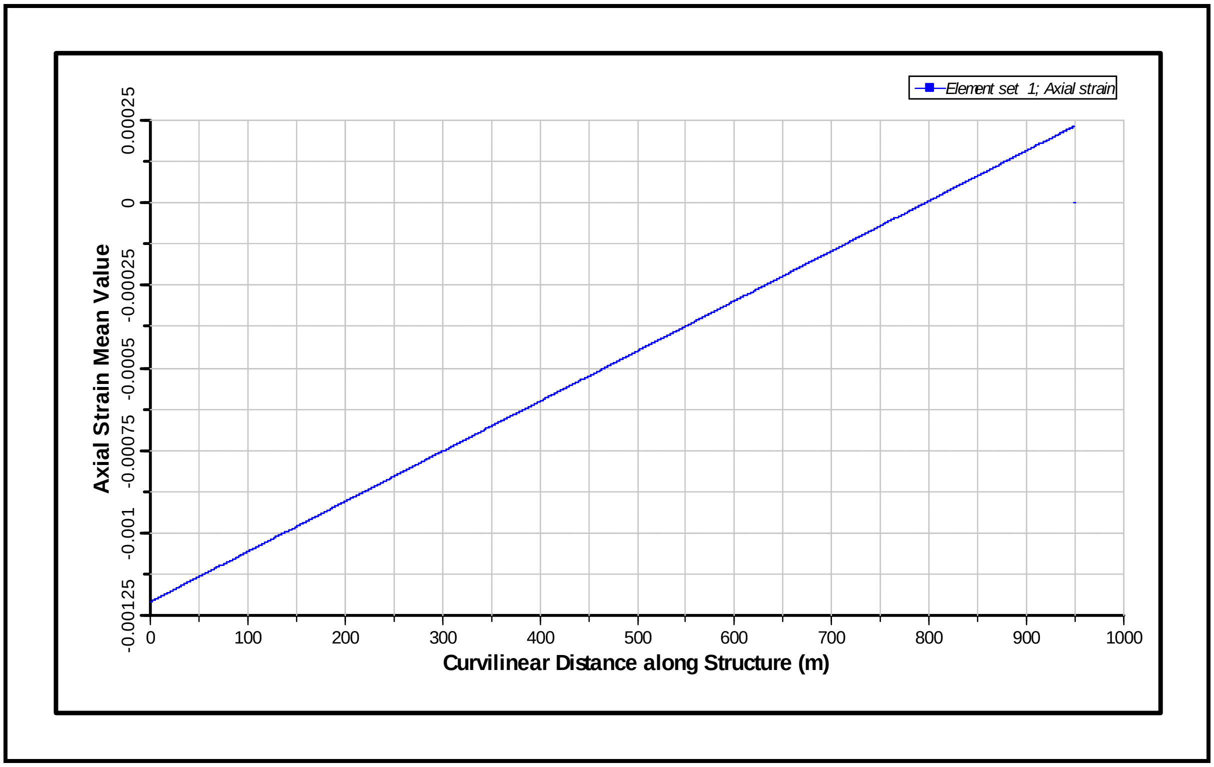


Figure 267: Mean Axial Strain for 1000 m CWP for Bin 13 (from Bottom to Top)

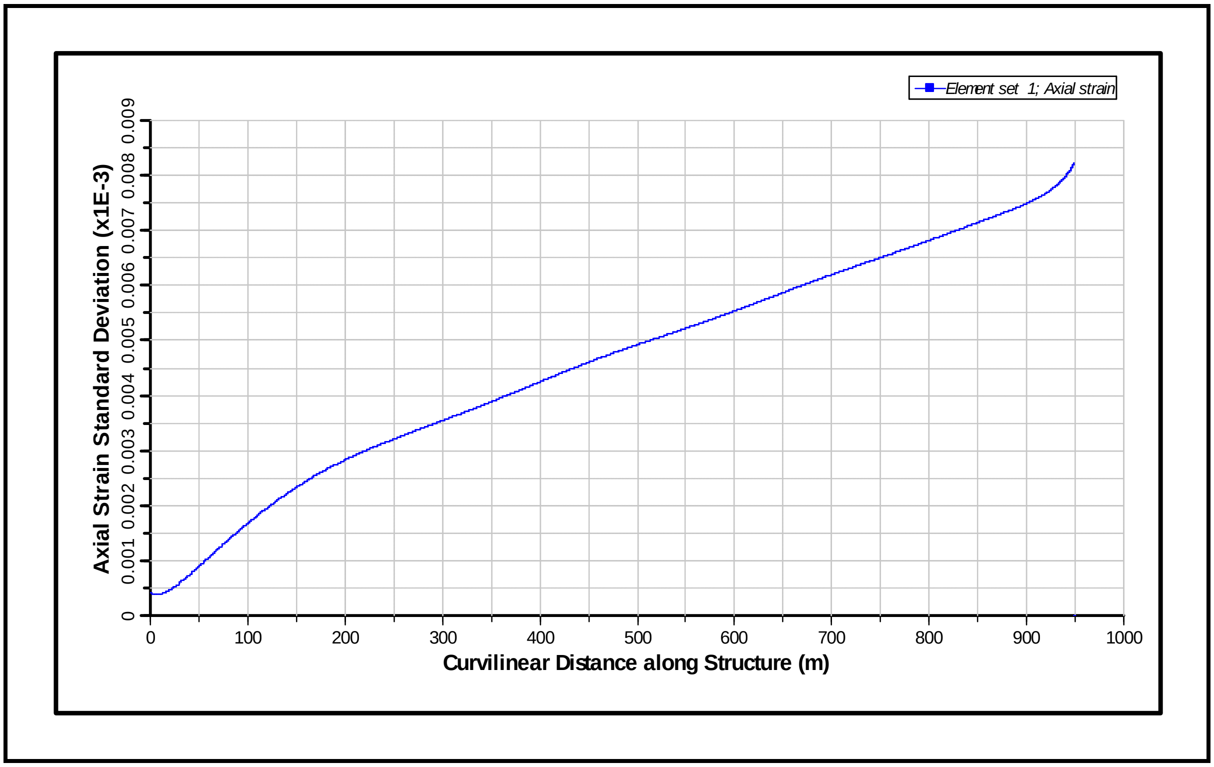


Figure 268: Standard Deviation of Axial Strain for 1000 m CWP for Bin 13 (from Bottom to Top)

6.1 Bin 14

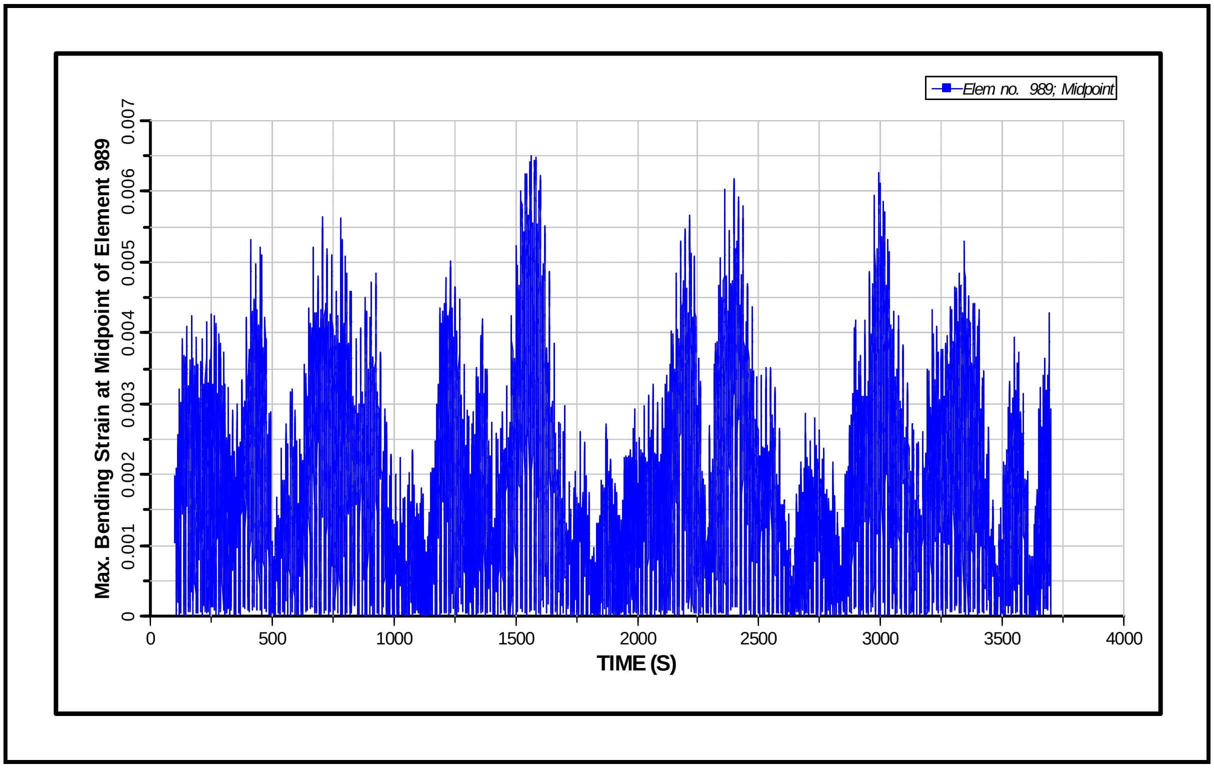


Figure 269: Maximum Bending Strain Time History at Top of CWP for Bin 14

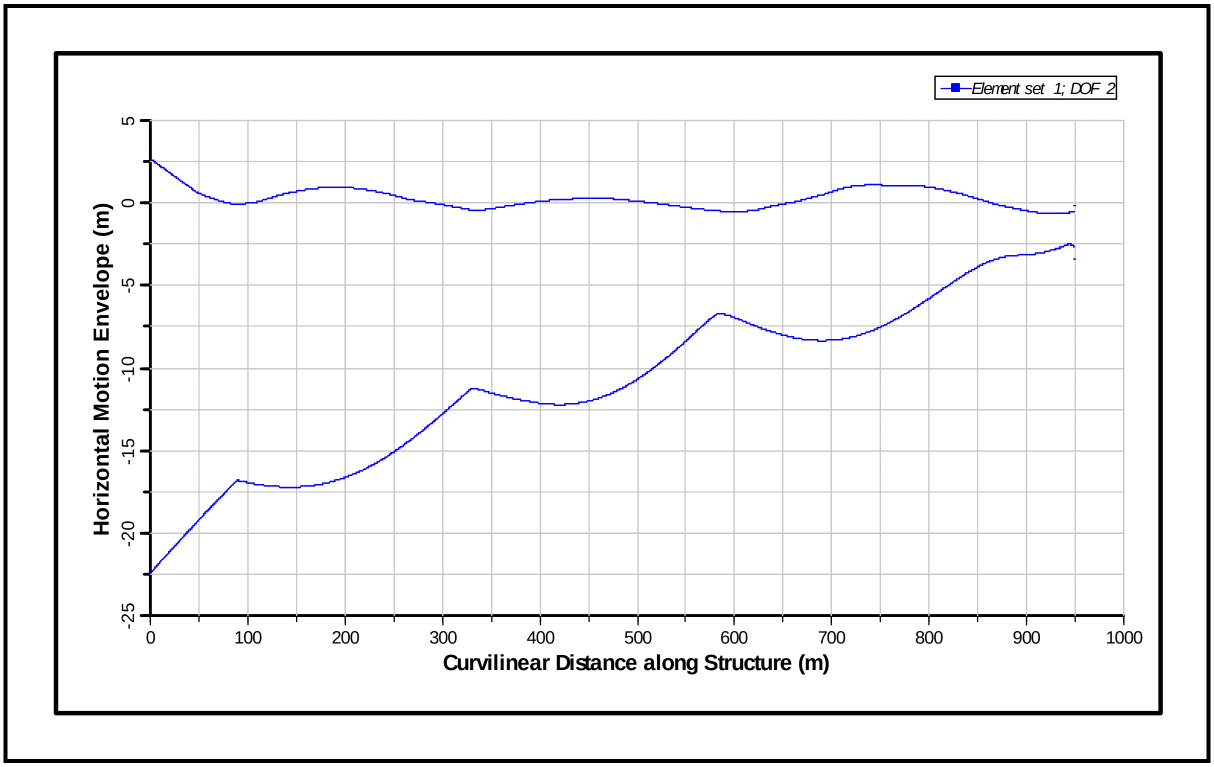


Figure 270: Motion Envelope for 1000 m CWP for Bin 14 (from Bottom to Top)

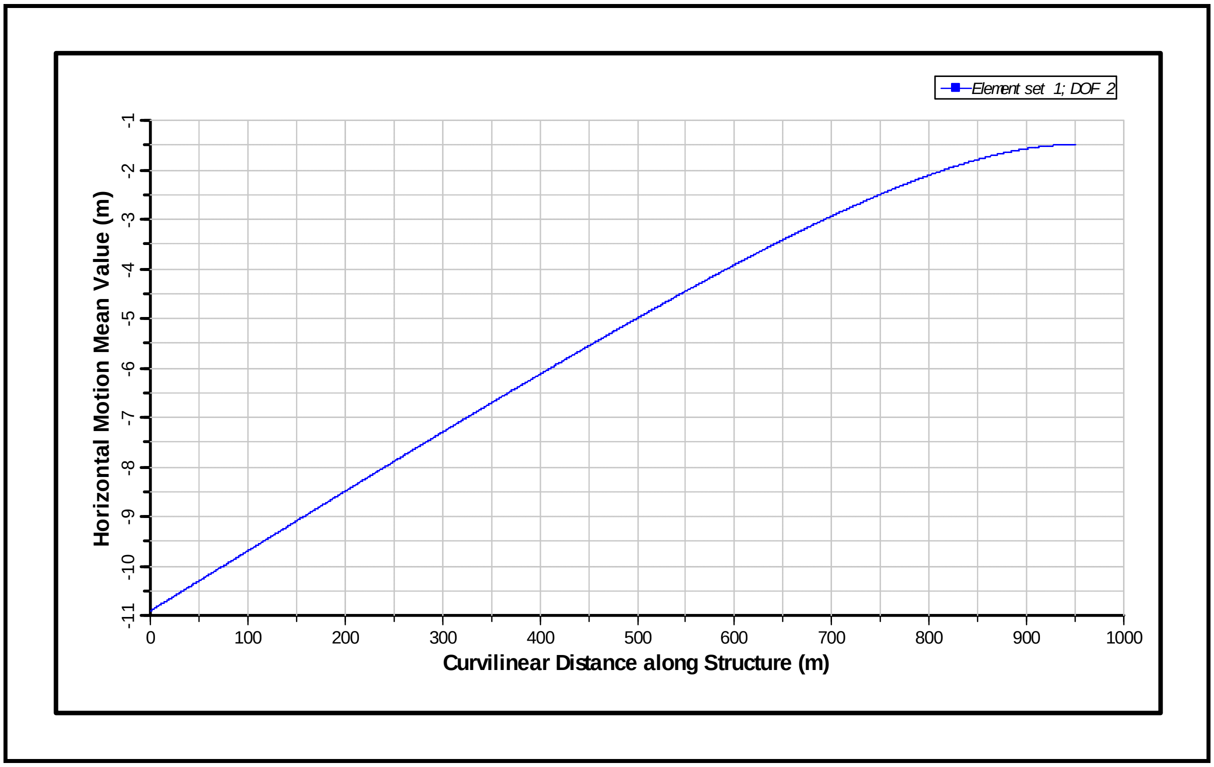


Figure 271: Mean Motion for 1000 m CWP for Bin 14 (from Bottom to Top)

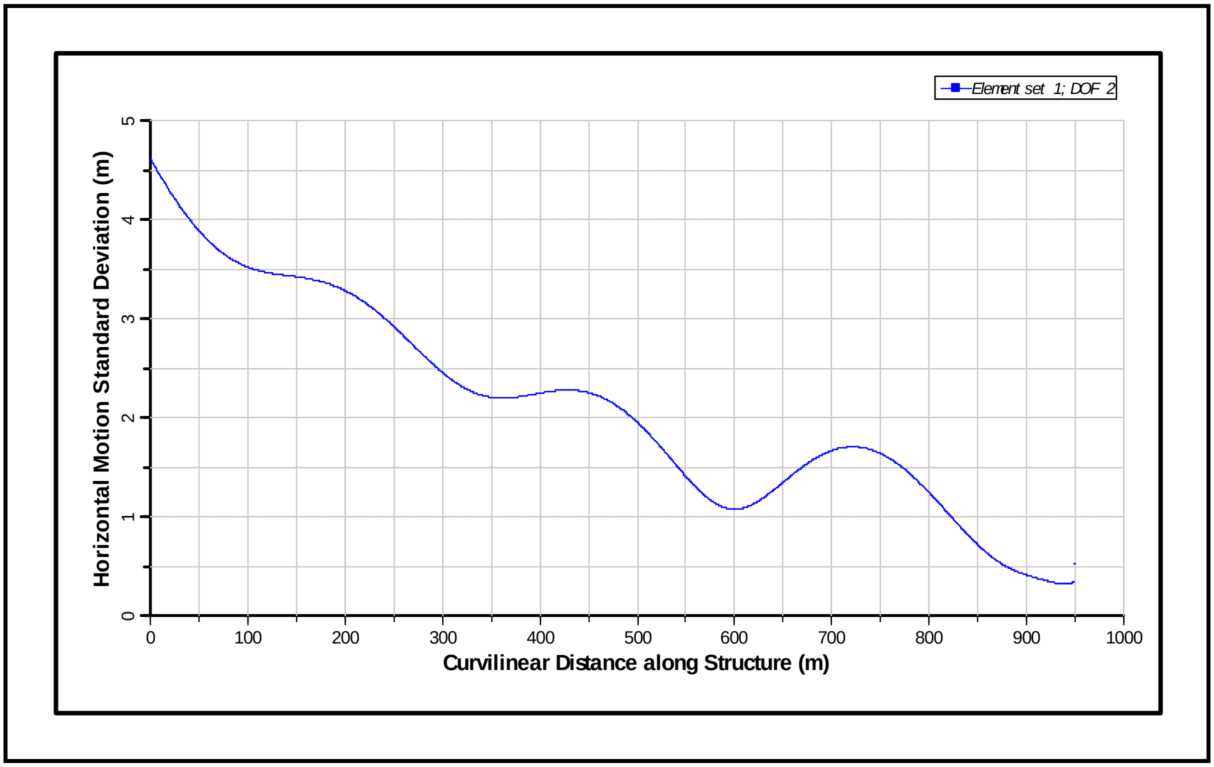


Figure 272: Standard Deviation of Motion for 1000 m CWP for Bin 14 (from Bottom to Top)

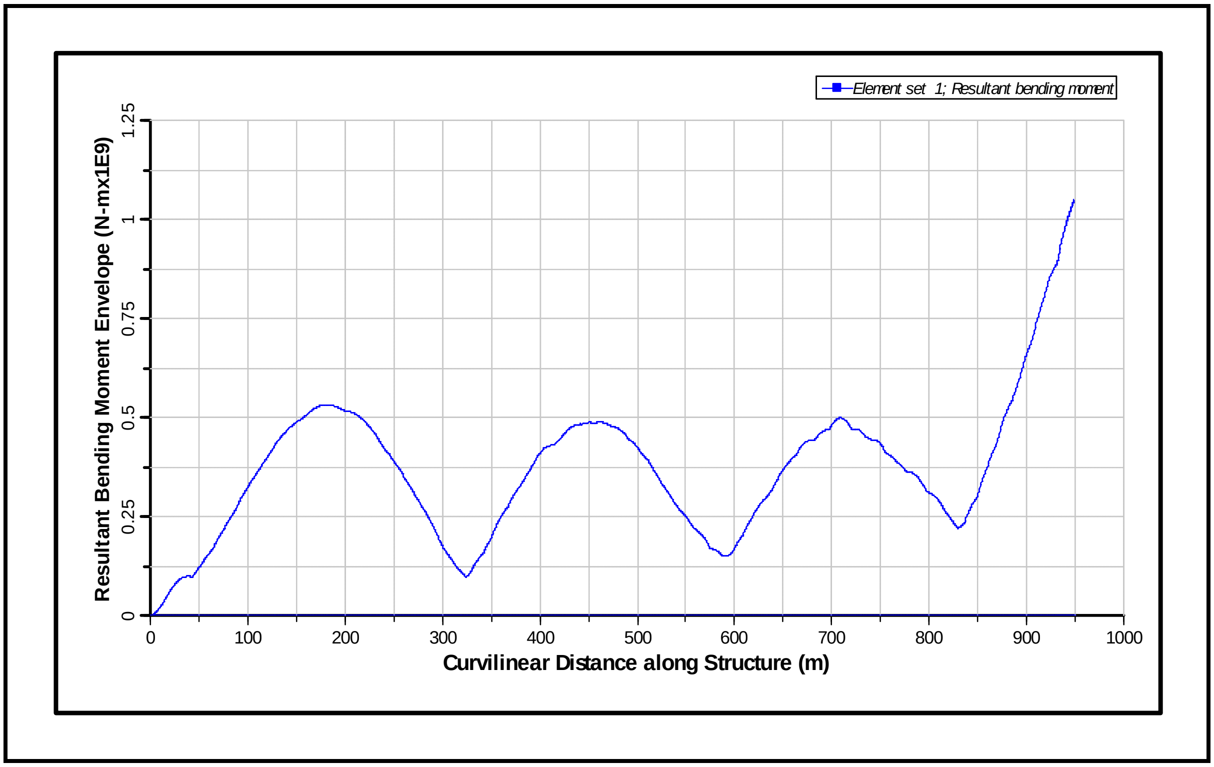


Figure 273: Bending Moment Envelope for 1000 m CWP for Bin 14 (from Bottom to Top)

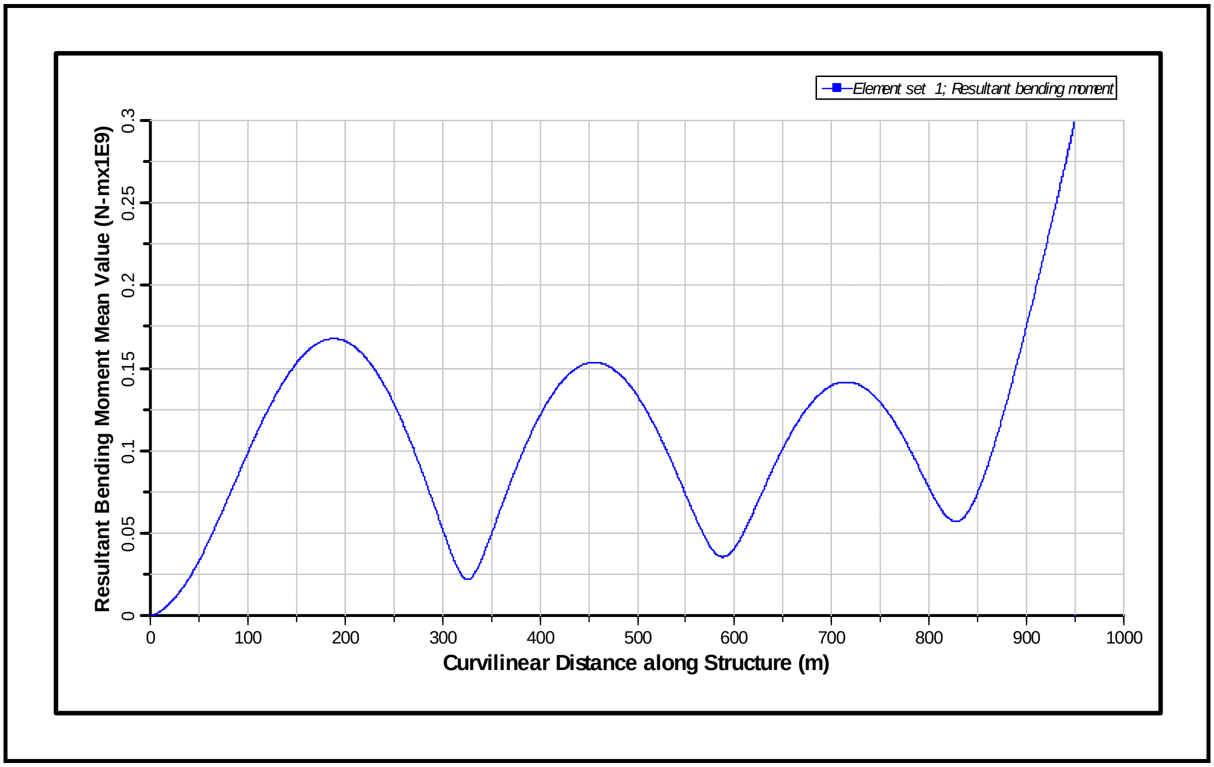


Figure 274: Mean Bending Moment for 1000 m CWP for Bin 14 (from Bottom to Top)

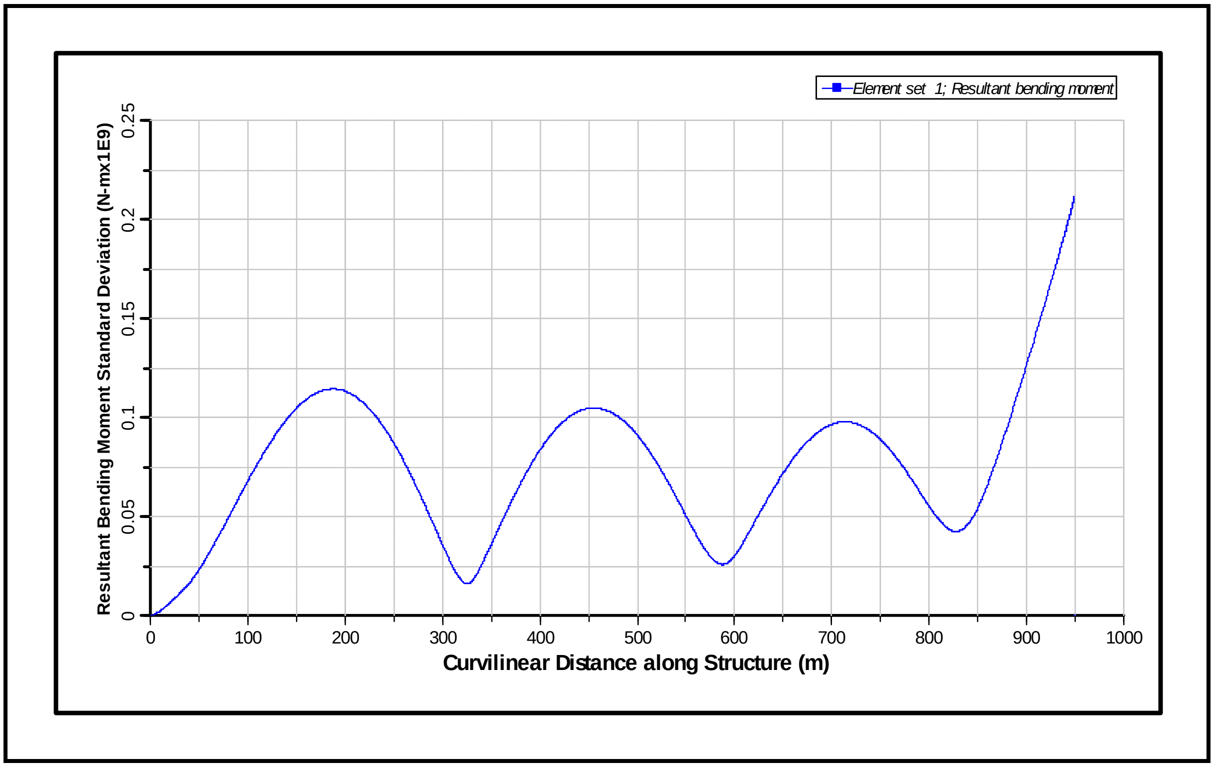


Figure 275: Standard Deviation of Bending Moment for 1000 m CWP for Bin 14 (from Bottom to Top)

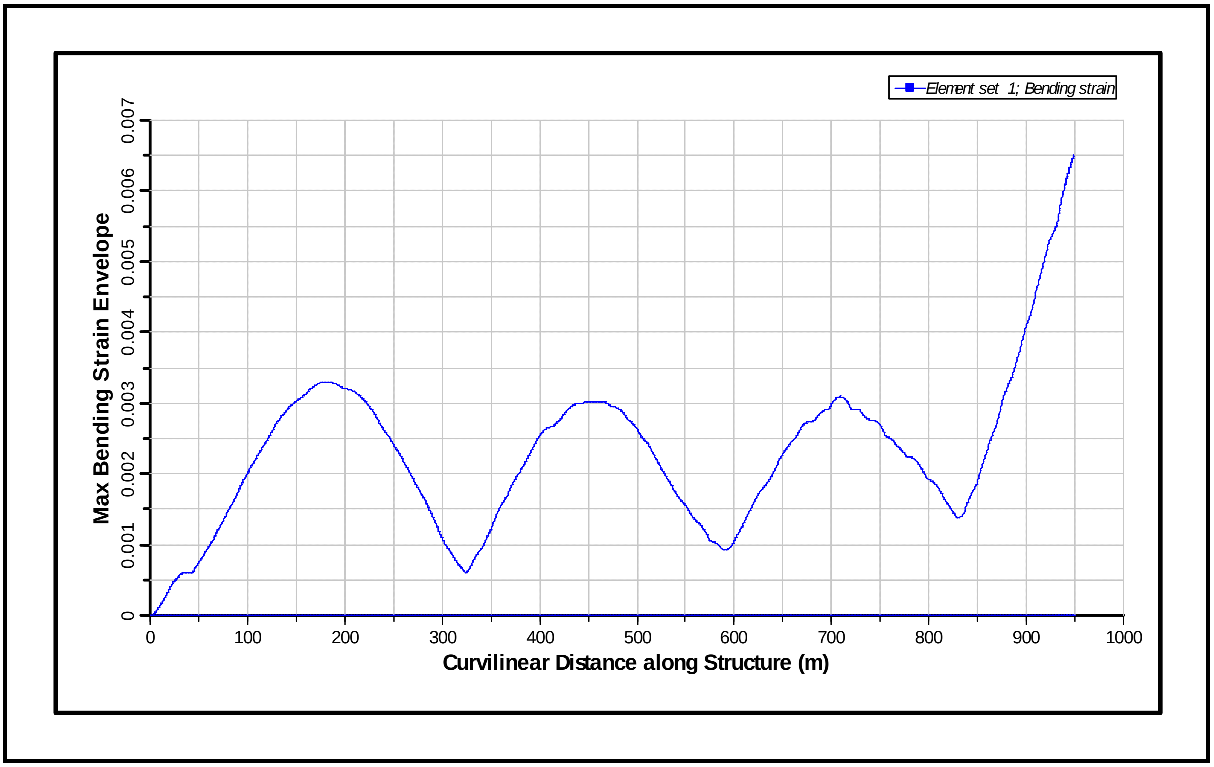


Figure 276: Bending Strain Envelope for 1000 m CWP for Bin 14 (from Bottom to Top)

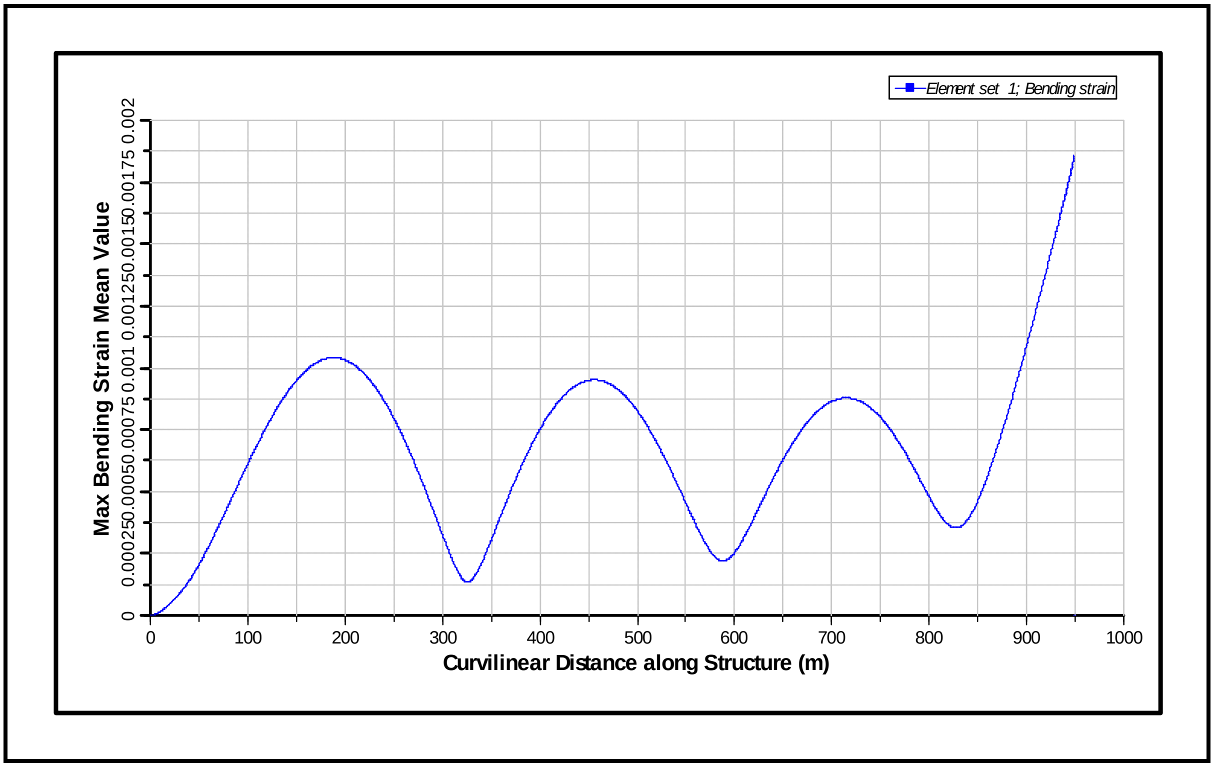


Figure 277: Mean Bending Strain for 1000 m CWP for Bin 14 (from Bottom to Top)

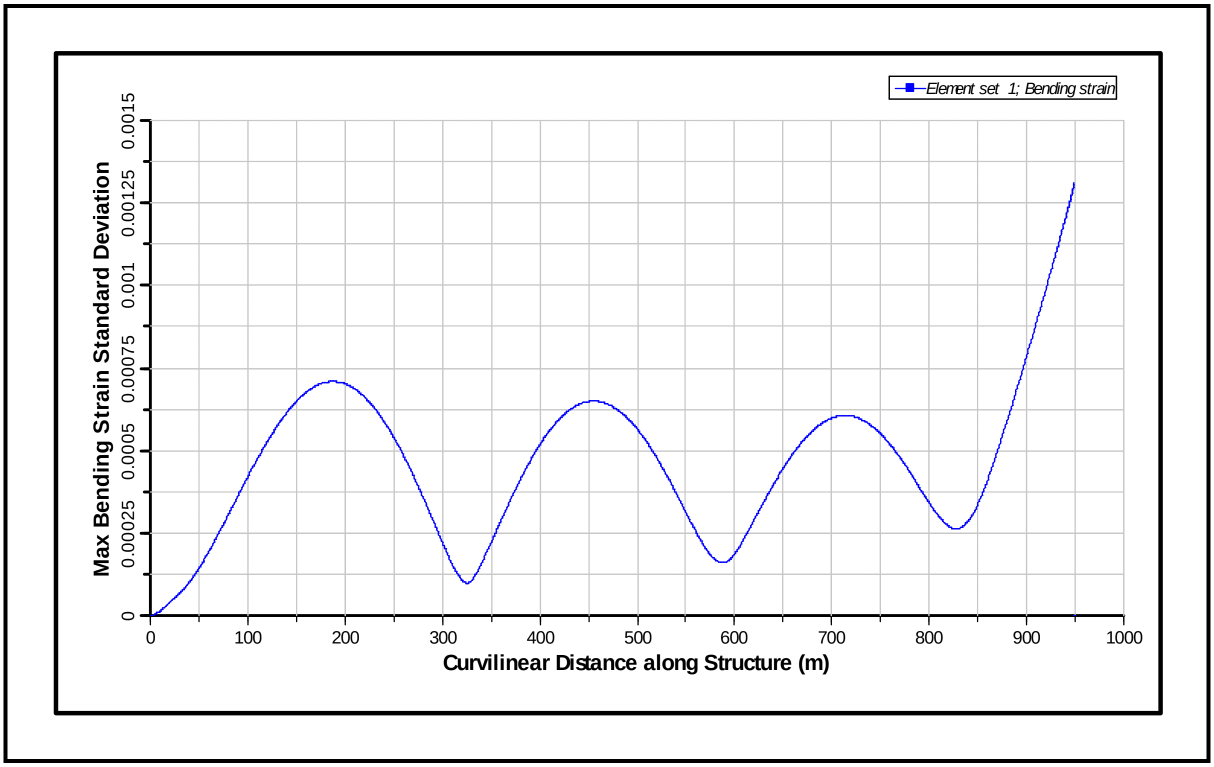


Figure 278: Standard Deviation of Bending Strain for 1000 m CWP for Bin 14 (from Bottom to Top)

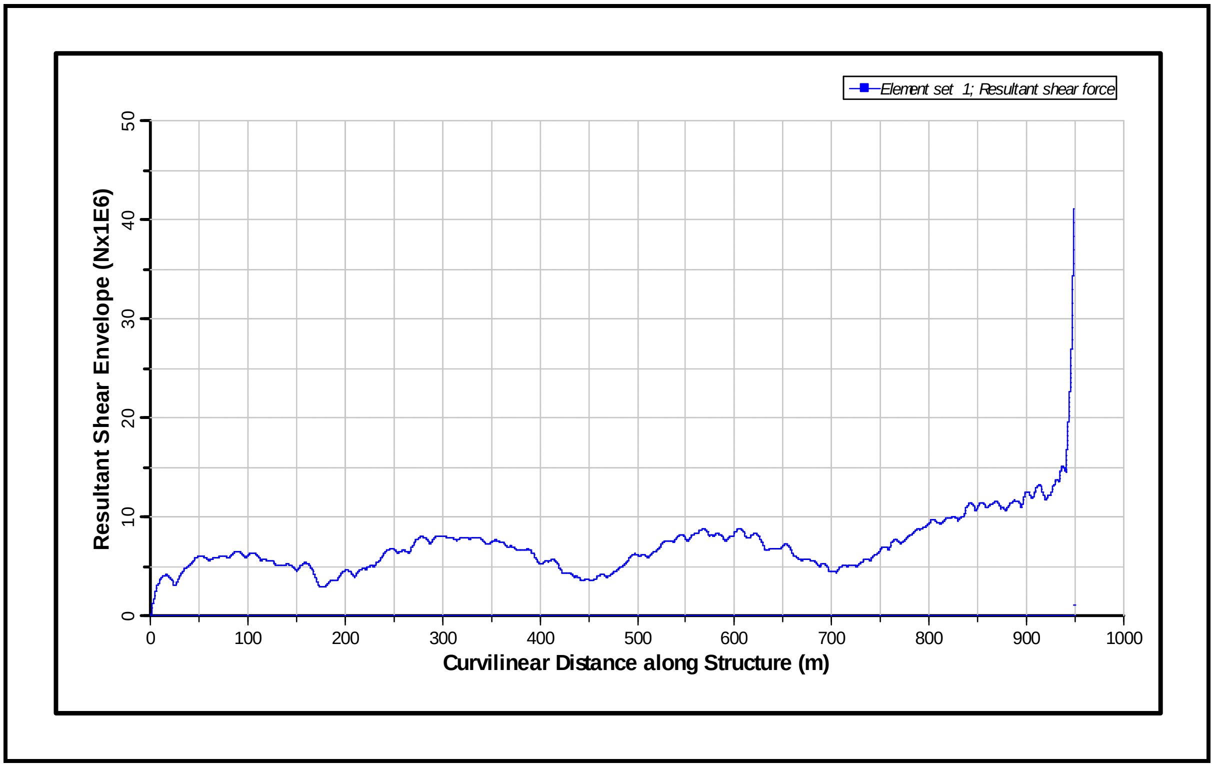


Figure 279: Shear Force Envelope for 1000 m CWP for Bin 14 (from Bottom to Top)

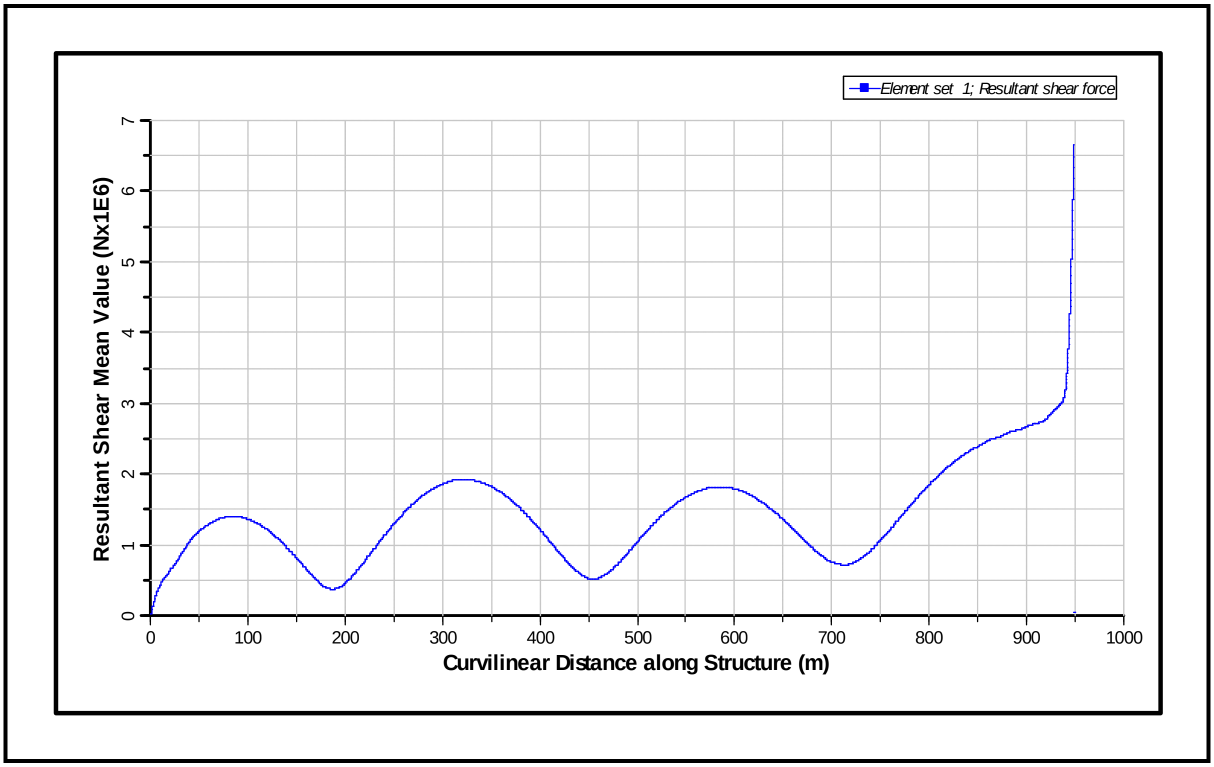


Figure 280: Mean Shear Force for 1000 m CWP for Bin 14 (from Bottom to Top)

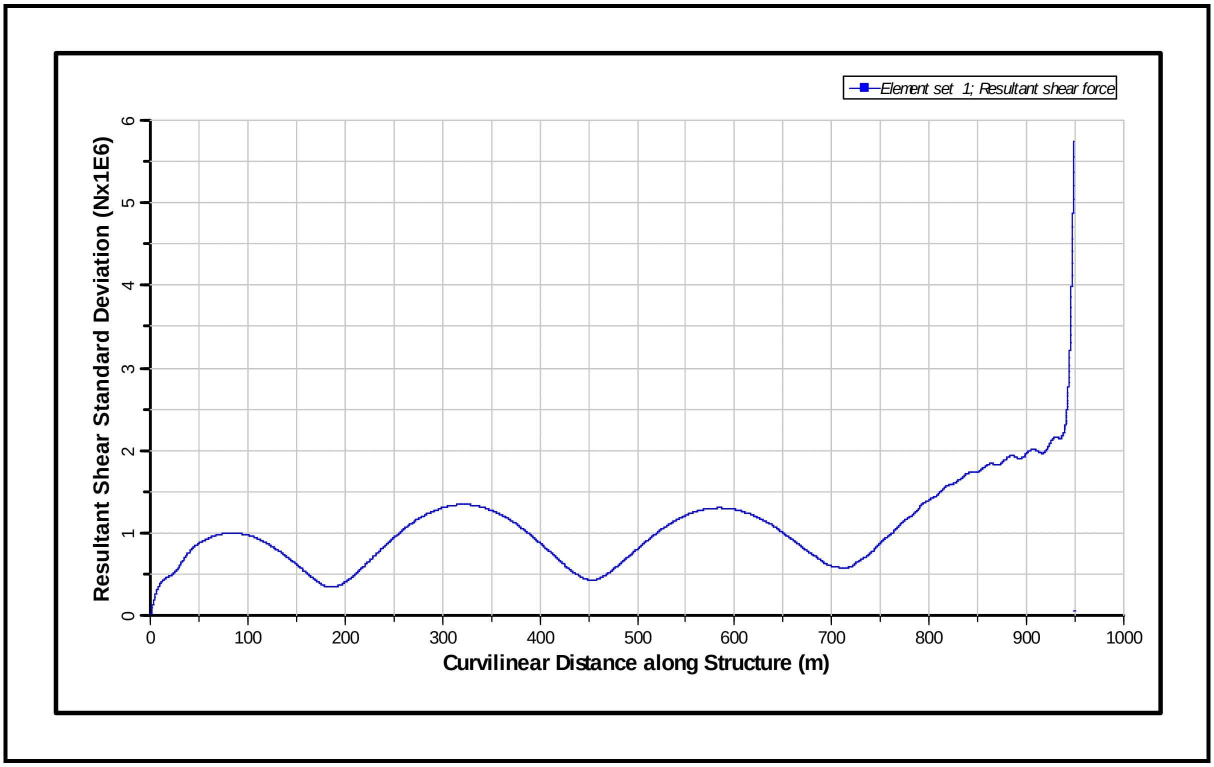


Figure 281: Standard Deviation of Shear Force for 1000 m CWP for Bin 14 (from Bottom to Top)

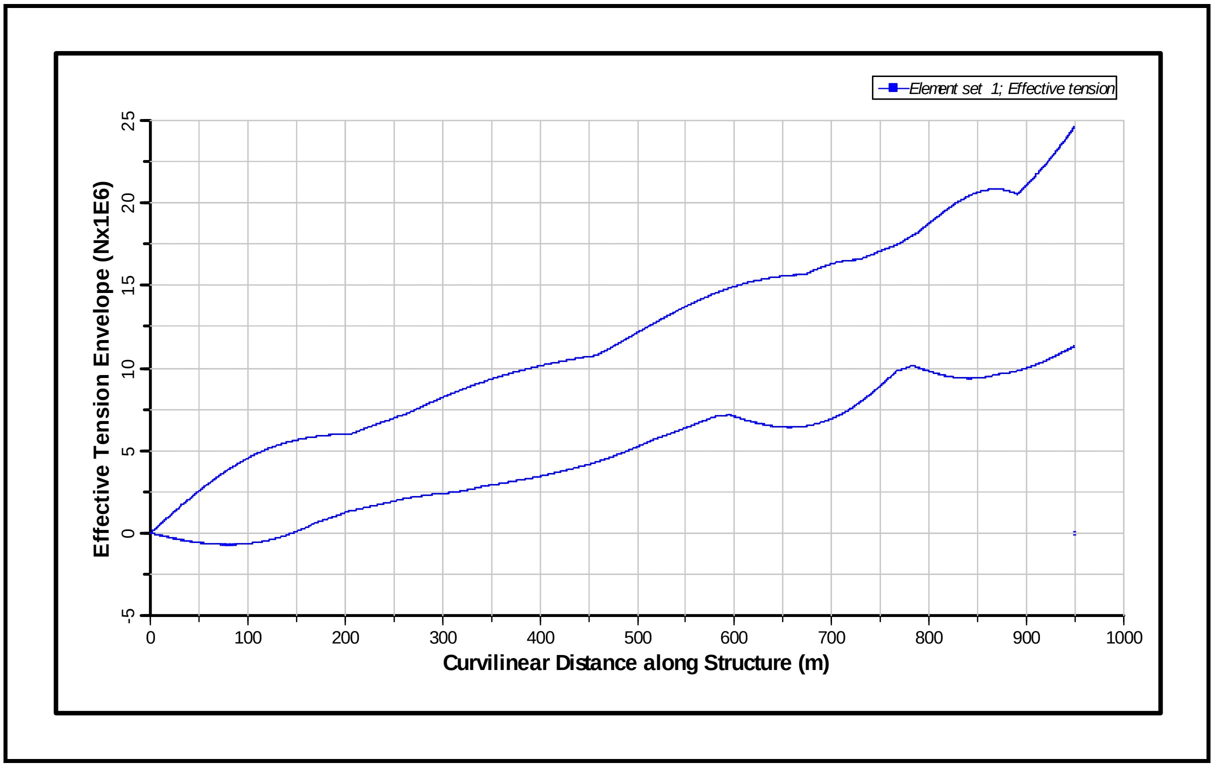


Figure 282: Axial Tension Envelope for 1000 m CWP for Bin 14 (from Bottom to Top)

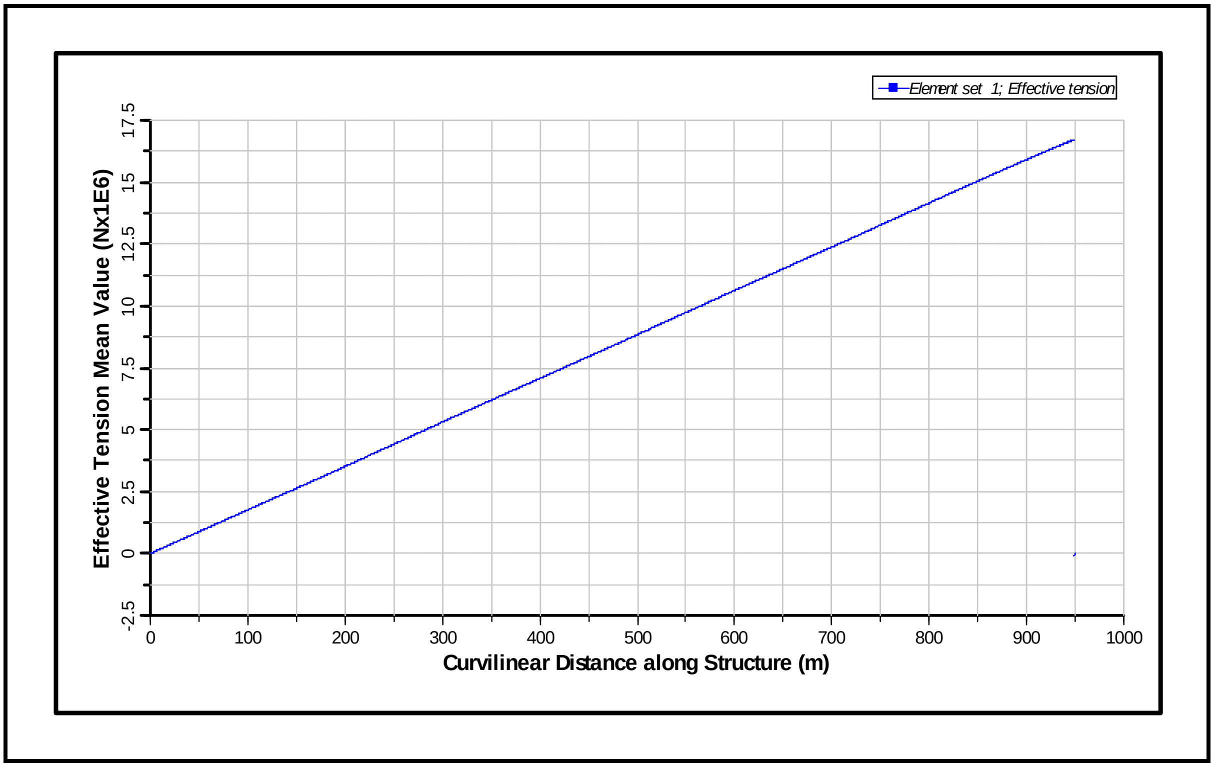


Figure 283: Mean Axial Tension for 1000 m CWP for Bin 14 (from Bottom to Top)

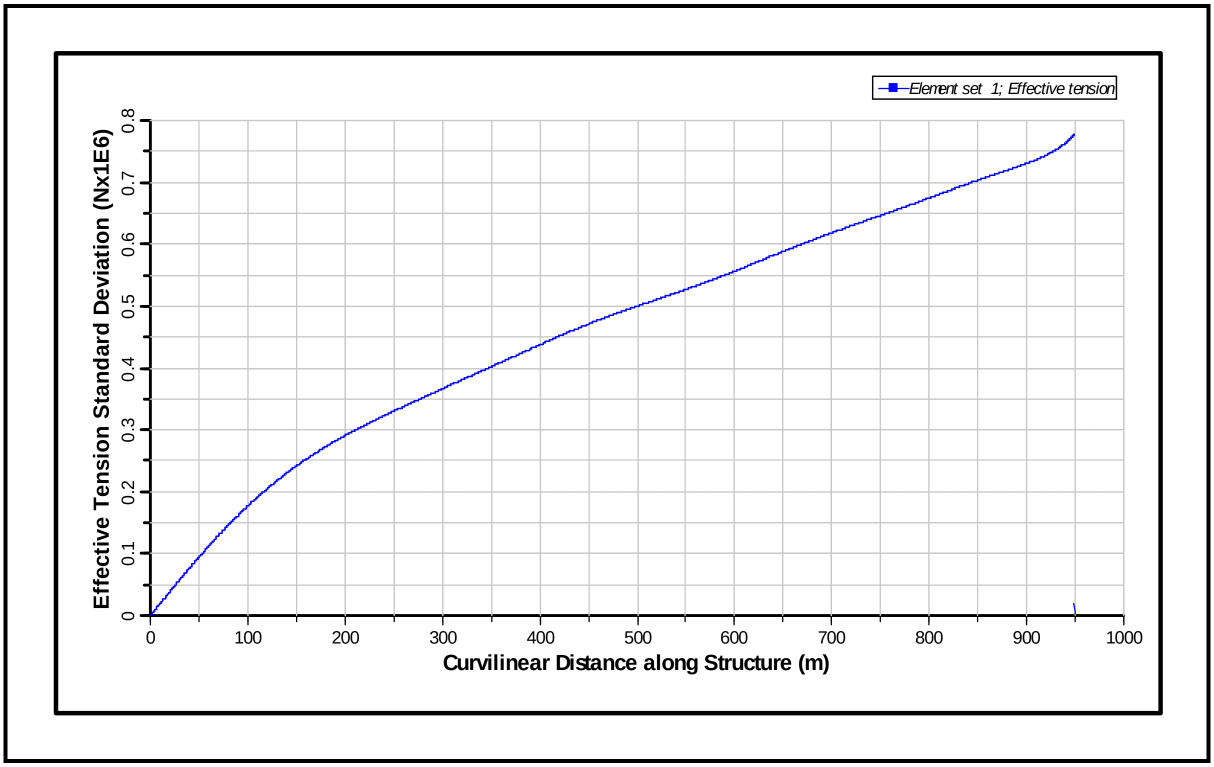


Figure 284: Standard Deviation of Axial Tension for 1000 m CWP for Bin 14 (from Bottom to Top)

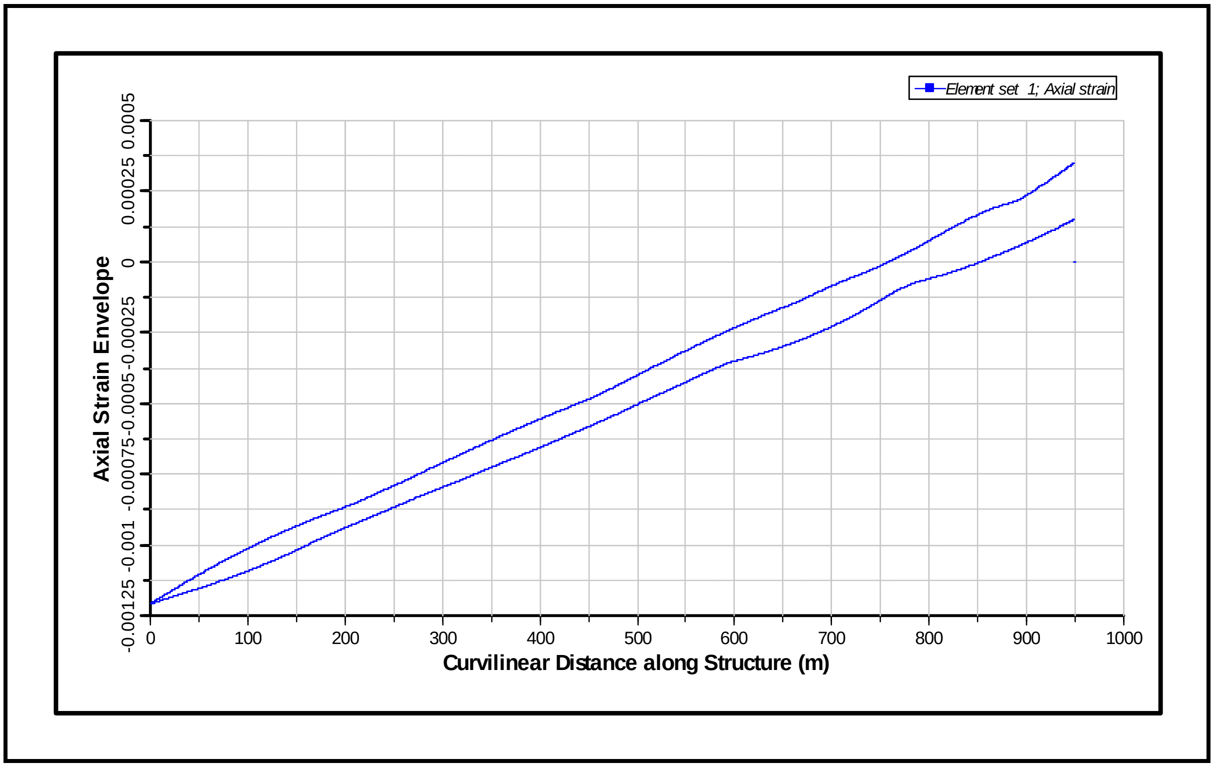


Figure 285: Axial Strain Envelope for 1000 m CWP for Bin 14 (from Bottom to Top)

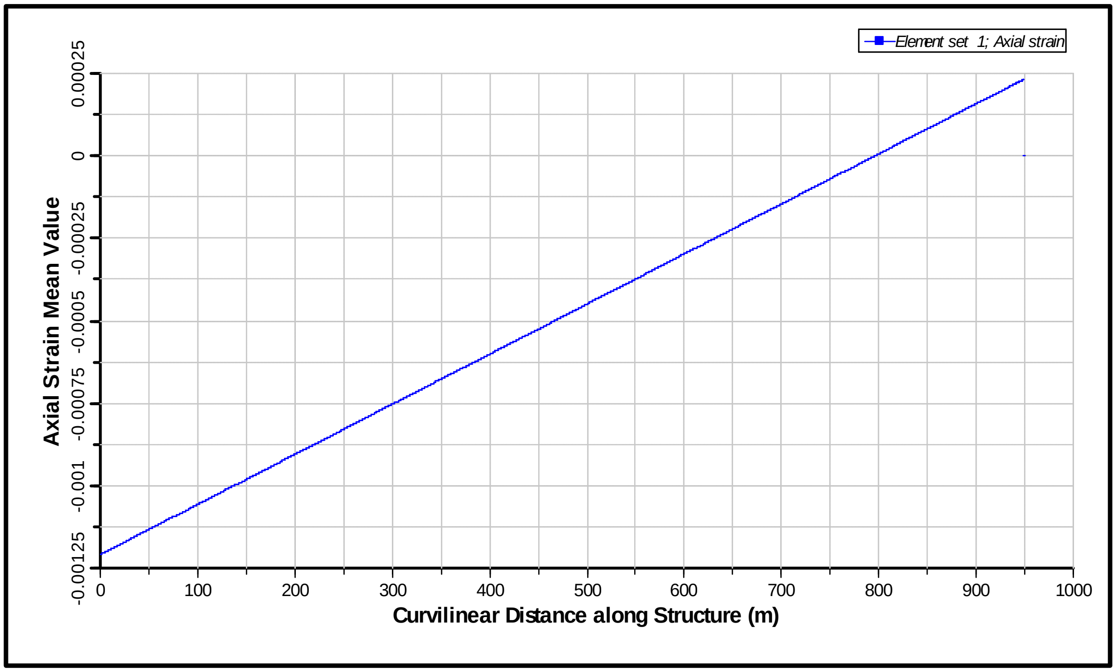


Figure 286: Mean Axial Strain for 1000 m CWP for Bin 14 (from Bottom to Top)

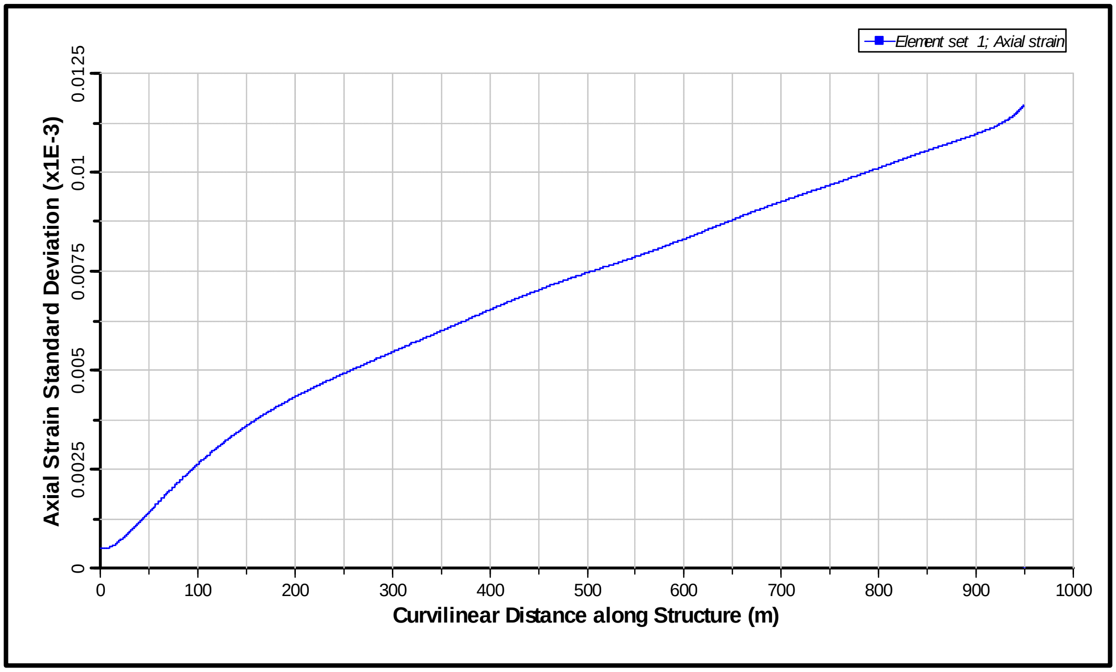


Figure 287: Standard Deviation of Axial Strain for 1000 m CWP for Bin 14 (from Bottom to Top)

6.1 Bin 15

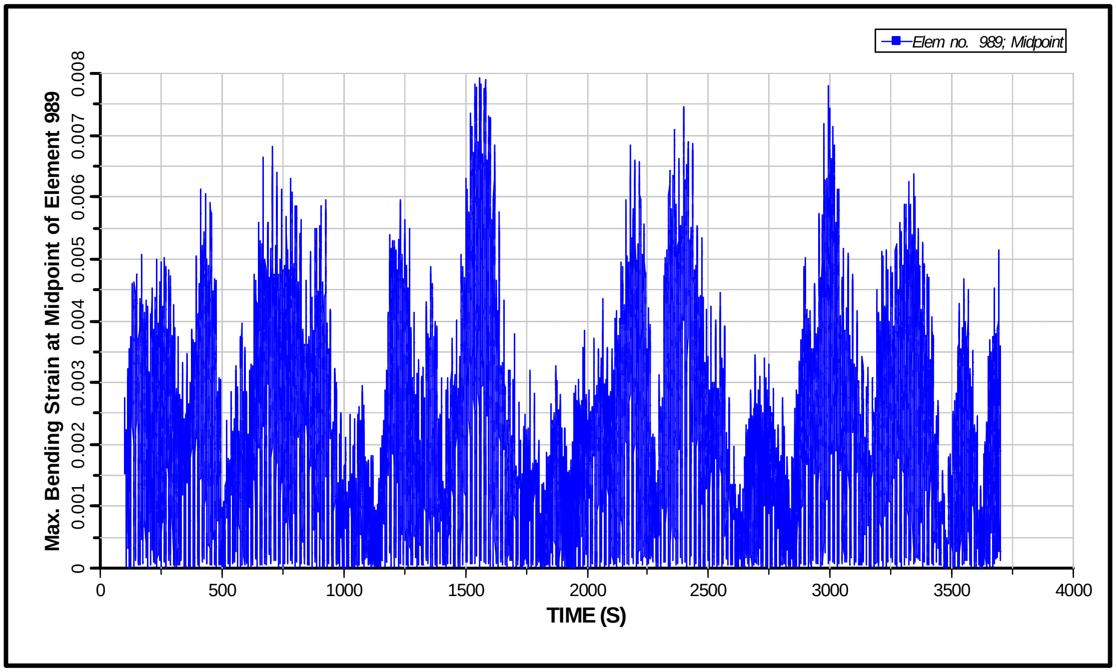


Figure 288: Maximum Bending Strain Time History at Top of CWP for Bin 15

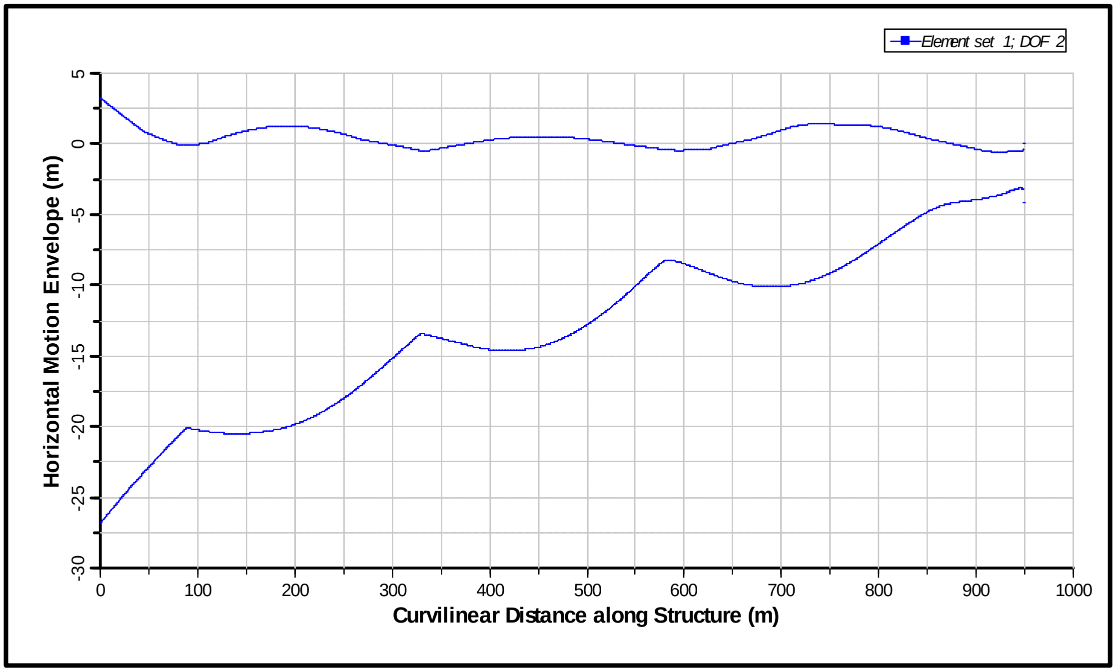


Figure 289: Motion Envelope for 1000 m CWP for Bin 15 (from Bottom to Top)

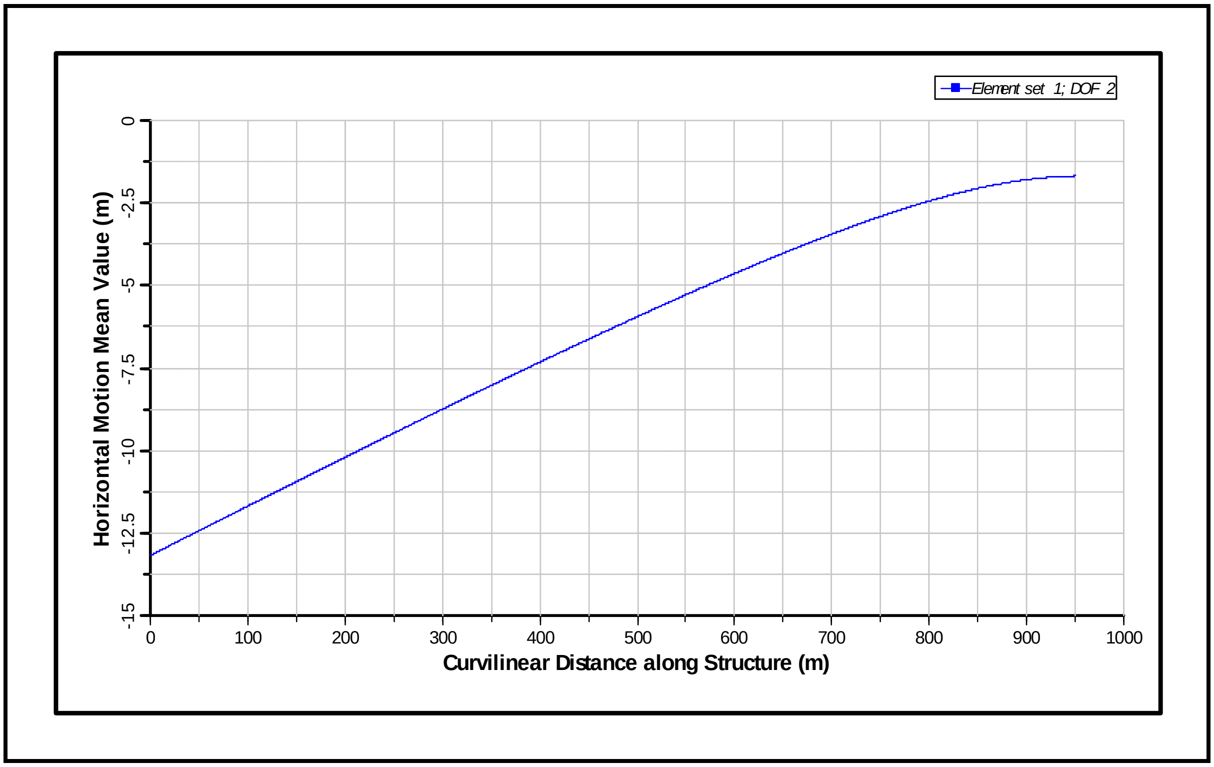


Figure 290: Mean Motion for 1000 m CWP for Bin 15 (from Bottom to Top)

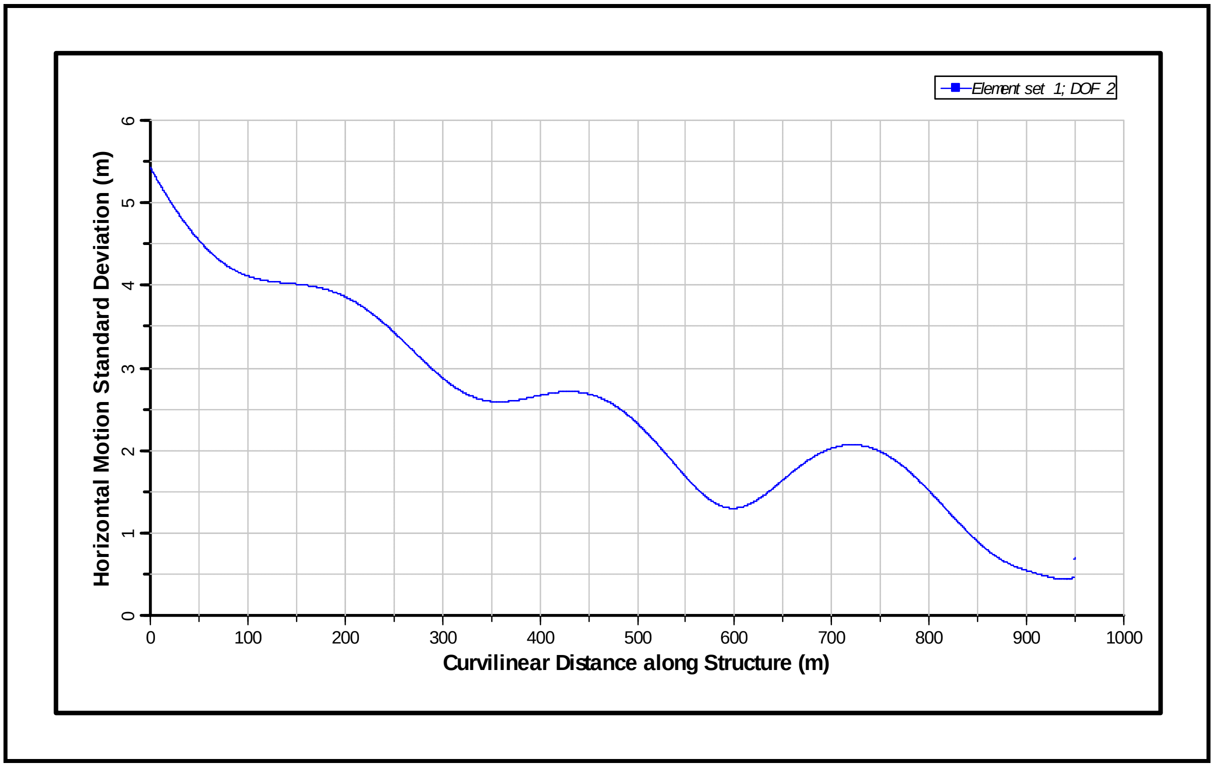


Figure 291: Standard Deviation of Motion for 1000 m CWP for Bin 15 (from Bottom to Top)

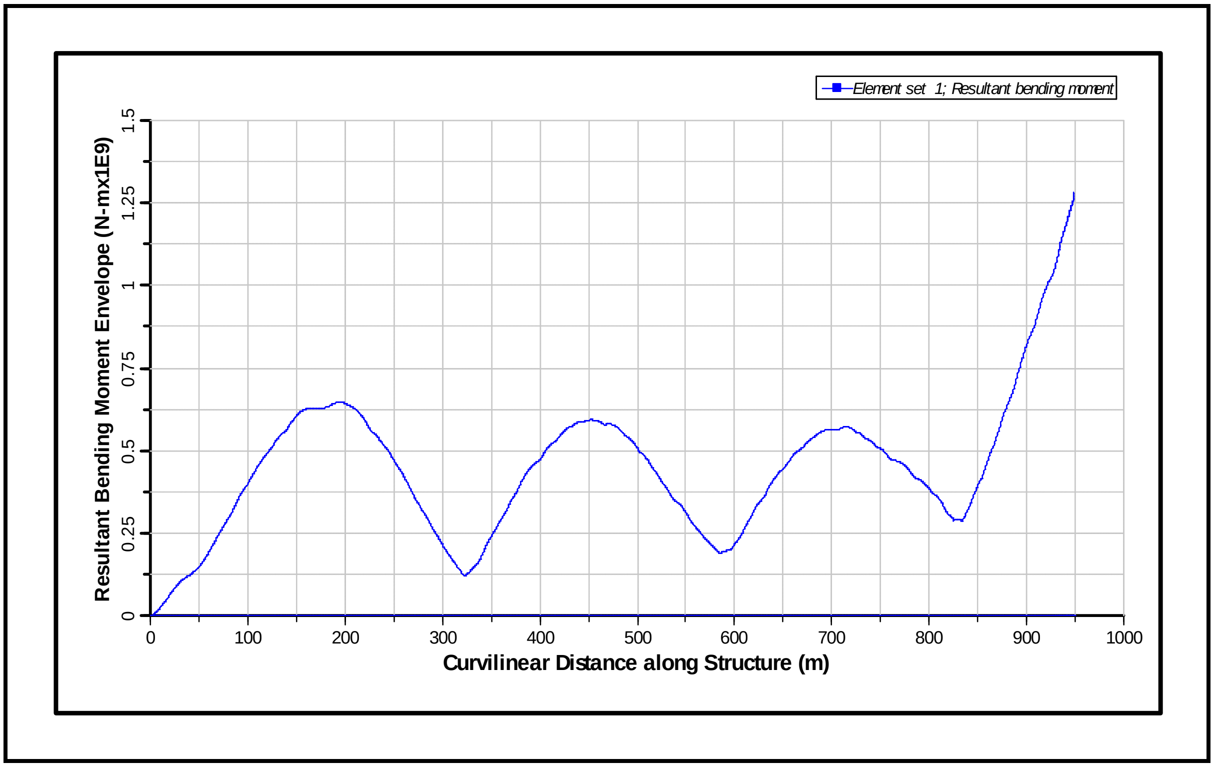


Figure 292: Bending Moment Envelope for 1000 m CWP for Bin 15 (from Bottom to Top)

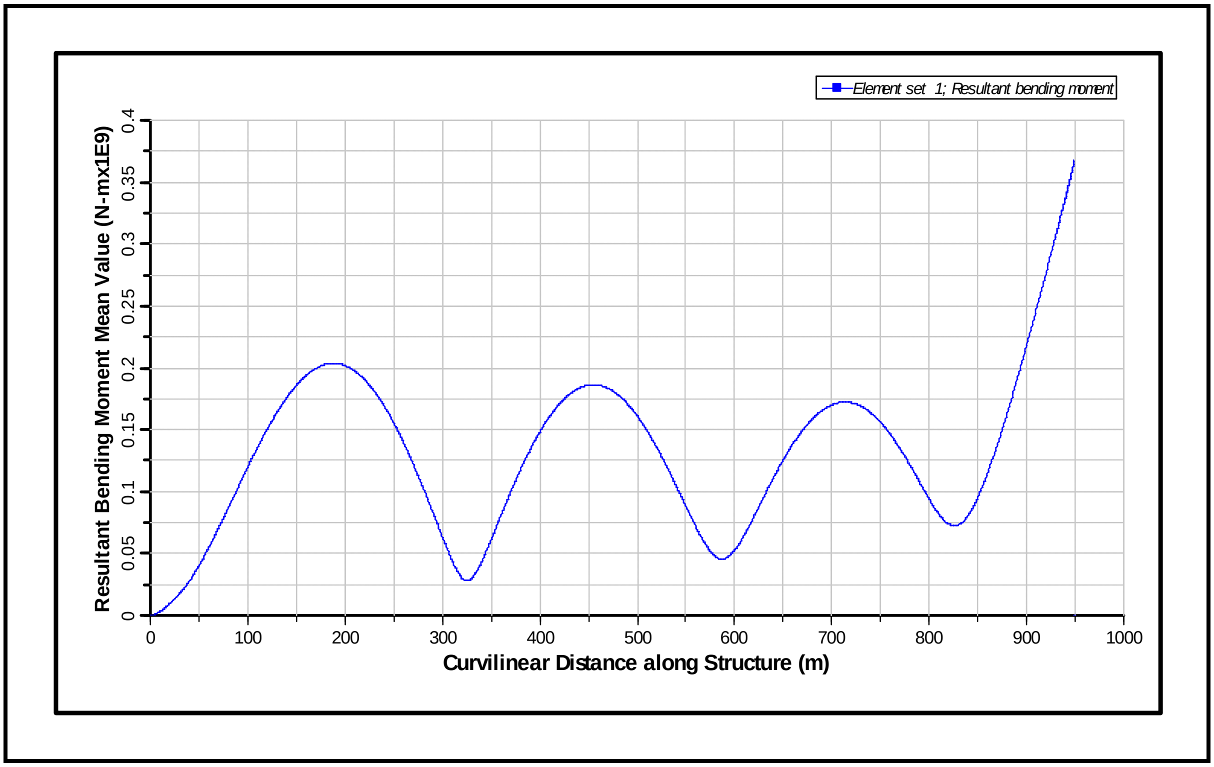


Figure 293: Mean Bending Moment for 1000 m CWP for Bin 15 (from Bottom to Top)

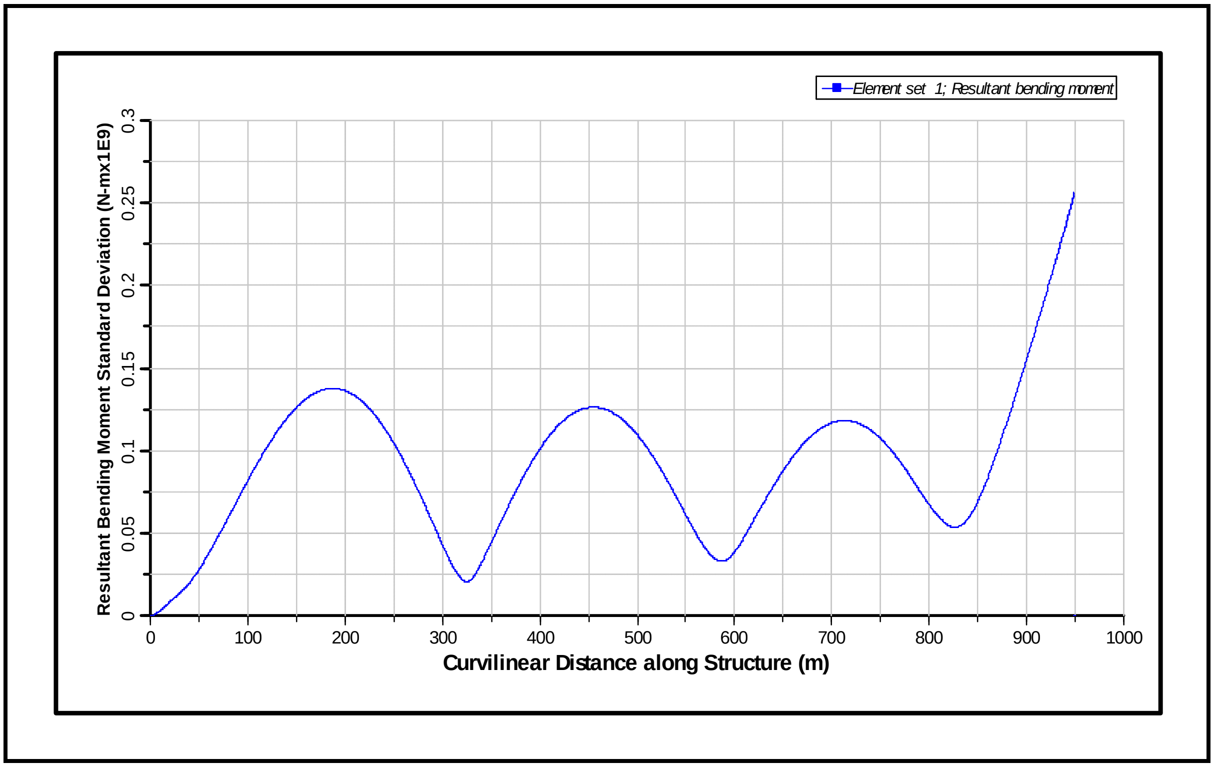


Figure 294: Standard Deviation of Bending Moment for 1000 m CWP for Bin 15 (from Bottom to Top)

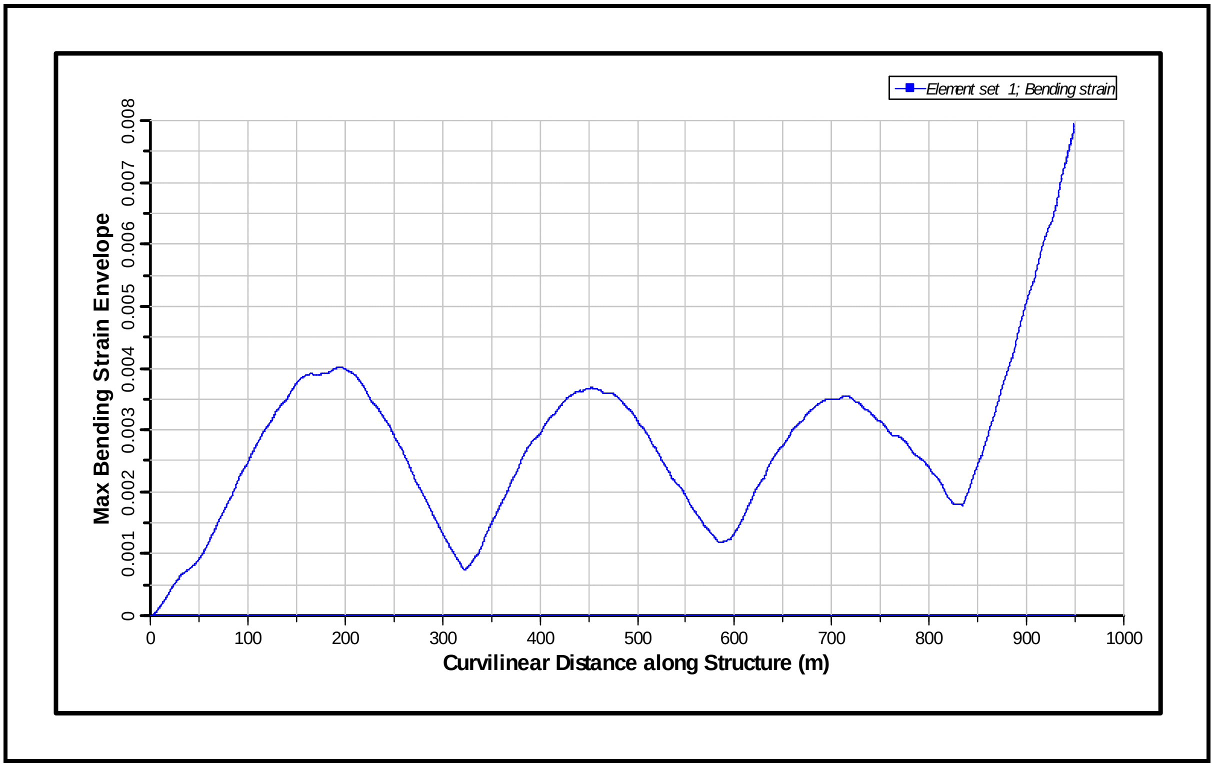


Figure 295: Bending Strain Envelope for 1000 m CWP for Bin 15 (from Bottom to Top)

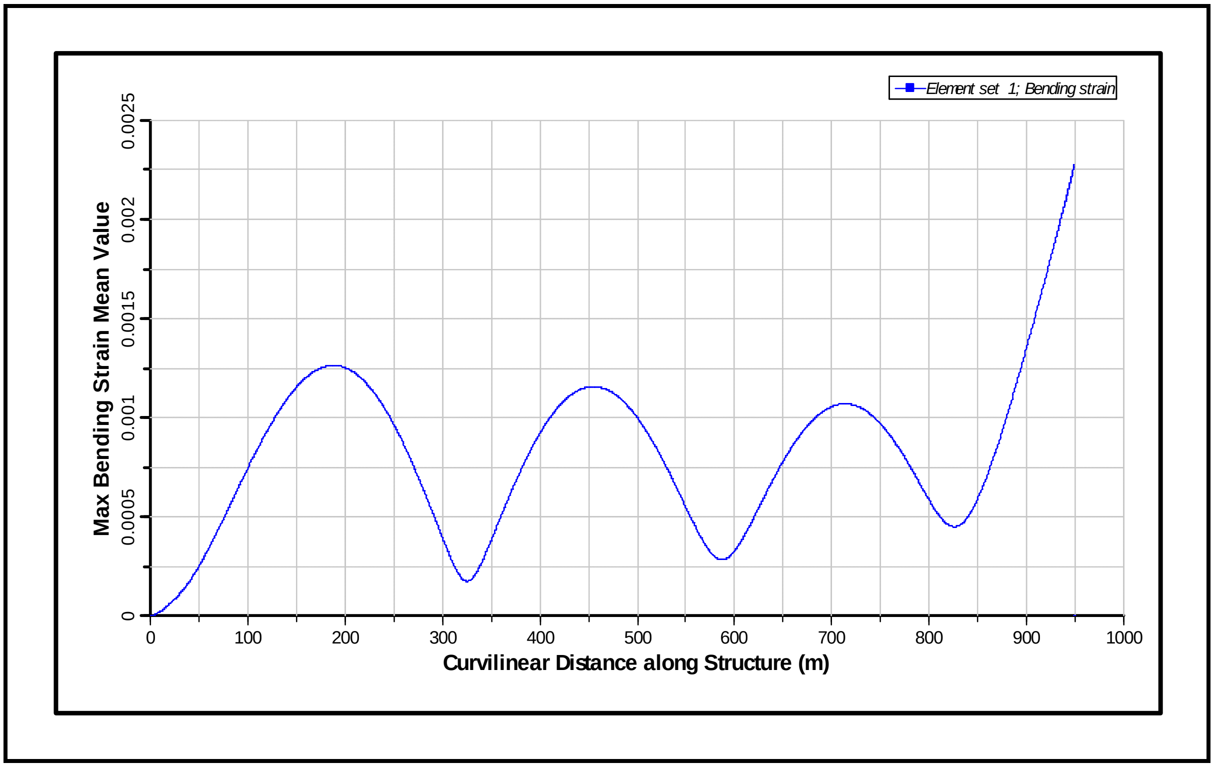


Figure 296: Mean Bending Strain for 1000 m CWP for Bin 15 (from Bottom to Top)

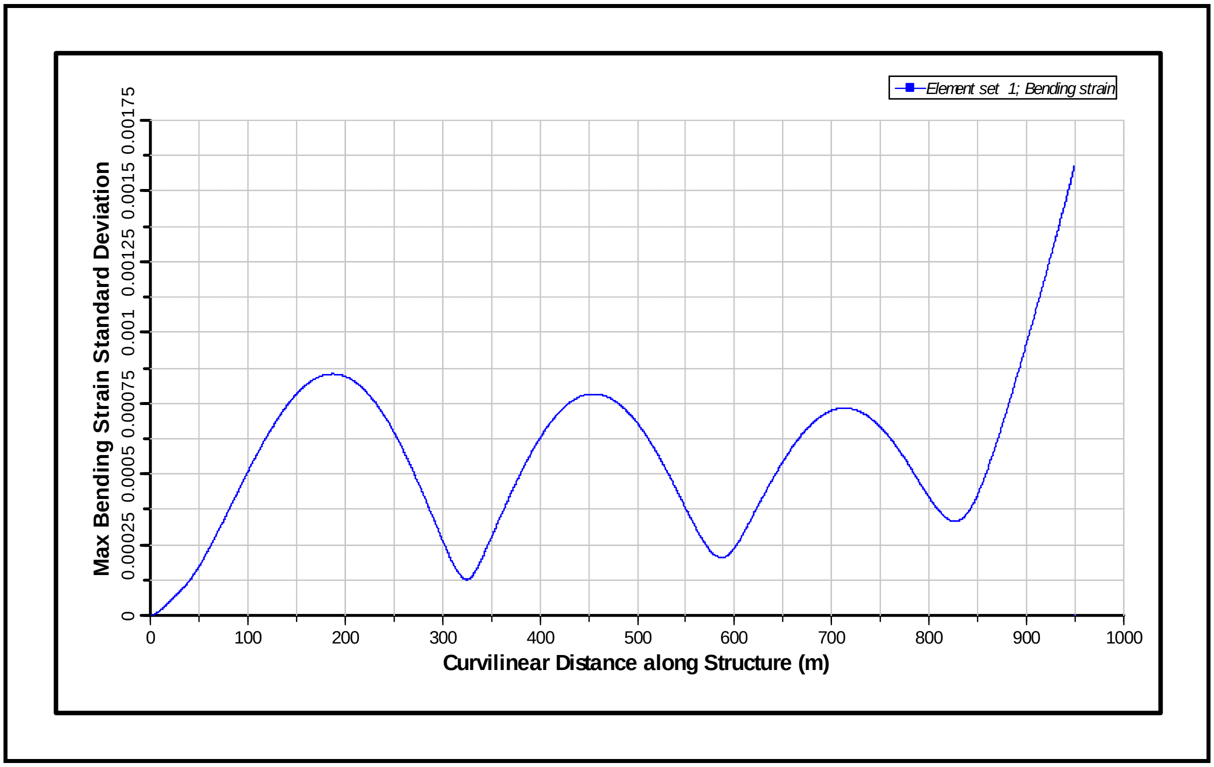


Figure 297: Standard Deviation of Bending Strain for 1000 m CWP for Bin 15 (from Bottom to Top)

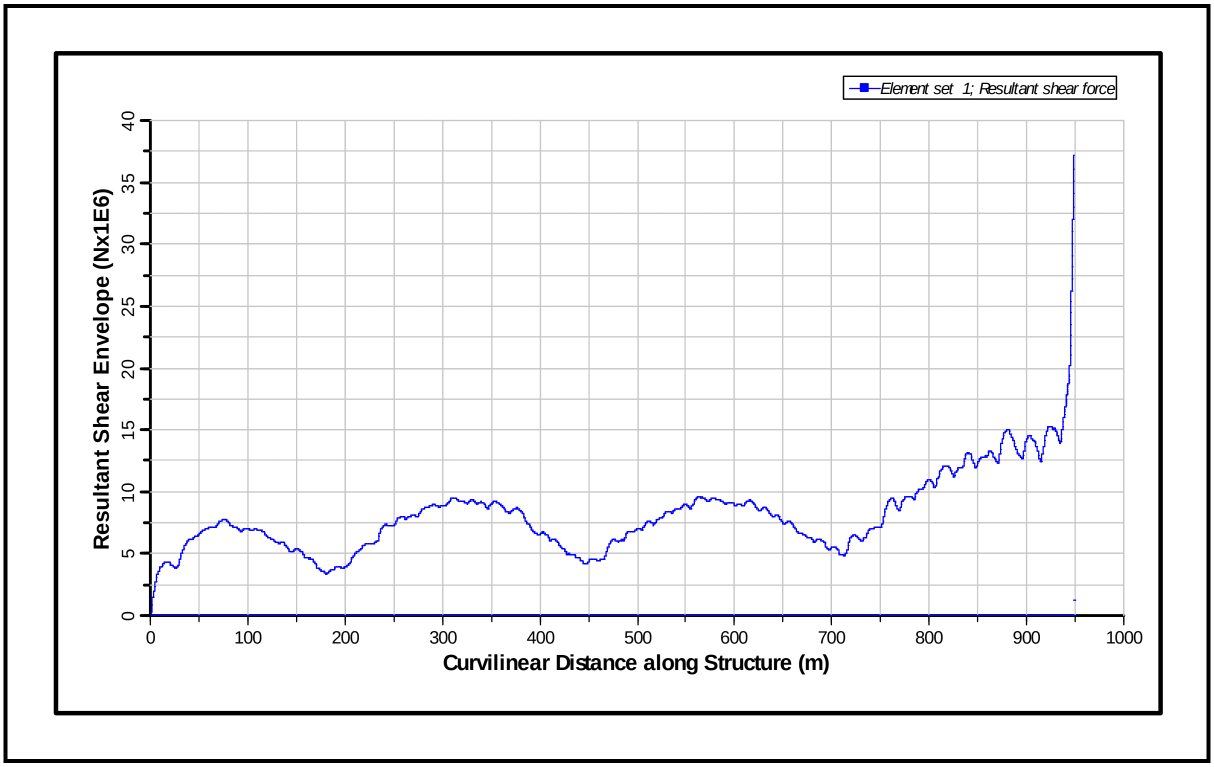


Figure 298: Shear Force Envelope for 1000 m CWP for Bin 15 (from Bottom to Top)

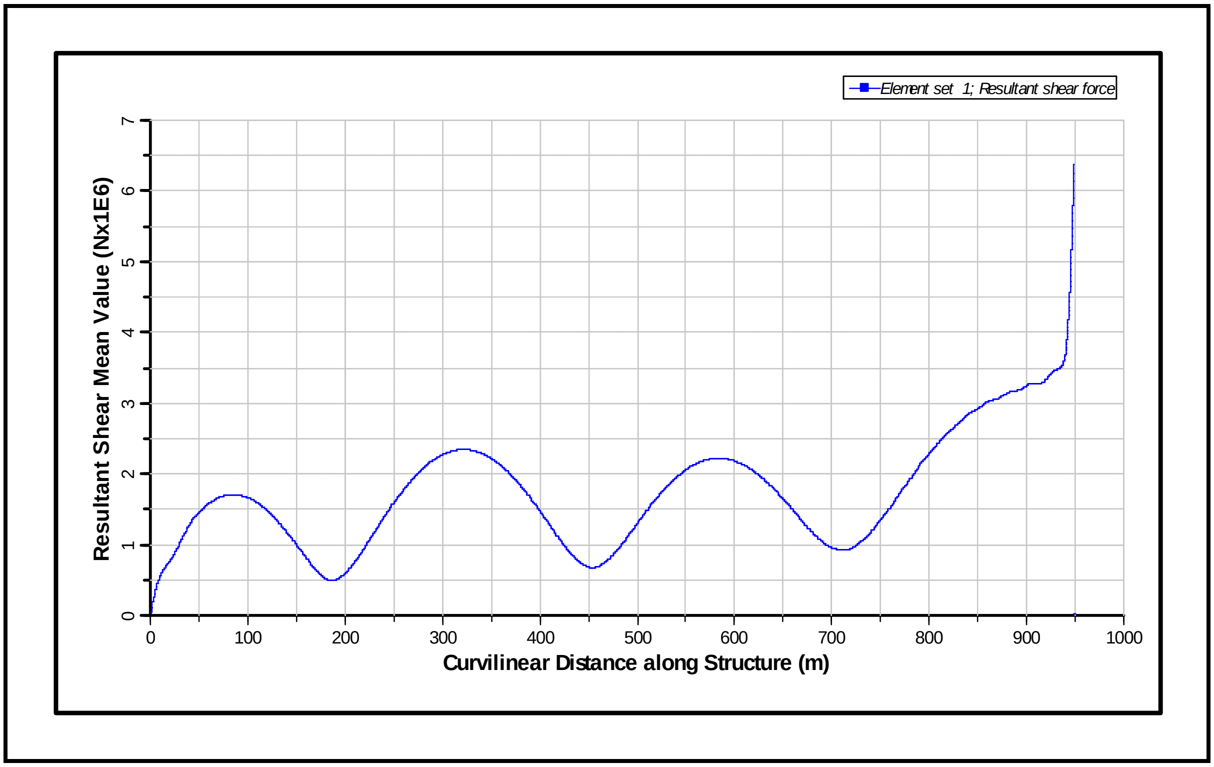


Figure 299: Mean Shear Force for 1000 m CWP for Bin 15 (from Bottom to Top)

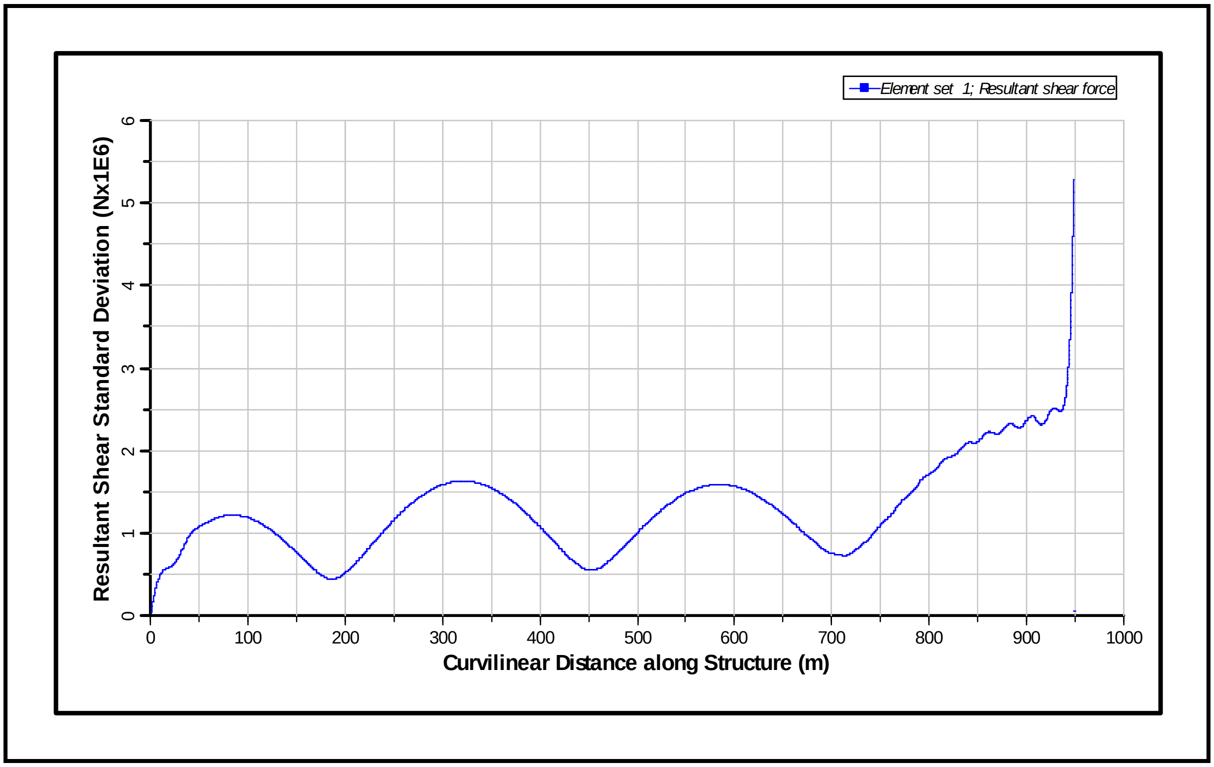


Figure 300: Standard Deviation of Shear Force for 1000 m CWP for Bin 15 (from Bottom to Top)

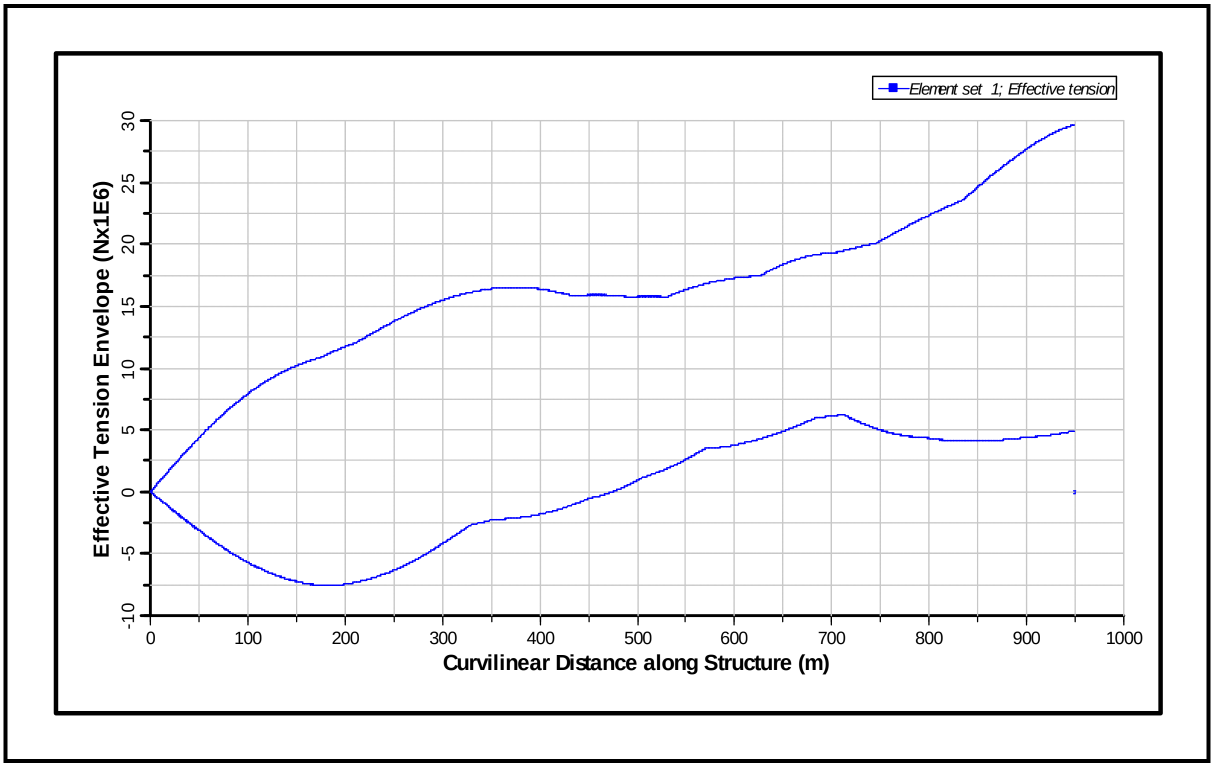


Figure 301: Axial Tension Envelope for 1000 m CWP for Bin 15 (from Bottom to Top)

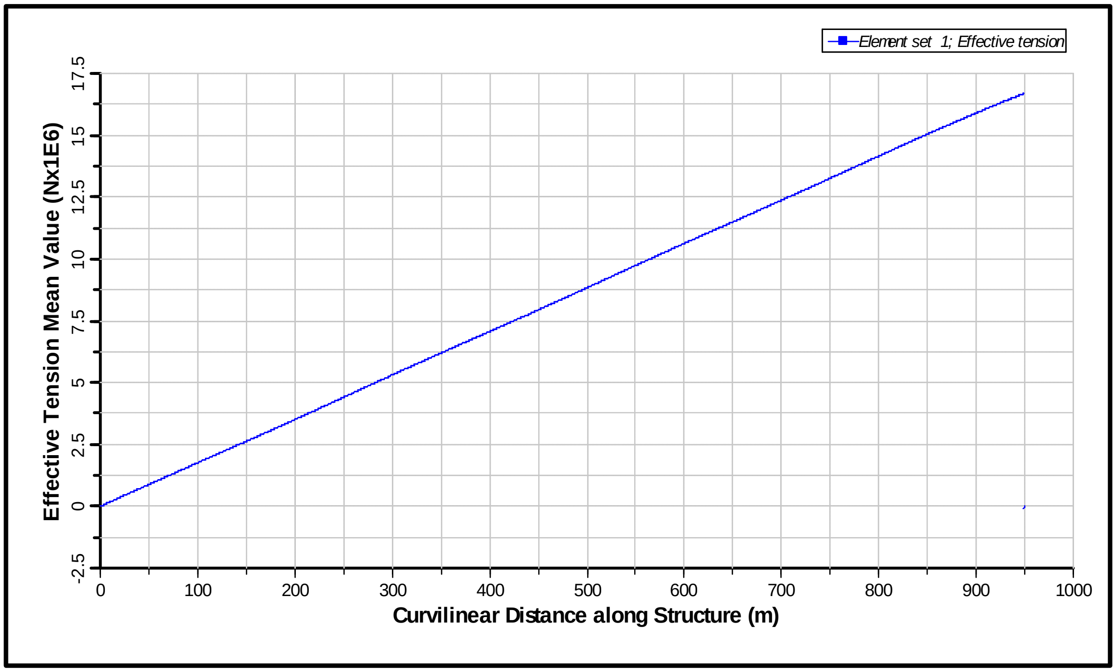


Figure 302: Mean Axial Tension for 1000 m CWP for Bin 15 (from Bottom to Top)

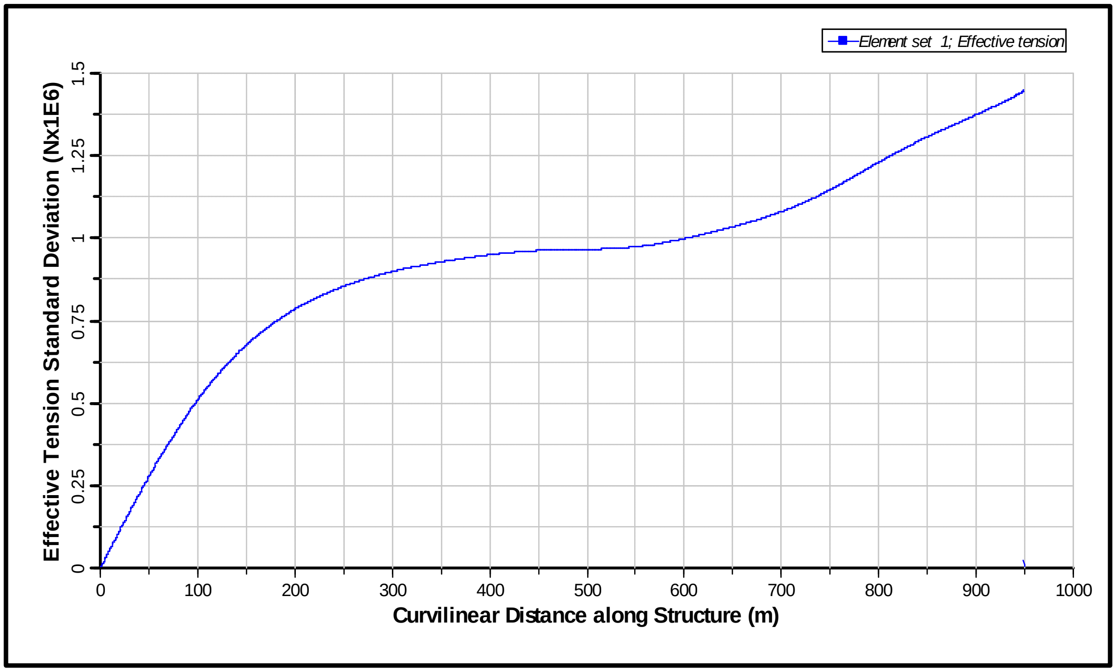


Figure 303: Standard Deviation of Axial Tension for 1000 m CWP for Bin 15 (from Bottom to Top)

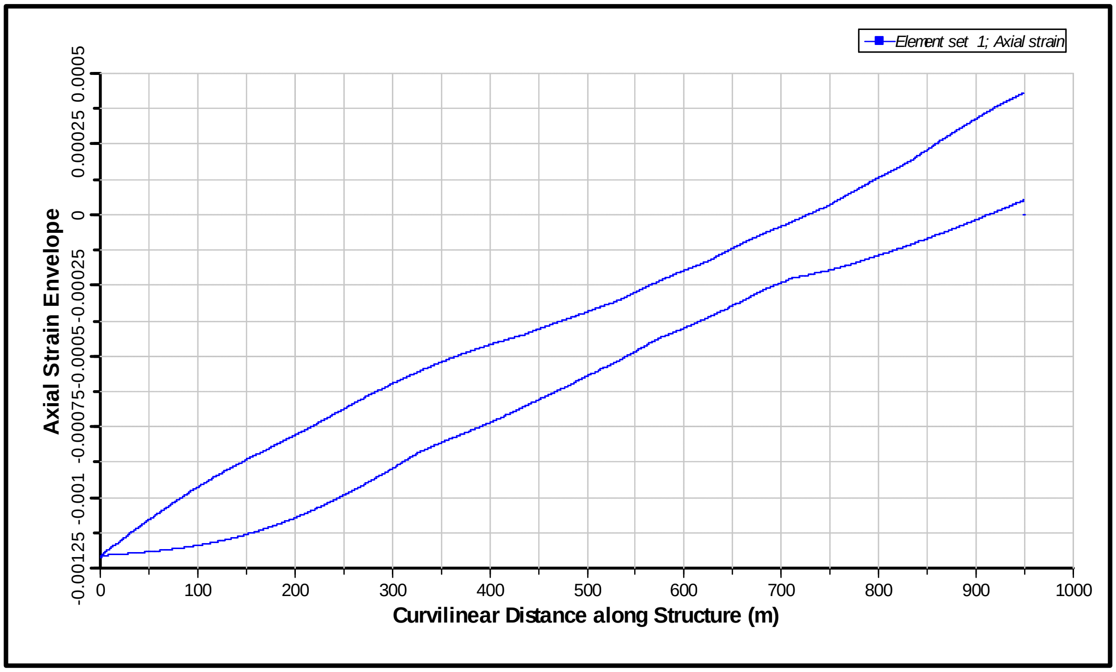


Figure 304: Axial Strain Envelope for 1000 m CWP for Bin 15 (from Bottom to Top)

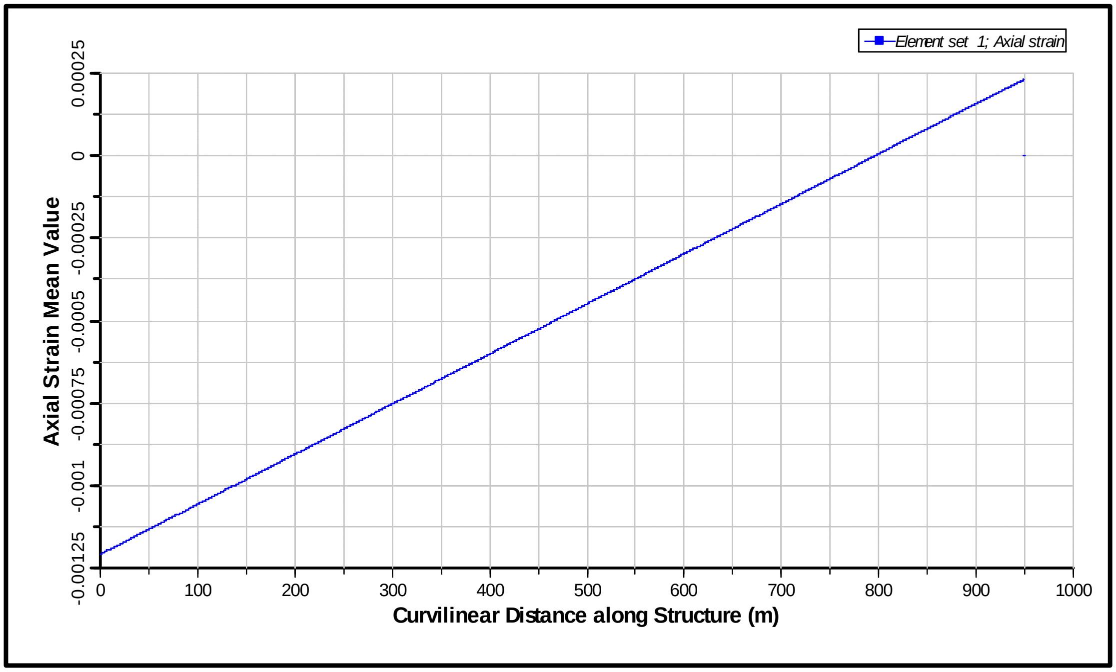


Figure 305: Mean Axial Strain for 1000 m CWP for Bin 15 (from Bottom to Top)

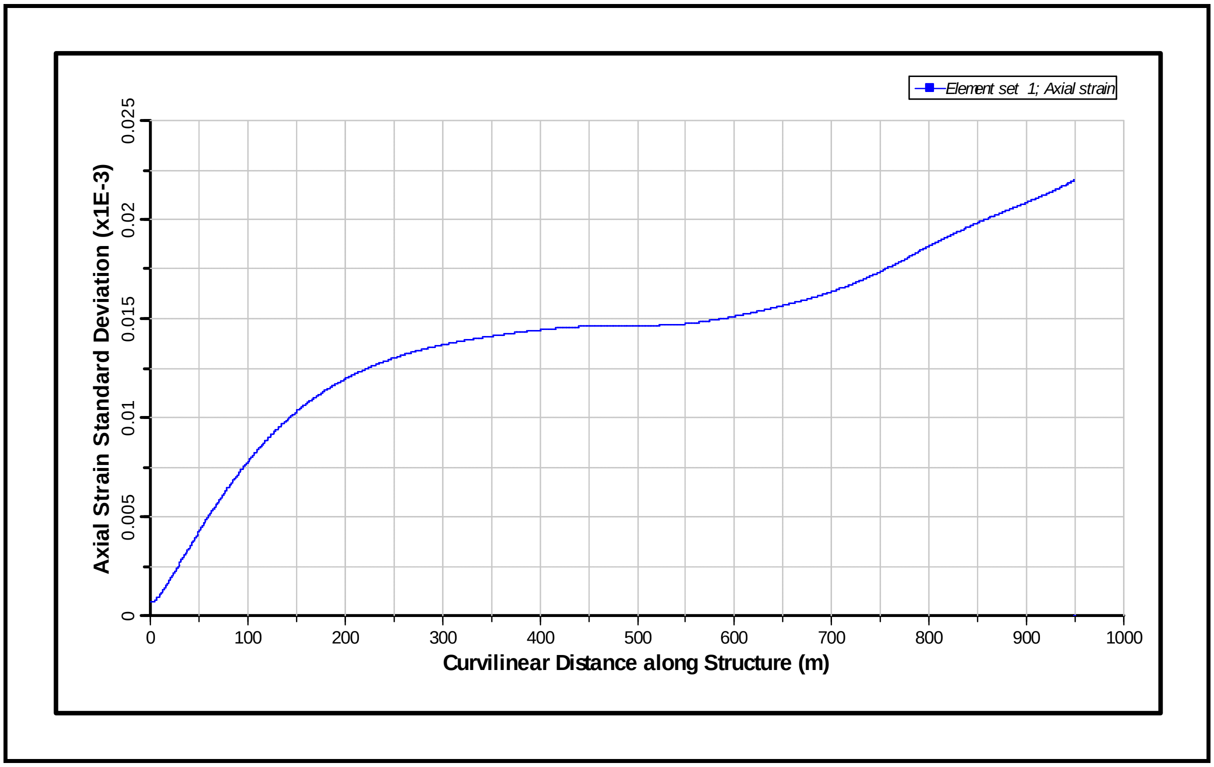


Figure 306: Standard Deviation of Axial Strain for 1000 m CWP for Bin 15 (from Bottom to Top)

6.1 Bin 16

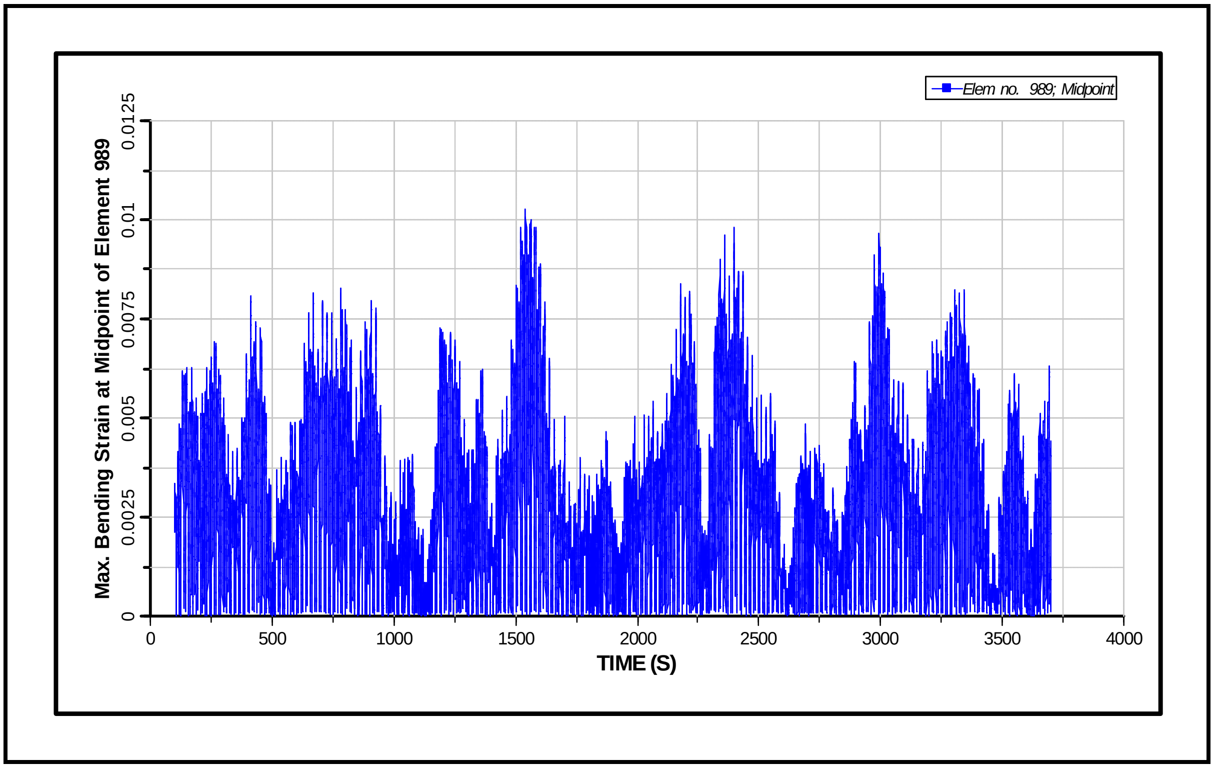


Figure 307: Maximum Bending Strain Time History at Top of CWP for Bin 16

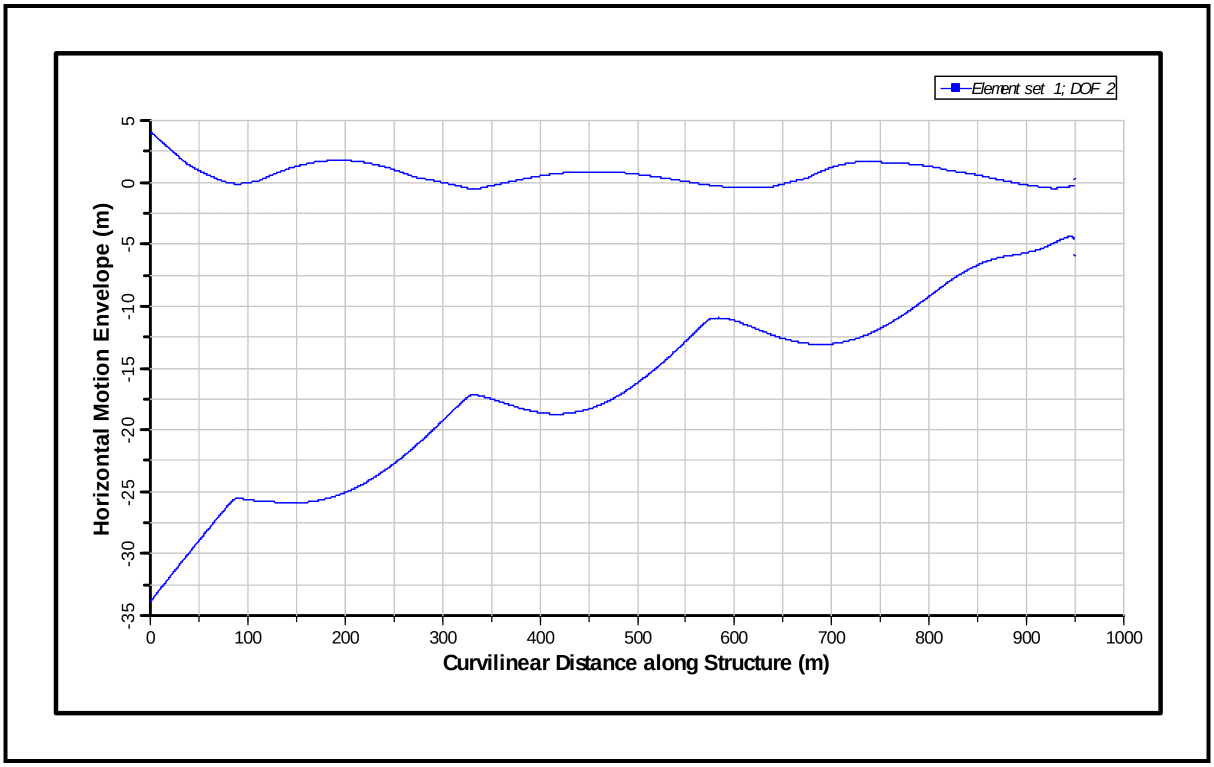


Figure 308: Motion Envelope for 1000 m CWP for Bin 16 (from Bottom to Top)

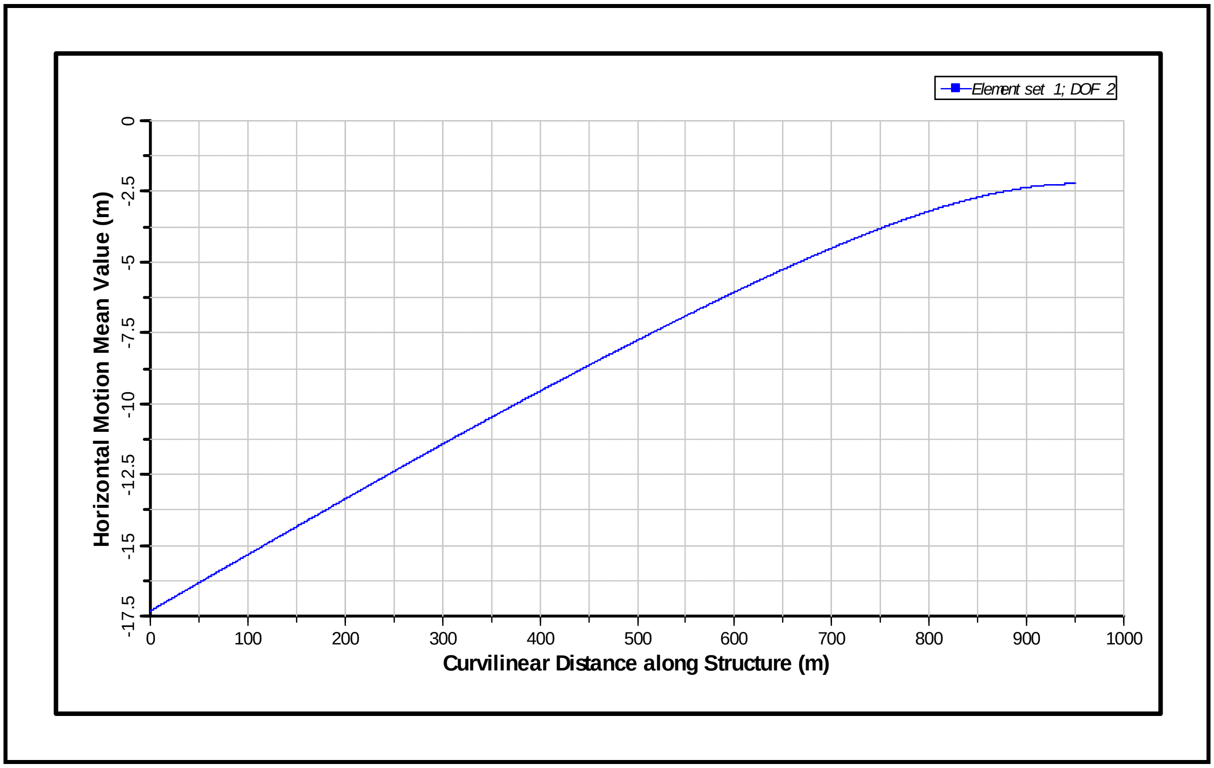


Figure 309: Mean Motion for 1000 m CWP for Bin 16 (from Bottom to Top)

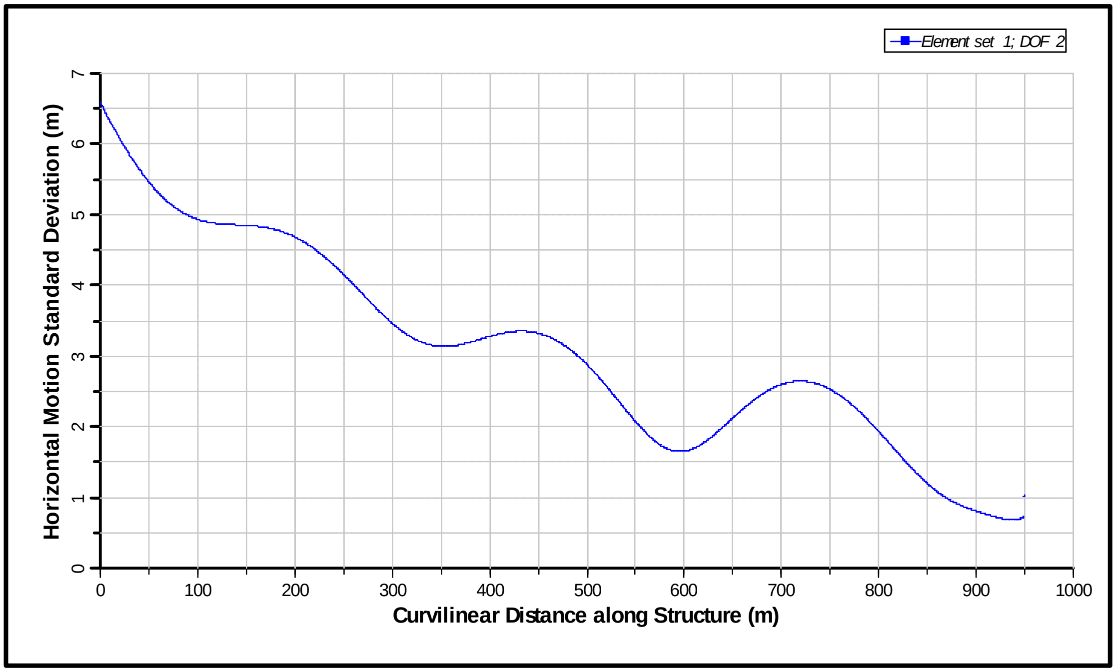


Figure 310: Standard Deviation of Motion for 1000 m CWP for Bin 16 (from Bottom to Top)

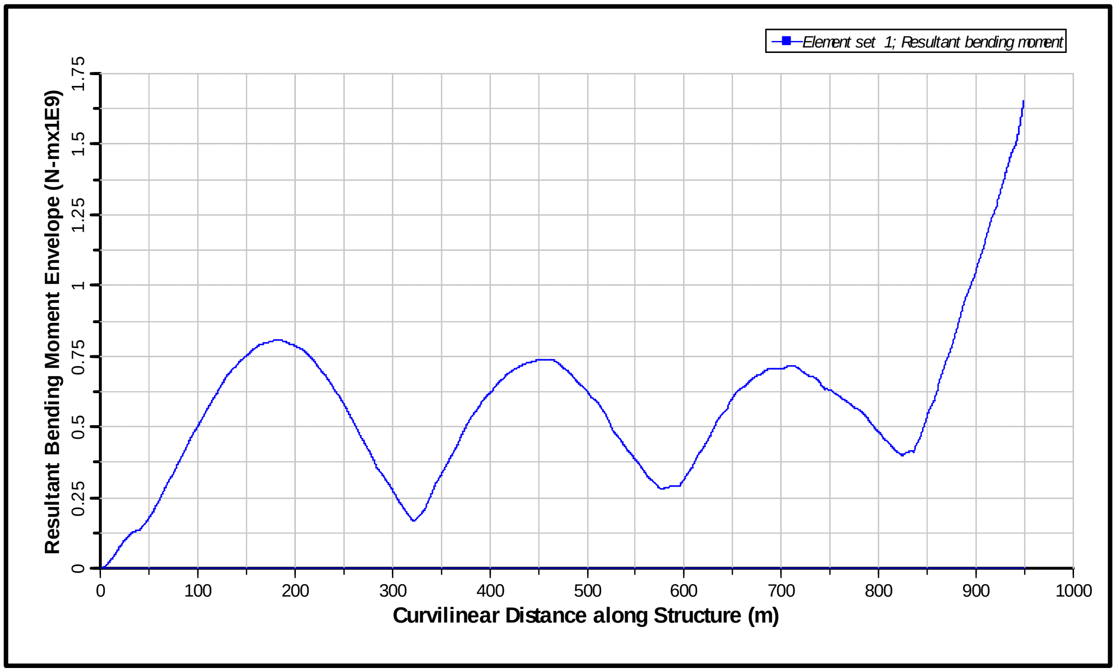


Figure 311: Bending Moment Envelope for 1000 m CWP for Bin 16 (from Bottom to Top)

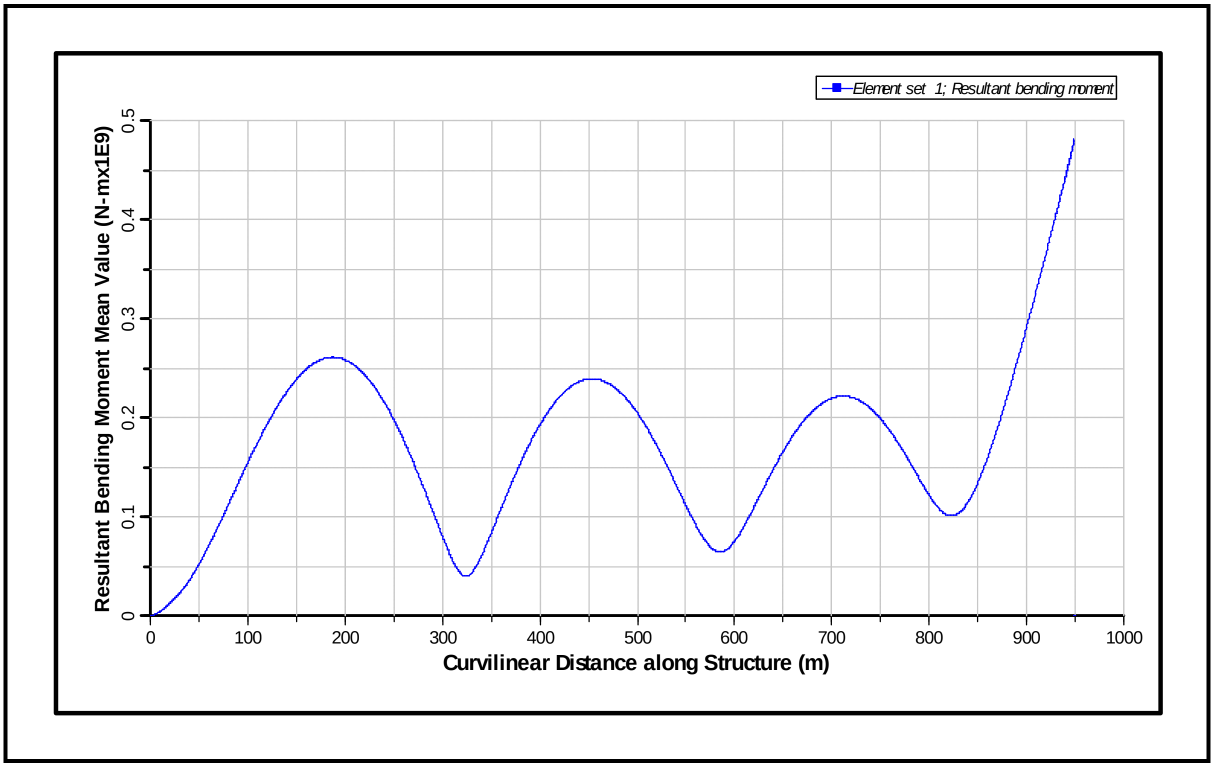


Figure 312: Mean Bending Moment for 1000 m CWP for Bin 16 (from Bottom to Top)

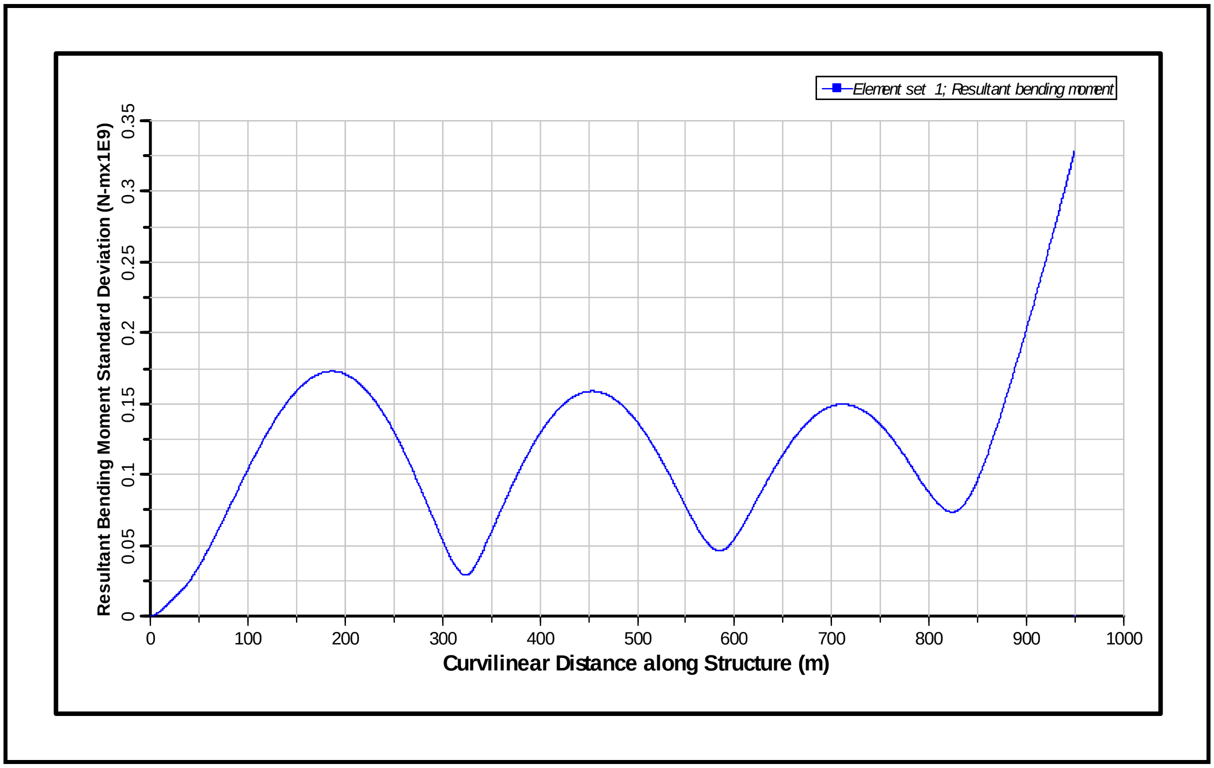


Figure 313: Standard Deviation of Bending Moment for 1000 m CWP for Bin 16 (from Bottom to Top)

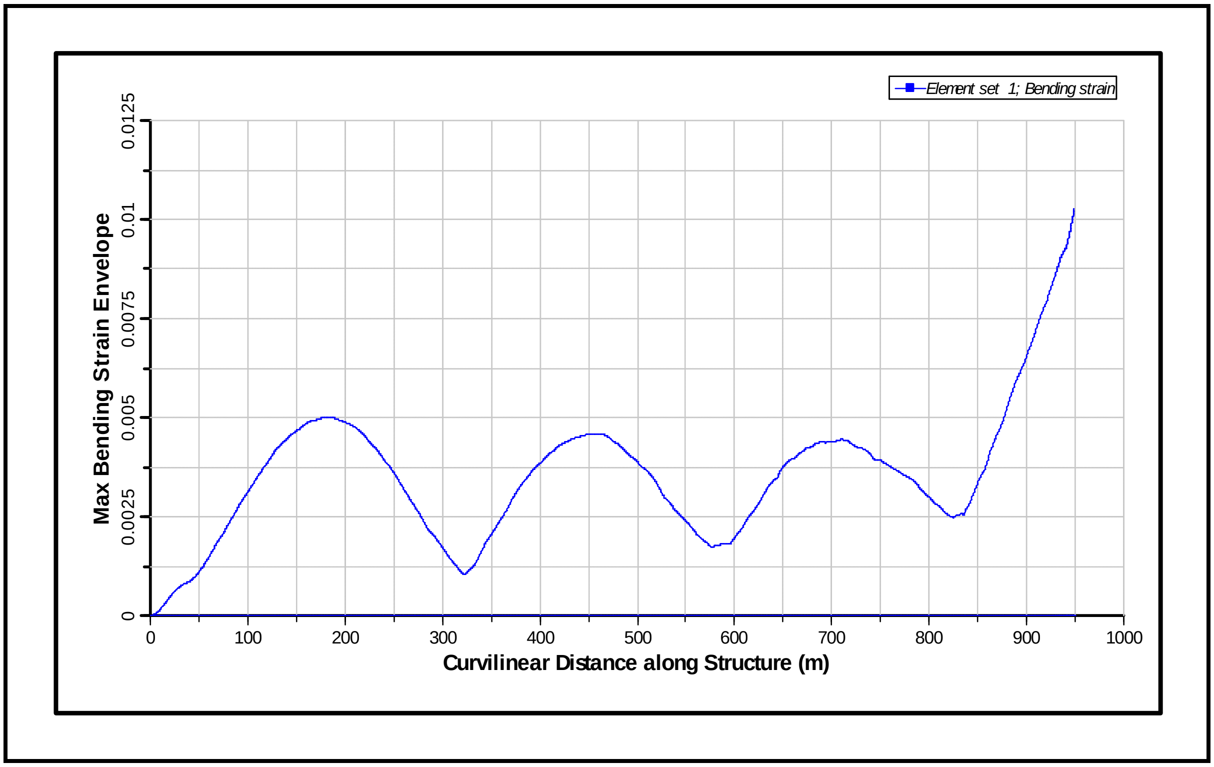


Figure 314: Bending Strain Envelope for 1000 m CWP for Bin 16 (from Bottom to Top)

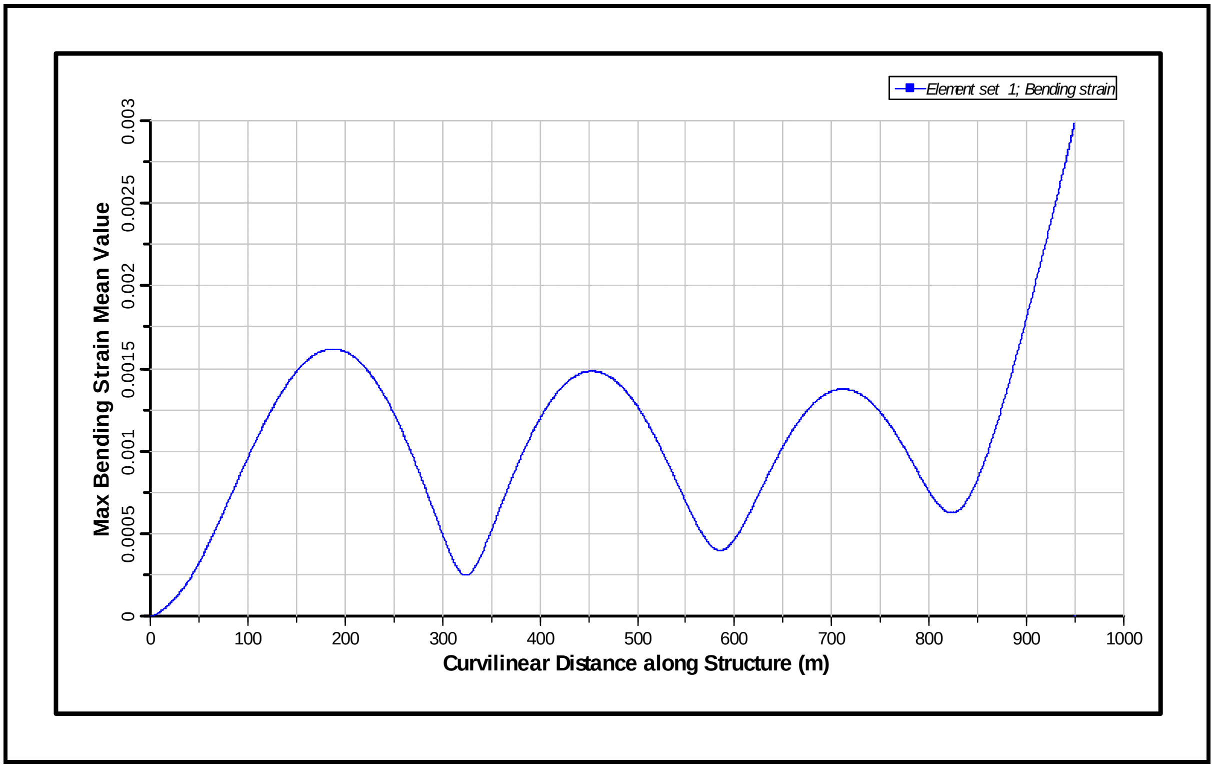


Figure 315: Mean Bending Strain for 1000 m CWP for Bin 16 (from Bottom to Top)

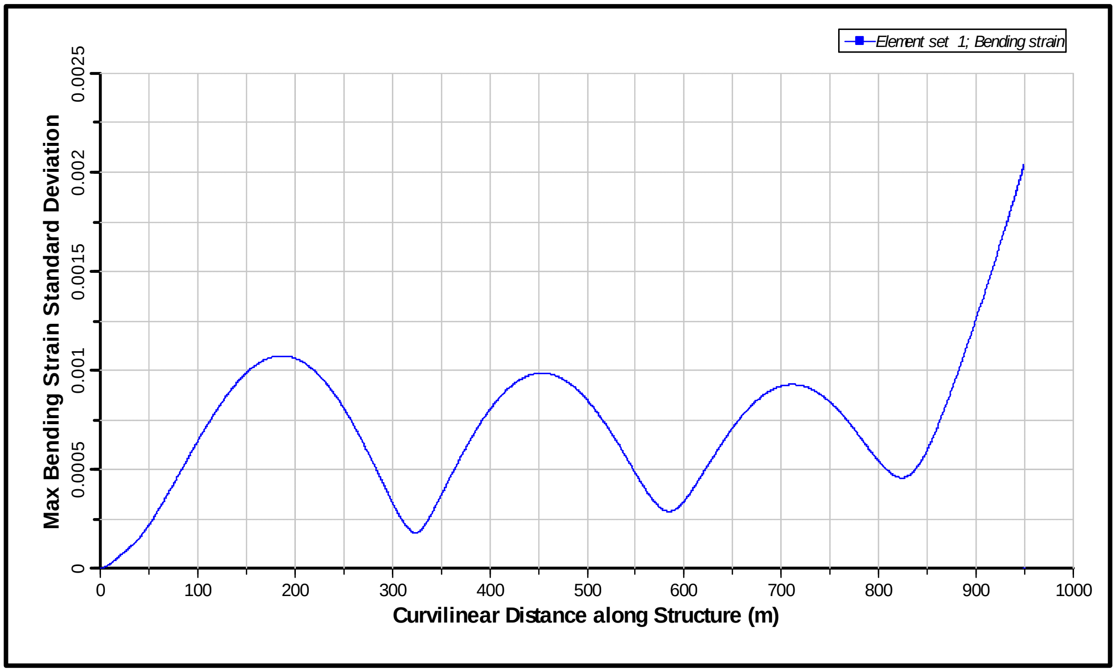


Figure 316: Standard Deviation of Bending Strain for 1000 m CWP for Bin 16 (from Bottom to Top)

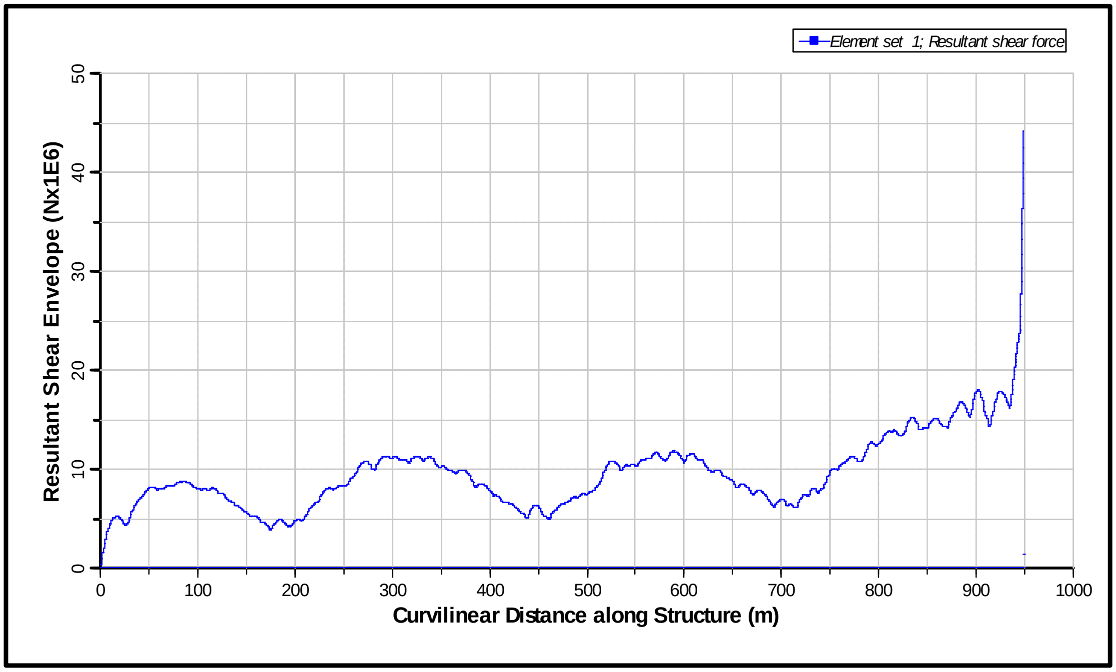


Figure 317: Shear Force Envelope for 1000 m CWP for Bin 16 (from Bottom to Top)

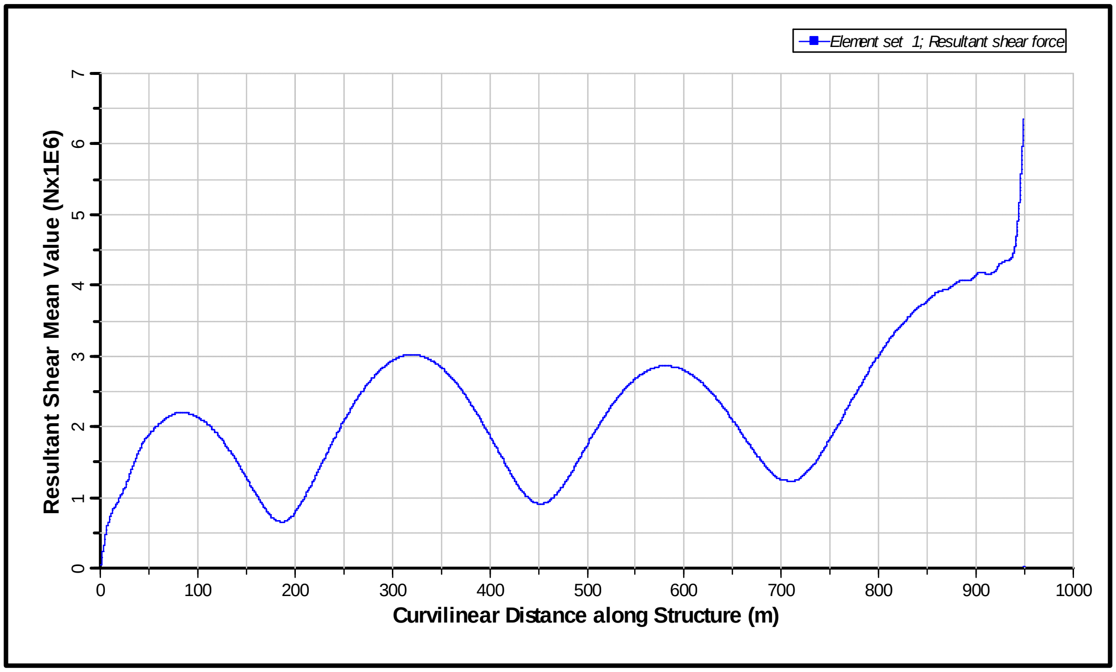


Figure 318: Mean Shear Force for 1000 m CWP for Bin 16 (from Bottom to Top)

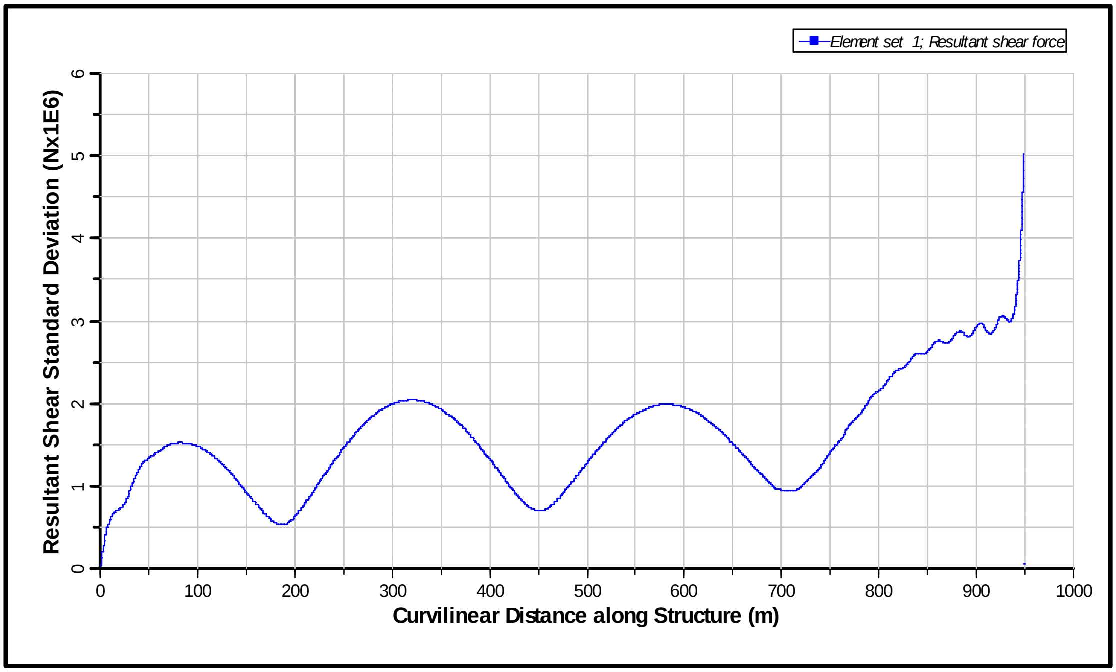


Figure 319: Standard Deviation of Shear Force for 1000 m CWP for Bin 16 (from Bottom to Top)

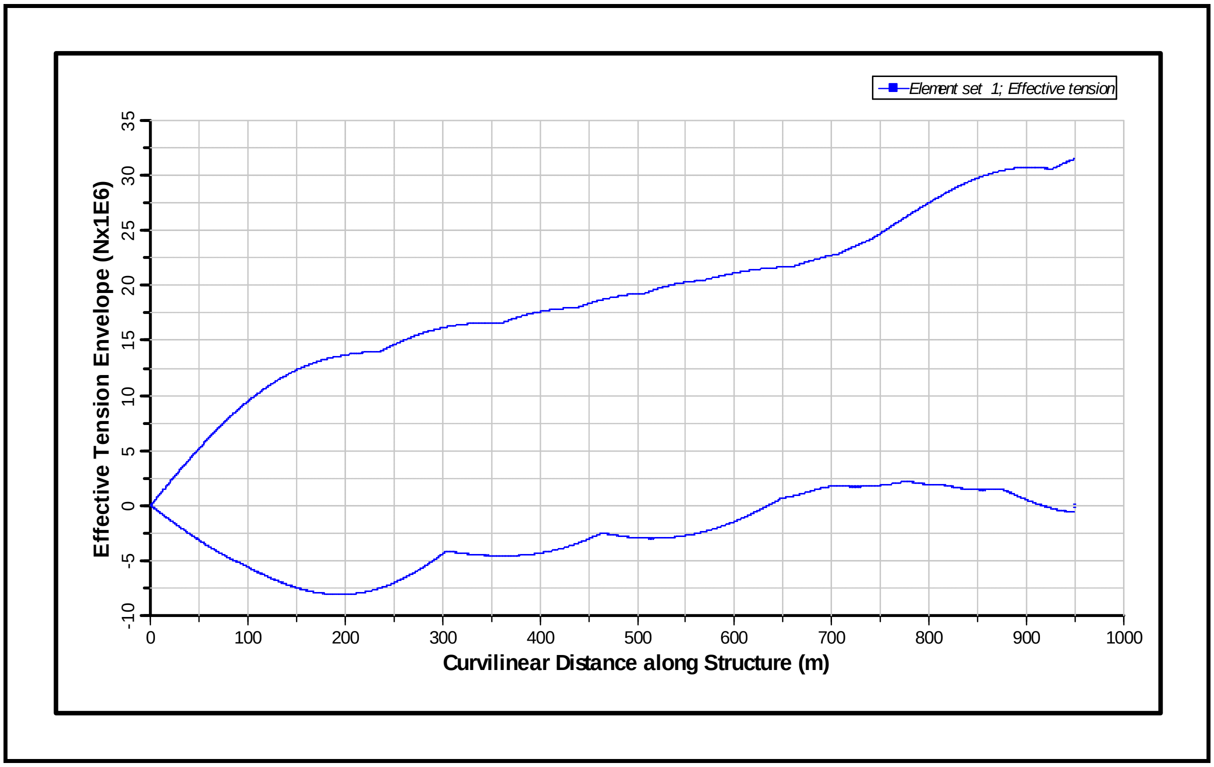


Figure 320: Axial Tension Envelope for 1000 m CWP for Bin 16 (from Bottom to Top)

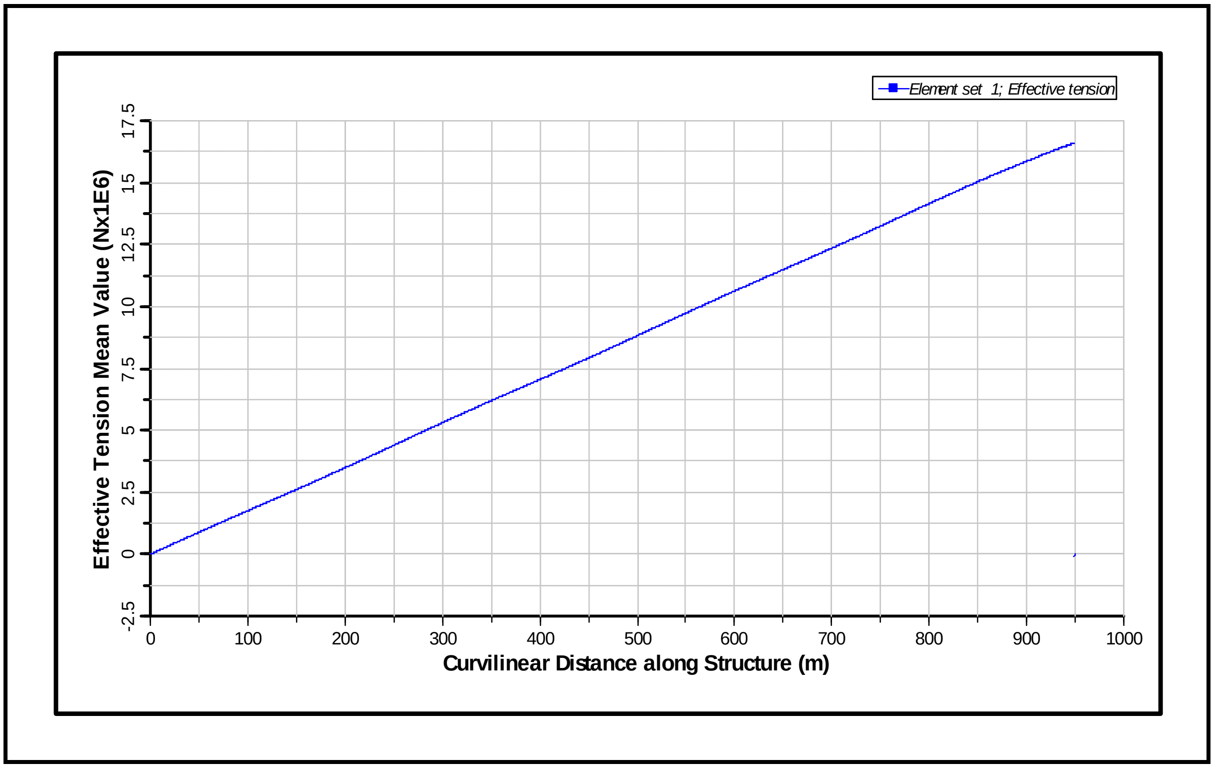


Figure 321: Mean Axial Tension for 1000 m CWP for Bin 16 (from Bottom to Top)

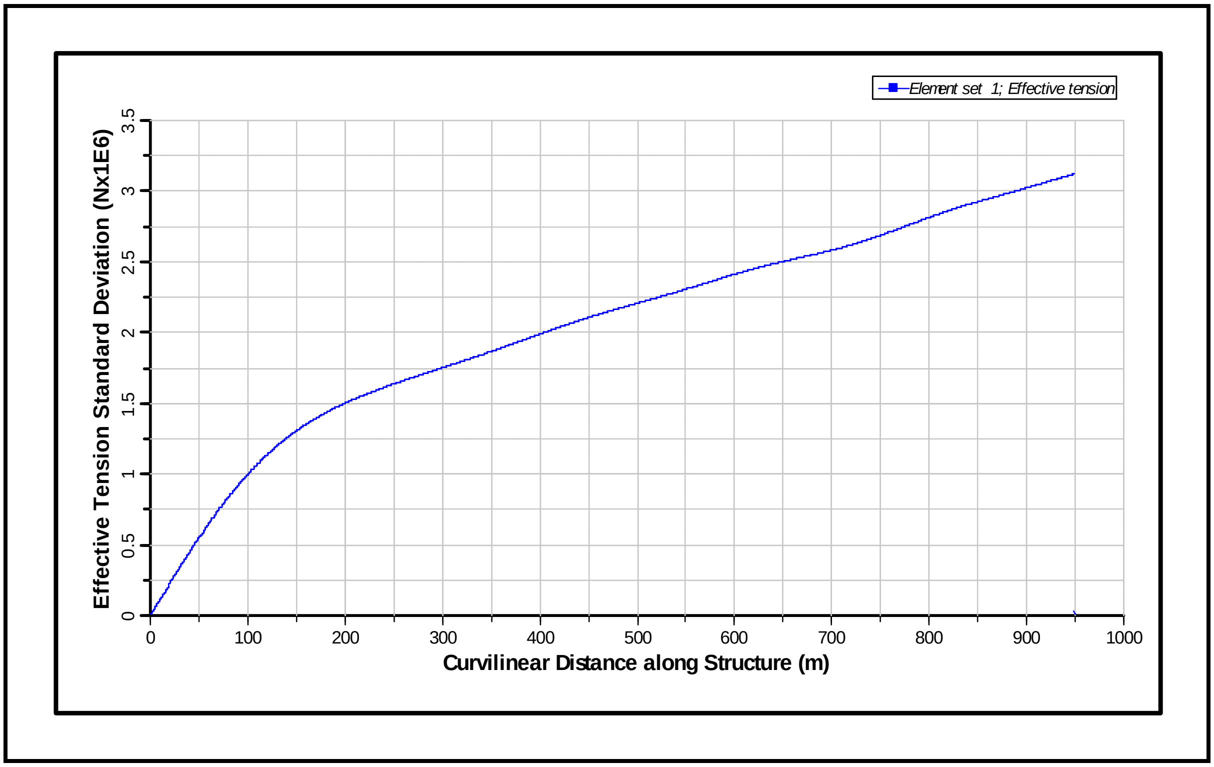


Figure 322: Standard Deviation of Axial Tension for 1000 m CWP for Bin 16 (from Bottom to Top)

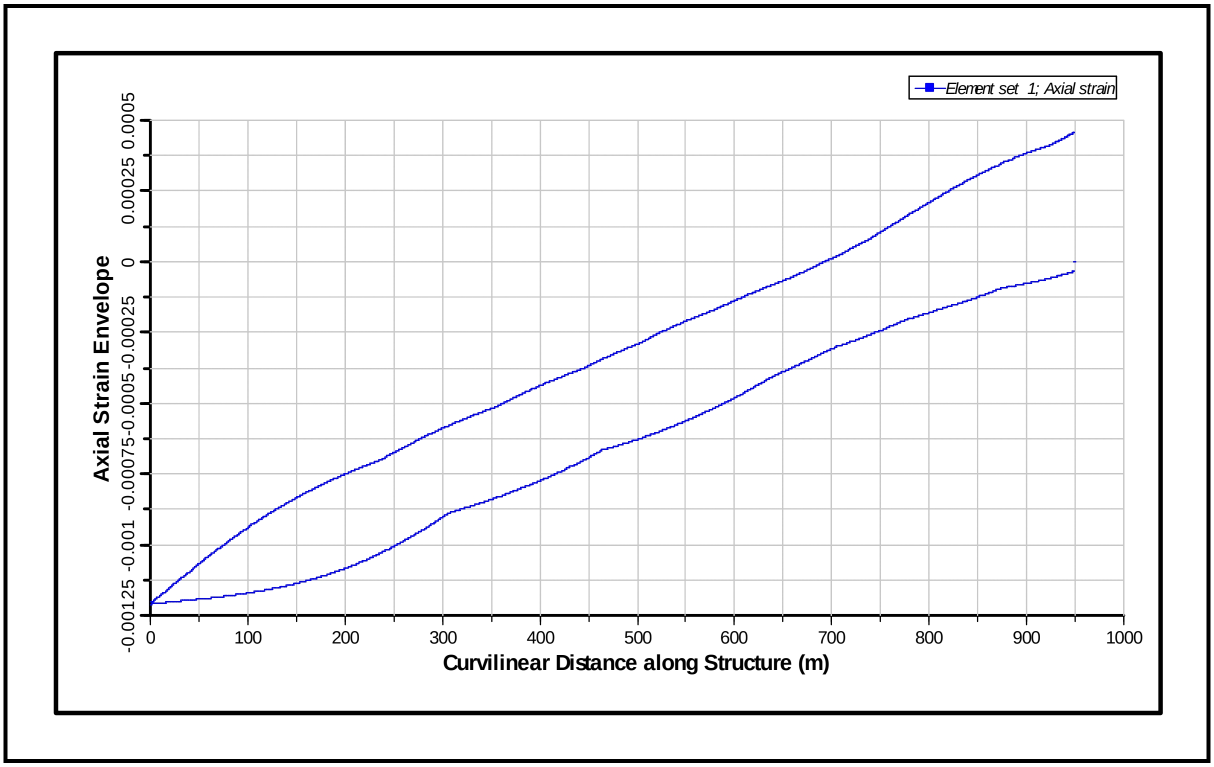


Figure 323: Axial Strain Envelope for 1000 m CWP for Bin 16 (from Bottom to Top)

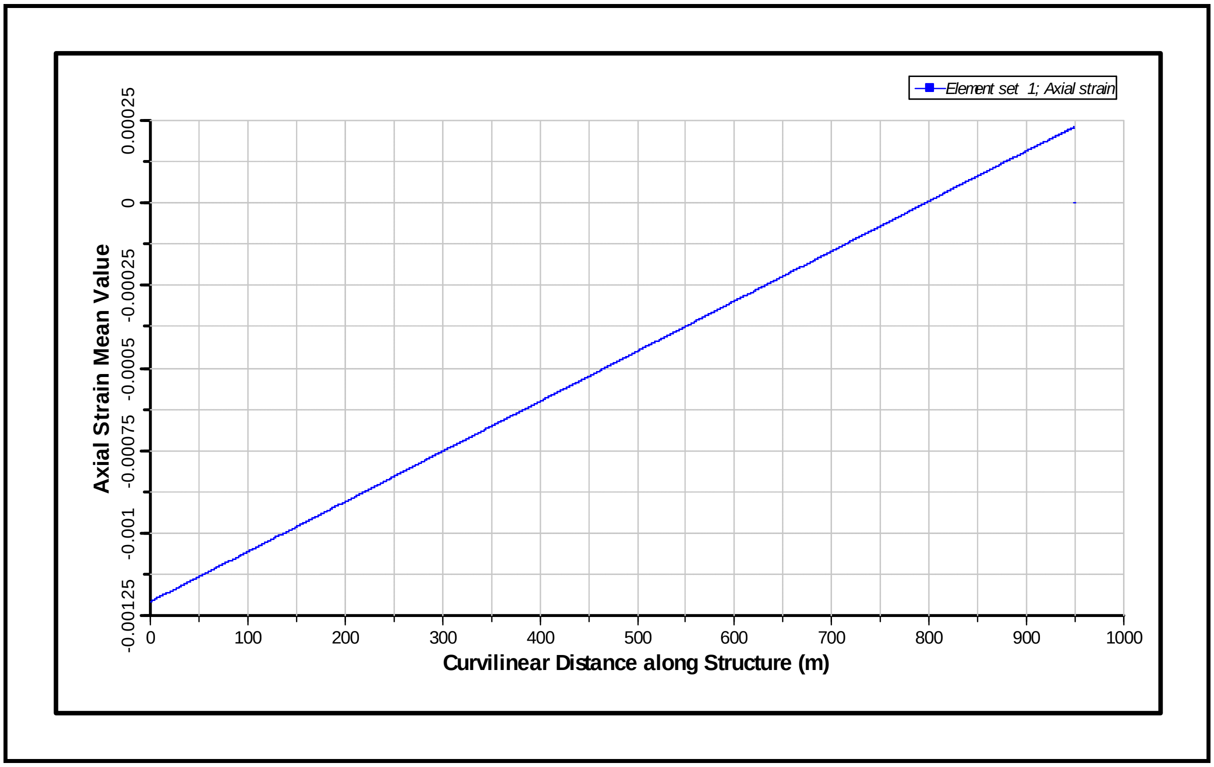


Figure 324: Mean Axial Strain for 1000 m CWP for Bin 16 (from Bottom to Top)

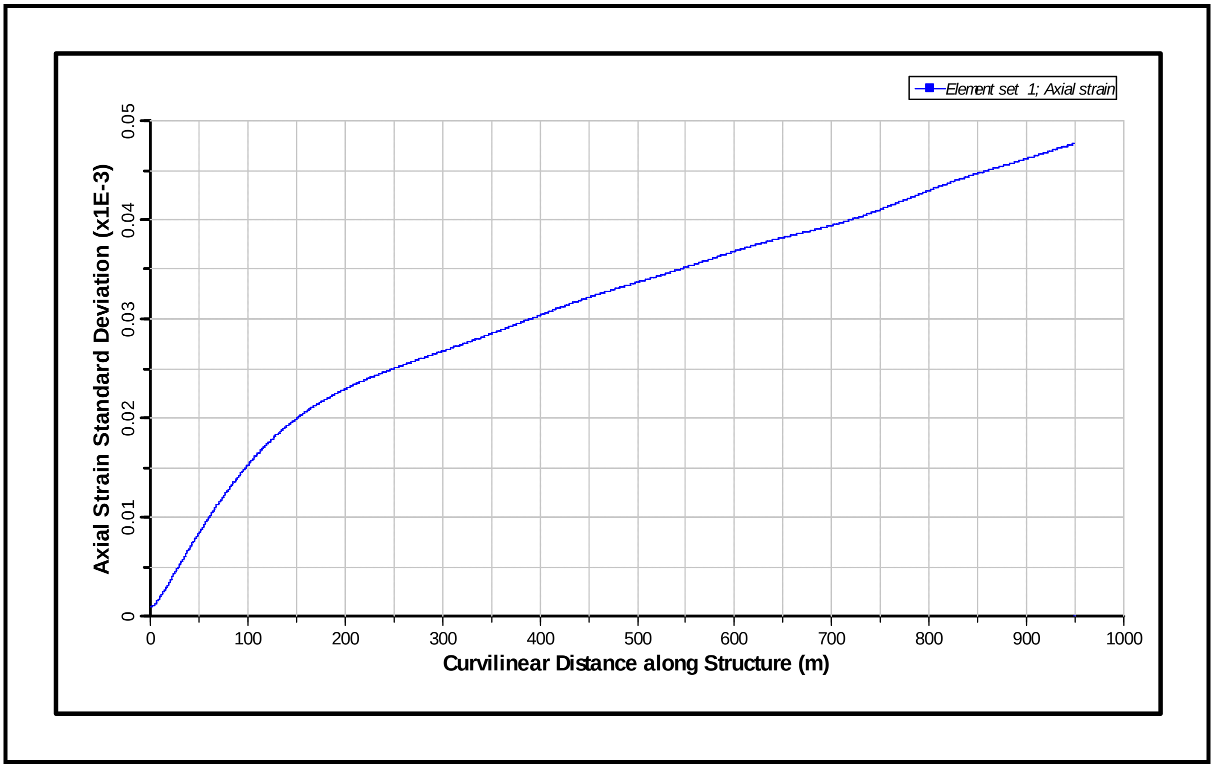
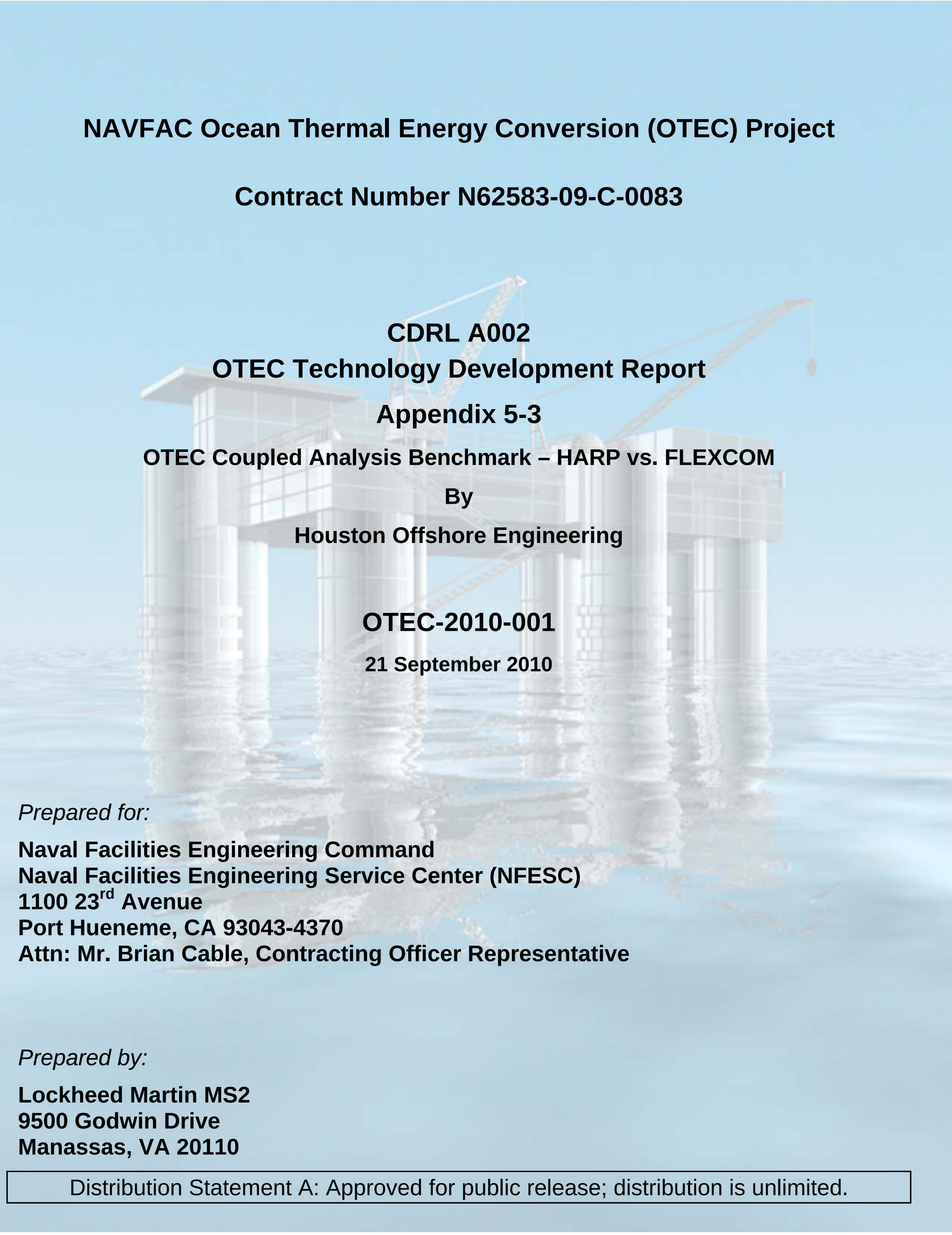


Figure 325: Standard Deviation of Axial Strain for 1000 m CWP for Bin 16 (from Bottom to Top)



NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report

Appendix 5-3

OTEC Coupled Analysis Benchmark – HARP vs. FLEXCOM

By

Houston Offshore Engineering

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
Naval Facilities Engineering Service Center (NFESC)
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OTEC Coupled Analysis Benchmark

HARP vs. Flexcom

April 15, 2010

HOE-OTEC	B	April 15, 2010	Initial rELEASE	NVK	SS	JHA
HOE-OTEC	1	March, 2010	Issue for information	NVK	SS	JHA
Doc. No.	**Rev**	**Date**	**Description**	**By**	**Appr.**	**Client**

Houston Offshore
ENGINEERING

1 SUMMARY

The objective of the study is to benchmark HARP coupled analysis results using another coupled analysis program Flexcom. The following issues will be investigated by performing comparable coupled analyses using the two programs.

(1) CWP strains evaluated form the two coupled analysis programs
(2) Vessel motion comparison for the cases using a rigid, a large rotational spring and a soft rotational spring at CWP top connections.

2 DESIGN DATA

2.1 Vessel Data

The 100MW Semi with eight (8) remoras, see Figures 2.1.1 and 2.1.2 are modeled and analyzed in this comparison study. Details of the OTEC platform is defined in the document “TN-10-102 OTEC Platform Data for Benchmarking of Pipe – Platform Analysis”.

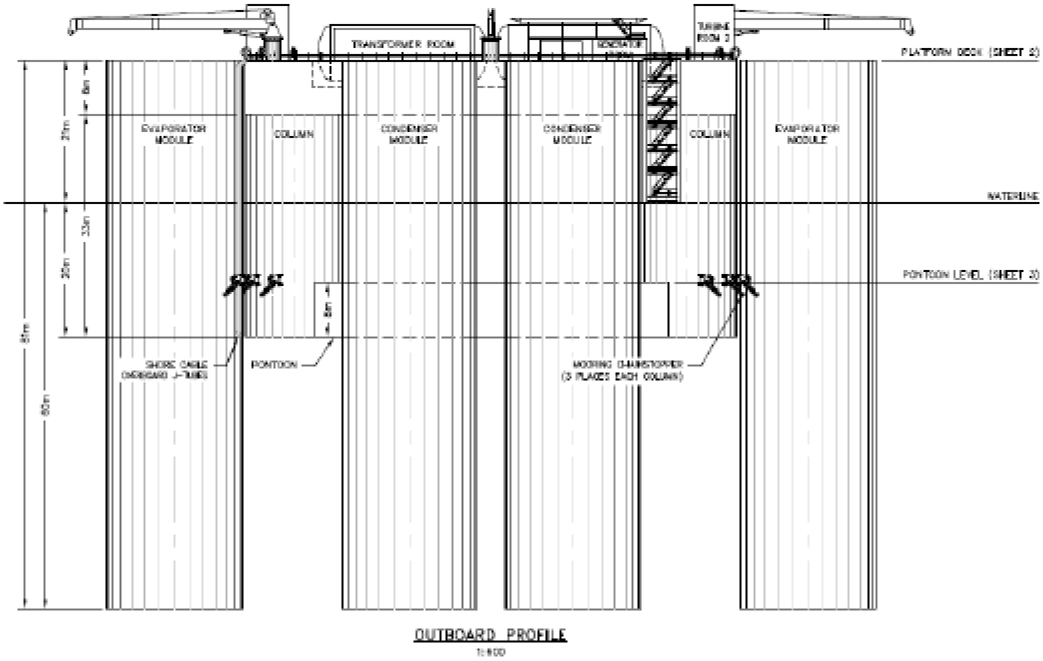


Figure 2.1.1 100MW OTEC Platform, Outboard Profile

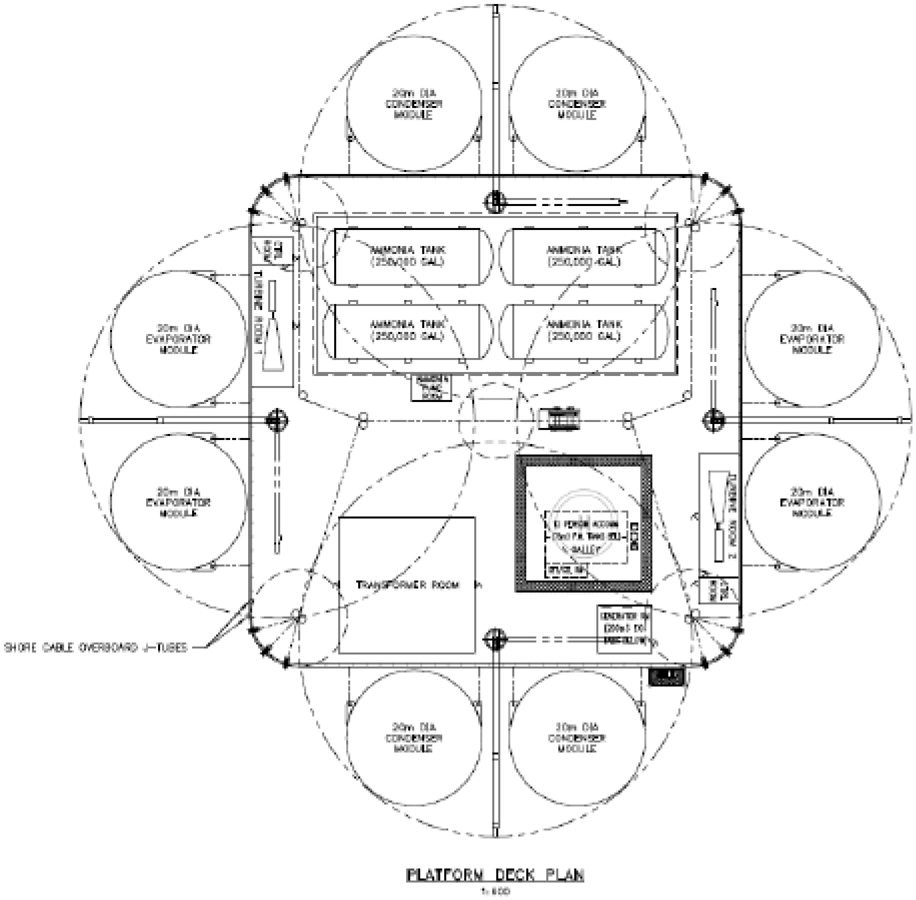


Figure 2.1.2 100MW OTEC Platform, Deck Plan

2.2 CWP Properties

All Models were analyzed with CWP Version 2 properties

Property					
Inside Diameter	394	in		10.01	m
Outside Diameter	413.8	in		10.509	m
Wall Thickness	9.9	in		11.25	m
Outside Circumference	1299.9	in		33.02	m
Length below transition	39400	in		1,000.8	m
Cross sectional area, solid:	3366.013706	in ^2		2.17162	m^2
Void inside core, cross sectional area	9167.70	in^2		5.91	m^2
% wall that is void	73%			73%	
Density of composite, average	0.06716	lbm/in^3		1859	kg/m^3
Mass (excludes internal water)	226.1	lbm/in		4,036.9	kg/m
CWP (no bottom weight) Total Mass (excludes internal water)	8,906,625	lbm		4,039,977	kg
Mass including internal water in walls only	565.5	lbm/in		10,099	kg/m
Mass including internal water, FRP walls and interior wall water	5080.4	lbm/in		90,725	kg/m
Dry Weight CWP (no bottom weight)	226.1	lb/in		39,589	N/m
Total Dry Weight (no bottom weight)	8,906,625	lbs		39,619	kN
Total Dry Weight (no bottom weight)	8,906,625	lbs		4,040	tonnes
Wet weight (no bottom weight)	101.41	lb/in		1.811	tonnes/m
Total wet Weight (no bottom weight)	3,995,609	lbs		1,812	tonnes
Total wet Weight inc bottom weight	3,995,609	lbs		1,812	tonnes
EI of wall - bending (ignore internal ribs)	5.70E+07	lb-in^2/in		6.44E+03	kN-m^2/m
EA	1.47E+10	lbs		65,242,320	kN
EI	2.95E+14	lb-in^2		846,963,409	kN-m^2
Cm	2			2	
Cd	1			1	

Table 2.2.1: Properties of cold water pipe

3 COUPLED ANALYSIS MODELS

3.1 HARP Coupled Analysis Model

The HARP coupled analysis model is the same as defined in the document “TN-10-102 OTEC Platform Data for Benchmarking of Pipe – Platform Analysis”. HARP wave forces and vessel mass/stiffness are all defined with respect to MWL.

3.2 Flexcom Coupled Analysis Model

The Flexcom coupled analysis module is called Floating Body Module. It is a very new feature in Flexcom, it has just been added to the program. The version used in this study is new release of version 7.9.4. Flexcom coupled analysis module is able to directly obtain the vessel force RAOs form WAMIT output file. The program allows user to choose the RAO and vessel mass/stiffness definition reference points on the vessel. It could be either on the MWL or the platform CG.

The 100MW OTEC flexcom coupled analysis model (Figure 3.2.1) is generated in the same way of the HARP model was generated. The same WAMIT hydrodynamic analysis results are also used for the Flexcom model. See Figure 3.2.2 and 3.2.3, Morrison members with the same drag coefficients and integration points used in HARP are also modeled in Flexcom for constancy. Mooring lines and CWP are modeled using the same number of elements, locations, and pretensions.

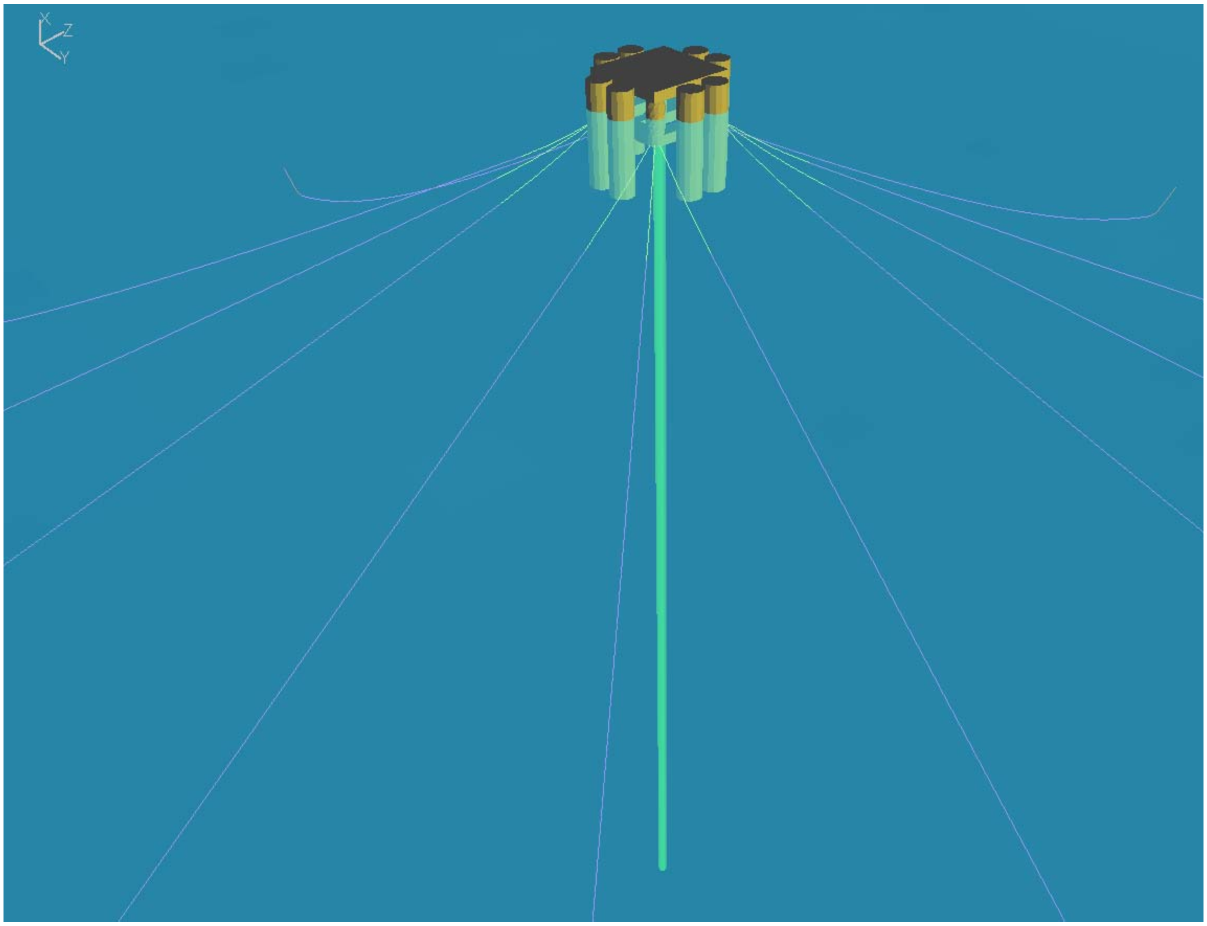


Figure 3.2.1 3D Flexcom Coupled Analysis Model

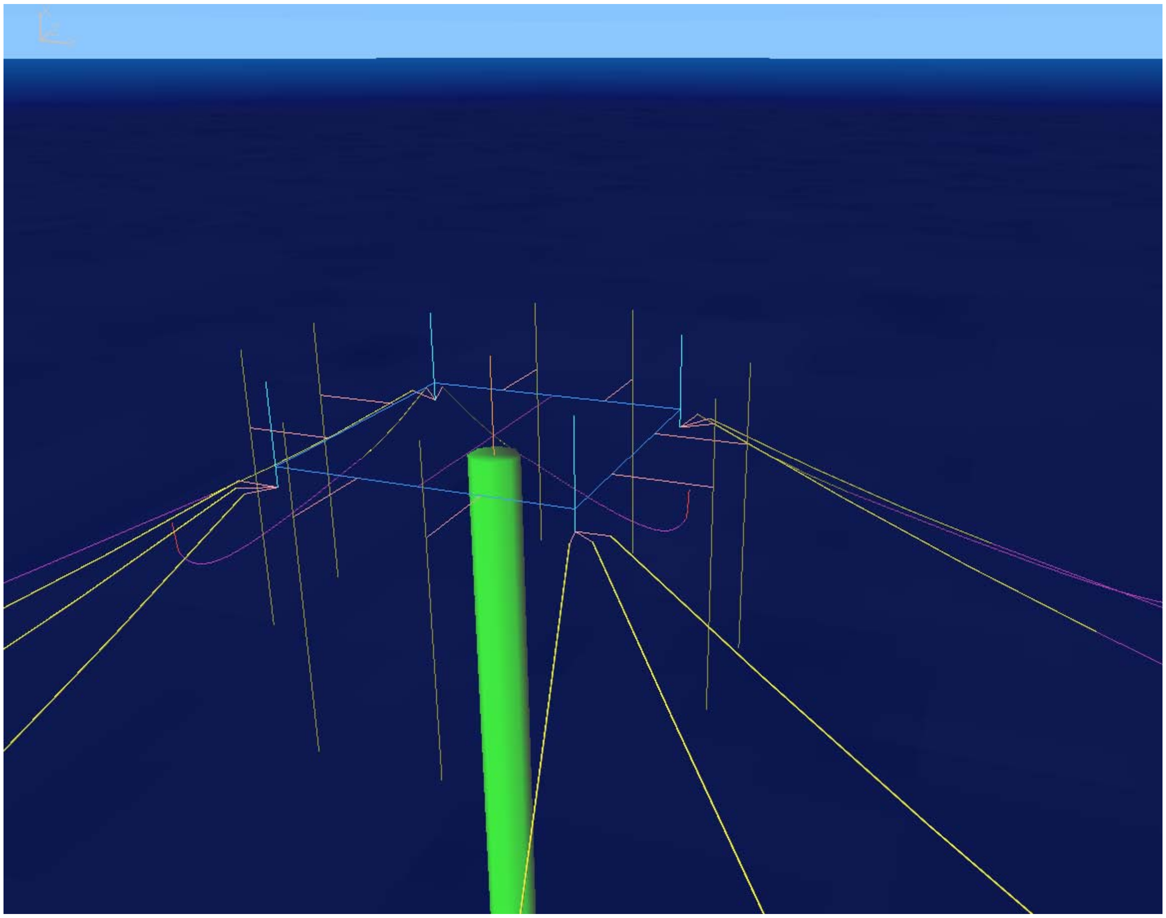


Figure 3.2.2 Vessel Morrison Members Model in Flexcom

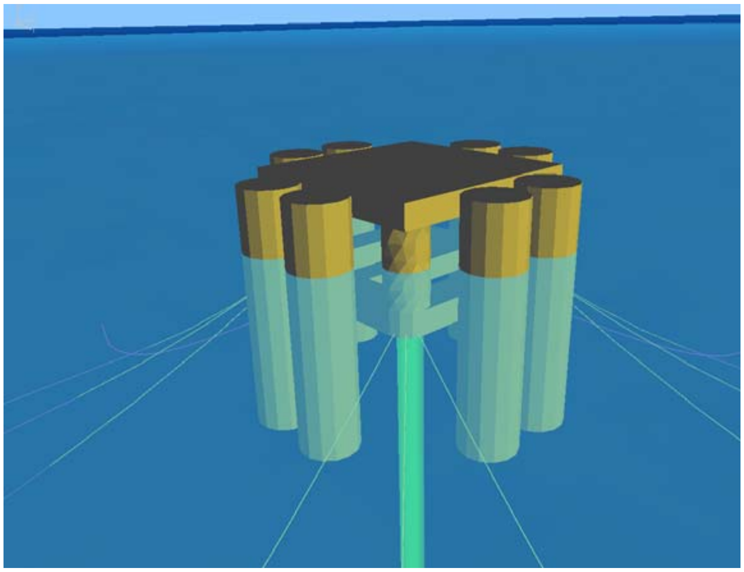


Figure 3.2.3 Vessel Model in Flexcom

4 ANALYSIS CASES AND RESULTS

4.1 Coupled Analysis Cases

The following cases were analyzed:

1. **Platform offset due to current only**

Water Depth (m)	Current Velocity (m/s)
0	0.232
-50	0.229
-100	0.161
-150	0.169
-350	0.106
-800	0.088
-1000	0.076

Table 4.1.1: Current Profile

2. **Random wave, fatigue bin16**

Hs (m)	2.47
Tp (Sec)	16.62
JONSWAP (gamma)	6
No Wind Applied due to Flexcom capability	
Water Depth	Current Velocity (cm/sec)
0 m	23.2
50 m	22.9
100 m	16.1
350 m	10.6
800 m	8.8
1000 m	7.6

Table 4.1.2: Environment Condition of Fatigue Bin 16

3. Flexcom Model with Different CWP Top Connection Stiffness

Case 1	CWP Top Rigid Connected to Platform
Case 2	CWP Top Connected to Platform with Rotational Spring Stiffness 1.0E13 N-m/rad
Case 3	CWP Top Connected to Platform with Rotational Spring Stiffness 1.0E8 N-m/rad

4.2 Current Only Analysis Results

Current profile defined in Table 4.1.1 is applied in this analysis. No other environmental load applied. The purpose of the current only analysis is to test the system drag and inertia is equivalent between the HARP and the Flexcom models. The current load is applied with a 100 second ramp. The platform surge is plotted in Figure 4.2.1 below. It can be seen that the HARP and Flexcom model has similar drag and surge period. The CWP strain envelope is presented in Figure 4.2.2.

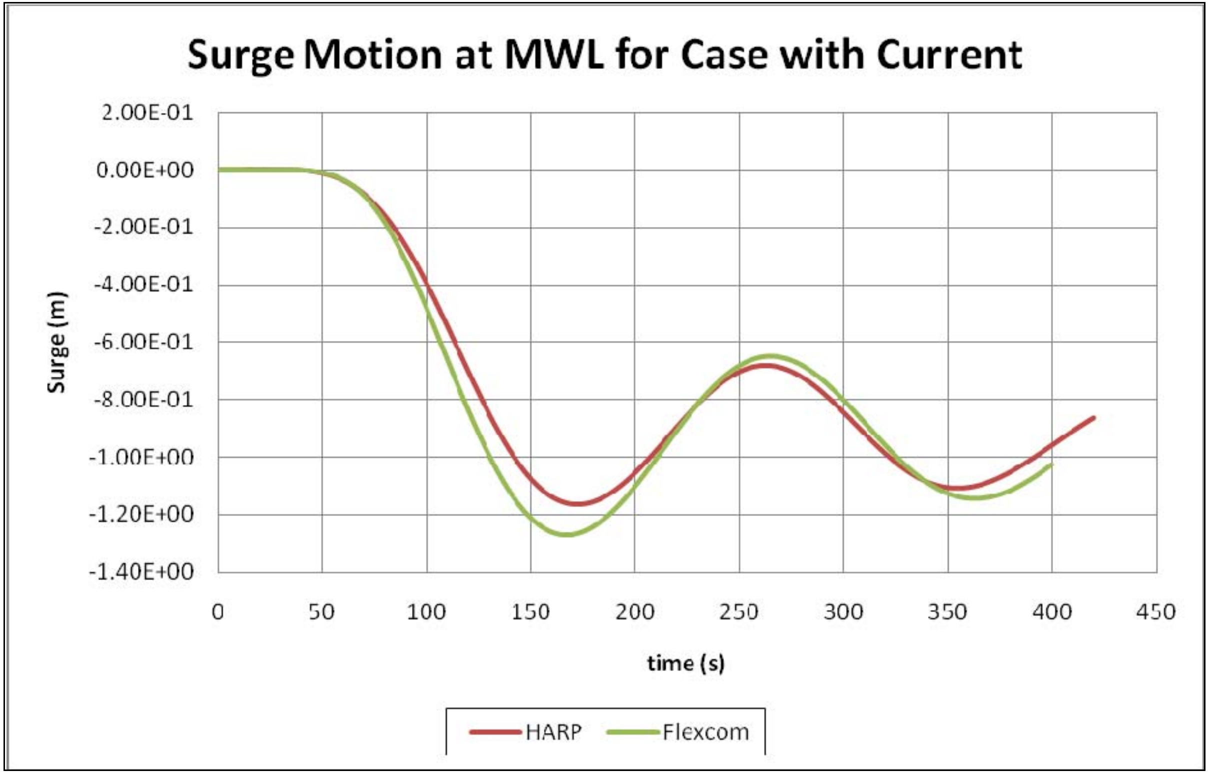


Figure 4.2.1: Platform Surge Motion of the Applied Current Profile

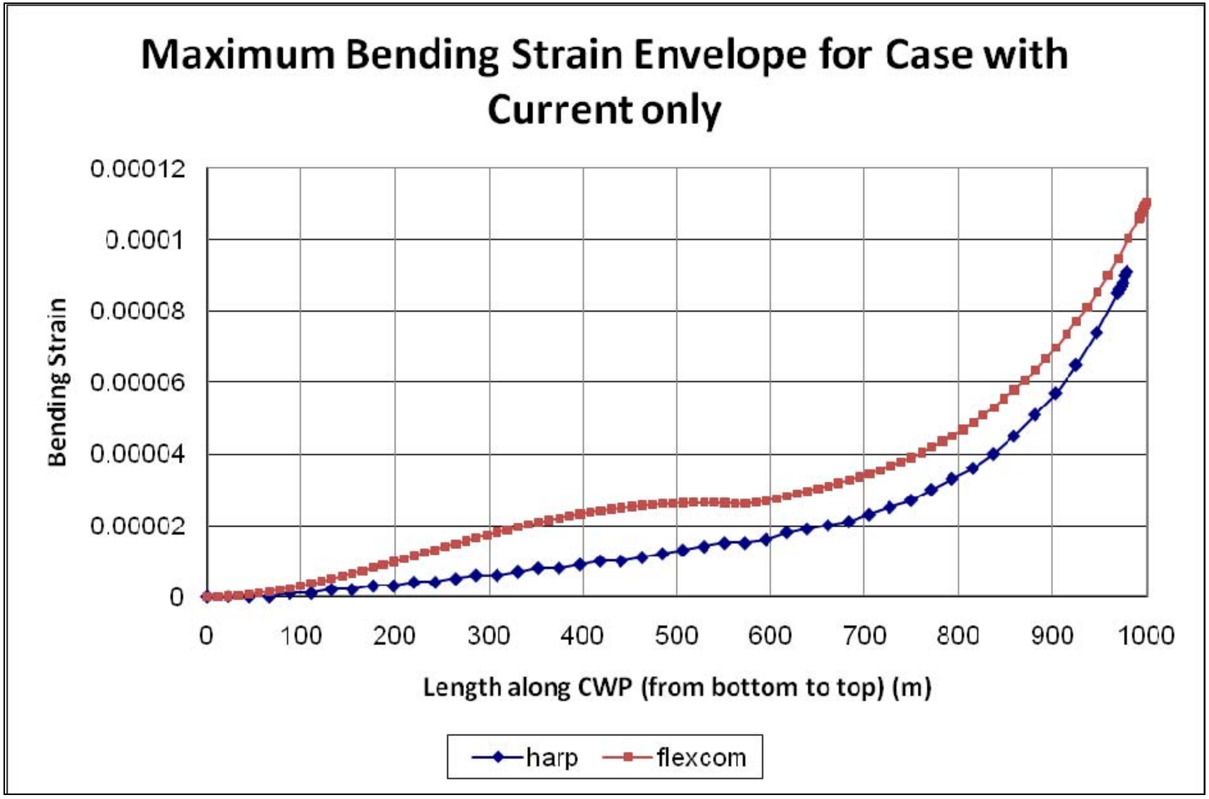


Figure 4.2.2: CWP Strain Envelope for the Current Only Case

4.3 Random Wave (Fatigue Bin 16, no wind) Analysis Results

Random wave analysis is performed for the Fatigue bin16 environmental condition. Calculated platform motions are shown in Figure 4.3.1 to 4.3.3. The motion statistics are presented in Table 4.3.1

Random Wave						
	HARP			FLEXCOM		
	Surge m	Heave m	Pitch deg	Surge m	Heave m	Pitch deg
MAX	0.88	2.47	3.00	0.88	2.44	2.89
MIN	-3.39	-2.50	-2.88	-5.53	-2.40	-2.66
MEAN	-0.85	-0.01	0.06	-1.95	0.03	0.10
STDDEV	0.81	0.92	1.20	0.91	0.73	1.04

Table 4.3.1: Motion Statistics

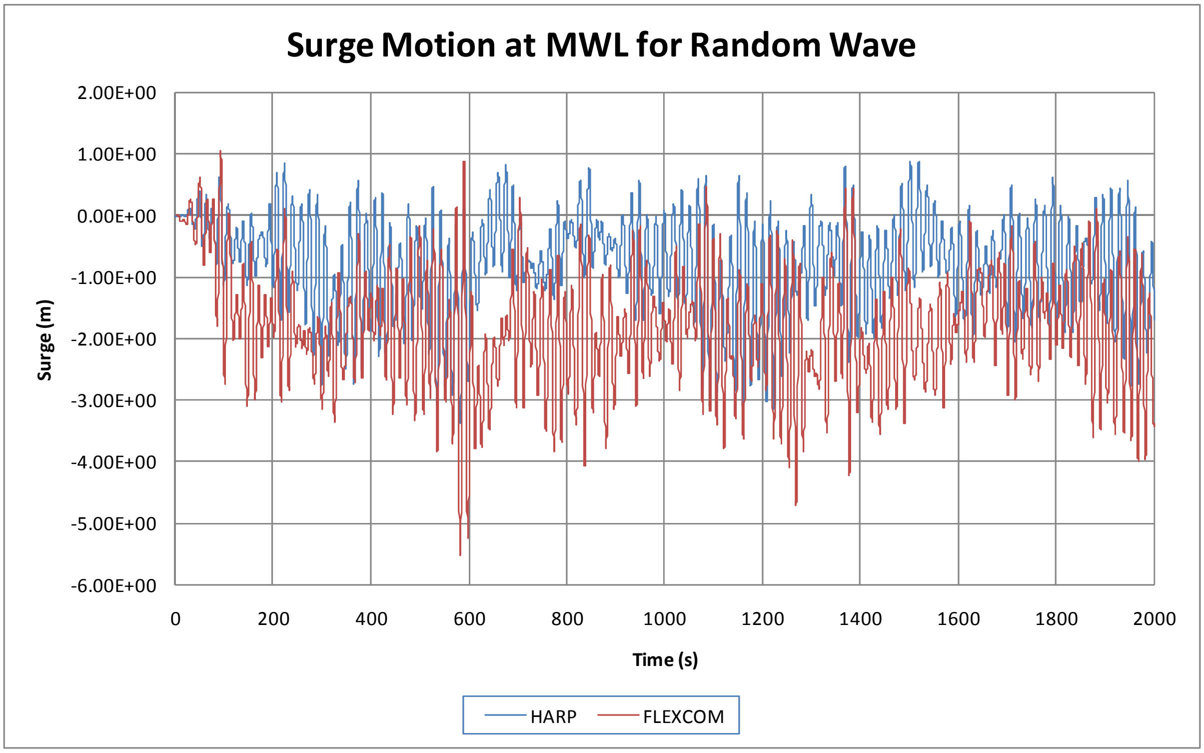


Figure 4.3.1: Surge Motion Time History Comparison

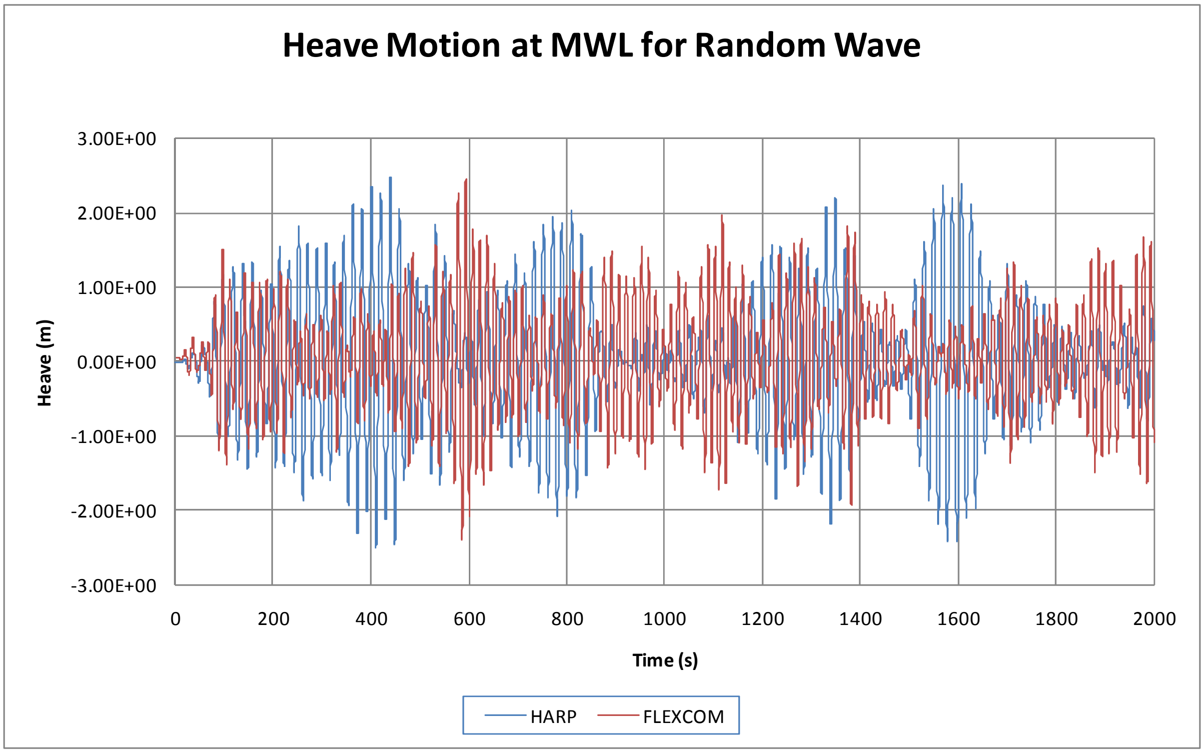


Figure 4.3.2: Heave Motion Time History Comparison

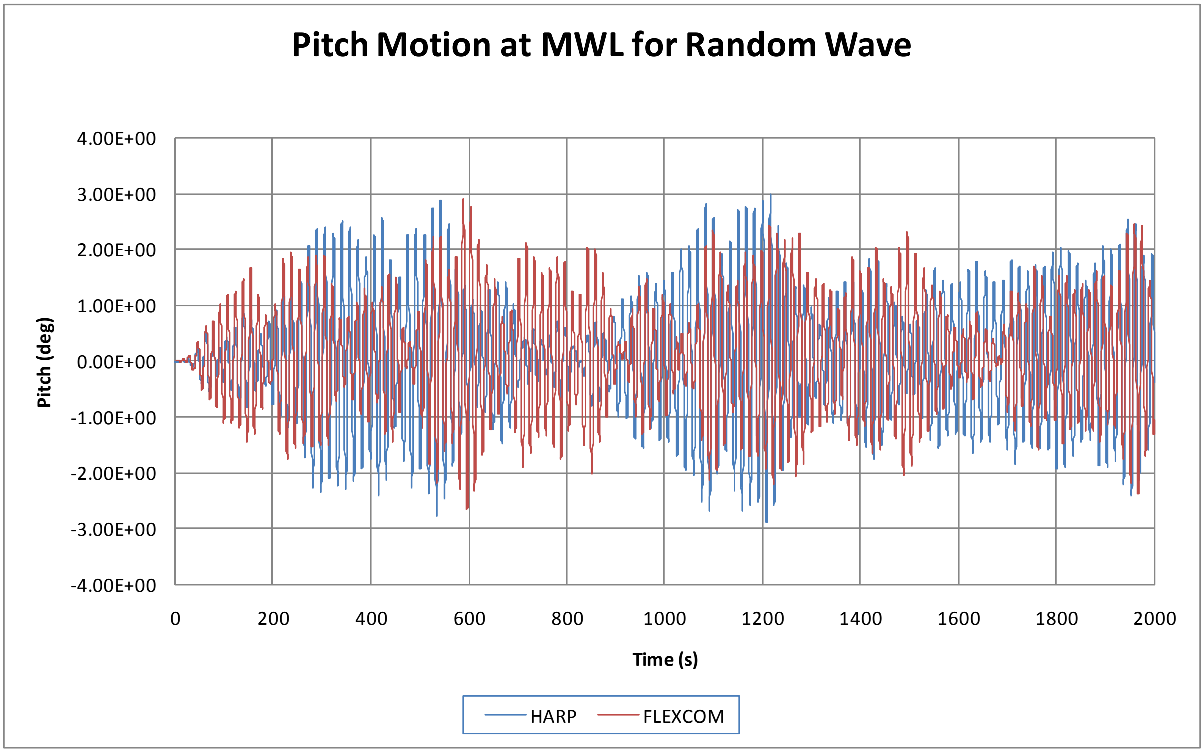


Figure 4.3.3: Pitch Motion Time History Comparison

The CWP strain results are plotted in Figures 4.3.4 below:

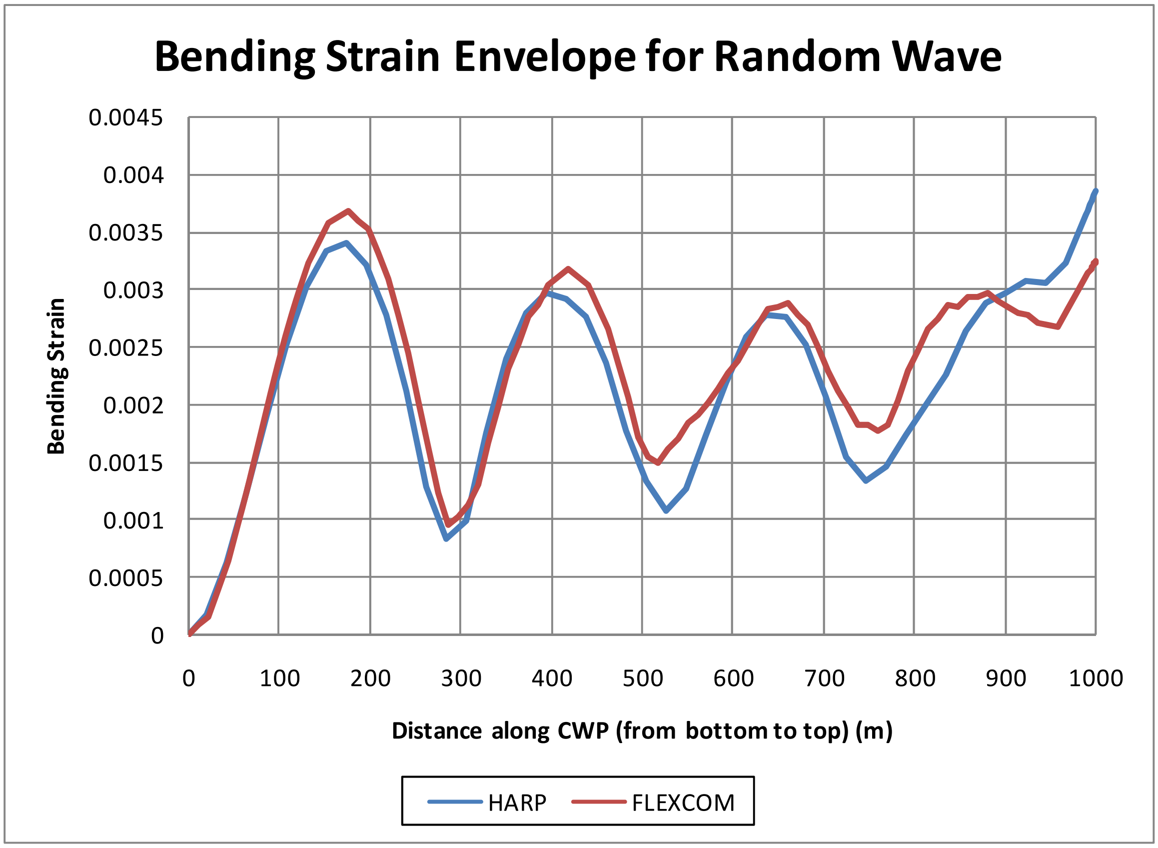


Figure 4.3.4: CWP Bending Strain Comparison

The CWP top connection bending strain time history and statistics are presented in the figure and table below:

BENDING STRAIN STATISTICS		
	HARP	**FLEXCOM**
MAX	3.10E-03	3.24E-03
MIN	-3.85E-03	-3.04E-03
MEAN	-2.64E-04	-3.08E-04
STDDEV	1.19E-03	9.15E-04

Table 4.3.2: CWP Top Connection Bending Strain Statistics

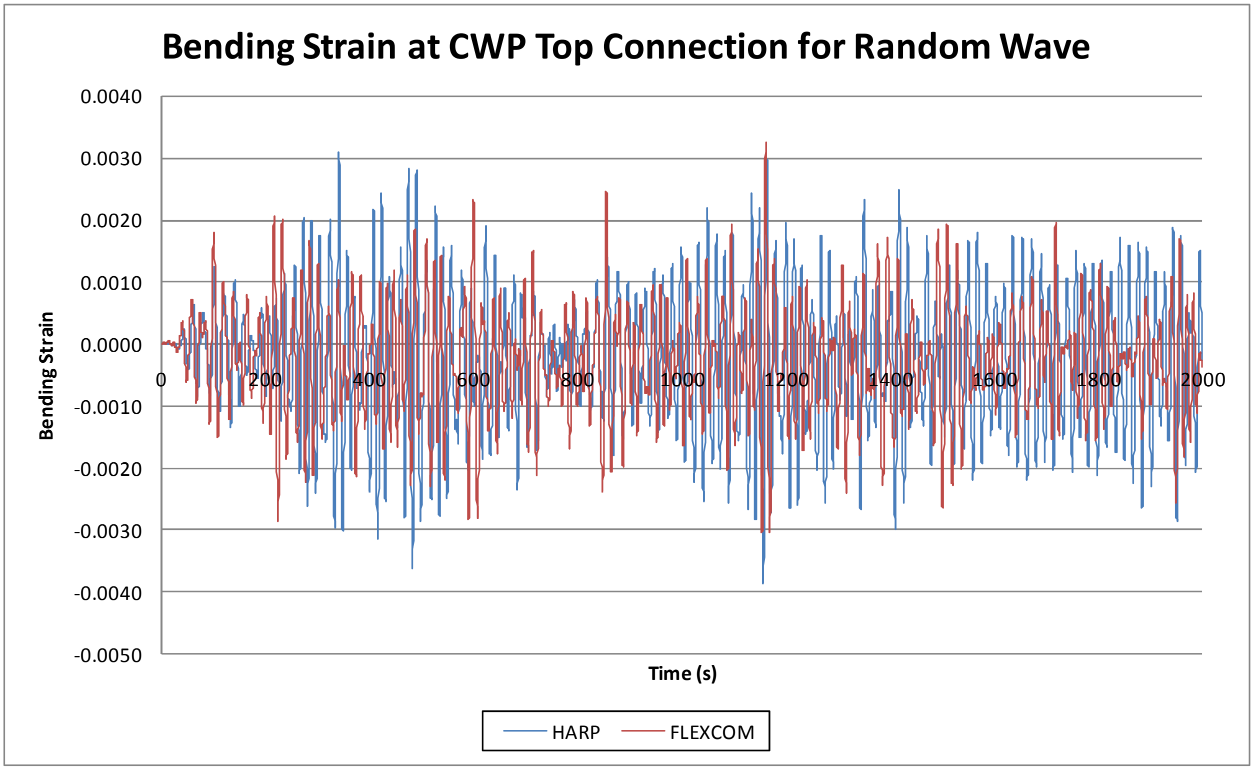


Figure 4.3.5: CWP Top Connection Bending Strain Time History Comparison

4.4 Flexcom Analysis for Three Different CWP Top Connection Models

Three different CWP to platform connection models are analyzed using Flexcom. The 1st case, CWP is rigid connected to the platform. Rigid connection means the CWP top node is a part of the platform rigid nodes and elements system. The 2nd and the 3rd cases, the CWP top is connected to the platform rigid system through a rotational spring element with a defined rotational stiffness. The analyses were also performed for fatigue bin 16 environment condition.

Case 1: CWP Top Rigid Connected to Platform.

Case 2: CWP Top Connected to Platform with a Rotational Spring (Stiffness = 1.0E13 N-m/rad).

Case 3: CWP Top Connected to Platform with a Rotational Spring (Stiffness = 1.0E8 N-m/rad).

	HEAVE (m)			**SURGE (m)**			**PITCH (deg)**		
	Case 1 (Rigid)	**Case 2 (k=1E13 N-m/rad)**	**Case 3 (k=1E8 N-m/rad)**	**Case 1 (Rigid)**	**Case 2 (k=1E13 N-m/rad)**	**Case 3 (k=1E8 N-m/rad)**	**Case 1 (Rigid)**	**Case 2 (k=1E13 N-m/rad)**	**Case 3 (k=1E8 N-m/rad)**
MAX	2.42	2.43	2.42	-0.07	-0.04	-0.25	2.79	2.70	4.41
MIN	-2.38	-2.39	-2.37	-4.03	-4.00	-4.33	-2.51	-2.42	-4.16
MEAN	0.04	0.04	0.04	-2.19	-2.17	-2.21	0.12	0.12	0.04
STD DEV	0.73	0.73	0.73	0.64	0.64	0.70	1.00	0.98	1.63

Table 4.4.1: Motion Statistics

It can be seen that;

1. Case 1 of rigid connection and the Case 2 using large stiffness rotational spring will result very close platform motions and CWP strains.
2. Case 3 using rotational spring with small stiffness could increase platform pitch motions, small effect on surge (also due to pitch different), and very little effect on platform heave.

Conclusion is the CWP top rigid connection can be equivalently modeled as a large rotational spring with a amplitude up to 1.0E13 N-m/rad. The rotational stiffness of 1.0E13 N-m/rad used in HARP will not cause convergence problem and numerical error in platform pitch motions.

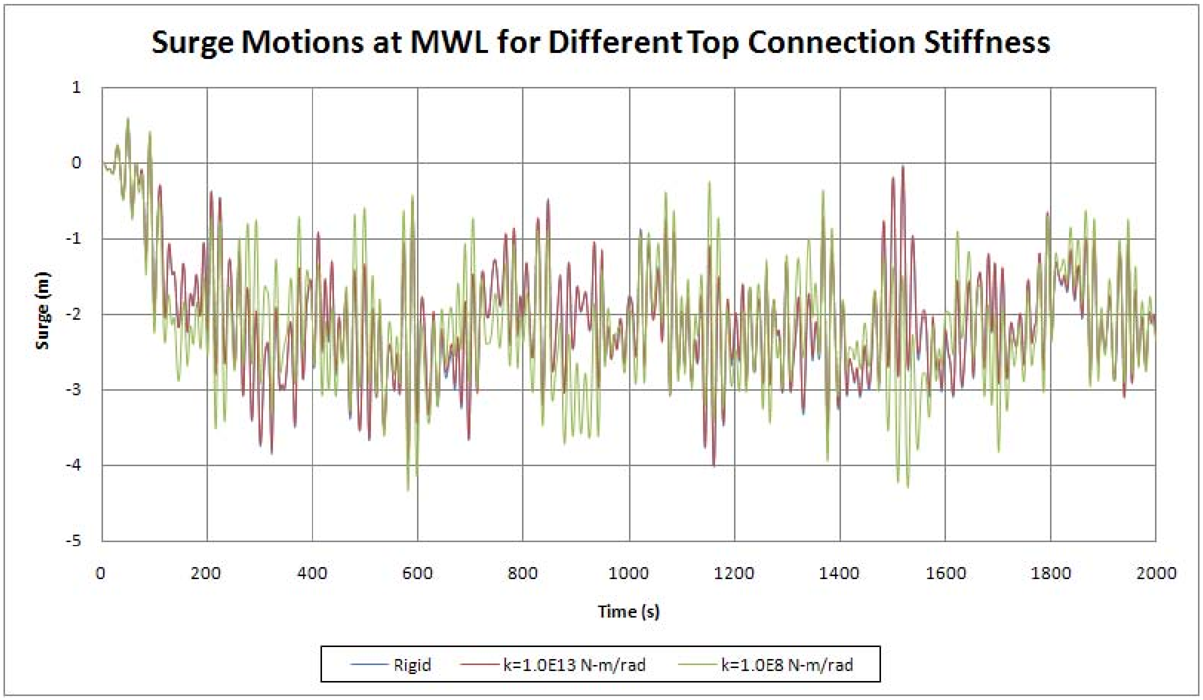


Figure 4.4.1: Surge Motion Time History Comparison

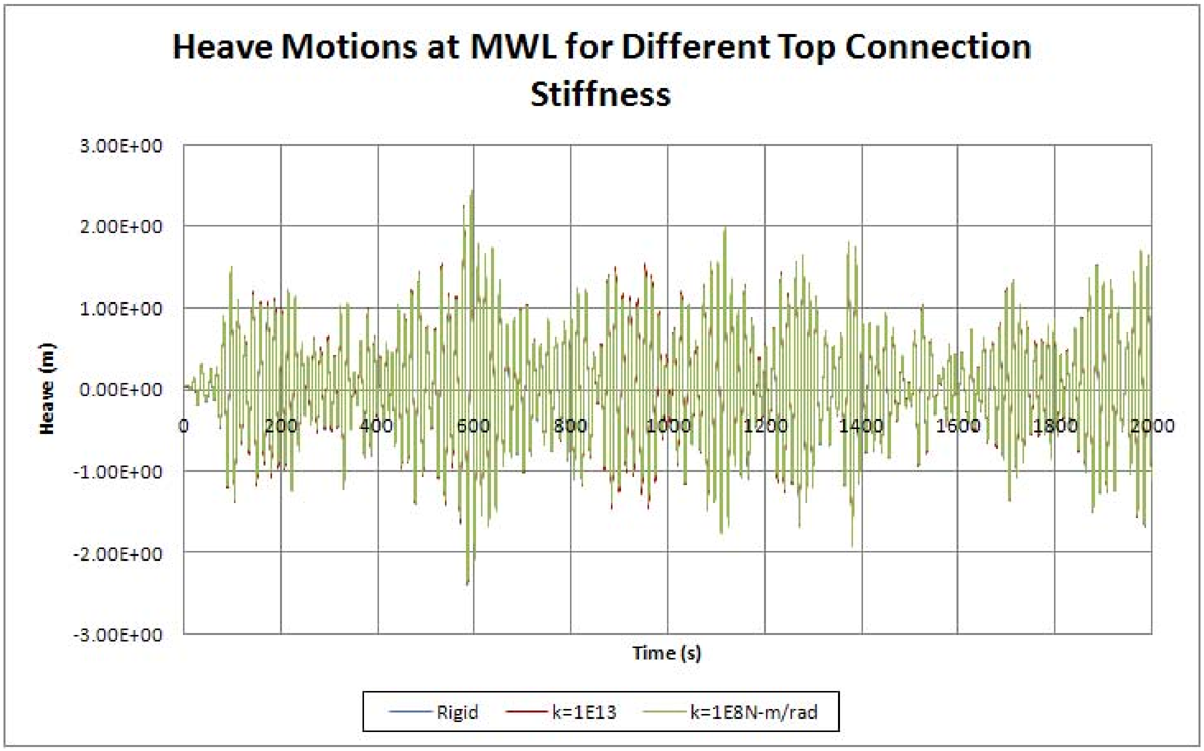


Figure 4.4.2: Heave Motion Time History Comparison

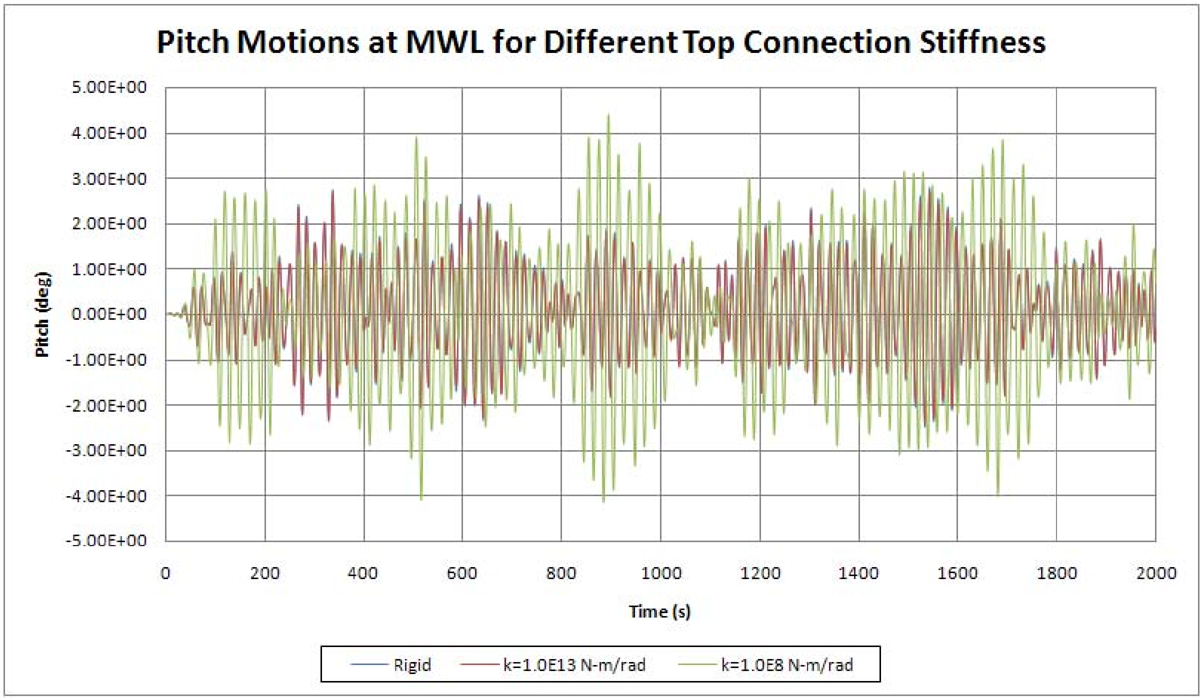
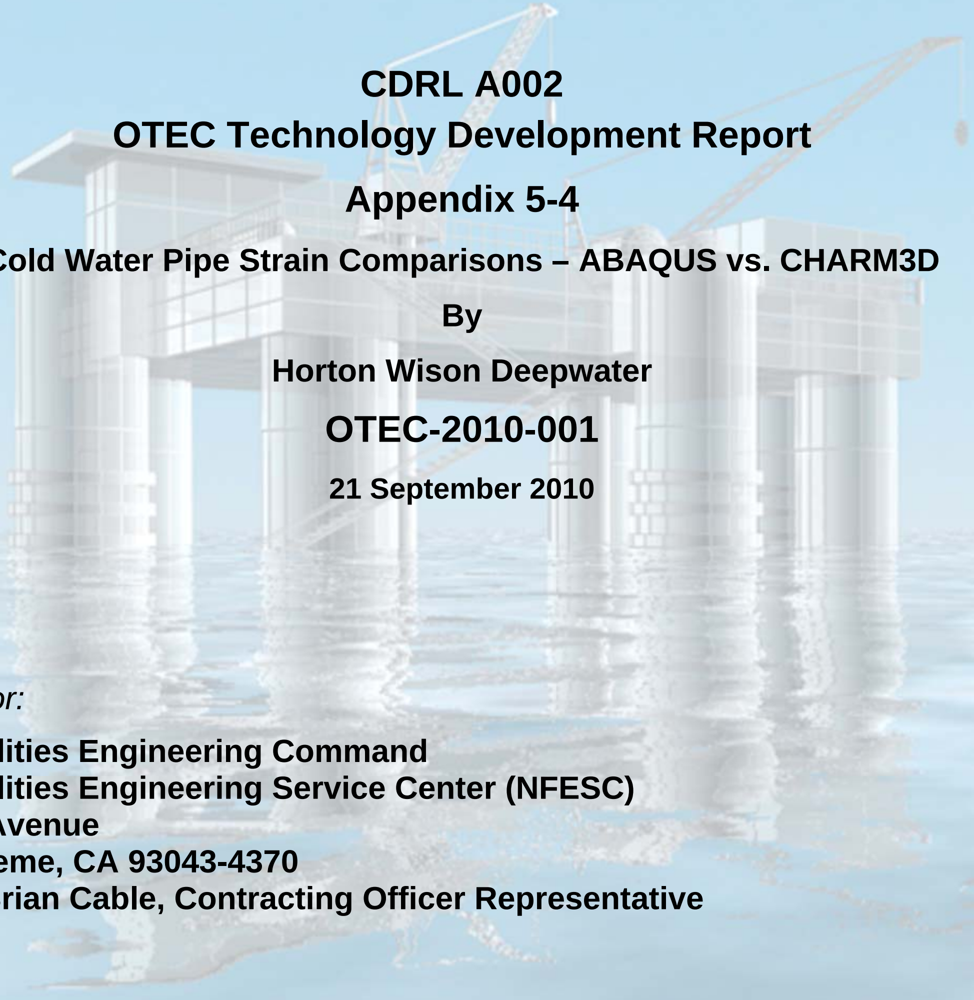


Figure 4.4.3: Pitch Motion Time History Comparison



NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report
Appendix 5-4
Cold Water Pipe Strain Comparisons – ABAQUS vs. CHARM3D

By

Horton Wison Deepwater

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
Naval Facilities Engineering Service Center (NFESC)
1100 23rd Avenue
Port Hueneme, CA 93043-4370
Attn: Mr. Brian Cable, Contracting Officer Representative

Prepared by:

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9500 Godwin Drive
Manassas, VA 20110

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Horton Wison Deepwater

Technical Notes

To:	John Halkyard	From:	Arcandra Tahar
CC:	Jim Maher and Lyle Finn	Date:	April 15, 2010
Subject:	Cold Water Pipe Strain Comparisons – ABAQUS Vs. CHARM3D		

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Introduction

Horton Wison Deepwater (HWD) was tasked to perform the strain analysis of Cold Water Pipe (CWP) hanging at the keel of the Multi Column Floater (MCF). CWP is one the major equipment for Ocean Thermal Energy Conversion.

One of the major challenges of conducting this analysis is that the mass of the CWP, including the entrained water inside the pipe, is comparable to the mass of the MCF. Therefore, a fully coupled model in the time domain is needed to capture the interaction between CWP and MCF.

HWD has been using two different coupled analysis software; HARP/CHARM3D and ABAQUS. HARP/CHARM3D program is written by Offshore Technology Research Center (OTRC), Texas A&M University while ABAQUS is written by Simulia.

Numerical Modeling

The comparisons have been done for the OTEC MCF during production phase. Figures 1 and 2 show the fully coupled model of the OTEC MCF using CHARM3D. As shown in Figure 2, CWP was connected to one end to the keel truss of MCF hull through spring-type of connection and the other end hanging above the sea floor. The stiffness coefficients for connection are shown in Table 1.

Figures 3 and 4 show the fully coupled model of the OTEC MCF using ABAQUS.

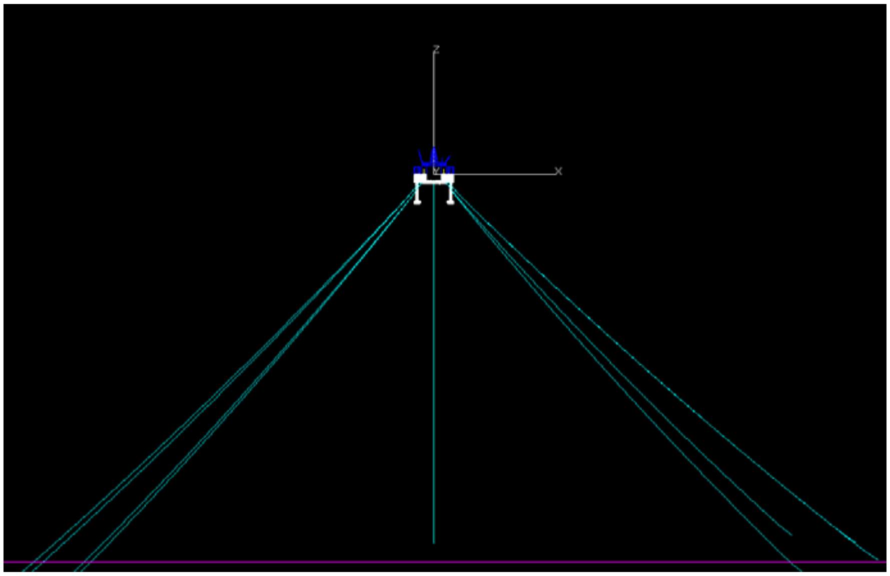


Figure 1 Fully-coupled Analysis Model (Global View) – CHARM3D

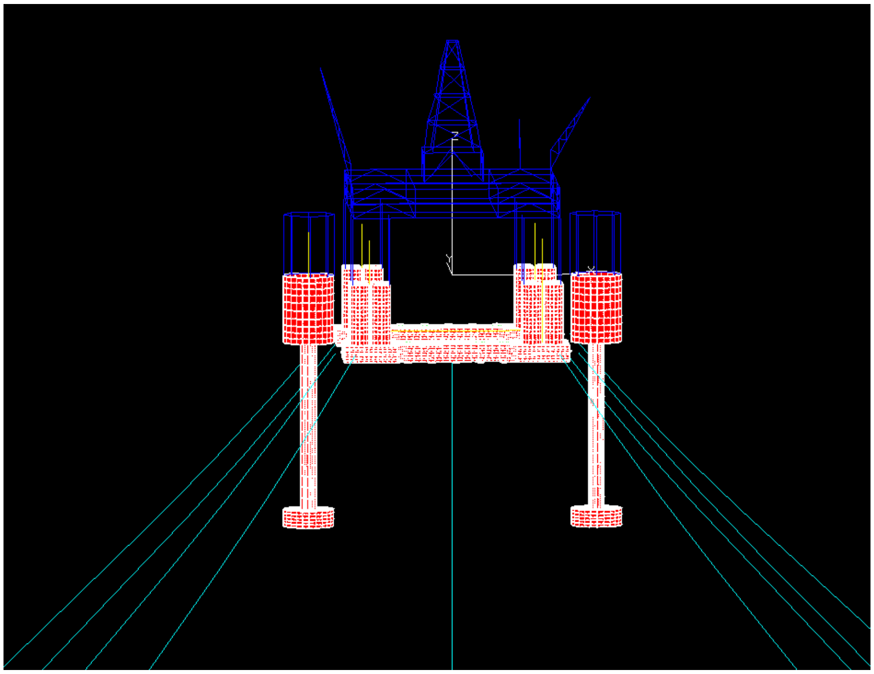


Figure 2 Fully-coupled Analysis Model (Detail View) – CHARM3D

Table 1 Stiffness Coefficients

Stiffness CWP to Truss				
Kx	6.85E+06	lb/ft	1.00E+08	N/m
Ky	6.85E+06	lb/ft	1.00E+08	N/m
Kz	6.85E+06	lb/ft	1.00E+08	N/m
Kxx	1.92E+10	lb.ft/rad	2.60E+10	N.m/rad
Kyy	1.92E+10	lb.ft/rad	2.60E+10	N.m/rad
Kzz	1.92E+10	lb.ft/rad	2.60E+10	N.m/rad

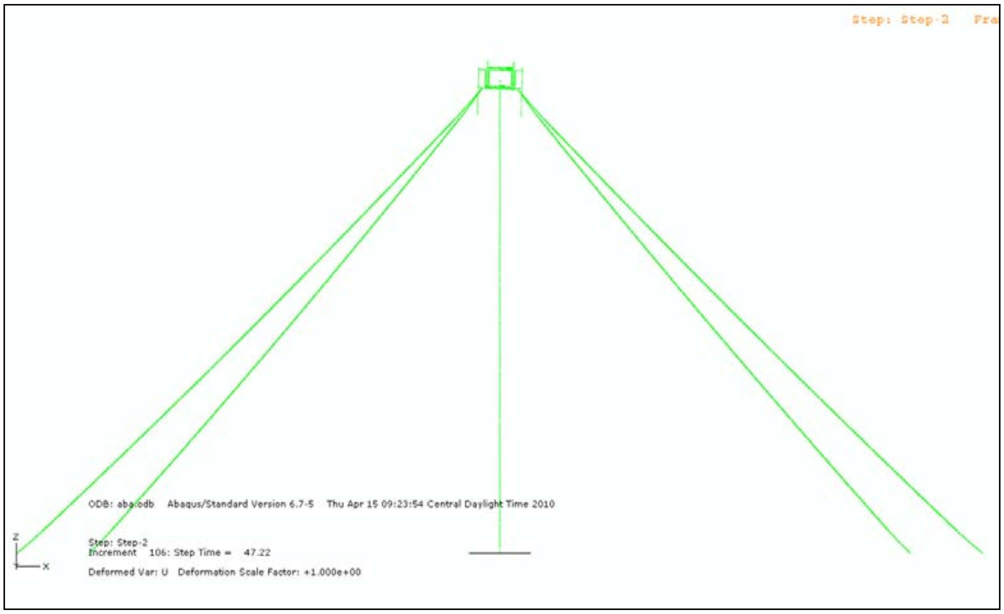


Figure 3 Fully-coupled Analysis Model (Global View) – ABAQUS

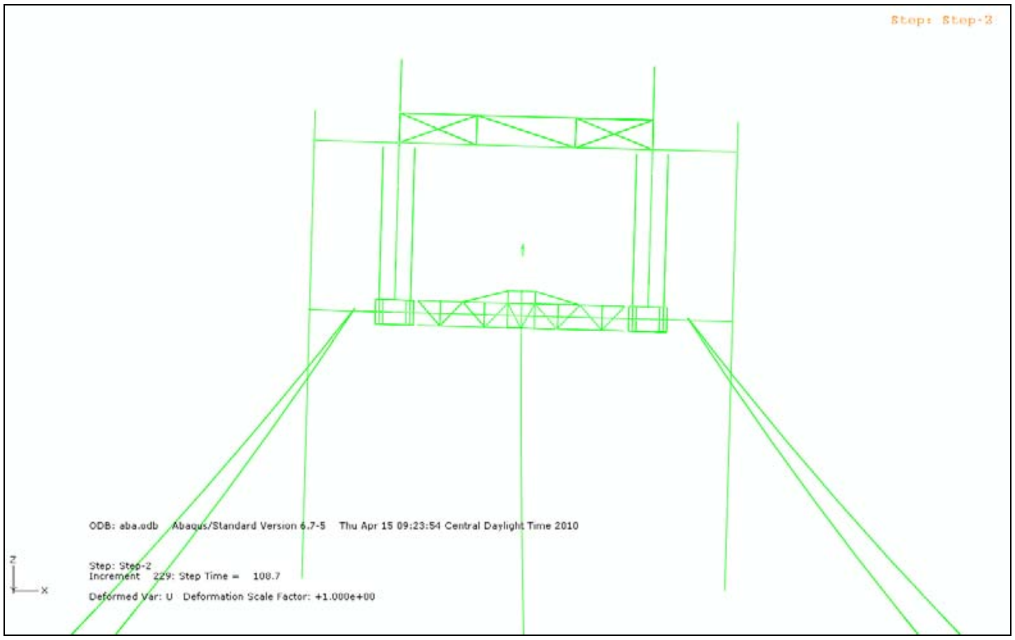


Figure 4 Fully-coupled Analysis Model (Detail View) – ABAQUS

Free Decay Test Results

Free decay tests are conducted to estimate the natural periods (Tn) and damping coefficients of the MCF. Figure 5 shows the pitch comparison between CHARM3D and ABAQUS. Other modes (surge and heave) are also comparable.

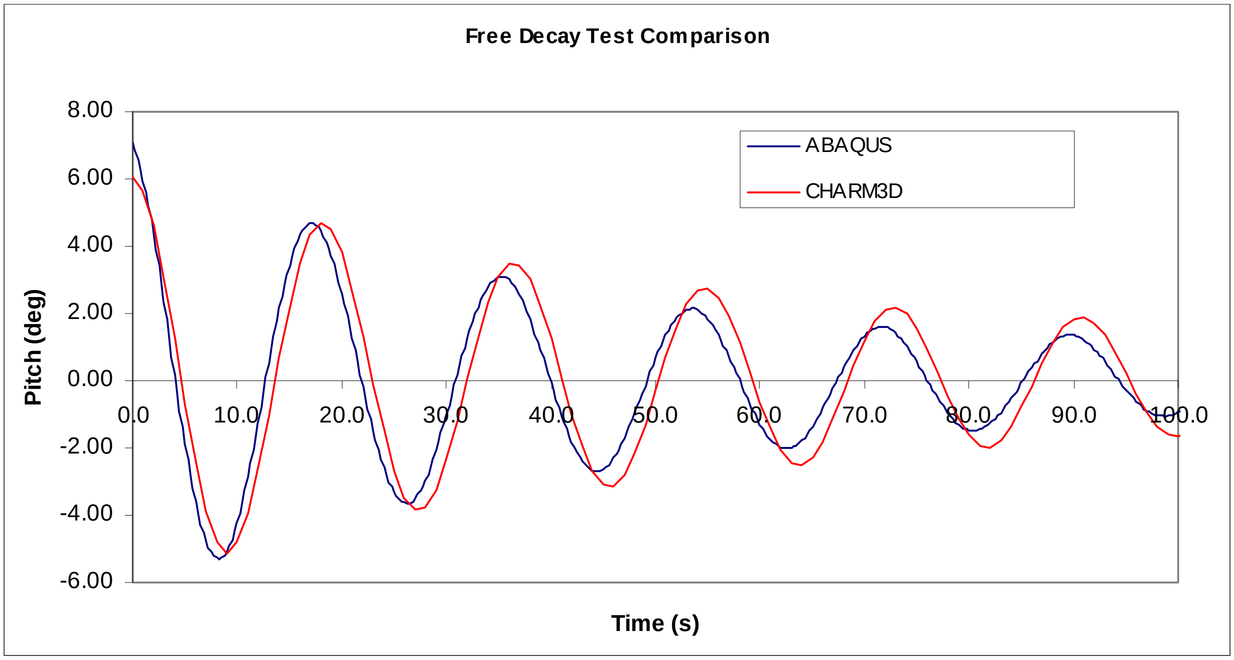


Figure 5 Free Decay Test Comparison during Production Phase

Motion Comparisons

Regular wave with 3.54 m of amplitude and 15.7 second of period was used in the analysis. For the cases with current, the current velocity and profile are shown in Table 2.

Table 2 Current Data

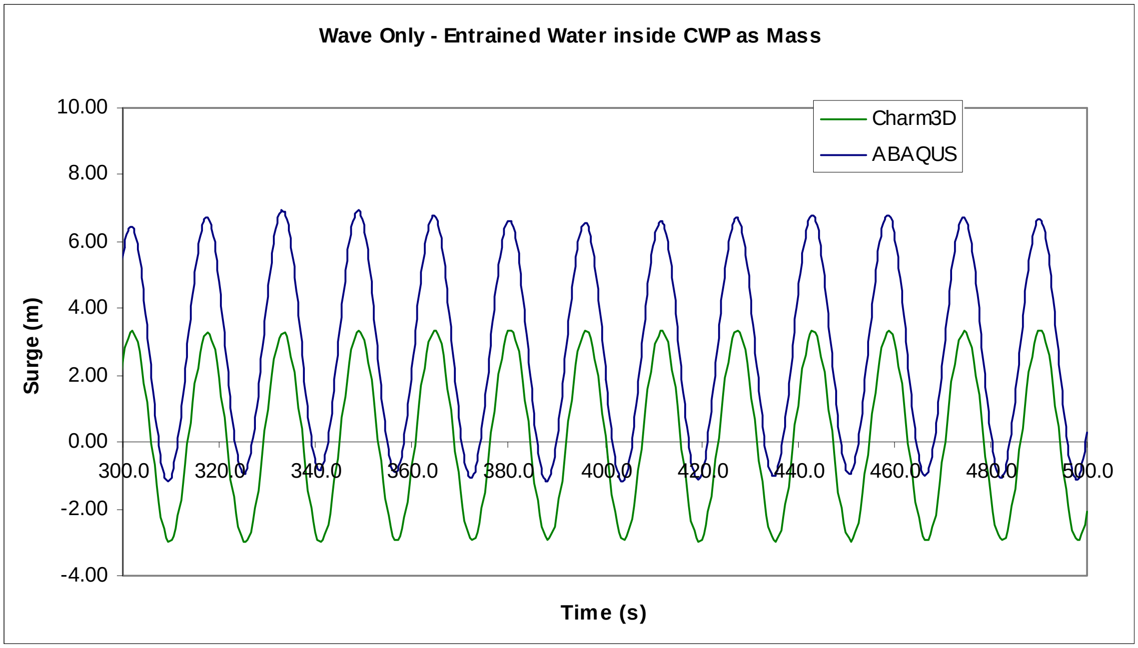
Current	Depth (m)	Vel (m/s)
	0.00	0.48
	-50.00	0.47
	-100.00	0.33
	-150.00	0.33
	-350.00	0.20
	-800.00	0.18
	-1000.00	0.15

Four load cases have been investigated and are listed below:

1. Wave only and entrained water inside CWP is modeled as mass in lateral and vertical
2. Wave+current and entrained water inside CWP is modeled as mass in lateral and vertical
3. Wave only and entrained water inside CWP is modeled as adjusted added mass coefficients (more accurate model)
4. Wave+current and entrained water inside CWP is modeled as adjusted added mass coefficients (more accurate model)

Figures 6 through 9 show surge and pitch comparison for each load case. Overall results are good with small discrepancy that can be explained as follow.

1. In the surge with wave only case (Figures 6 and 8), ABAQUS gives mean offset but CHARM3D is almost zero. It may be caused by the way polyester mooring modeled. For CHARM3D, there is no line length adjustment at the mean offset position. ABAQUS, adjusts the line length after the mean loads (from the wave) have been applied.
2. ABAQUS results are based on the Morrison approach while CHARM3D are from the first-order diffraction/radiation program WAMIT. It is well known that for small wave the Morrison approach give bigger wave frequency responses than those of diffraction approach. Since pitch of the OTEC MCF is in the wave frequency range, the pitch amplitude from ABAQUS is slightly bigger than CHARM3D.



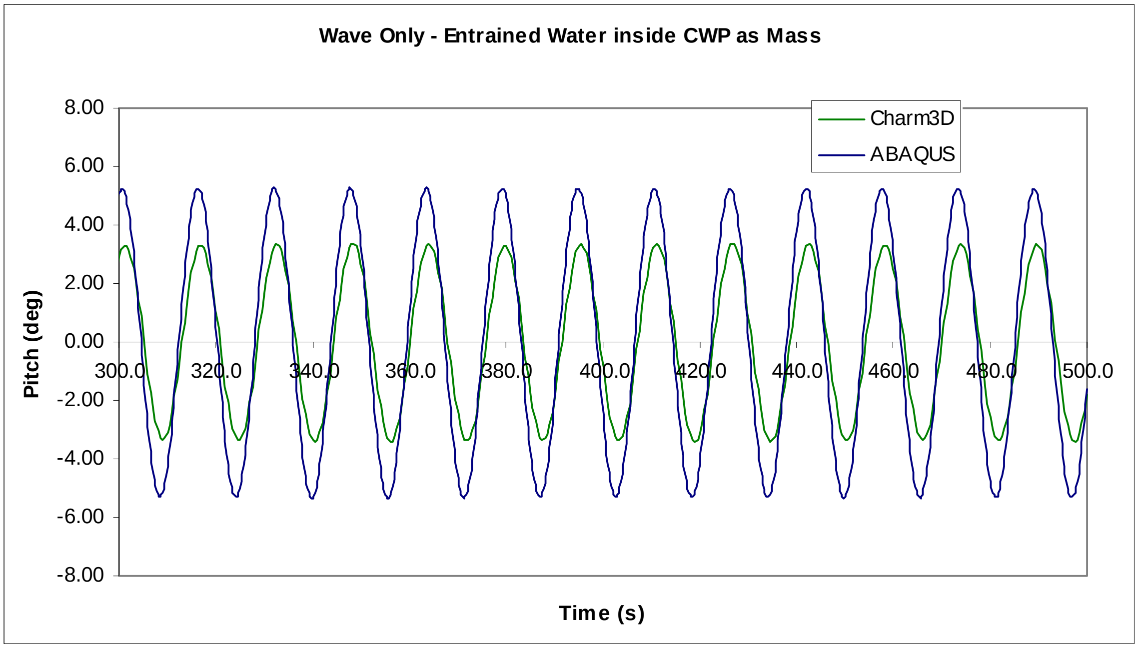
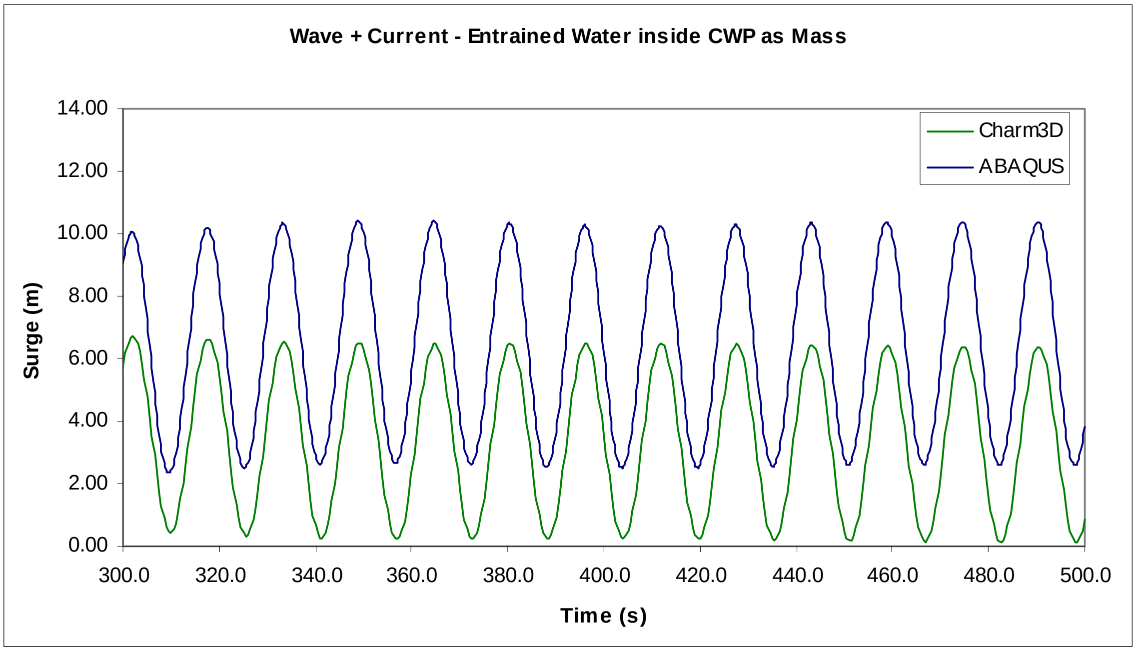


Figure 6 Surge and Pitch Comparison – Wave only Case and Entrained Water inside CWP Treated as Mass



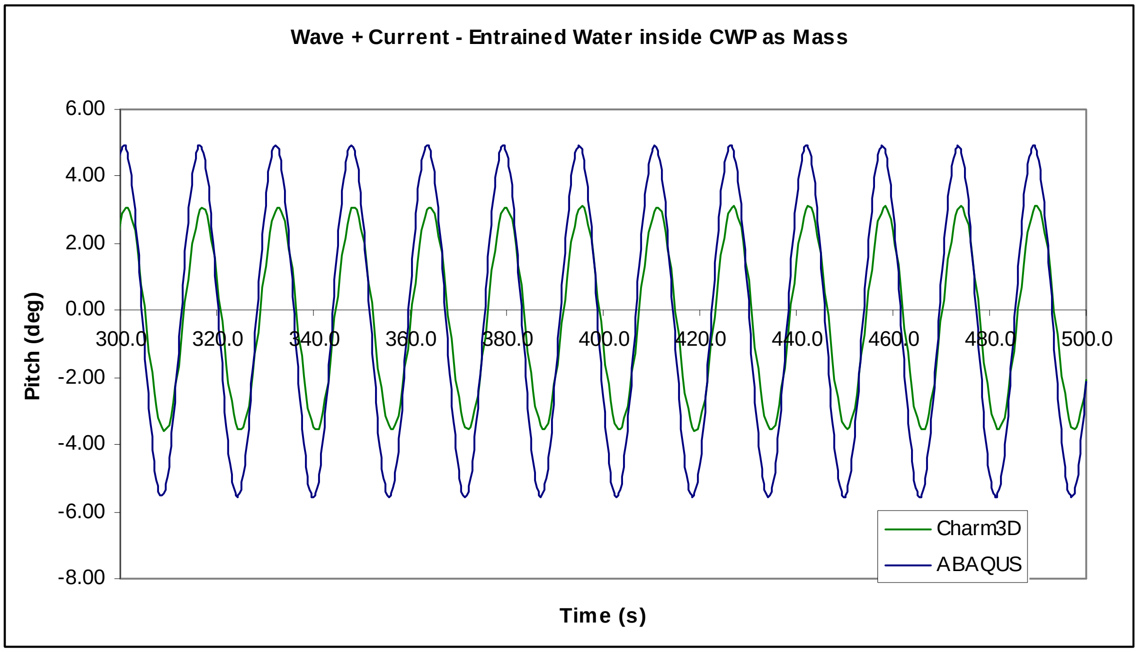
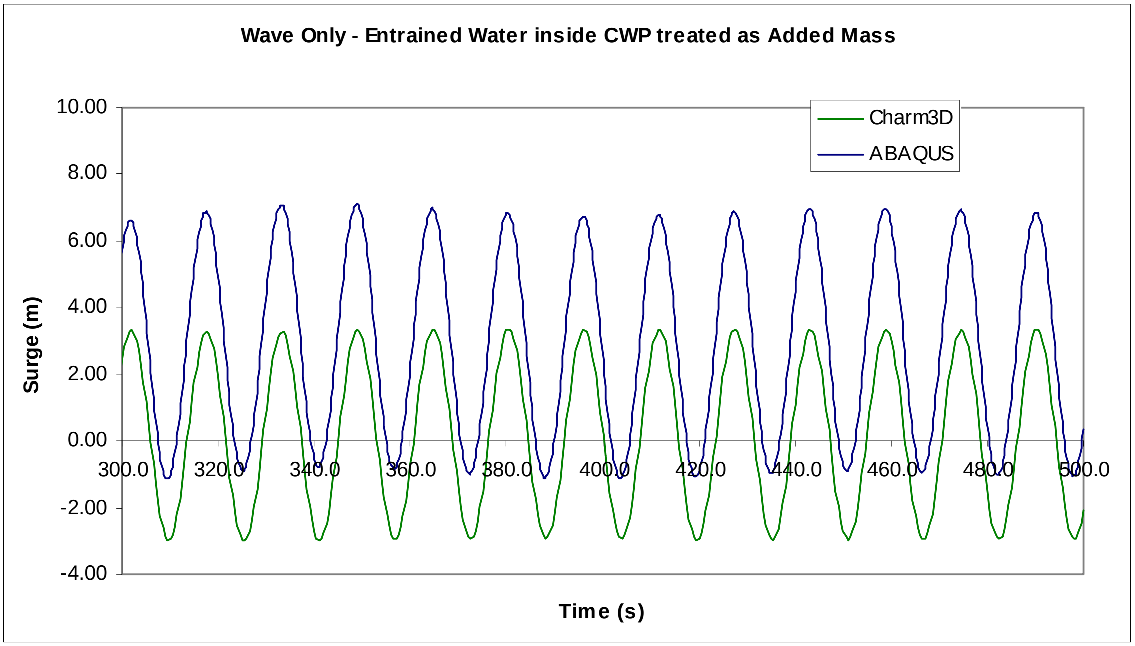


Figure 7 Surge and Pitch Comparison – Wave + Current Case and Entrained Water inside CWP Treated as Mass



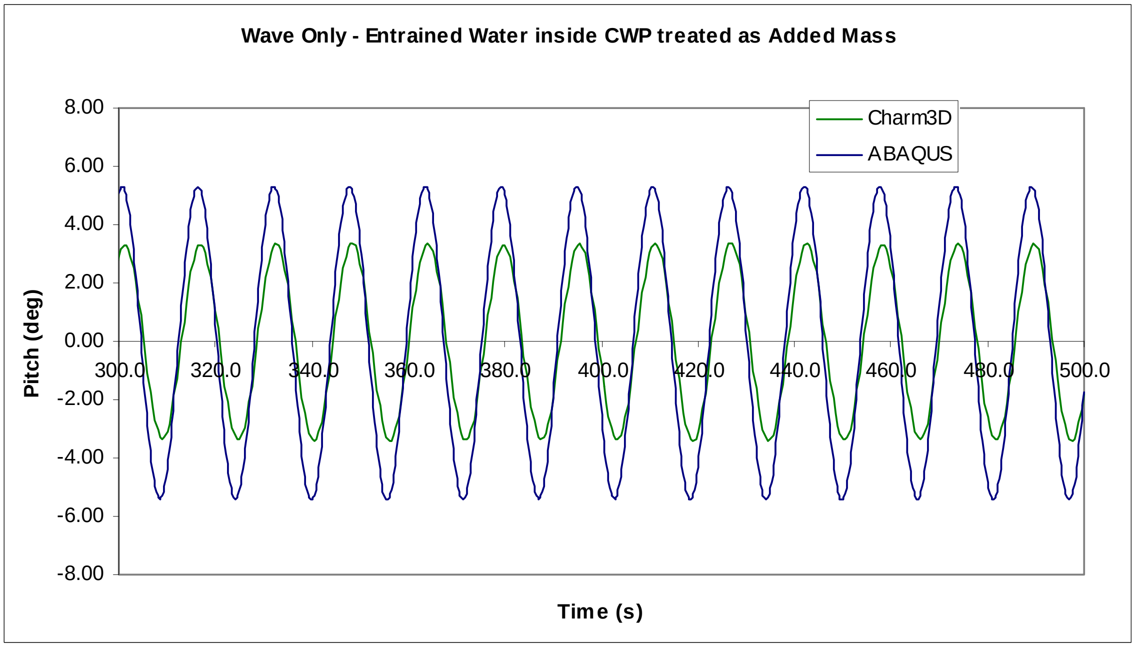
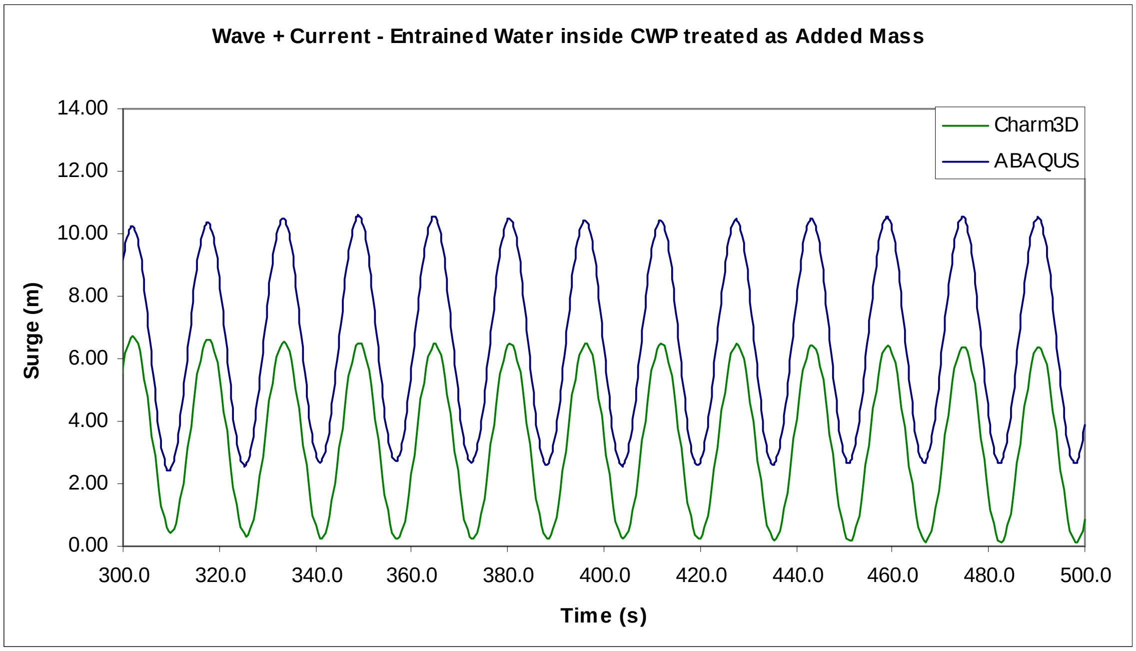


Figure 8 Surge and Pitch Comparison – Wave only Case and Entrained Water inside CWP Treated as adjusted Added Mass (in ABAQUS only)



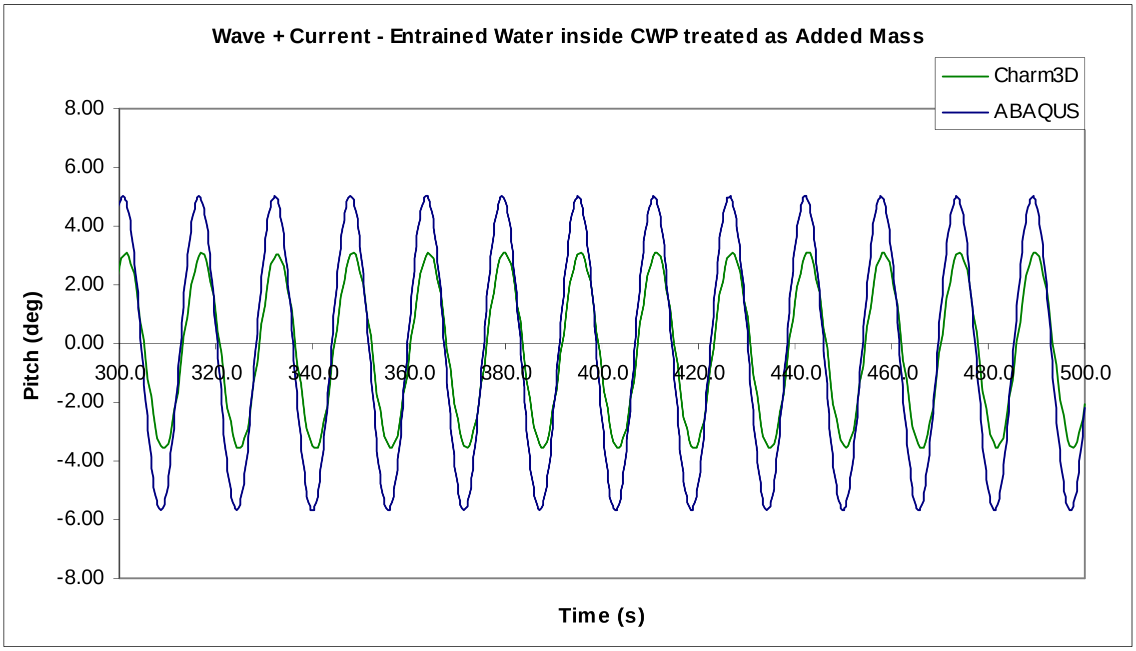


Figure 9 Surge and Pitch Comparison – Wave + Current Case and Entrained Water inside CWP Treated as Adjusted Added Mass (in ABAQUS only)

Strain Comparisons

Figures 10 and 11 show the strain comparison between ABAQUS results and those from CHARM3D. Strains were derived from the Von Misses stress divided by the Young Modulus of the CWP. One can say that CHARM3D and ABAQUS agree each other. Slightly higher strain form ABAQUS especially on the region close to MCF keel might be attributed to higher pitch motion than CHARM3D.

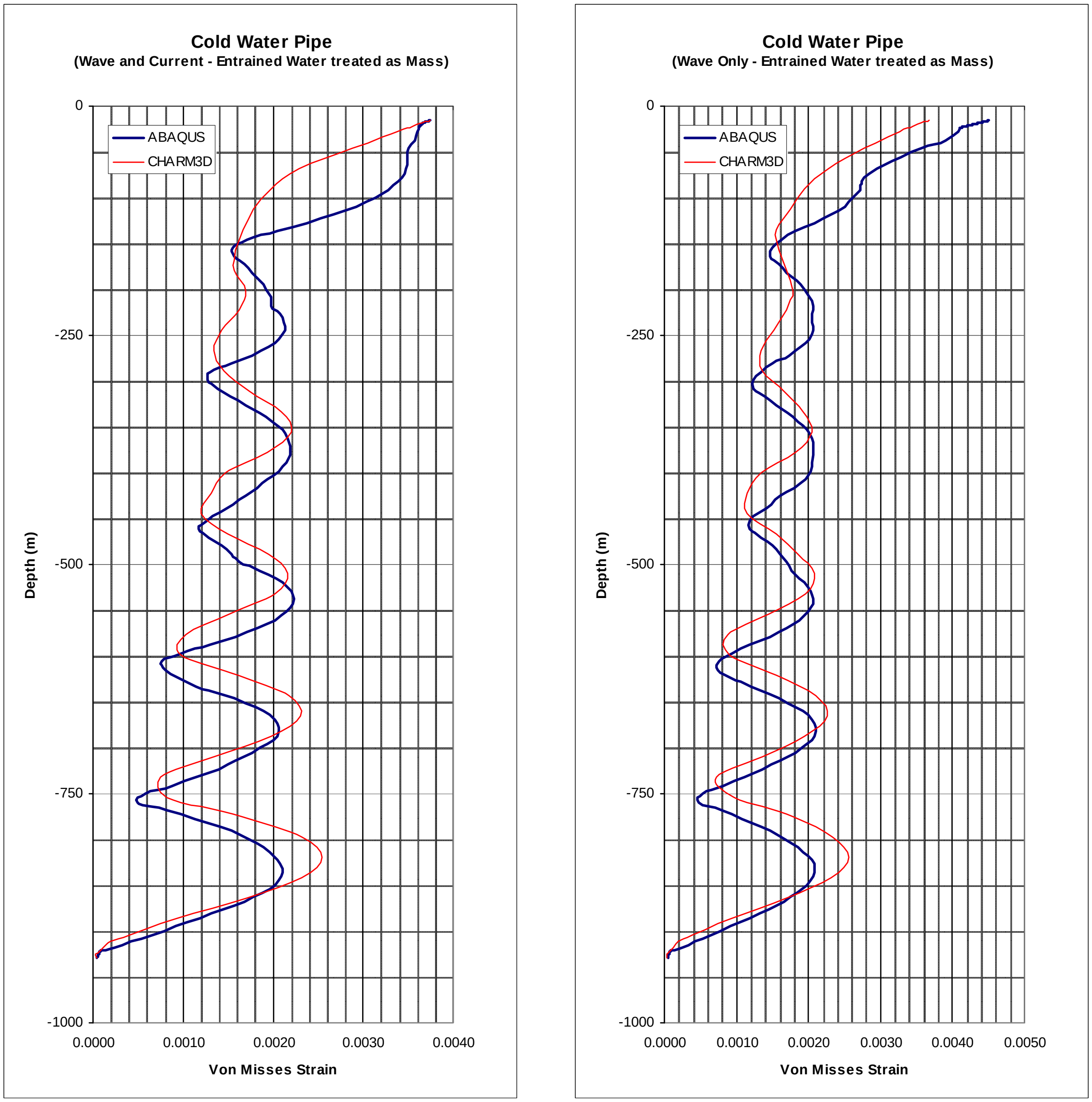


Figure 10 Strain Comparison –Entrained Water inside CWP Treated as Mass

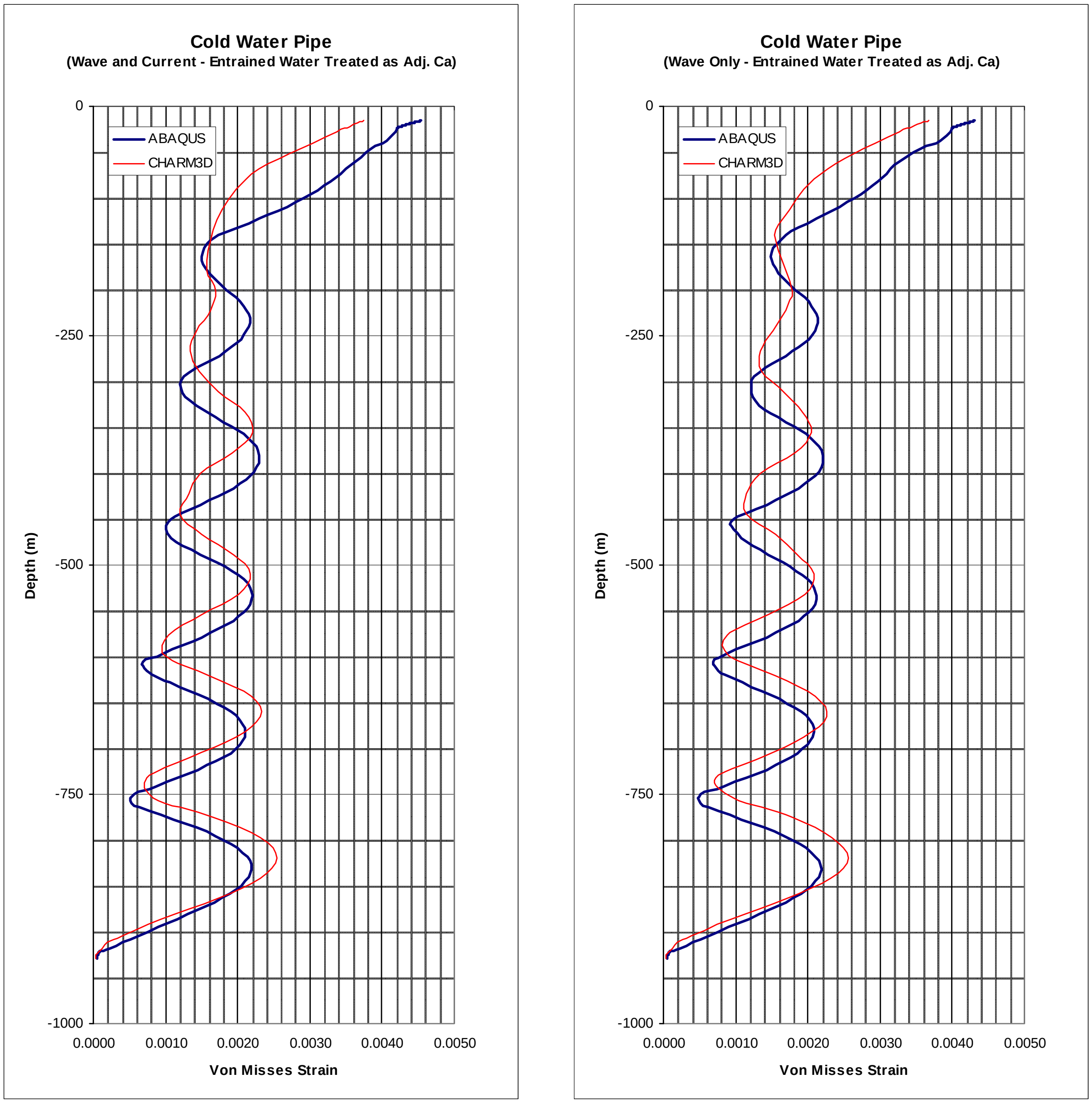
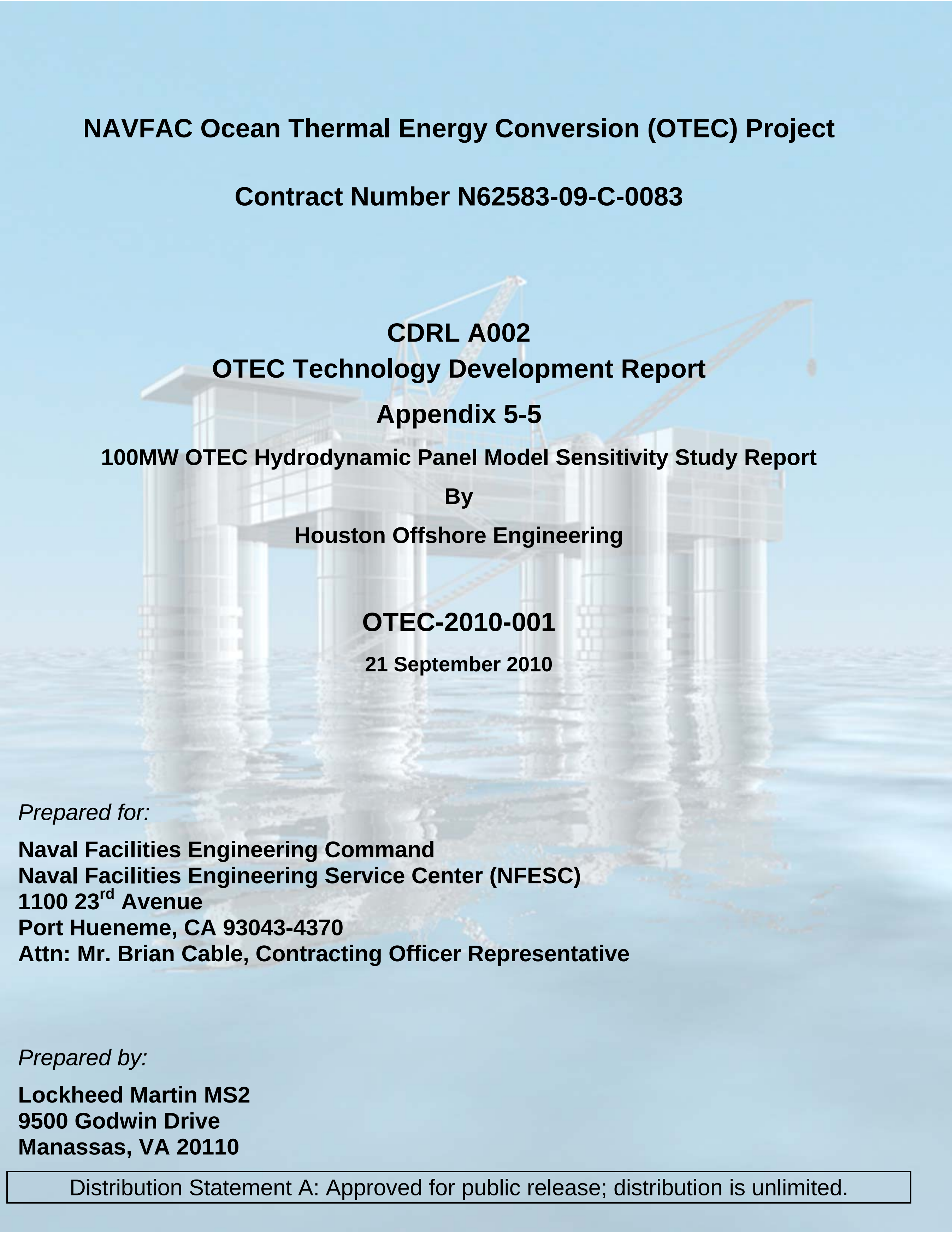


Figure 11 Strain Comparison –Entrained Water inside CWP Treated as Adjusted Added Mass (in ABAQUS only)



NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report

Appendix 5-5

100MW OTEC Hydrodynamic Panel Model Sensitivity Study Report

By

Houston Offshore Engineering

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
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Port Hueneme, CA 93043-4370
Attn: Mr. Brian Cable, Contracting Officer Representative

Prepared by:

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Manassas, VA 20110

100MW OTEC Hydrodynamic Panel Model Sensitivity Study Report

May 26, 2010

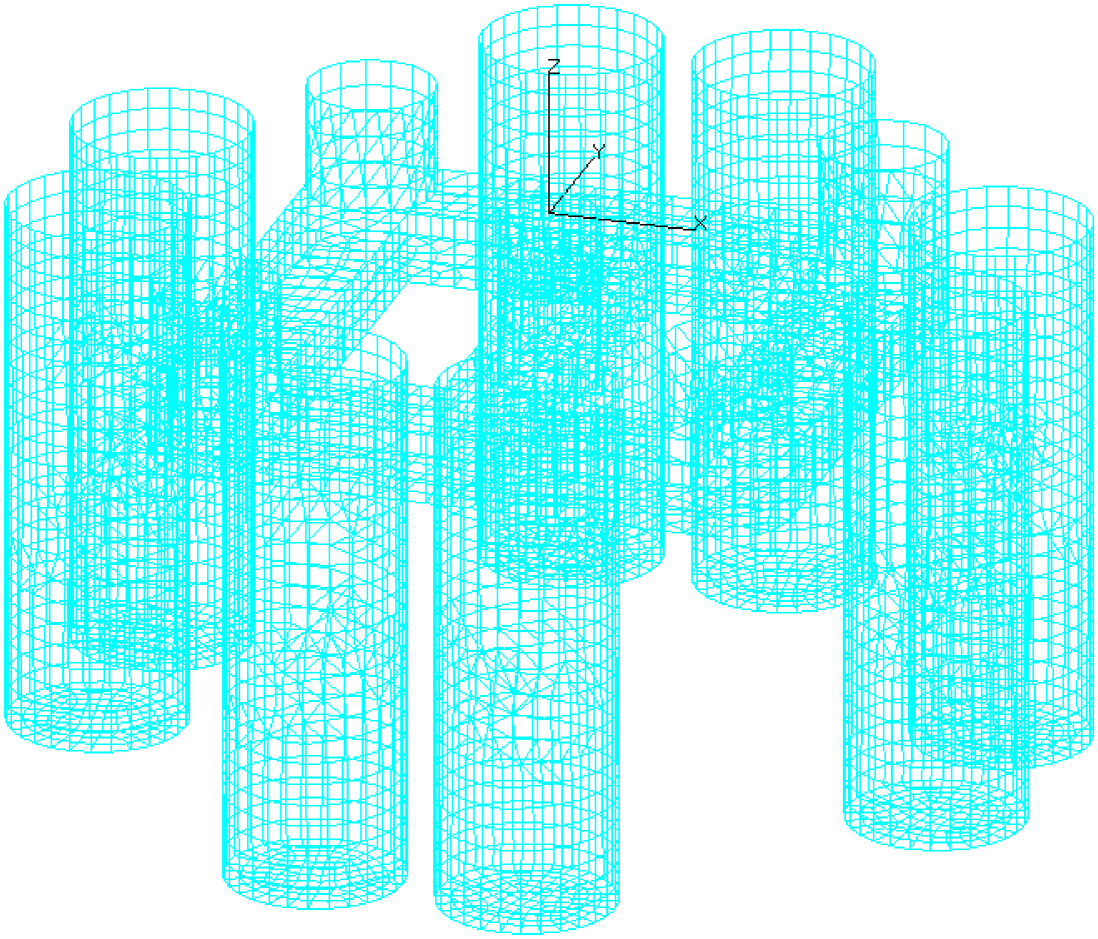
Doc. No.	Rev.	Date	Description	By	Appr.	Client

Houston Offshore
ENGINEERING

1 SUMMARY

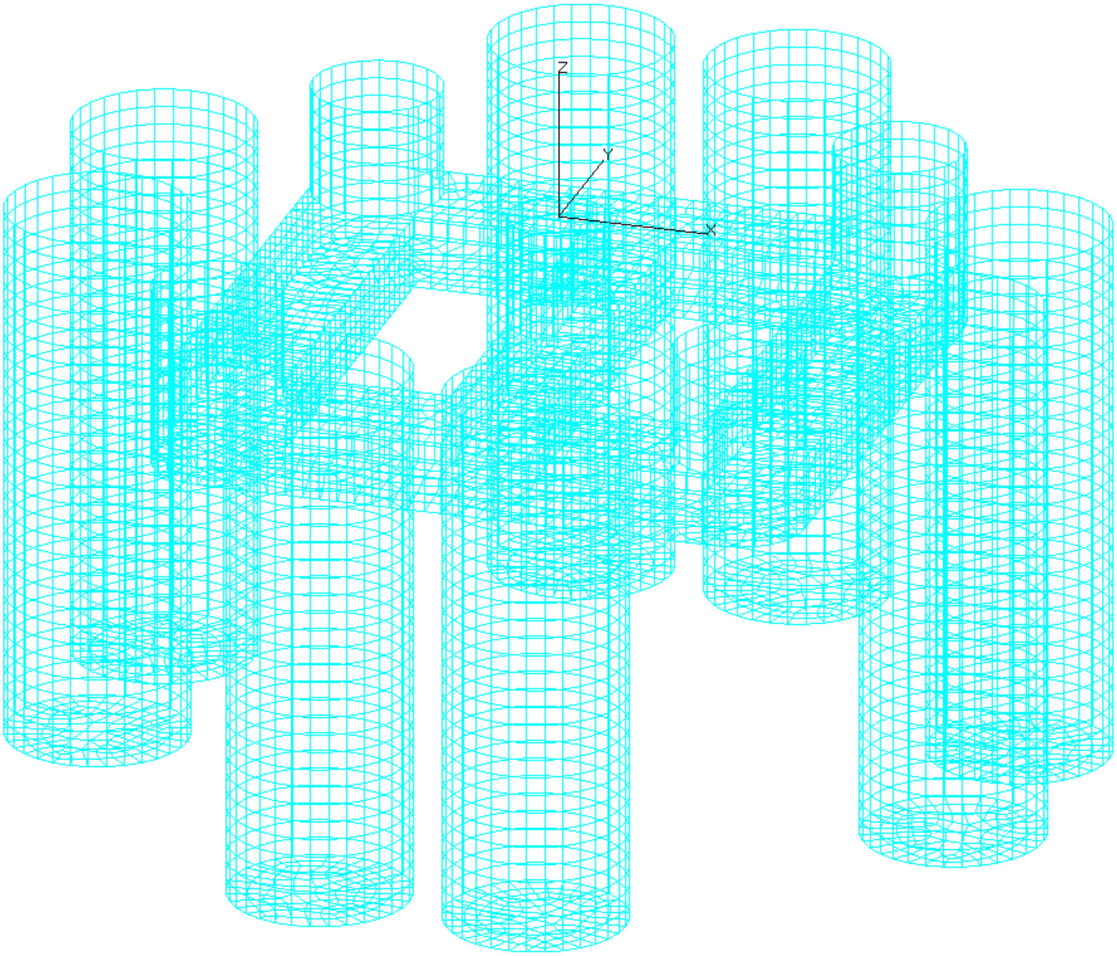
The report presents the results comparing the current meshing configuration with the finer meshing configuration.

Current Mesh Used the Analysis:



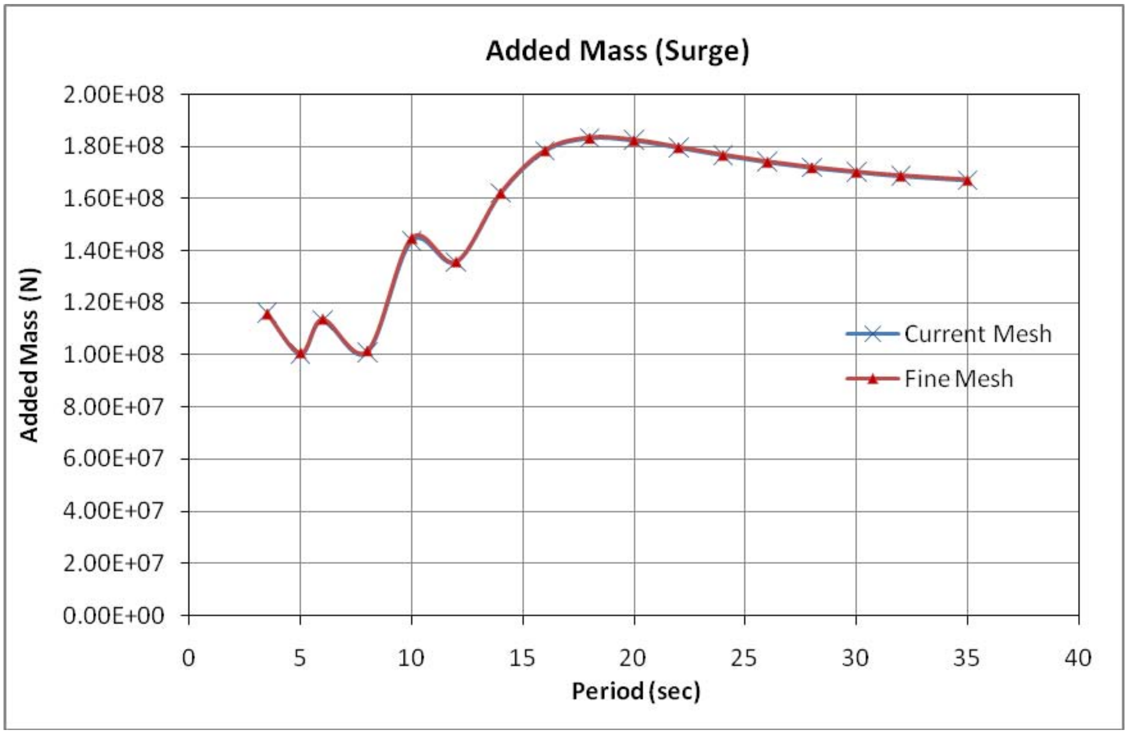
Total hull panel number for the current meshing configuration is **2224**

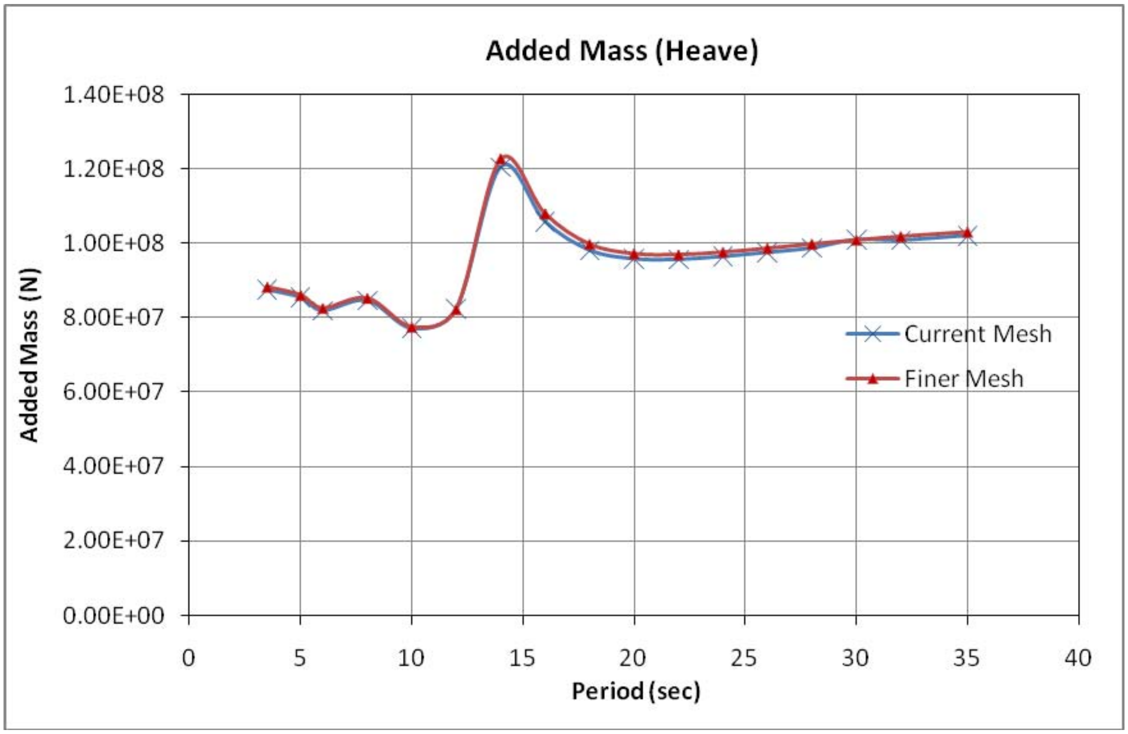
Finer Mesh:

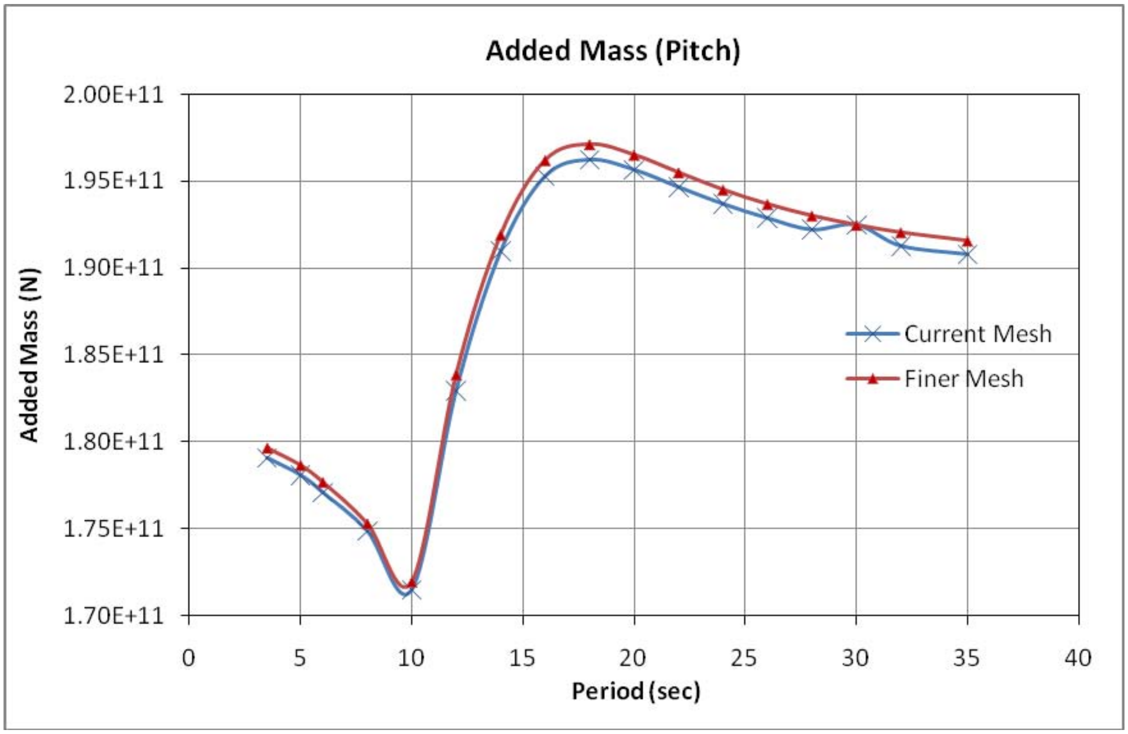


Total hull panel number for the finer mesh is **3056**

The wave analysis program WAMIT is used to evaluate the hydrodynamic coefficients including: Added Mass, Radiation Damping, Linear Wave Force for both the current meshing as well the finer meshing configurations. Comparison plots are shown below. It can be seen that the current model with 2224 panels provide converged results, no irregular frequency is observed for the model.


Added Mass (Surge)
Added Mass (N)
2.00E+08
1.80E+08
1.60E+08
1.40E+08
1.20E+08
1.00E+08
8.00E+07
6.00E+07
4.00E+07
2.00E+07
0.00E+00
0
5
10
15
20
25
30
35
40
Period (sec)
Current Mesh
Fine Mesh


Added Mass (Heave)
Added Mass (N)
1.40E+08
1.20E+08
1.00E+08
8.00E+07
6.00E+07
4.00E+07
2.00E+07
0.00E+00
0
5
10
15
20
25
30
35
40
Period (sec)
Current Mesh
Finer Mesh


Added Mass (Pitch)
Added Mass (N)
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1.95E+11
1.90E+11
1.85E+11
1.80E+11
1.75E+11
1.70E+11
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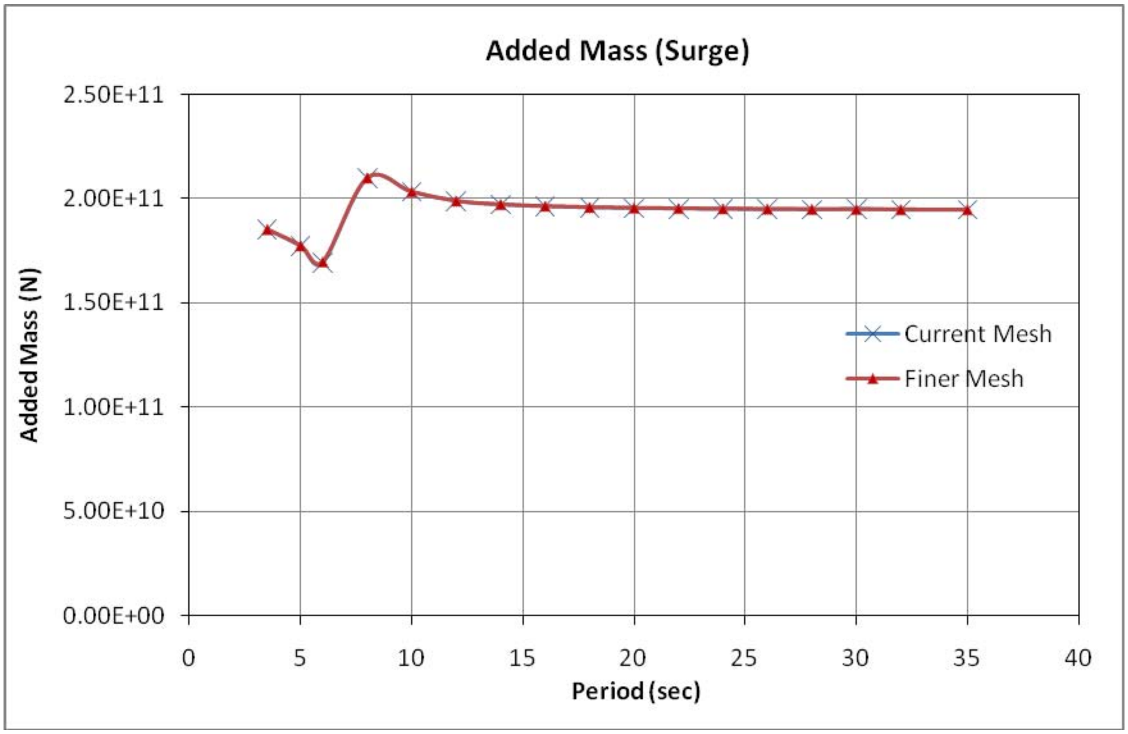
5
10
15
20
25
30
35
40
Period (sec)
Current Mesh
Finer Mesh


Added Mass (Surge)
Added Mass (N)
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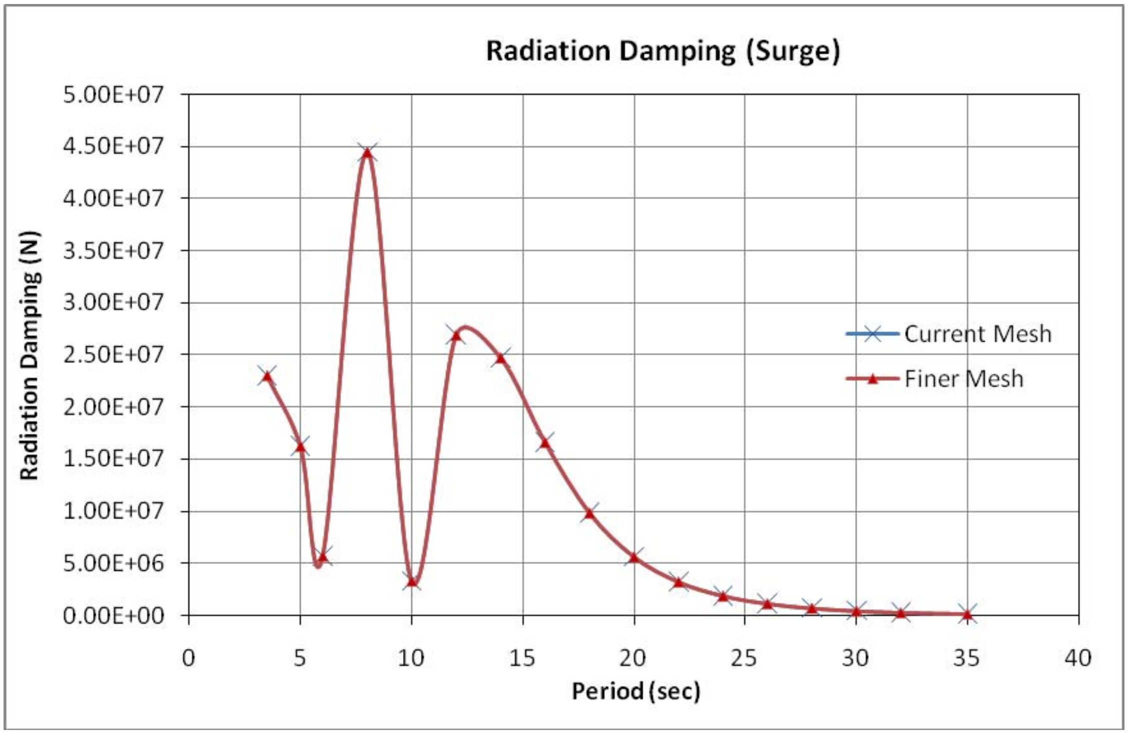
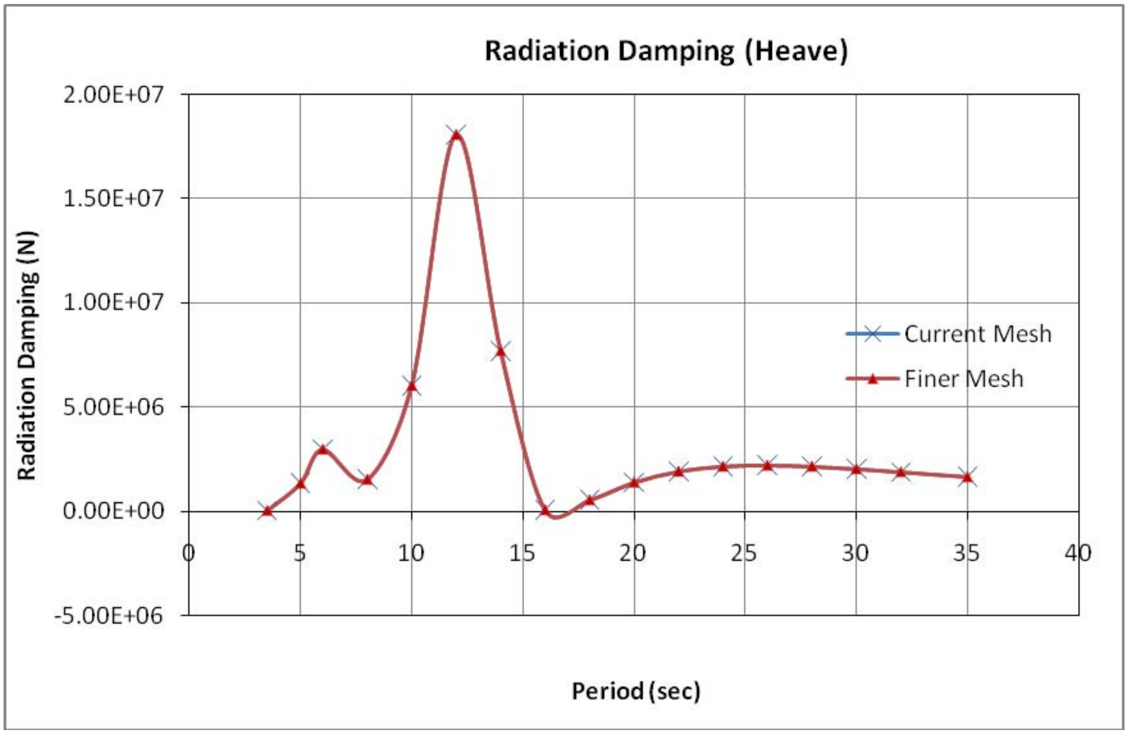
2.00E+11
1.50E+11
1.00E+11
5.00E+10
0.00E+00
0
5
10
15
20
25
30
35
40
Period (sec)
Current Mesh
Finer Mesh


Radiation Damping (Surge)
Radiation Damping (N)
5.00E+07
4.50E+07
4.00E+07
3.50E+07
3.00E+07
2.50E+07
2.00E+07
1.50E+07
1.00E+07
5.00E+06
0.00E+00
0
5
10
15
20
25
30
35
40
Period (sec)
Current Mesh
Finer Mesh


Radiation Damping (Heave)
Radiation Damping (N)
2.00E+07
1.50E+07
1.00E+07
5.00E+06
0.00E+00
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0
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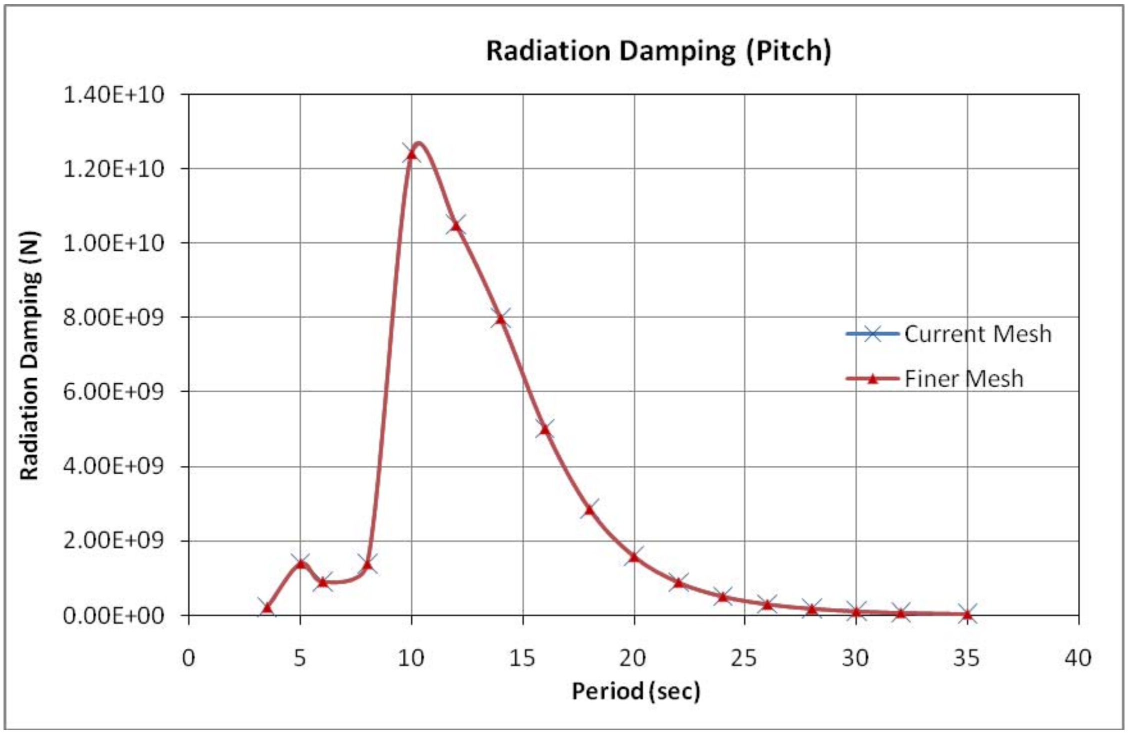
10
15
20
25
30
35
40
Period (sec)
Current Mesh
Finer Mesh


Radiation Damping (Pitch)
Radiation Damping (N)
1.40E+10
1.20E+10
1.00E+10
8.00E+09
6.00E+09
4.00E+09
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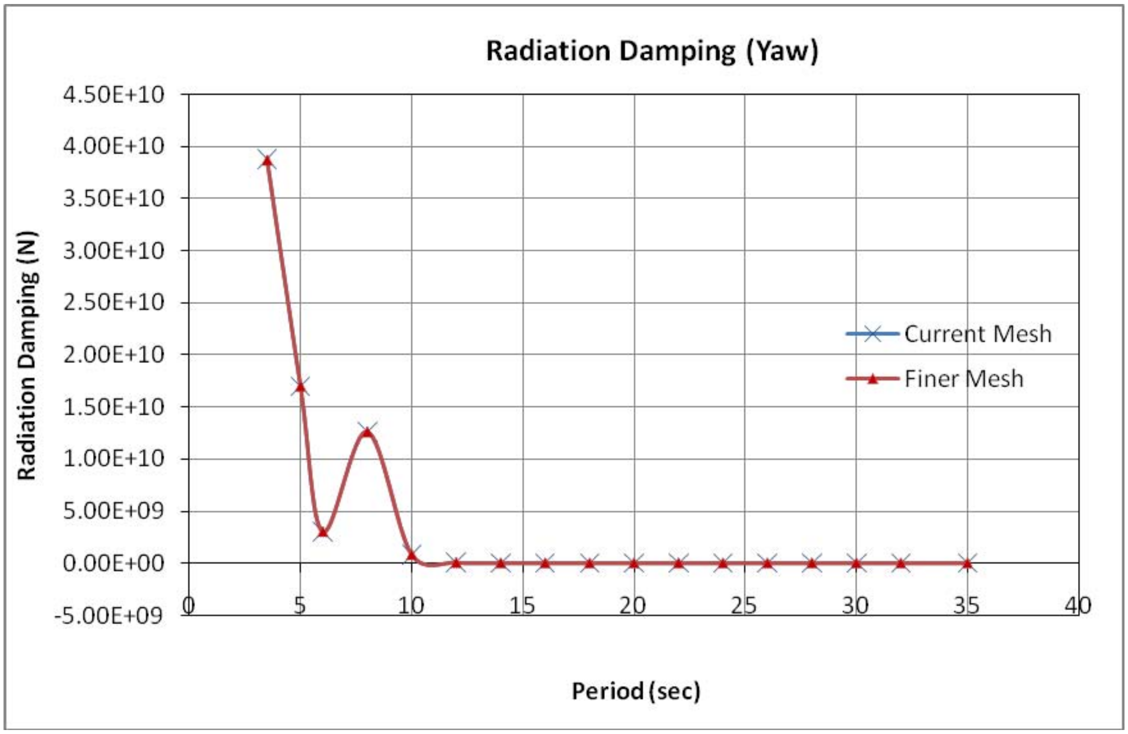
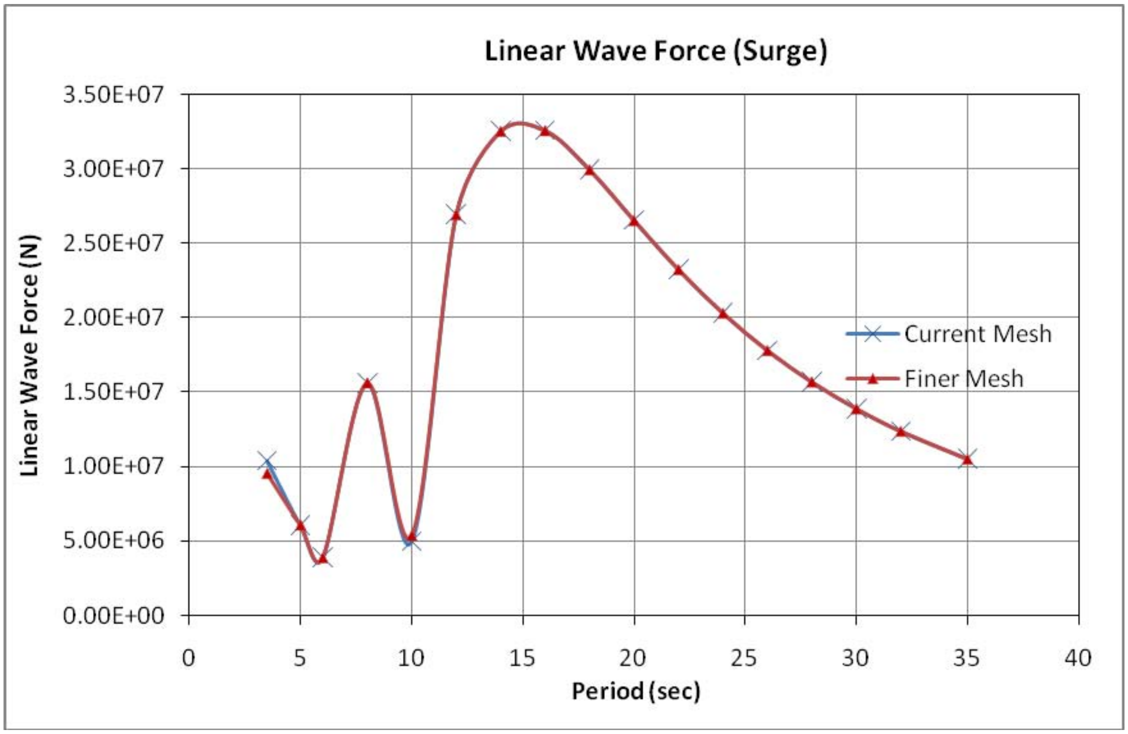
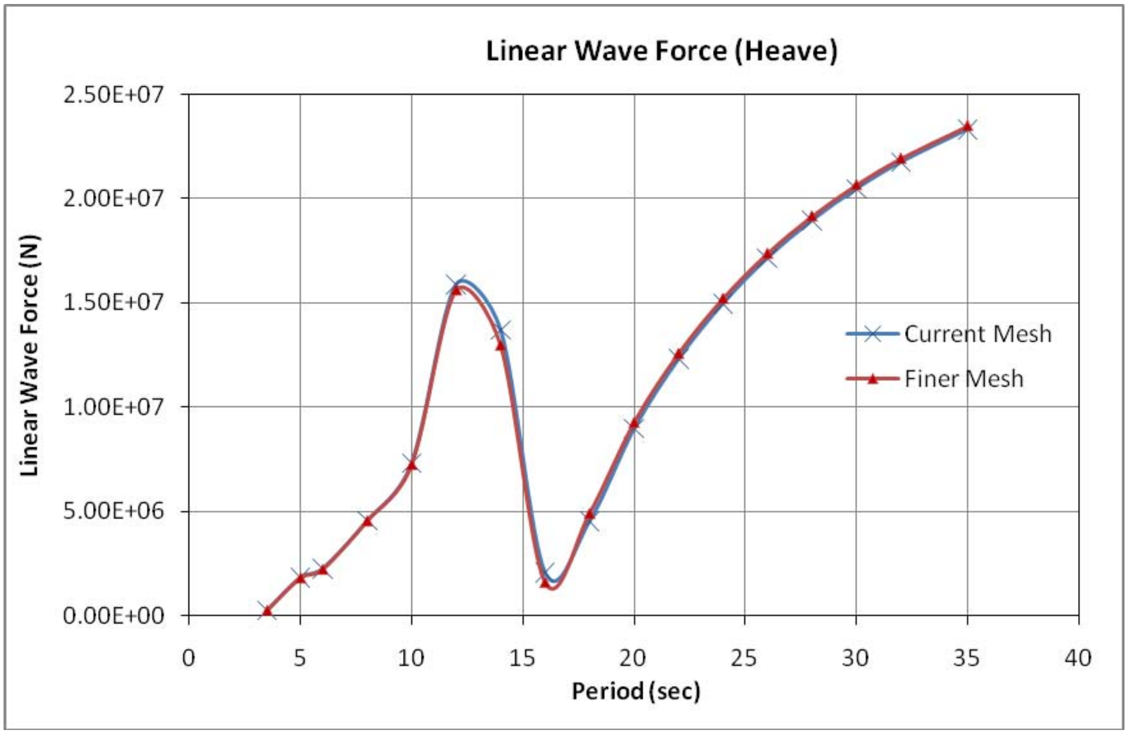
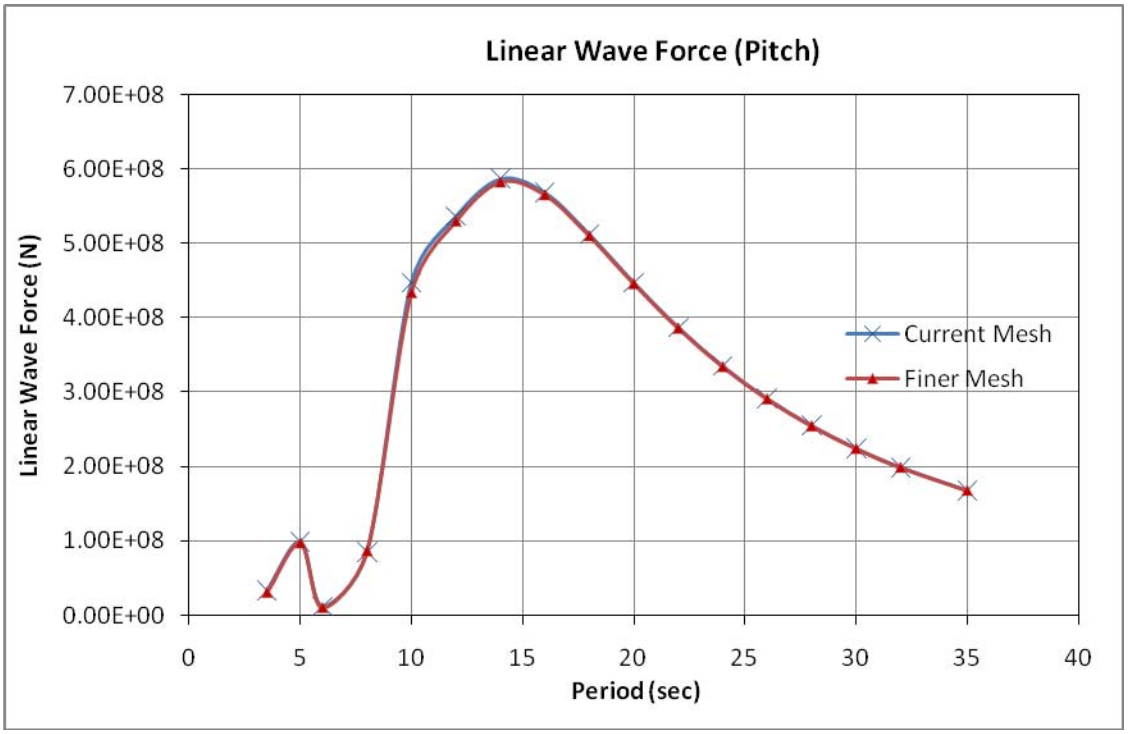
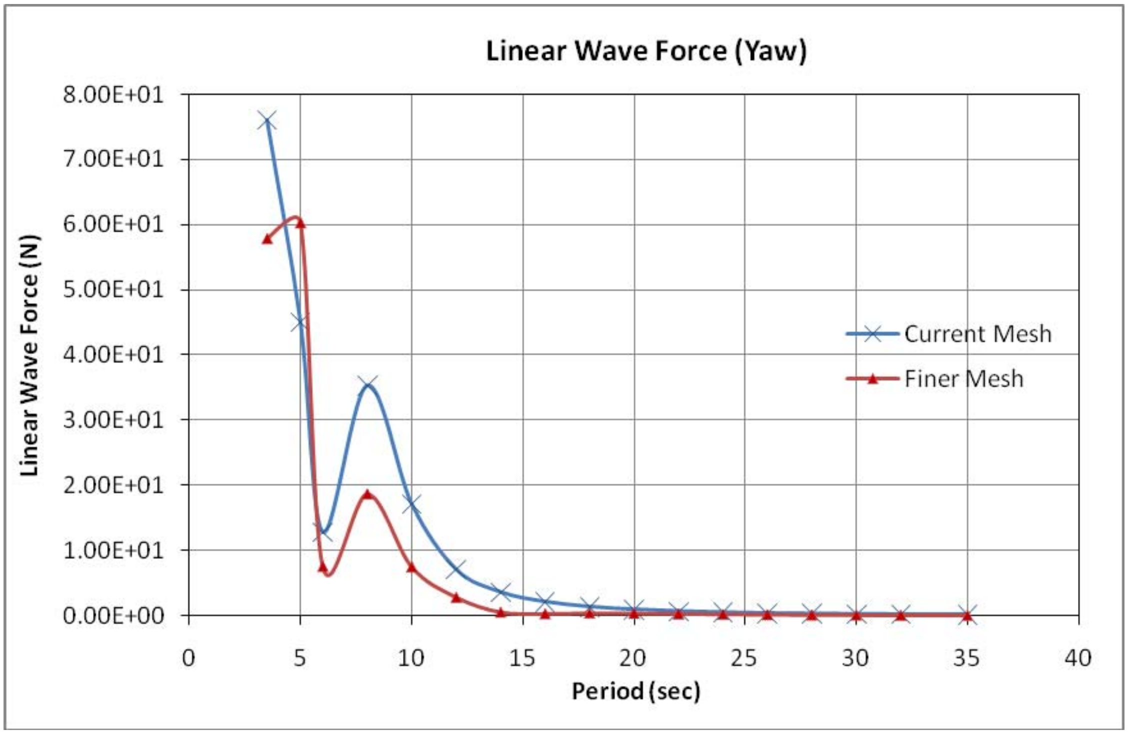
40
Period (sec)
Current Mesh
Finer Mesh

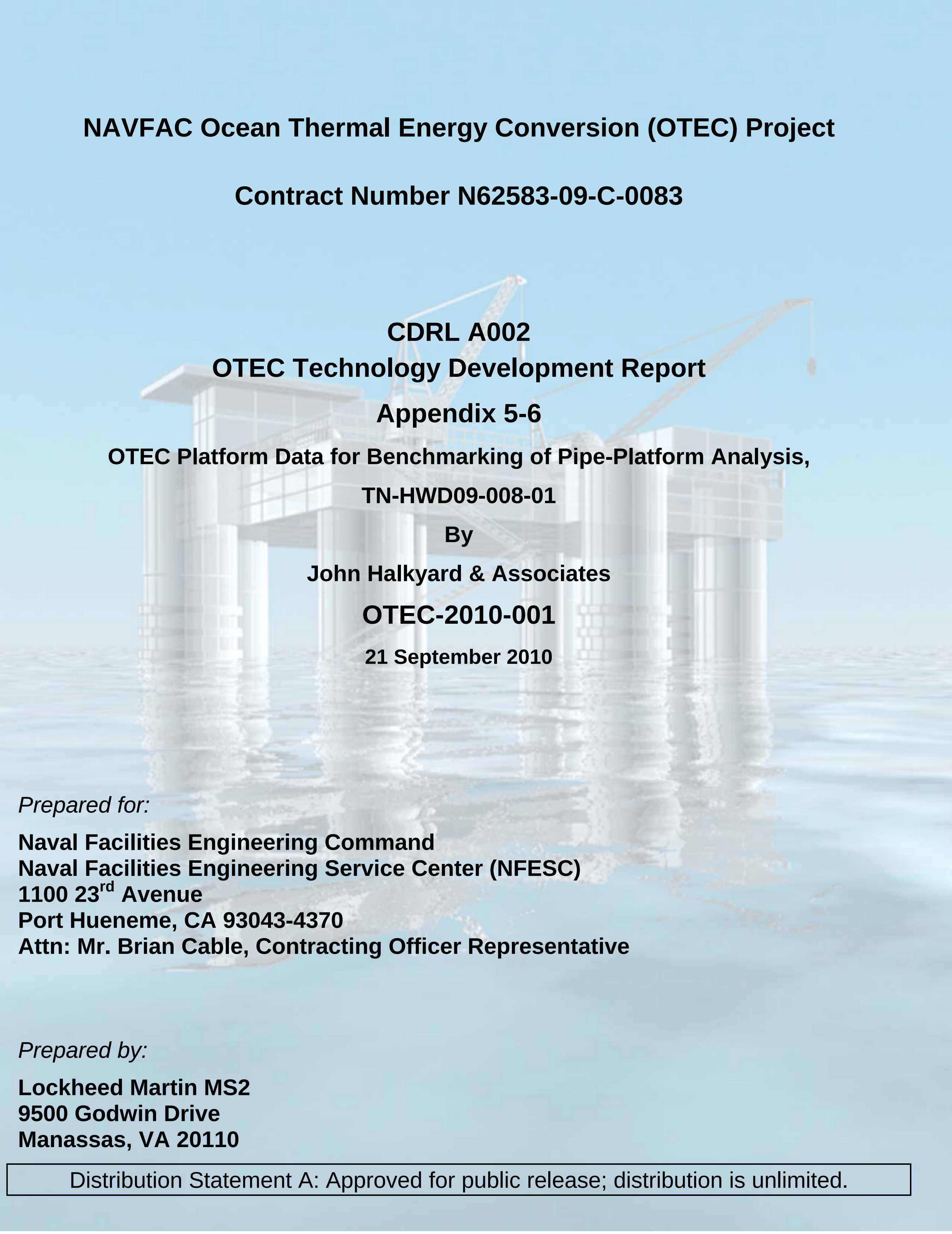

Radiation Damping (Yaw)
Radiation Damping (N)
4.50E+10
4.00E+10
3.50E+10
3.00E+10
2.50E+10
2.00E+10
1.50E+10
1.00E+10
5.00E+09
0.00E+00
-5.00E+09
0
5
10
15
20
25
30
35
40
Period (sec)
Current Mesh
Finer Mesh


Linear Wave Force (Surge)
Linear Wave Force (N)
3.50E+07
3.00E+07
2.50E+07
2.00E+07
1.50E+07
1.00E+07
5.00E+06
0.00E+00
0
5
10
15
20
25
30
35
40
Period (sec)
Current Mesh
Finer Mesh


Linear Wave Force (Heave)
Linear Wave Force (N)
2.50E+07
2.00E+07
1.50E+07
1.00E+07
5.00E+06
0.00E+00
0
5
10
15
20
25
30
35
40
Period (sec)
Current Mesh
Finer Mesh


Linear Wave Force (Pitch)
Linear Wave Force (N)
7.00E+08
6.00E+08
5.00E+08
4.00E+08
3.00E+08
2.00E+08
1.00E+08
0.00E+00
0
5
10
15
20
25
30
35
40
Period (sec)
Current Mesh
Finer Mesh


Linear Wave Force (Yaw)
Linear Wave Force (N)
8.00E+01
7.00E+01
6.00E+01
5.00E+01
4.00E+01
3.00E+01
2.00E+01
1.00E+01
0.00E+00
0
5
10
15
20
25
30
35
40
Period (sec)
Current Mesh
Finer Mesh



NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report
Appendix 5-6
OTEC Platform Data for Benchmarking of Pipe-Platform Analysis,

TN-HWD09-008-01

By

John Halkyard & Associates

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
Naval Facilities Engineering Service Center (NFESC)
1100 23rd Avenue
Port Hueneme, CA 93043-4370
Attn: Mr. Brian Cable, Contracting Officer Representative

Prepared by:

Lockheed Martin MS2
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Manassas, VA 20110

Distribution Statement A: Approved for public release; distribution is unlimited.

OTEC Platform Data for Benchmarking of Pipe – Platform Analysis

Technical Note

TN-10-102

John Halkyard / Shan Shi

Rev	Date	Description
0	10 Mar 2010	Initial Release
1	30 Mar 2010	Units added to Table 12

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Contents

Figures

Tables

1. Introduction

This document describes the basis for benchmarking analysis to be performed in order to verify results for the OTEC 100MW platform motions and pipe strains. Analyses are planned with three independent programs:

1. HARP
2. Flexcom (Ver. 5 Floating Platform option)
3. Ansys AQWA

Houston Offshore Engineering will perform the analysis using HARP and Flexcom. NAVFAC will perform the analysis using AQWA. Further background may be found in the minutes of a meeting on March 3, 2010[1].

2. Units and Coordinates

Unless otherwise noted all units are metric as follows:

Length – meters (m)
Force/Weight – Newtons (N)
Mass – kilogram (kg)

Forces are often given in kN or tonnef (t) = 9806 N..

Angles are by default in radians unless noted to be in degrees.

The coordinate system is centered on the mean waterline in the geometric center of the platform. X is positive to the right and it follows the right hand rule.

3. Platform

The benchmarking will be performed on two configurations of the platform: Pipe Fabrication configuration and operational configuration. The main difference is the presence of eight “Remoras”, or external pods used to house the heat exchangers. These will be in place during operations but not during the pipe fabrication.

3.1. Operational Case (with Remoras)

Table 1 gives the principle particulars. Where there is a discrepancy between these values and the mass properties given below in Section 3, use those given in Section 3.

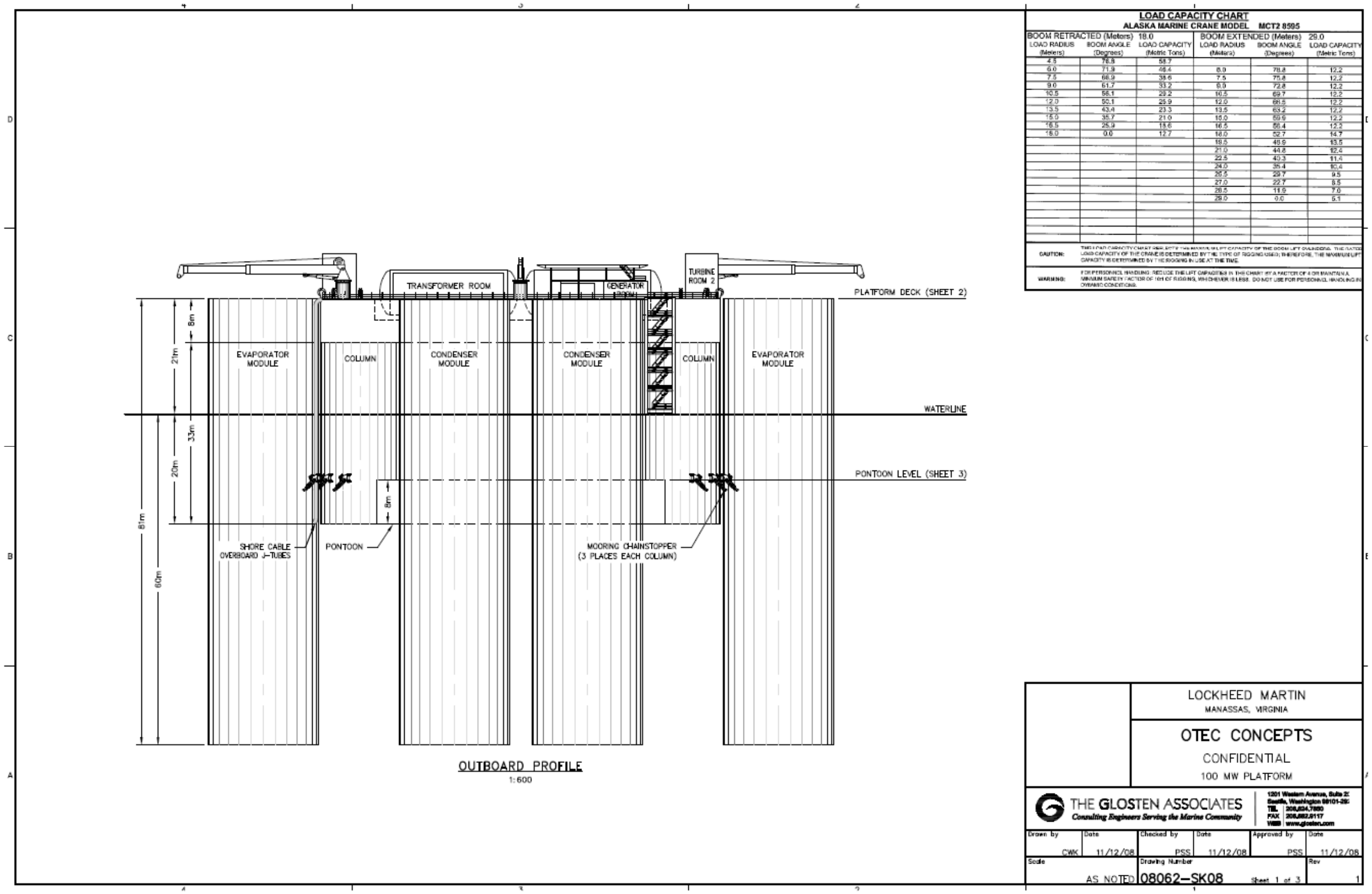
Figure 1, Figure 2 and Figure 3 show the outboard profile, the deck plan and the pontoon level plan respectively.

---

[1] John Halkyard and Associates, Memo, March 5, 2010

Table 1 Particulars for the 100 MW OTEC Platform (with Remoras)

	100 MW
Topsides Equipment Weight, t	4600.0
Draft (hull), m	20.0
Draft (Remora), m	38.0
Freeboard, m	21.0
Air Gap, m	13.0
Column Spacing, m	58.0
Column Diameter, m	14.3
Topsides Weight, t	9091.1
Hull Weight, t	5864.1
Ballast Weight, t	15253.0
Entrained Water Weight, t	3419.7
OTEC Module Weight, t	155253.6
Total Weight, t	188881.5
CG, m (from waterline)	-29.2
External Vertical Loads, m	3500.0
Total Displacement, t	192381.5
GM, m	20.4



LOAD CAPACITY CHART

ALASKA MARINE CRANE MODEL MCT2 8595

BOOM RETRACTED (Meters) 18.0			BOOM EXTENDED (Meters) 29.0		
LOAD RADIUS (Meters)	BOOM ANGLE (Degrees)	LOAD CAPACITY (Metric Tons)	LOAD RADIUS (Meters)	BOOM ANGLE (Degrees)	LOAD CAPACITY (Metric Tons)
4.5	76.8	58.7			
6.0	71.9	46.4	6.0	78.8	12.2
7.5	66.9	38.6	7.5	75.8	12.2
9.0	61.7	33.2	9.0	72.8	12.2
10.5	56.1	29.2	10.5	69.7	12.2
12.0	50.1	25.9	12.0	66.5	12.2
13.5	43.4	23.3	13.5	63.2	12.2
15.0	35.7	21.0	15.0	59.9	12.2
16.5	25.9	18.6	16.5	56.4	12.2
18.0	0.0	12.7	18.0	52.7	14.7
			19.5	48.9	13.5
			21.0	44.8	12.4
			22.5	40.3	11.4
			24.0	35.4	10.4
			25.5	29.7	9.5
			27.0	22.7	8.5
			28.5	11.9	7.0
			29.0	0.0	6.1

CAUTION: THIS LOAD CAPACITY CHART REFLECTS THE MAXIMUM LIFT CAPACITY OF THE BOOM LIFT CYLINDERS. THE RATED LOAD CAPACITY OF THE CRANE IS DETERMINED BY THE TYPE OF RIGGING USED; THEREFORE, THE MAXIMUM LIFT CAPACITY IS DETERMINED BY THE RIGGING IN USE AT THE TIME.

WARNING: FOR PERSONNEL HANDLING: REDUCE THE LIFT CAPACITIES IN THE CHART BY A FACTOR OF 4 OR MAINTAIN A MINIMUM SAFETY FACTOR OF 10:1 OF RIGGING, WHICHEVER IS LESS. DO NOT USE FOR PERSONNEL HANDLING IN DYNAMIC CONDITIONS.

Figure 1 Outboard Profile, 100 MW OTEC Platform

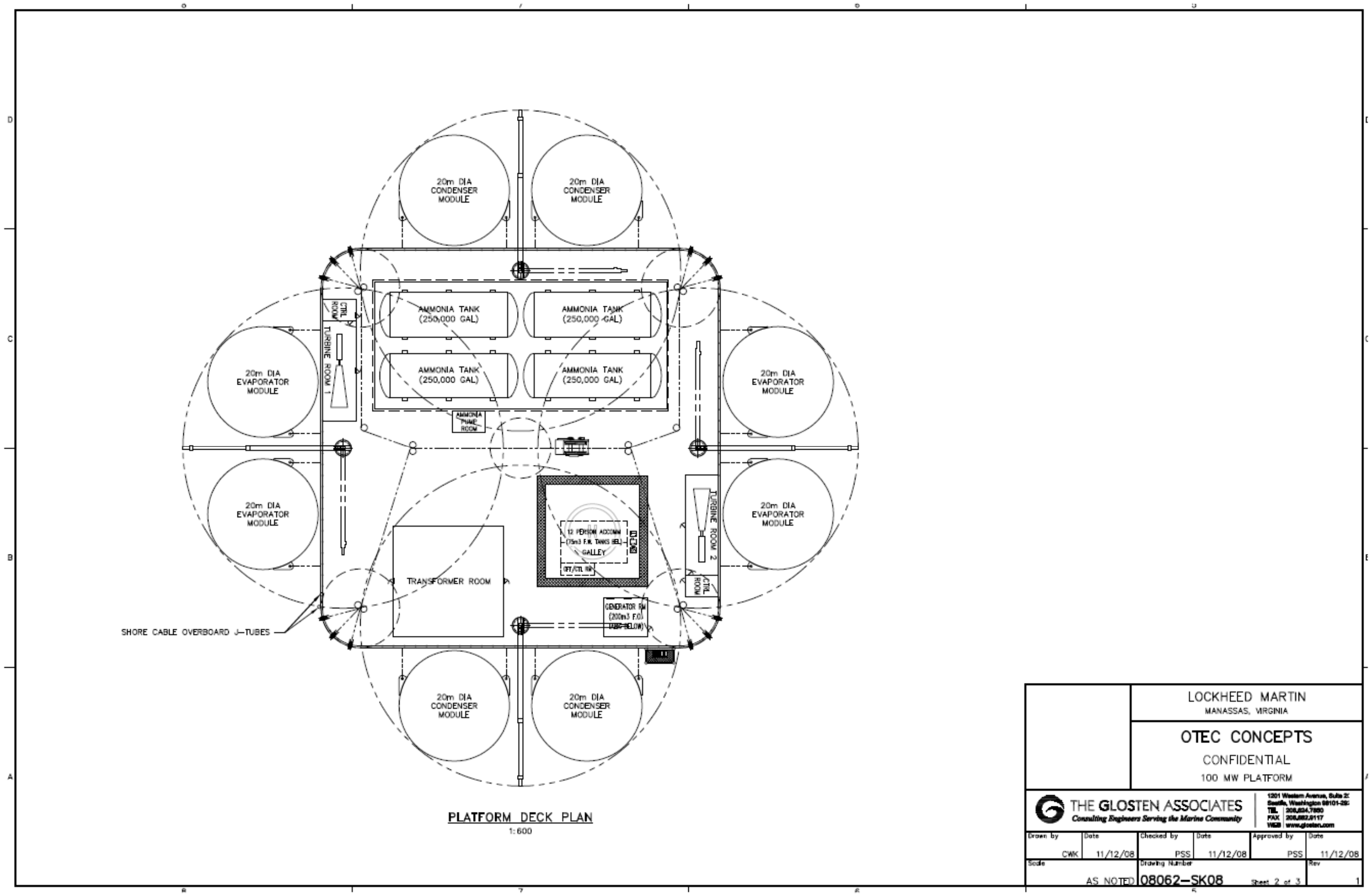


Figure 2 Deck Plan, 100 MW OTEC Platfrom

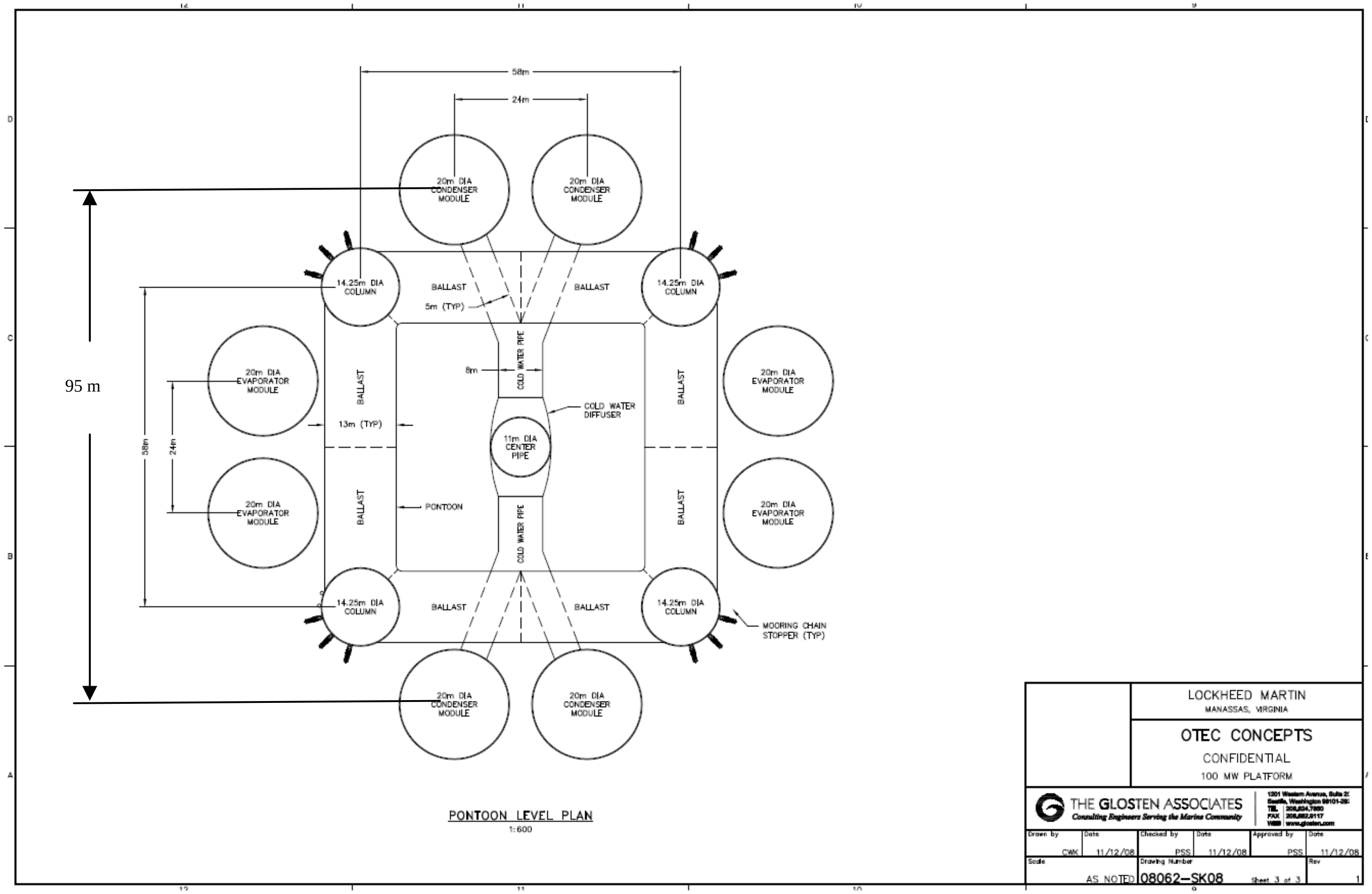


Figure 3 Pontoon Level Plan, 100 MW OTEC Platfrom

3.2. Fabrication Case (no Remoras)

There will be no Remoras attached during fabrication of the pipe, which presents a new platform model. Table 2 shows the particulars for the platform without Remoras.

Table 2 Particulars for the 100 MW OTEC Platfrom (without Remoras)

Draft (hull), m	20.0
Draft (Remora), m	38.0
Freeboard, m	21.0
Air Gap, m	13.0
Column Spacing, m	58.0
Column Diameter, m	14.3
Topsides Weight, t	9091.1
Hull Weight, t	5864.1
Ballast Weight, t	15637.8
Entrained Water Weight, t	3419.7
OTEC Module Weight, t	1.0
Total Weight, t	34013.7
CG, m (from waterline)	-4.3
External Vertical Loads, m	3500.0
Total Displacement, t	37513.7
GM, m	5.6

4. Hydrodynamic Modeling

4.1. Radiation and Diffraction

4.1.1. Operational Case – With Remoras

Radiation and Diffraction has been calculated using WAMIT. Figure 4 shows the full panel model used for this. Panel input is given for a quarter of the structure since it is asymmetric about two axis. The panel coordinates are included as an Addendum for reference.

Data for computing hydrostatic and mass properties is shown in Figure 5. Table 3 and Table 4 give the Hydrostatic Stiffness and Structural Mass matrices, respectively.

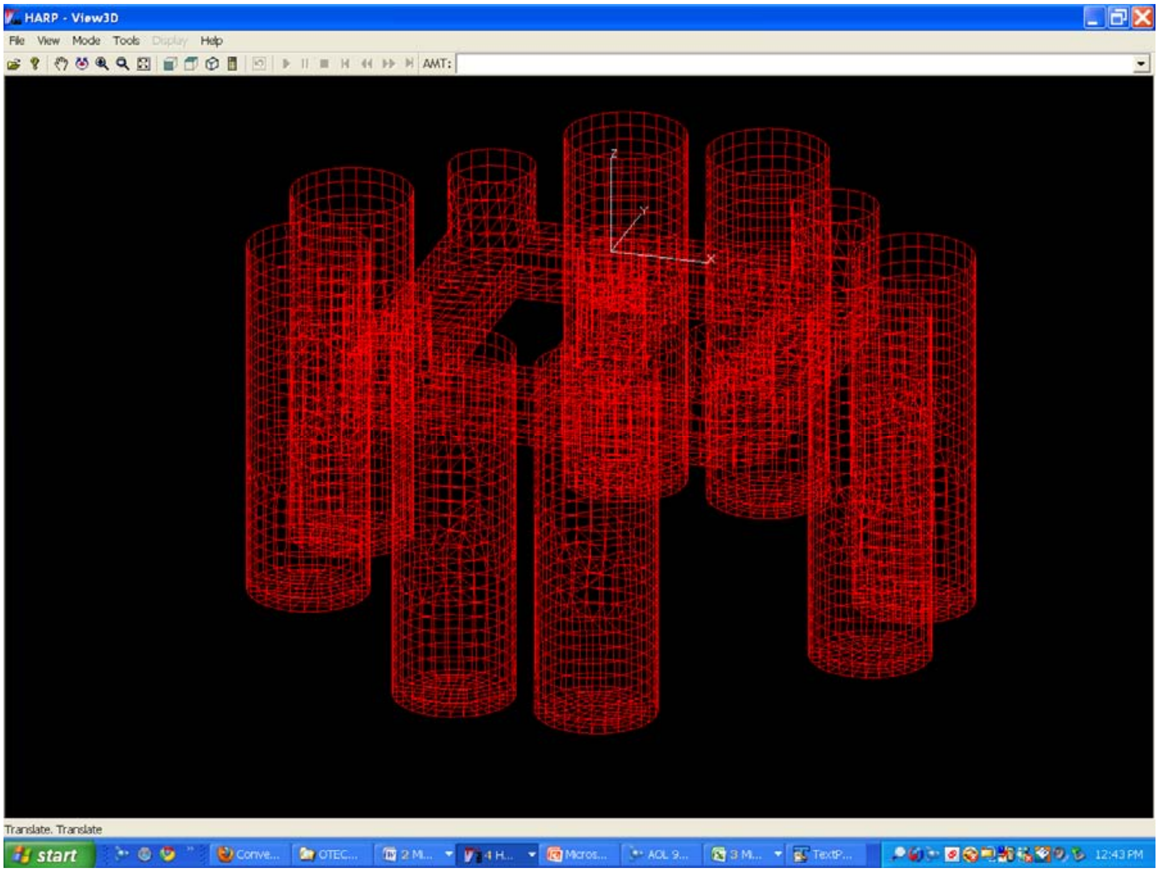
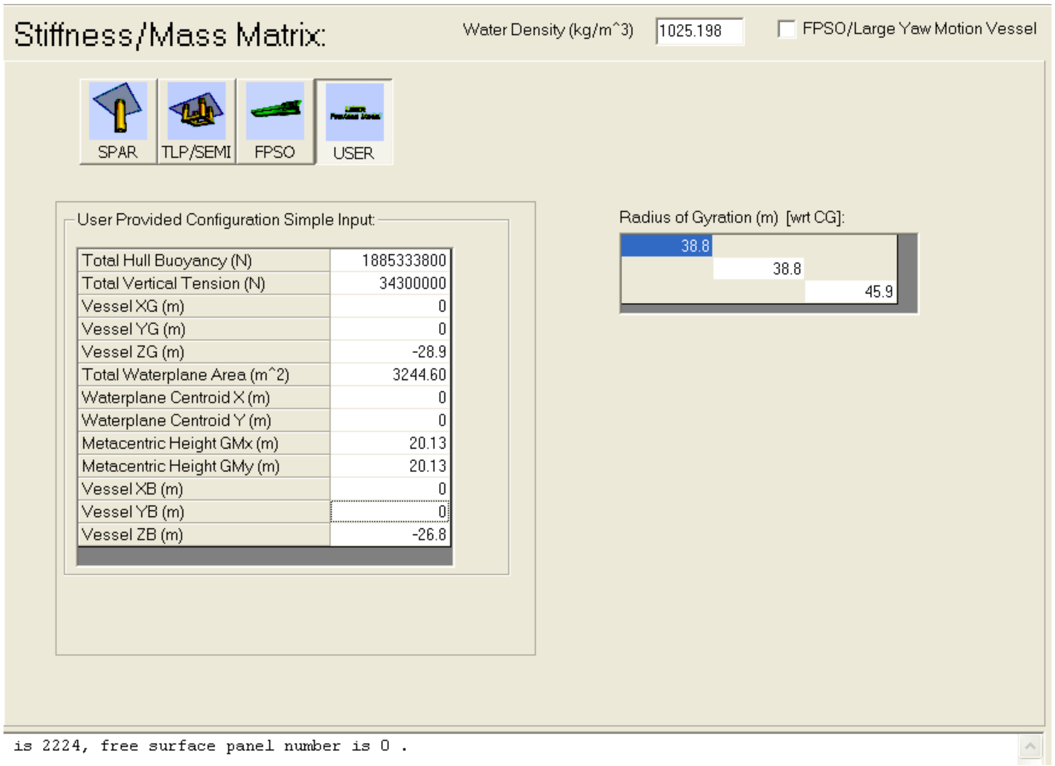


Figure 4 Full Panel Model (Ref file: OTEC_100MW_Full.gdf)



Stiffness/Mass Matrix:

Water Density (kg/m^3) 1025.198

☐ FPSO/Large Yaw Motion Vessel

User Provided Configuration Simple Input:

Total Hull Buoyancy (N)	1885333800
Total Vertical Tension (N)	34300000
Vessel XG (m)	0
Vessel YG (m)	0
Vessel ZG (m)	-28.9
Total Waterplane Area (m^2)	3244.60
Waterplane Centroid X (m)	0
Waterplane Centroid Y (m)	0
Metacentric Height GMx (m)	20.13
Metacentric Height GMy (m)	20.13
Vessel XB (m)	0
Vessel YB (m)	0
Vessel ZB (m)	-26.8

Radius of Gyration (m) [wrt CG]:

38.8		
	38.8	
		45.9

```
is 2224, free surface panel number is 0 .
```

Figure 5 Data for Computing Hydrostatics and Mass Properties

Table 3 Hydrostatic Stiffness

0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	3.26E+07	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	3.70E+10	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.70E+10	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00

Table 4 Structural Mass Matrix

1.89E+08	0.00E+00	0.00E+00	0.00E+00	-5.46E+09	0.00E+00
0.00E+00	1.89E+08	0.00E+00	5.46E+09	0.00E+00	0.00E+00
0.00E+00	0.00E+00	1.89E+08	0.00E+00	0.00E+00	0.00E+00
0.00E+00	5.46E+09	0.00E+00	4.42E+11	0.00E+00	0.00E+00
-5.46E+09	0.00E+00	0.00E+00	0.00E+00	4.42E+11	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.98E+11

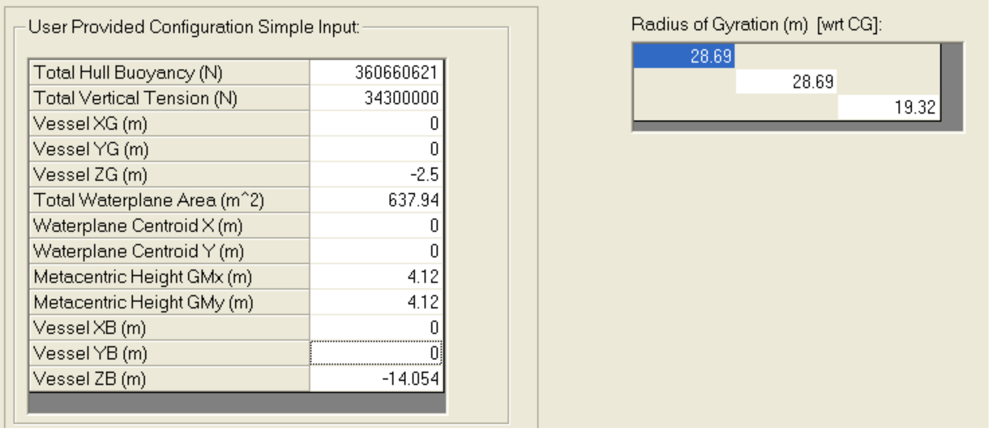
Table 5 Periods

Period
3.5
5
6
8
10
12
14
16
18
20
22
24
26
28
30
32
35

Table 5 shows the 17 periods used to compute wave radiation (added mass and damping) and diffraction (excitation force) coefficients.

4.1.2. Installation Case – No Remoras

The following Tables present the hydrostatic stiffness and mass matrices for the installation case.



User Provided Configuration Simple Input:

Total Hull Buoyancy (N)	360660621
Total Vertical Tension (N)	34300000
Vessel XG (m)	0
Vessel YG (m)	0
Vessel ZG (m)	-2.5
Total Waterplane Area (m^2)	637.94
Waterplane Centroid X (m)	0
Waterplane Centroid Y (m)	0
Metacentric Height GMx (m)	4.12
Metacentric Height GMy (m)	4.12
Vessel XB (m)	0
Vessel YB (m)	0
Vessel ZB (m)	-14.054

Radius of Gyration (m) [wrt CG]:

28.69		
	28.69	
		19.32

Figure 6 Data for Computing Hydrostatic and Mass Properties (No Remoras)

Table 6 Hydrostatic Stiffness Matrix - No Remoras

0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	6.41E+06	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	1.40E+09	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.40E+09	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00

Table 7 Mass Matrix - No Remoras

3.33E+07	0.00E+00	0.00E+00	0.00E+00	-8.32E+07	0.00E+00
0.00E+00	3.33E+07	0.00E+00	8.32E+07	0.00E+00	0.00E+00
0.00E+00	0.00E+00	3.33E+07	0.00E+00	0.00E+00	0.00E+00
0.00E+00	8.32E+07	0.00E+00	2.76E+10	0.00E+00	0.00E+00
-8.32E+07	0.00E+00	0.00E+00	0.00E+00	2.76E+10	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E+10

The full hydrodynamic mesh without Remoras is shown in Figure 7. Panel coordinates will be provided in an Addendum.

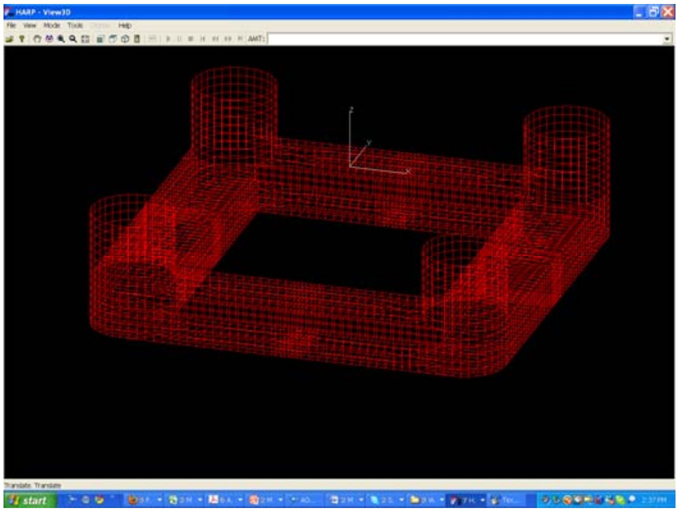


Figure 7 Hydrodynamic Mesh without Remoras (1684 Elements, Ref file: 100MW_semionly_Full.gdf))

4.2. Drag

Drag forces are represented by Morison “Stick” elements and plate elements (to represent drag on the lower surfaces of the columns) as shown in Figure 1. Properties for the stick and plate elements are shown in Table 8 and Table 9 respectively.

Note that viscous forces are uncertain and require testing and/or computational fluid mechanics to verify.

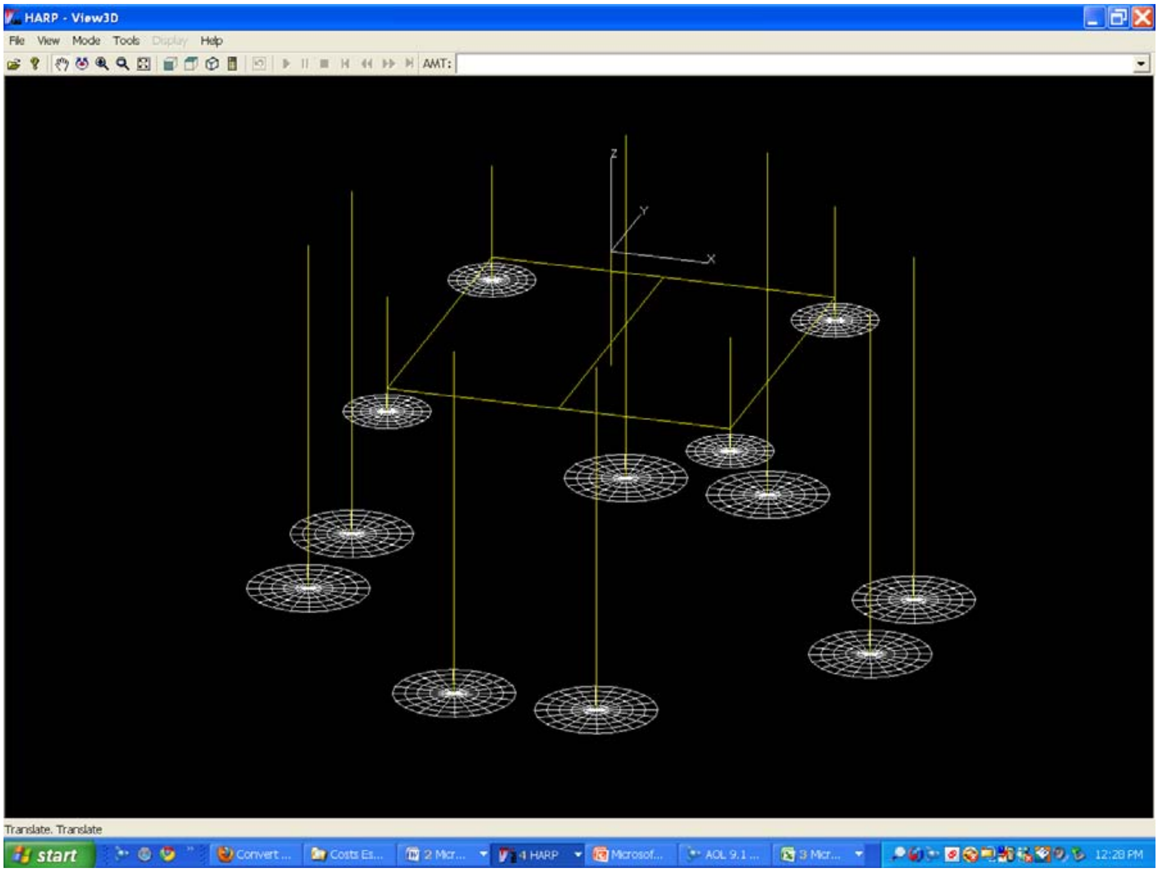


Figure 8 Stick and Plate Elements

Table 8 Properties of Stick Elements

Item	X1	Y1	Z1	X2	Y2	Z2	D	Ca	Cfk	Cd
Column	29	29	0	29	29	-20	14.25	0	0	0.8
Column	-29	29	0	-29	29	-20	14.25	0	0	0.8
Column	-29	-29	0	-29	-29	-20	14.25	0	0	0.8
Column	29	-29	0	29	-29	-20	14.25	0	0	0.8
Center	0	0	0	0	0	-20	11	0	0	0.8
Pontoon	29	-29	-16	29	29	-16	14.25	0	0	2
Pontoon	29	29	-16	-29	29	-16	14.25	0	0	2
Pontoon	-29	29	-16	-29	-29	-16	14.25	0	0	2
Pontoon	-29	-29	-16	29	-29	-16	14.25	0	0	2
Duct	0	-29	-16	0	29	-16	9	0	0	2
Remora	47.5	-12	0	47.5	-12	-60	20	0	0	0.7
Remora	47.5	12	0	47.5	12	-60	20	0	0	0.7
Remora	12	47.5	0	12	47.5	-60	20	0	0	0.7
Remora	-12	47.5	0	-12	47.5	-60	20	0	0	0.7
Remora	-47.5	12	0	-47.5	12	-60	20	0	0	0.7
Remora	-47.5	-12	0	-47.5	-12	-60	20	0	0	0.7
Remora	-12	-47.5	0	-12	-47.5	-60	20	0	0	0.7

Remora	12	-47.5	0	12	-47.5	-60	20	0	0	0.7

Table 9 Plate Element Properties

	X	Y	Z	EX	EY	EZ	D	Ca	Cfk	Cd
Column	29	29	-20	0	0	1	14.25	0	0	2
Column	-29	29	-20	0	0	1	14.25	0	0	2
Column	-29	-29	-20	0	0	1	14.25	0	0	2
Column	29	-29	-20	0	0	1	14.25	0	0	2
Remora	47.5	-12	-60	0	0	1	20	0	0	2
Remora	47.5	12	-60	0	0	1	20	0	0	2
Remora	12	47.5	-60	0	0	1	20	0	0	2
Remora	-12	47.5	-60	0	0	1	20	0	0	2
Remora	-47.5	12	-60	0	0	1	20	0	0	2
Remora	-47.5	-12	-60	0	0	1	20	0	0	2
Remora	-12	-47.5	-60	0	0	1	20	0	0	2
Remora	12	-47.5	-60	0	0	1	20	0	0	2

EX, EY and EZ refer to the direction cosines for a vector normal to the surface of the plate.

Modeling without the Remoras simply excludes the Remoras from these stick and plate models.

4.3. Wind Area

The platform effective wind area at 0/180 deg heading is 2979 m^2 and the center of pressure is 12.9 m above the mean water level.

The same wind area shall be used for both the fabrication and operational cases. This is probably not necessarily realistic, but the pipe manufacturing equipment has not been incorporated into this model as of yet.

5. Mooring

The OTEC platform is moored in 1100 m[2] of water using a taut mooring system consisting of platform chain, polyester and anchor chain. Figure 9 and **Error! Reference source not found.** show the static configuration of the mooring. Table 10 shows the mooring line properties.

Pretension on all lines is 2500 kN.

---

[2] Anchor locations are shown at -974.4 m. Check this.

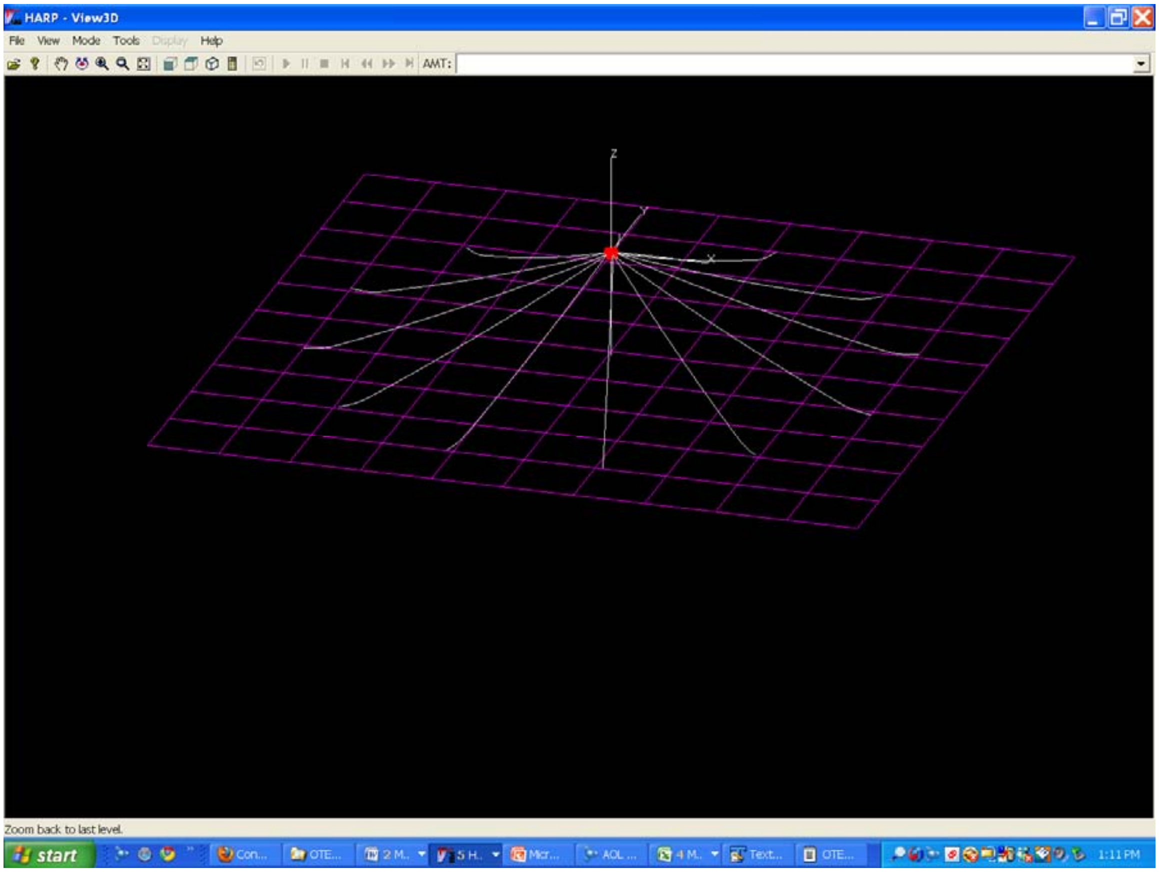


Figure 9 Mooring Spread

Table 10 Mooring Line Properties

	Properties
Number of Lines	12
Platform Chain	
Diameter, mm	145
Length, m	95
Wet Weight, kg/m	380.2
Dry Weight, kg/m	437
EA, kN	1383579
Min Breaking Strength, kN	18679
Min Breaking Strength Corroded, kN	17086
Polyester Line	
Diameter, mm	240
Length, m	2500
Wet Weight, kg/m	10.1
Dry Weight, kg/m	38.8
EA (max storm), kN	624000
Min Breaking Strength, kN	17084
Min Breaking Strength Corroded, kN	17084
Anchor Chain	
Diameter, mm	145
Length, m	95
EA, kN	1383579
Wet Weight, kg/m	380.2
Dry Weight, kg/m	437
Min Breaking Strength, kN	18679
Min Breaking Strength Corroded, kN	17086

Table 11 Fairlead and Anchor Coordinates and Azimuthal Angle

Line No.	Angle, deg	Xf	Yf	Zf	To	Xa	Ya	Za
1	15	35.88	30.84	-19	2500	2672.853	737.415	-974.399
2	45	34.04	34.04	-19	2500	1964.438	1964.438	-974.399
3	75	30.84	35.88	-19	2500	737.415	2672.853	-974.399
4	105	-30.84	35.88	-19	2500	-737.415	2672.853	-974.399
5	135	-34.04	34.04	-19	2500	-1964.44	1964.438	-974.399
6	165	-35.88	30.84	-19	2500	-2672.85	737.415	-974.399
7	195	-35.88	-30.84	-19	2500	-2672.85	-737.415	-974.399
8	225	-34.04	-34.04	-19	2500	-1964.44	-1964.44	-974.399
9	255	-30.84	-35.88	-19	2500	-737.415	-2672.85	-974.399
10	285	30.84	-35.88	-19	2500	737.415	-2672.85	-974.399
11	315	34.04	-34.04	-19	2500	1964.438	-1964.44	-974.399
12	345	35.88	-30.84	-19	2500	2672.853	-737.415	-974.399

6. Cold Water Pipe

6.1. Pipe Properties

The Cold Water Pipe is suspended from the center/keel of the platform. Table 12 shows the CWP Properties to be used for this analysis.

Table 12 Cold Water Pipe Properties (10m Ver. 2) [3]

CWP Properties	Operational	Fabrication
Length	1000.8	500
Wet Weight (kg/m)	1811	1811
Mass With Entrapped Water in Core[1] (kg/m)	10099	10099
Mass With All Entrapped Water [2] (kg/m)	90725	90725
EA, kN	65242320	65242320
EI, kN-m**2	8.47E+08	846963409
OD, m	10.509	10.509
Cm (1+Ca)	2	2
Cd	1	1
Pipe Tension, kN	17773.05	8879.4236

Note 1. Includes strucural mass and entrapped water in the FRP Core Structure. Use for vertical mass.

Note 2. Includes all internal water. Use for horizontal mass.

6.2. Pipe Attachment Stiffness

The stiffness of the pipe attachment affects platform motion. Table 13 shows the nominal stiffnesses for this analysis. Sensitivity on these stiffnesses will be included in the runs proposed below.

Table 13 Nominal Pipe/Platform Attachment Stiffness

	Op Case	Fabrication
Kx	1.00E+11	1.00E+11
Ky	1.00E+11	1.00E+11
Kz	1.00E+11	1.00E+11
Kxx	1.00E+13	1.30E+11
Kyy	1.00E+13	1.30E+11

---

[3] Reference spreadsheet: CWPProperties4mand10mfordynamicsandgripperREV4.xls 28 Feb 2010 (Joe Van Ryzin)

The lower end of the pipe hangs free. HARP analysis has been run with a very small stiffness, 1 N/m in the x, y, z directions and 100 N-m/rad rotational stiffness. Small values are required by the solver.

6.3. *Vertical Loads on Platform*

The platform mass properties depend on the vertical loads. A nominal value is used for WAMIT runs (in order to compute RAOs) as shown in Figure 5 and Figure 6.

The total vertical tensions based on the above data are:

Operational Case: 33177.8 kN
Fabrication Case: 24283.8 kN

Note these values are slightly different than shown in Figures 5&6. An adjustment may be made to the platform mass assuming the CG of the hull remains the same.

7. Environments

7.1. *Parameters*

Benchmarking shill be based on the following environments:

Operational Case (with Remoras) – Fatigue Bin 16
Fabrication Case (No Remoras) – 10-yr Swell

Table 14 lists the parameters for these environments.

Table 14 Environments for Benchmarking

	Fatigue Bin 16	10-Yr Swell
Hs	2.47	4
Tp	16.62	16
JONSWAP γ	6	6
Uwind (1-hr ave)	7	14.3
Ucurrent @ (cm/sec)		
0 m	23.2	47.8
50 m	22.9	47.3
100 m	16.1	32.7
150 m	16.9	32.7
350 m	10.6	20.4
800 m	8.8	18.2
1000 m	7.6	15.3

7.2. Wave Spectrum

The three-parameter Jonswap wave spectrum shall be used for the analysis of storm waves.

$$S(f) = \frac{a}{f^5} \exp\left[-1.25 \cdot T_p^2 \cdot f^4\right] \cdot \gamma^q$$

$$a = \frac{H_s^2 \cdot F}{T_p^4}$$

$$F = \frac{.0624}{.23 + .0336\gamma - \frac{.185}{1.9 + \gamma}}$$

$$q = \frac{1}{\exp\left[\frac{(T_p \cdot f - 1)^2}{2\sigma^2}\right]}$$

$$\sigma = .07\left[f < f_p\right]$$

$$\sigma = .09\left[f \geq f_p\right]$$

Where

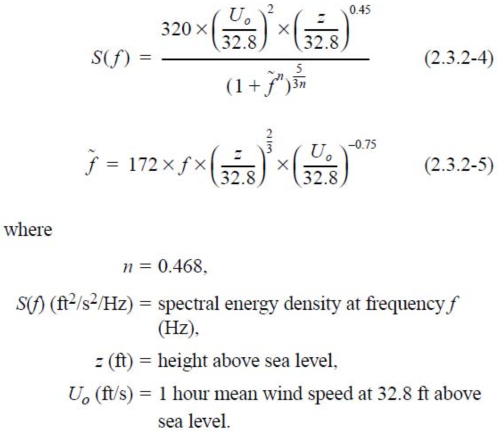
T_p = Peak spectral period

$f_p = 1/T_p$

γ = Jonswap peakedness parameter

7.3. Wind Spectrum

The gust spectrum for Hurricane Winds proposed in the latest edition of API RP 2A shall be used. The formulation is shown here.



$$S(f) = \frac{320 \times \left(\frac{U_o}{32.8}\right)^2 \times \left(\frac{z}{32.8}\right)^{0.45}}{(1+\tilde{f}^n)^{\frac{5}{3n}}} \qquad (2.3.2\text{-}4)$$

$$\tilde{f} = 172 \times f \times \left(\frac{z}{32.8}\right)^{\frac{2}{3}} \times \left(\frac{U_o}{32.8}\right)^{-0.75} \qquad (2.3.2\text{-}5)$$

where

n = 0.468,

$S(f)$ (ft^2/s^2/Hz) = spectral energy density at frequency f (Hz),

z (ft) = height above sea level,

U_o (ft/s) = 1 hour mean wind speed at 32.8 ft above sea level.

Figure 10 API Wind Spectrum (Source: API RP2A WSD, 21st Edition)

8. Benchmarking Cases

8.1. Cases

Six benchmarking cases were identified at the meeting of March 3[4]. These are listed in Table 15.

All cases shall be run for a collinear wave/wind and current heading of 180 deg (environments approaching from the right).

Runs shall consist of time domain simulations of 30-minute length.

Table 15 Benchmarking Cases

Case	Description	Pipe Length	Pipe Spec	Platform	Remoras	Pipe/Platform Stiffness	Environment
1	Fab Case	500 m	10m Ver 2	2008 100MW	None	1.3E11 N-m/rad	10-Yr Swell
2	Fab Case Stiffness Sensitivity	"	"	"	"	1E10 N-m/Rad	"
3	Fab Case Stiffness Sensitivity	"	"	"	"	1E12 N-m/rad	"
4	Ops Case 1	1000 m	"	"	Eight (8)	1E10 N-m/rad	Fatigue Bin 16
5	Ops Case 2	"	"	"	"	1E11 N-m/rad	"
6	Ops Case 3	"	"	"	"	1E12 N-m/rad	"

8.2. Mesh Sensitivity and Wave Descritization

HOE is in the process of performing sensitivities to mesh size and the number of waves use to descritize the spectrum using HARP. For purposes of this exercise the mesh provided shall be used and the spectral descritization shall consist of 100 waves.

8.3. Results

Results shall be compared statistically basedo n the following outputs.

Platform natural periods with pipe attached:

Surge
Heave
Pitch

The mean, standard deviation, maximum and minimum of the following parameters shall be tabulated.

Platform Surge
Platform Sway*
Platform Heave
Platform Roll*
Platform Pitch
Platform Yaw*
Pipe Top Global Moment (about Y-axis)

---

[4] See John Halkyard & Company Meeting Minutes, March 3, 2010.

Pipe Top Global Shear (in X-direction)
Pipe Top Axial Tension
Envelope of maximum and minimum bending strain along the length of the pipe.

* - Sway, Roll and Yaw should nominally be zero for 180 deg heading.

Addenda – Panel Coordinates

Panel Coordinates for

1. Operational Case (with Remoras) see File *OTEC_100MW_Full.gdf*
2. Fabrication Case (without Remoras) see File *100MW_semionly_Full.gdf*

NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report

Appendix 5-7

OTEC Termination Study

By

Houston Offshore Engineering

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
Naval Facilities Engineering Service Center (NFESC)
1100 23rd Avenue
Port Hueneme, CA 93043-4370
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Distribution Statement A: Approved for public release; distribution is unlimited.

OTEC Termination Study

24th June 2010

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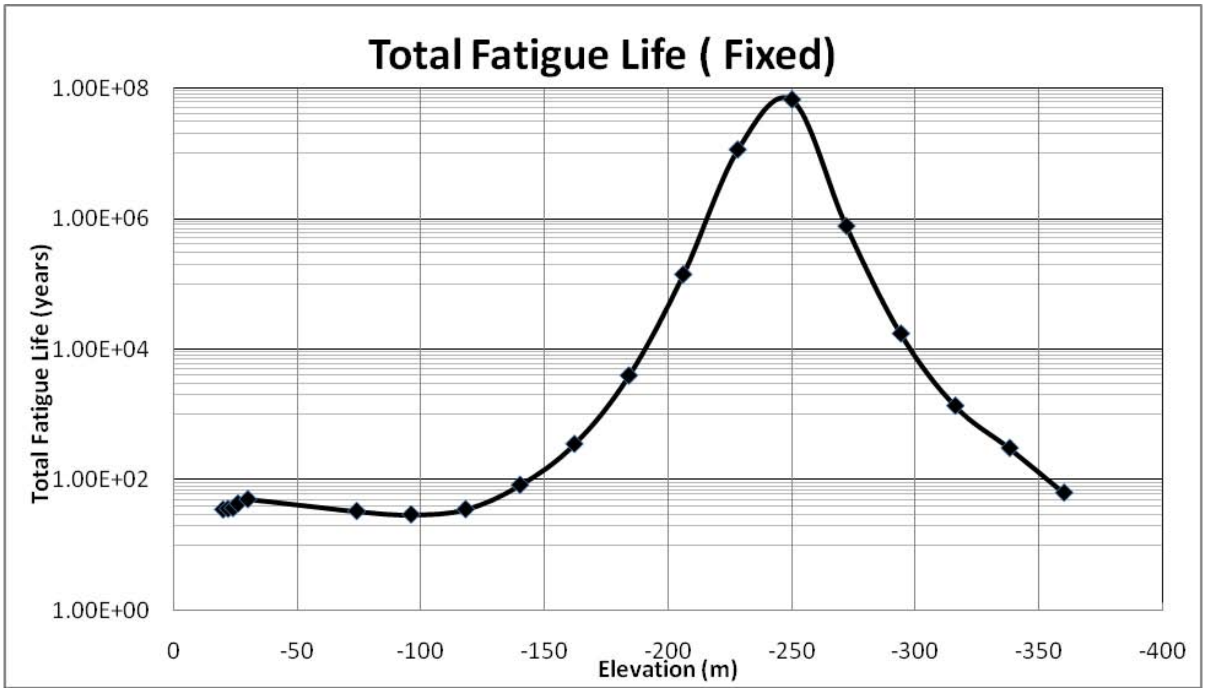
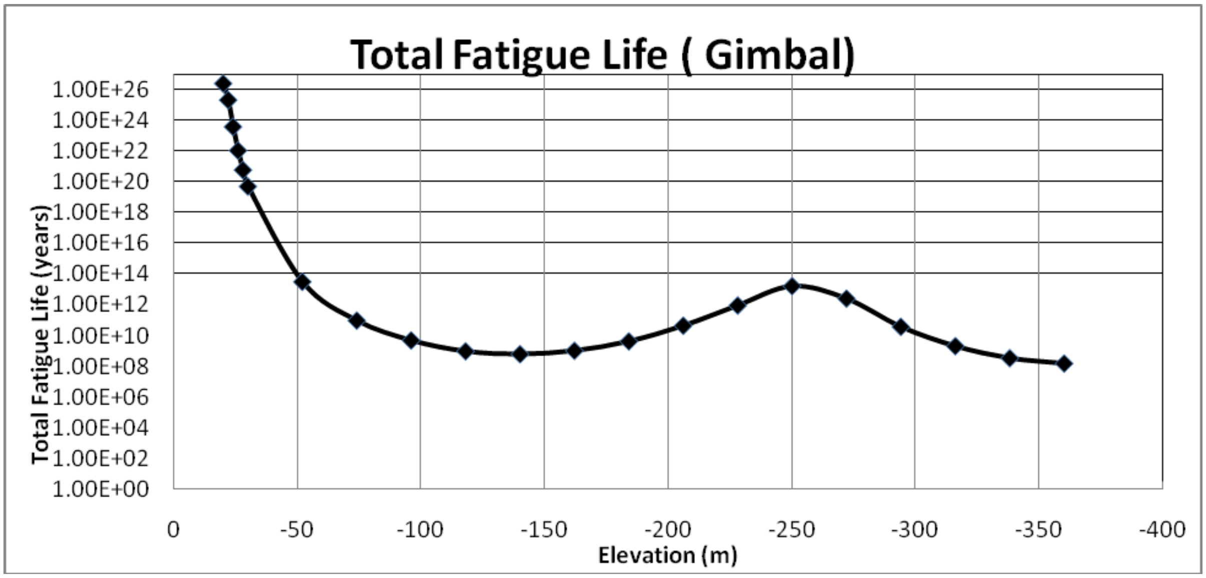
Houston Offshore
ENGINEERING

1 SUMMARY

2 RESULTS

2.1 10 M Gimbal and Fixed Fatigue Analysis Results:

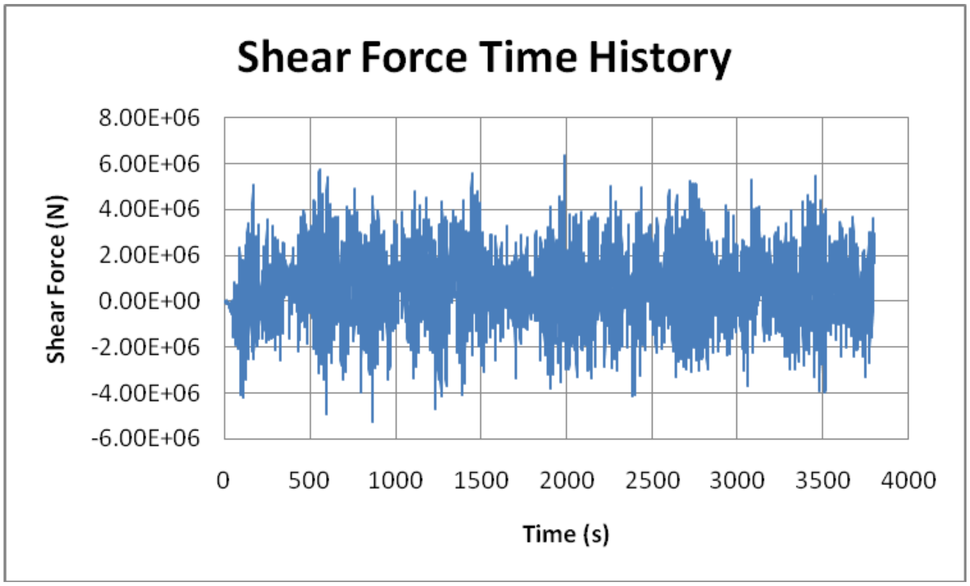


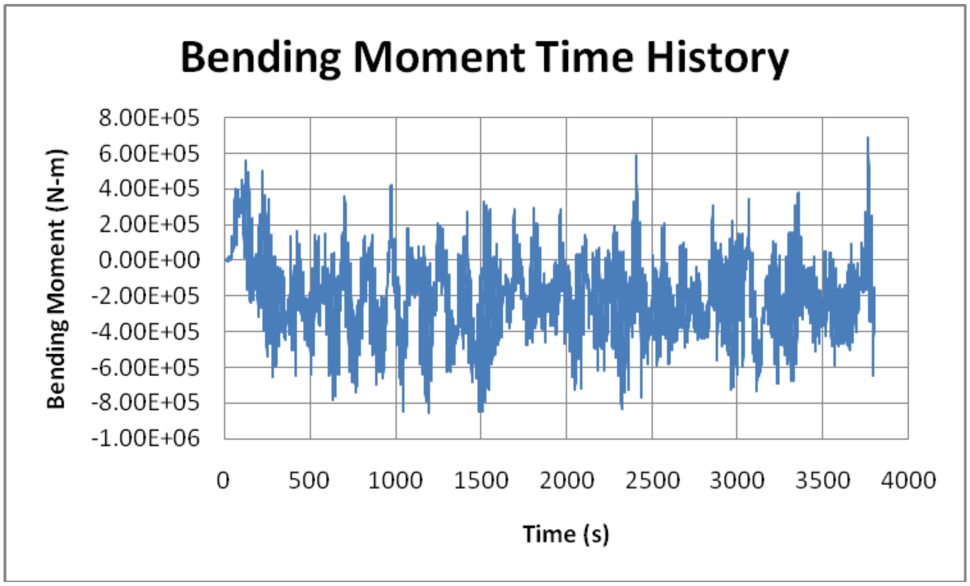


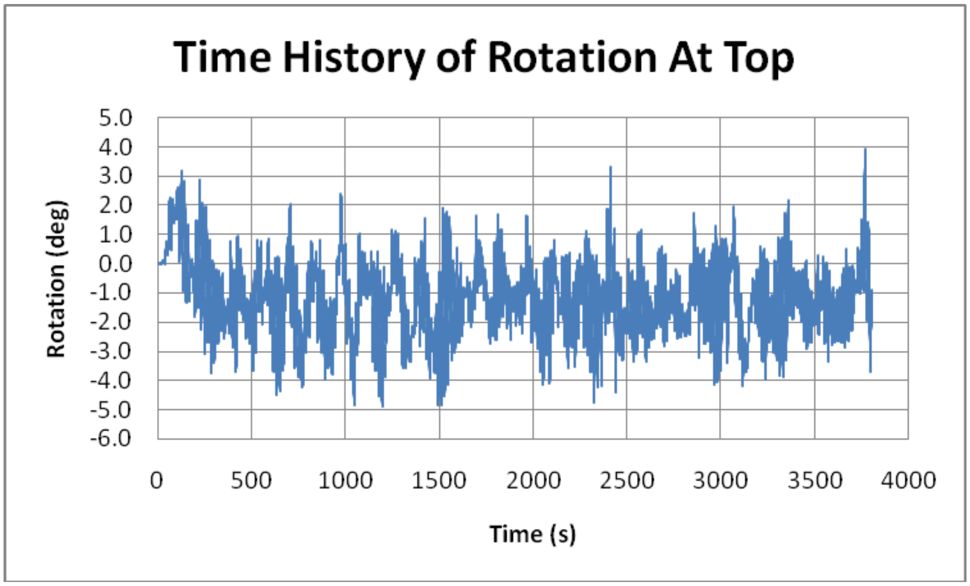
2.2 10 M Gimbal Study

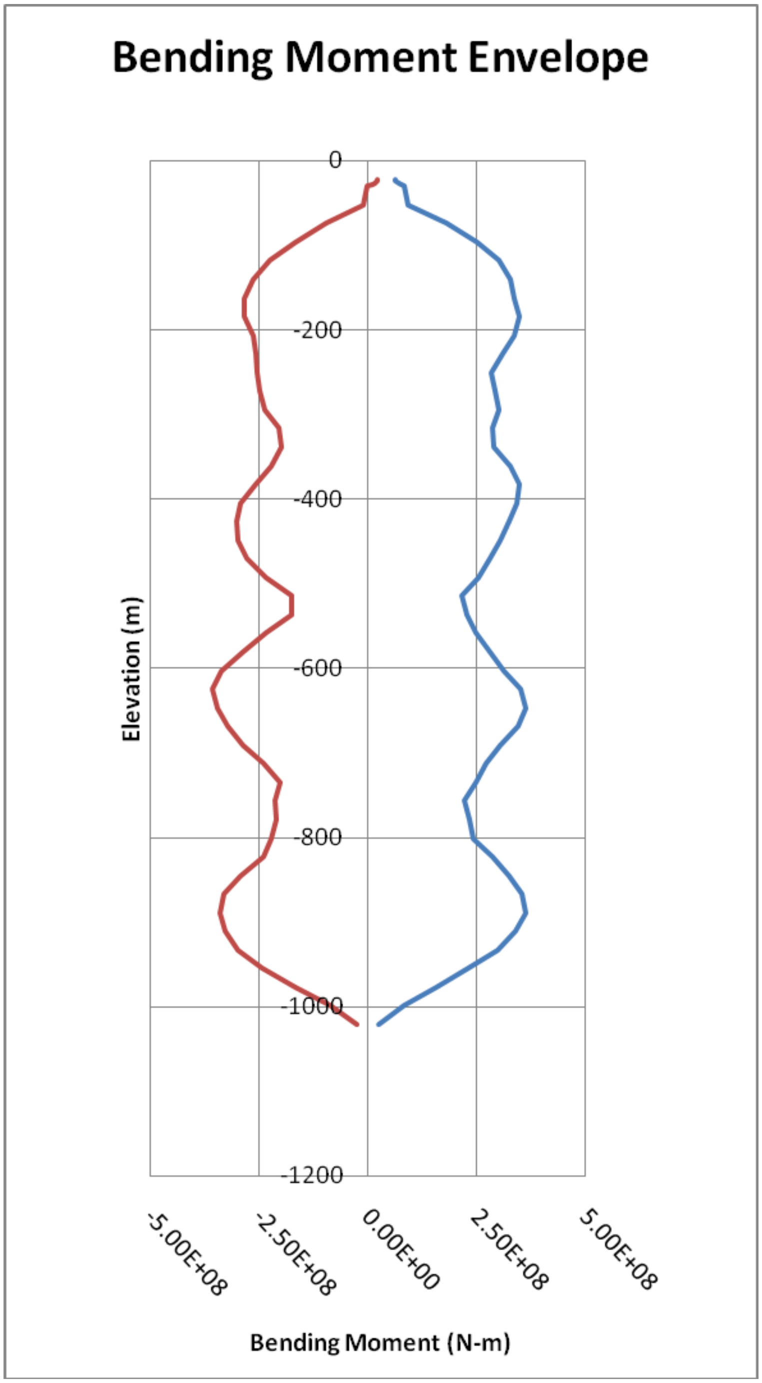
2.2.1 Case 1: k=1e7

	Shear Force at Top N	Bending Moment at Top N-m	Rotation at Top deg
Maximum	6.37E+06	6.87E+05	3.94
Minimum	-5.25E+06	-8.57E+05	-4.91
Mean	5.41E+05	-2.11E+05	-1.21
Std Dev	1.75E+06	2.38E+05	1.37





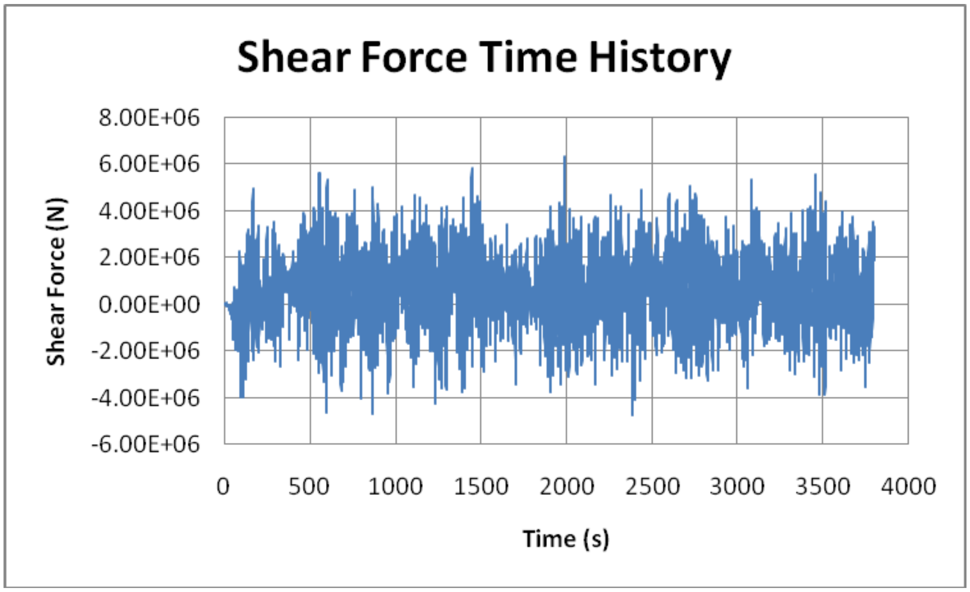

Time History of Rotation At Top
Rotation (deg)
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
0
500
1000
1500
2000
2500
3000
3500
4000
Time (s)

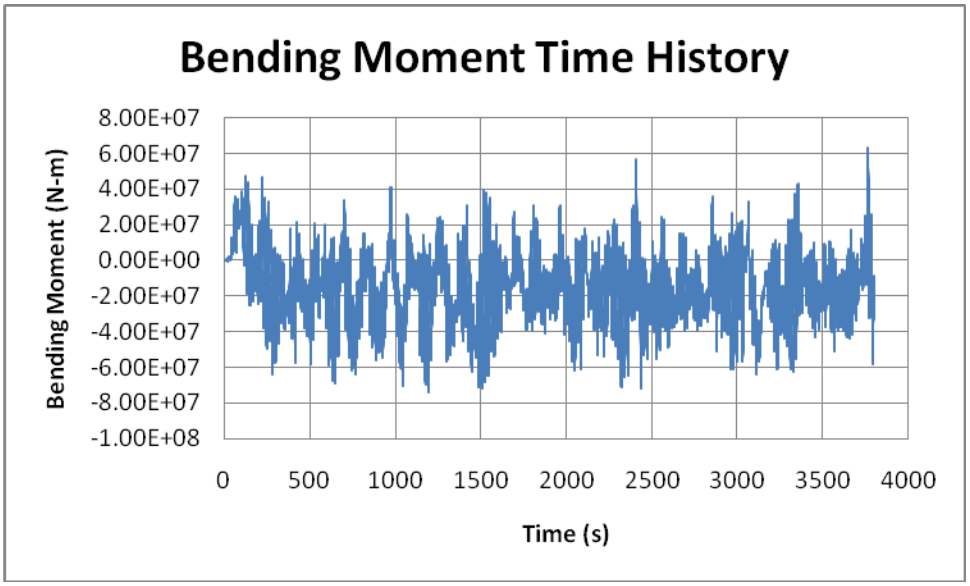

Bending Moment Envelope
0
-200
-400
-600
-800
-1000
-1200
Elevation (m)
-5.00E+08
-2.50E+08
0.00E+00
2.50E+08
5.00E+08
Bending Moment (N-m)

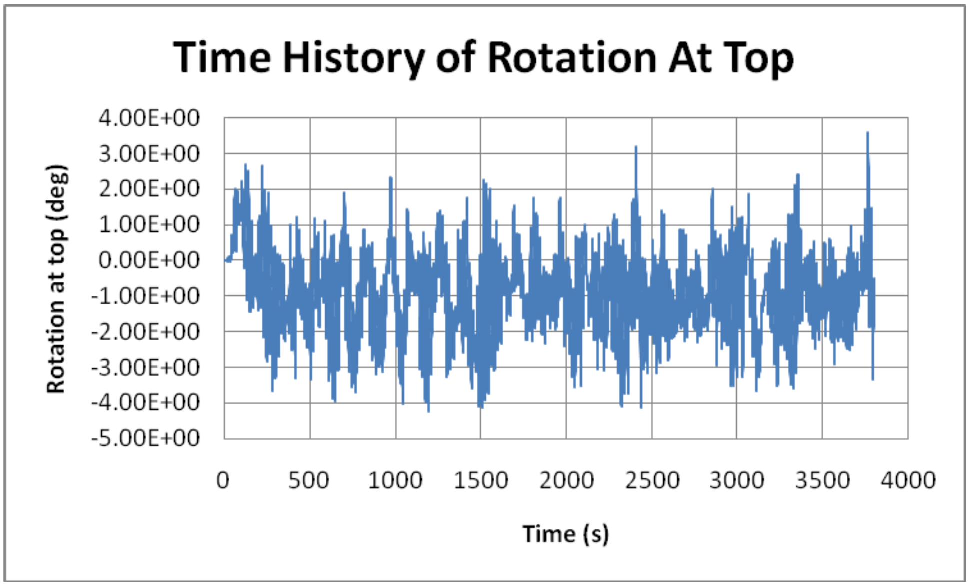
]

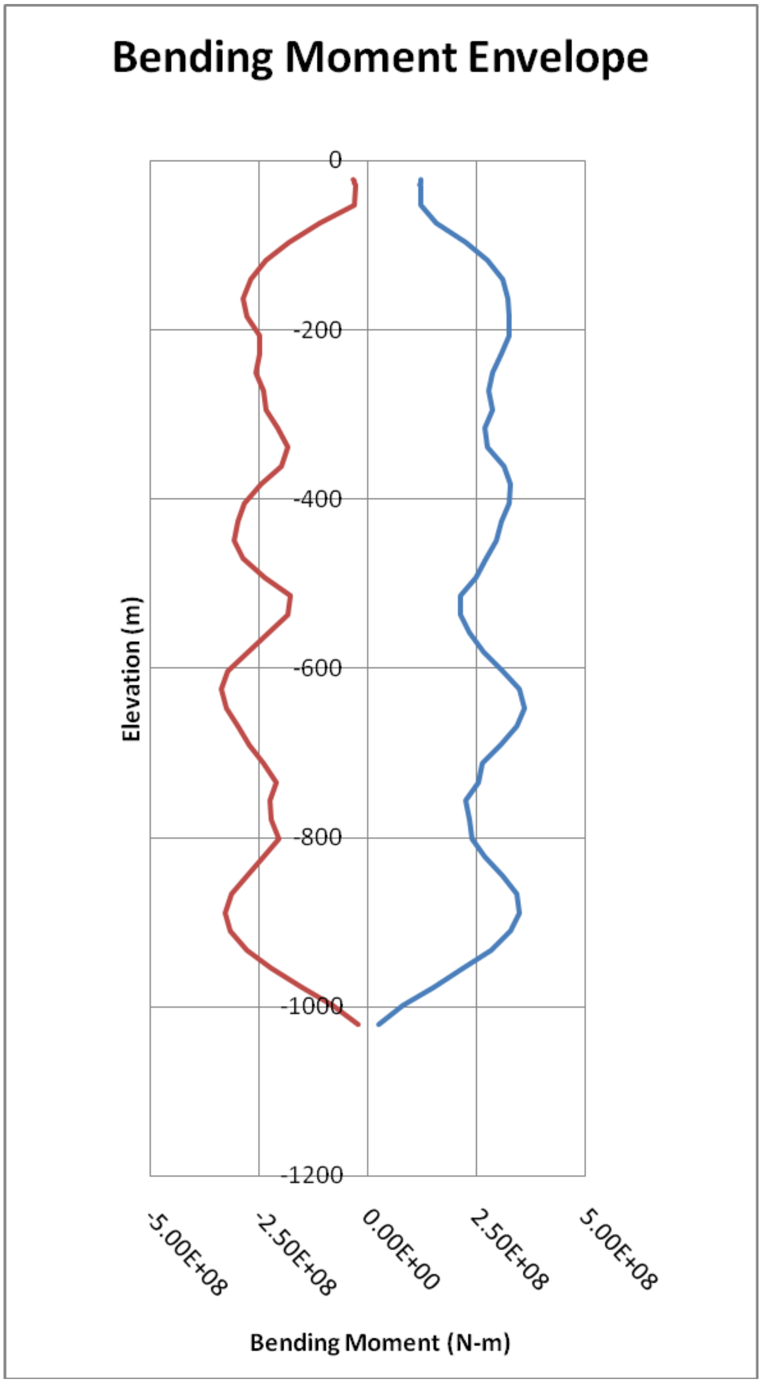
2.2.2 Case 2: k=1e9

	Shear Force at Top N	Bending Moment at Top N-m	Rotation at Top deg
Maximum	6.32E+06	6.29E+07	3.60
Minimum	-4.77E+06	-7.40E+07	-4.24
Mean	5.24E+05	-1.55E+07	-0.89
Std Dev	1.71E+06	2.17E+07	1.24



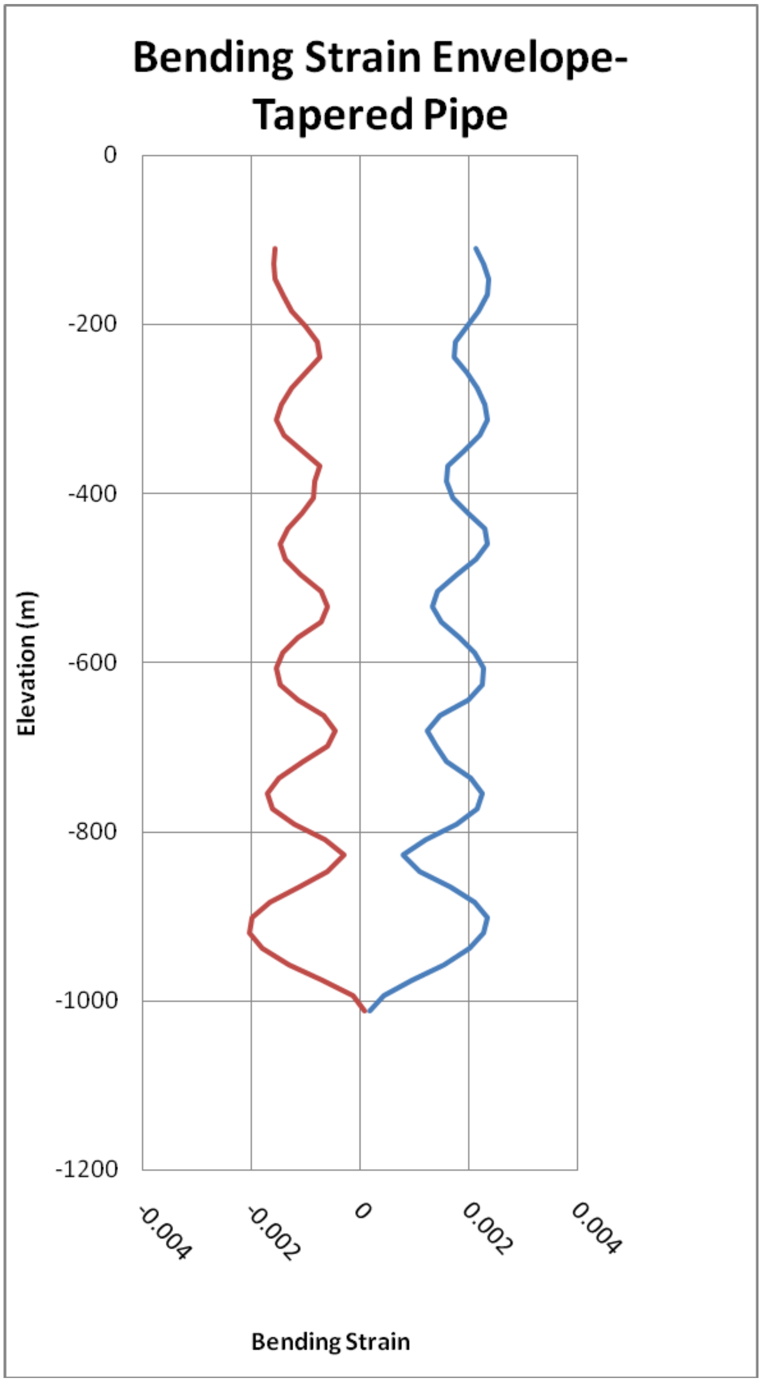



Time History of Rotation At Top
Rotation at top (deg)
4.00E+00
3.00E+00
2.00E+00
1.00E+00
0.00E+00
-1.00E+00
-2.00E+00
-3.00E+00
-4.00E+00
-5.00E+00
0
500
1000
1500
2000
2500
3000
3500
4000
Time (s)

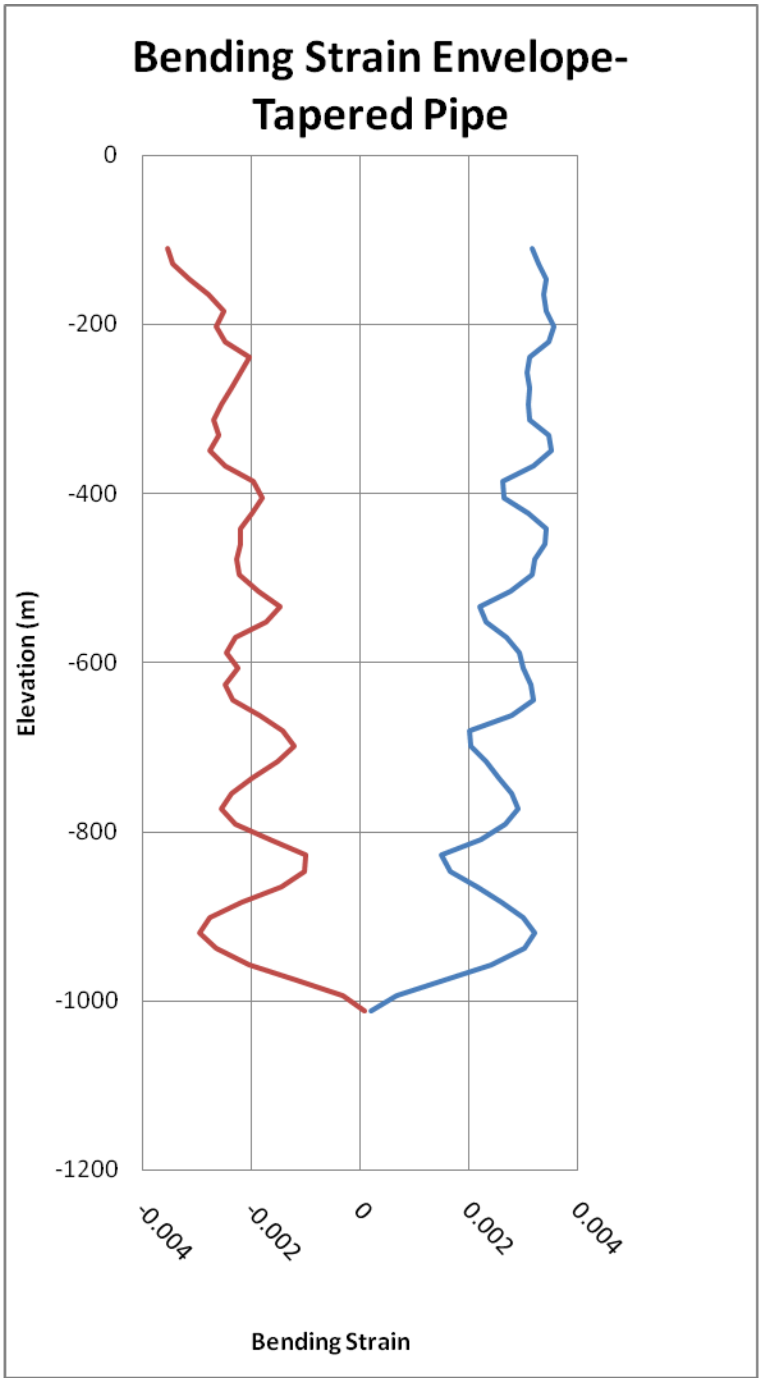

Bending Moment Envelope
Elevation (m)
0
-200
-400
-600
-800
-1000
-1200
-5.00E+08
-2.50E+08
0.00E+00
2.50E+08
5.00E+08
Bending Moment (N-m)

2.3 4 m Pipe - Tapered End (k=1.0E13)

2.3.1 25 Year Swell Case

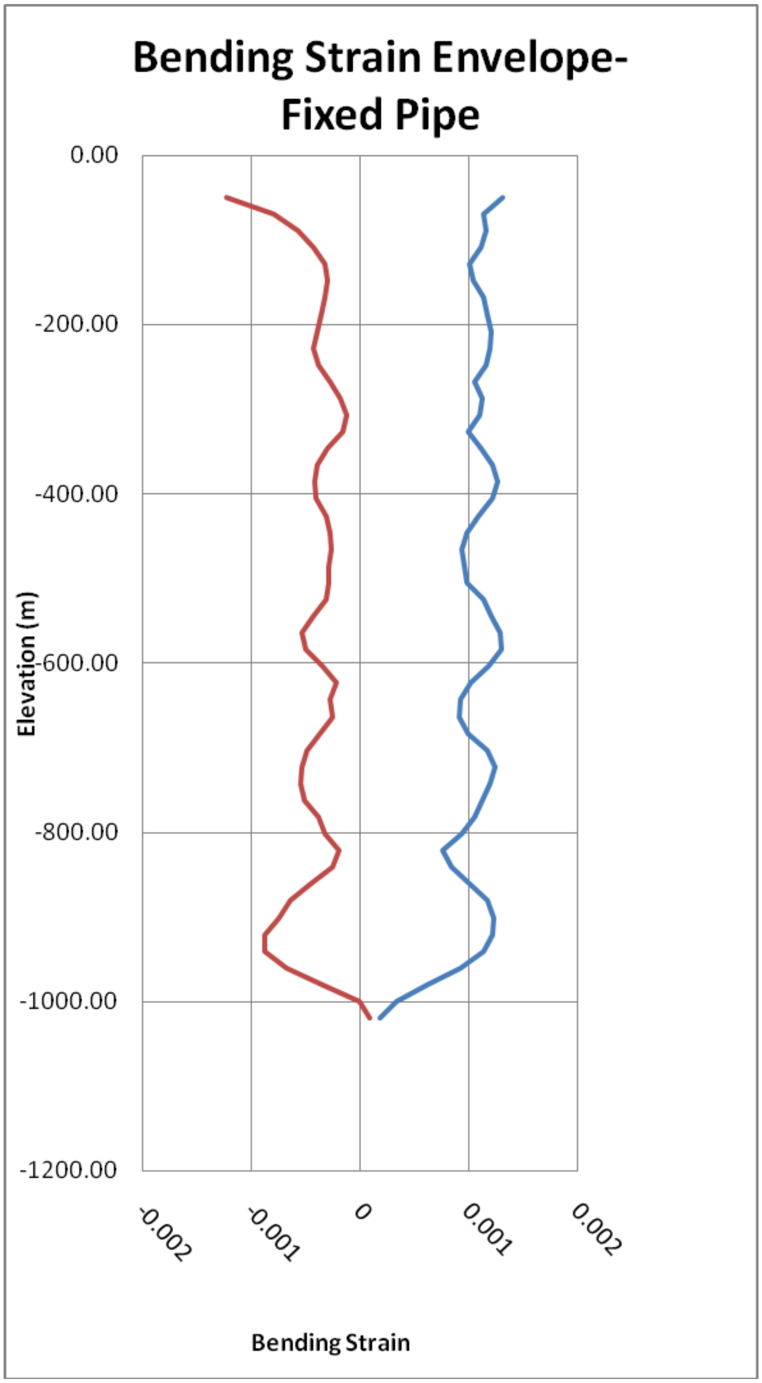


2.3.2 100 Year Cyclone Case

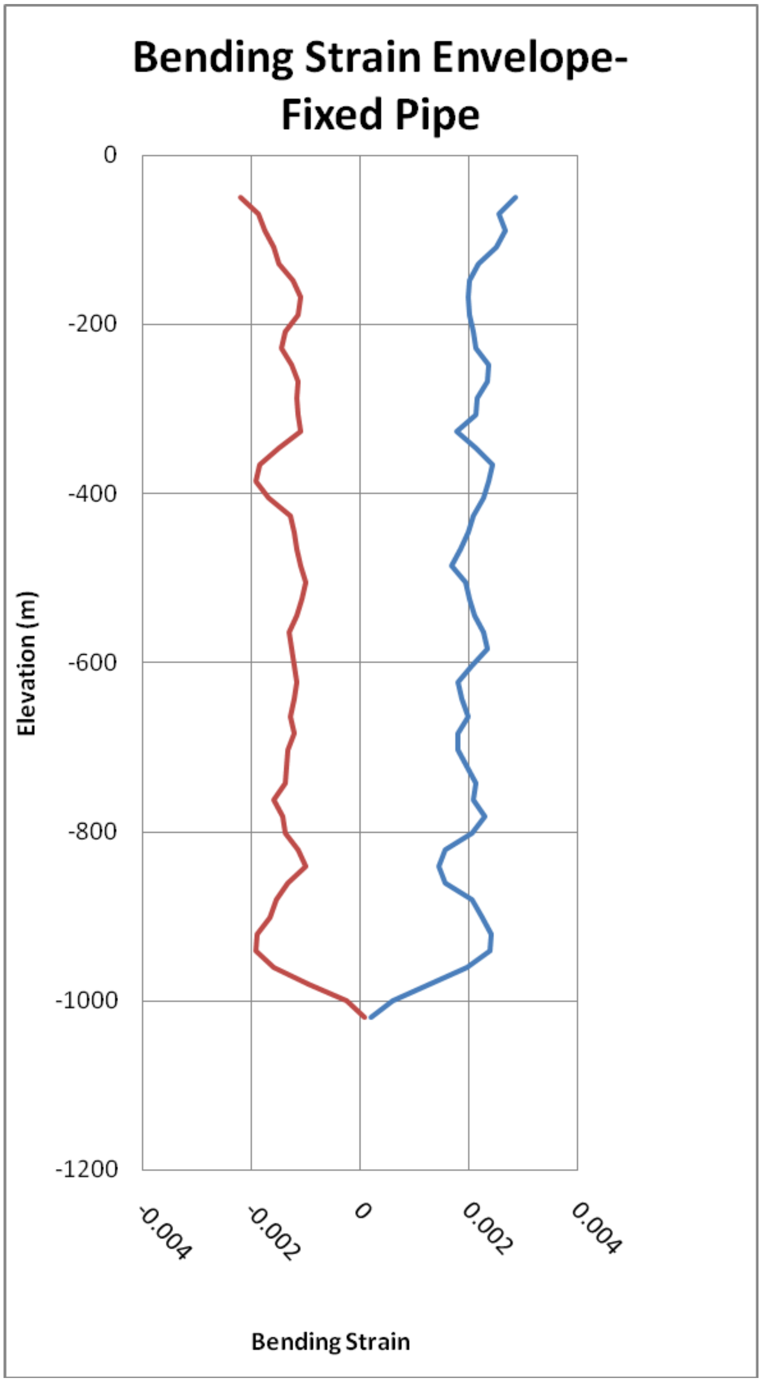


2.4 4 m Pipe Fixed End (K=1E13)

2.4.1 25 Year Swell Case

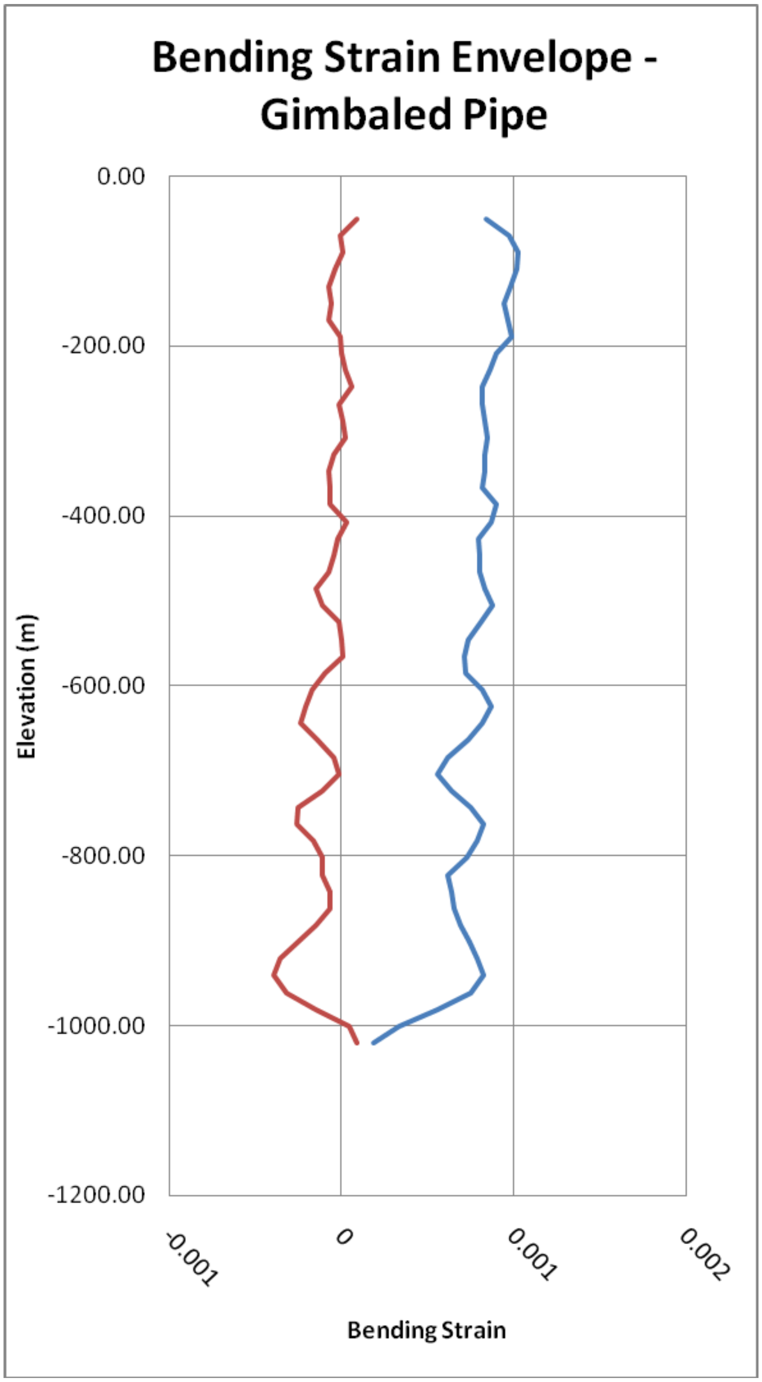


2.4.2 100 Year Cyclone Case

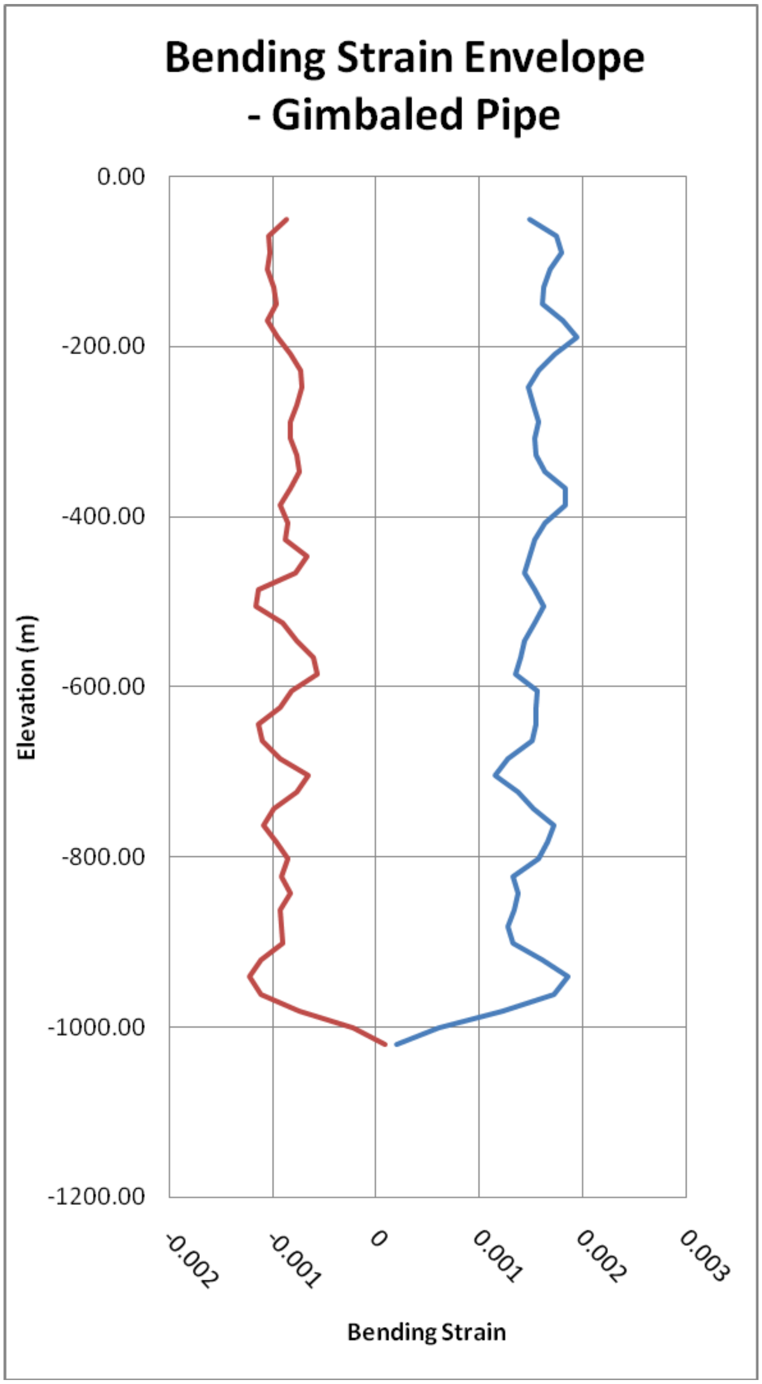


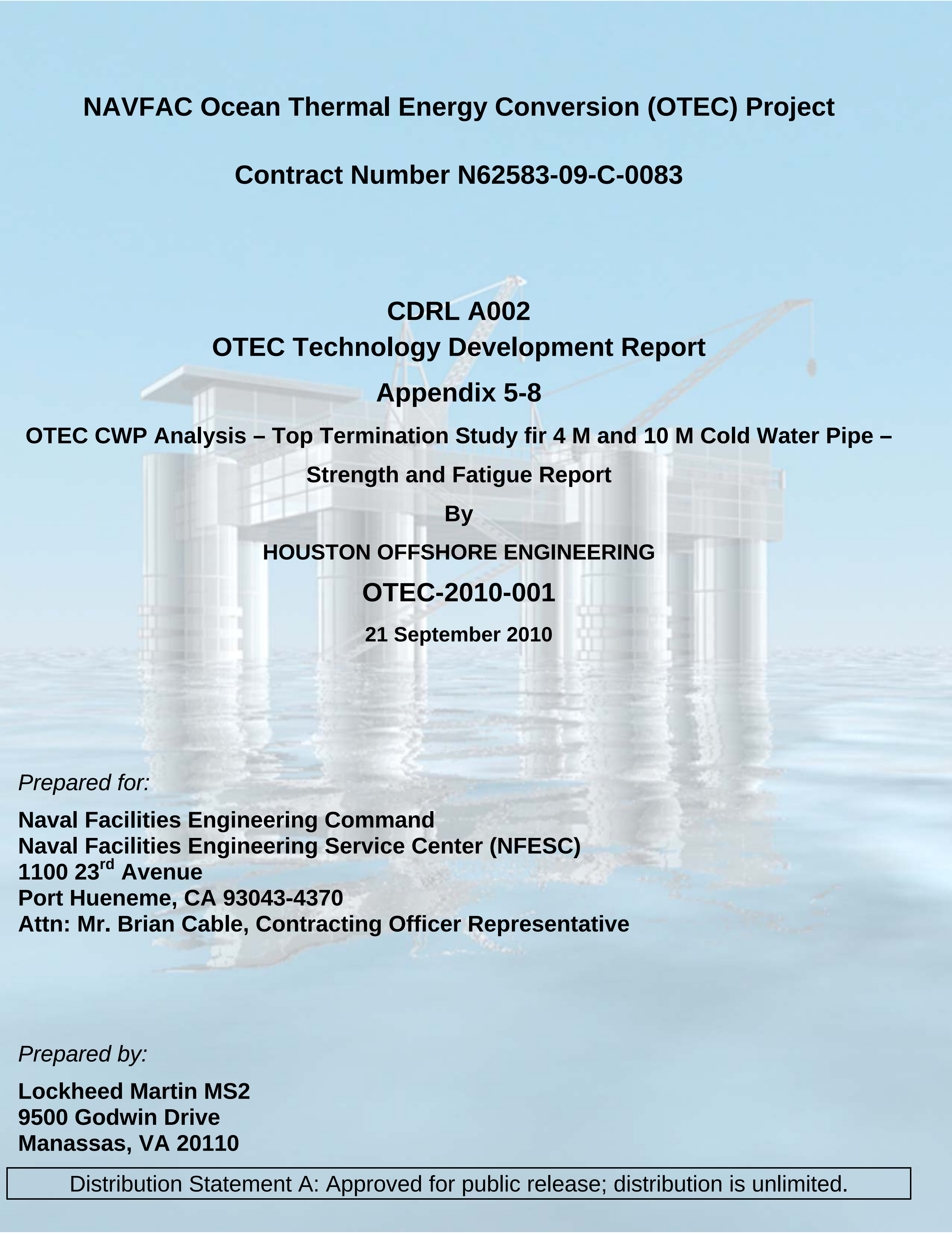
2.5 4 m Pipe - Gimbaled End (k=1E7)

2.5.1 25 Year Swell



2.5.2 100 Year Cyclone





NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report
Appendix 5-8
OTEC CWP Analysis – Top Termination Study fir 4 M and 10 M Cold Water Pipe – Strength and Fatigue Report

By

HOUSTON OFFSHORE ENGINEERING

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
Naval Facilities Engineering Service Center (NFESC)
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Attn: Mr. Brian Cable, Contracting Officer Representative

Prepared by:

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OTEC

Ocean Thermal Energy Conversion

OTEC CWP ANALYSIS

25th June 2010

Top Termination Study for 4 m and 10 m Cold Water Pipe – Strength and Fatigue Report

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Houston Offshore
ENGINEERING

1 EXECUTIVE SUMMARY

This report presents the fatigue and strength results for the cold water pipe (CWP) attached to a moored OTEC power plant. The coupled FEM program HARP was utilized for the analysis. Both the 4 m pipe for the 10 MW pilot plant and 10 m pipe for the 100 MW plant were analyzed. The summaries of results are shown in Table 1-1 and Table 1-2 below.

Table 1-1 : Summary of Results for 4 m Pipe

SUMMARY OF RESULTS - 4 m Pipe			
	Shear Force at Top N	Bending Moment at Top N-m	Rotation at Top deg
4 m CWP Fixed at Top (25 Yr Swell)			
Maximum	5.25E+05	1.36E+07	-
Minimum	-2.72E+05	-2.93E+07	-
Mean	1.48E+05	-7.58E+06	-
Std Dev	1.16E+05	6.68E+06	-
4 m CWP Fixed at Top (100 Yr Hurricane)			
Maximum	1.22E+06	4.26E+07	-
Minimum	-1.21E+06	-4.41E+07	-
Mean	1.19E+05	-5.07E+06	-
Std Dev	3.10E+05	1.34E+07	-
4 m CWP Gimbaled at Top (25 Yr Swell)			
Maximum	3.90E+05	1.49E+05	0.85
Minimum	-1.53E+05	-5.70E+05	-3.26
Mean	1.33E+05	-1.99E+05	-1.14
Std Dev	8.02E+04	1.34E+05	0.77
4 m CWP Gimbaled at Top (100 Yr Hurricane)			
Maximum	9.45E+05	4.12E+05	2.36
Minimum	-7.93E+05	-9.72E+05	-5.57
Mean	2.04E+05	-2.67E+05	-1.53
Std Dev	2.25E+05	2.34E+05	1.34
4 m Tapered CWP (25 Yr Swell)			
Maximum	1.26E+06	4.15E+07	-
Minimum	-6.31E+05	-7.83E+07	-
Mean	2.19E+05	-1.33E+07	-
Std Dev	2.28E+05	1.34E+07	-
4 m Tapered CWP (100 Yr Hurricane)			
Maximum	2.13E+06	7.89E+07	-
Minimum	-1.45E+06	-1.25E+08	-
Mean	3.99E+05	-2.23E+07	-
Std Dev	5.63E+05	3.11E+07	-

Table 1-1 : Summary of Results for 10 m Pipe

SUMMARY OF RESULTS - 10 m Pipe			
	Shear Force at Top	**Bending Moment at Top**	**Rotation at Top**
	N	**N-m**	**deg**
10 m CWP Gimbaled at Top (k = 1.0E07 N-m/rad)			
Maximum	6.37E+06	6.87E+05	3.94
Minimum	-5.25E+06	-8.57E+05	-4.91
Mean	5.41E+05	-2.11E+05	-1.21
Std Dev	1.75E+06	2.38E+05	1.37
10 m CWP Gimbaled at Top (k = 1.0E09 N-m/rad)			
Maximum	6.32E+06	6.29E+07	3.60
Minimum	-4.77E+06	-7.40E+07	-4.24
Mean	5.24E+05	-1.55E+07	-0.89
Std Dev	1.71E+06	2.17E+07	1.24

2 DESIGN DATA

The design data for both 4 m and 10 m CWP are presented in Table 2.1

Table 2-1: Design Data for CWP

10 m CWP for 100 MW Plant		
Parameter	Unit	Value
Length	m	1000.8
OD	m	10.509
EA	N	6.52E+10
EI	N-m	8.47E+11
4 m CWP for 10 MW Plant		
Parameter	Unit	Value
Length	m	1000.8
OD	m	4.21
EA	N	1.07E+10
EI	N-m	2.21E+10

3 ANALYSIS REQUIREMENTS

The load cases to be analyzed is shown in Table 3.1

Table 3-1: Load Case Table

Load Case Table						
Case	**OD (m)**	**Length (m)**	**Top Connection**	**Top Stiffness (N-m/rad)**	**Taper**	**Environment**
1	4.21	1000.8	Fixed	-	No	25 Year Swell
2	4.21	1000.8	Fixed	-	No	100 Year Cyclone
3	4.21	1000.8	Gimbal	1.00E+07	No	25 Year Swell
4	4.21	1000.8	Gimbal	1.00E+07	No	100 Year Cyclone
5	4.21	1000.8	Fixed	-	Yes	25 Year Swell
6	4.21	1000.8	Fixed	-	Yes	100 Year Cyclone
7	10.509	1000.8	Gimbal	1.00E+07	No	100Year Cyclone
8	10.509	1000.8	Gimbal	1.00E+09	No	100 Year Cyclone
9	10.509	1000.8	Fixed	-	No	Fatigue Bins (16 nos)
10	10.509	1000.8	Gimbal	1.00E+07	No	Fatigue Bins (16 nos)

4 ANALYSIS AND RESULTS

The results of the analysis are presented in the following sections.

4.1 4 m OD CWP FOR 10 MW PILOT PLANT

4.1.1 4 M PIPE WITH FIXED TOP CONNECTION - 25 YEAR SWELL

Table 4.1.1-1 : Force and Moment Statistics at Top Of Fixed Pipe

	Shear Force at Top	Bending Moment at Top
	N	N-m
Maximum	5.25E+05	1.36E+07
Minimum	-2.72E+05	-2.93E+07
Mean	1.48E+05	-7.58E+06
Std Dev	1.16E+05	6.68E+06

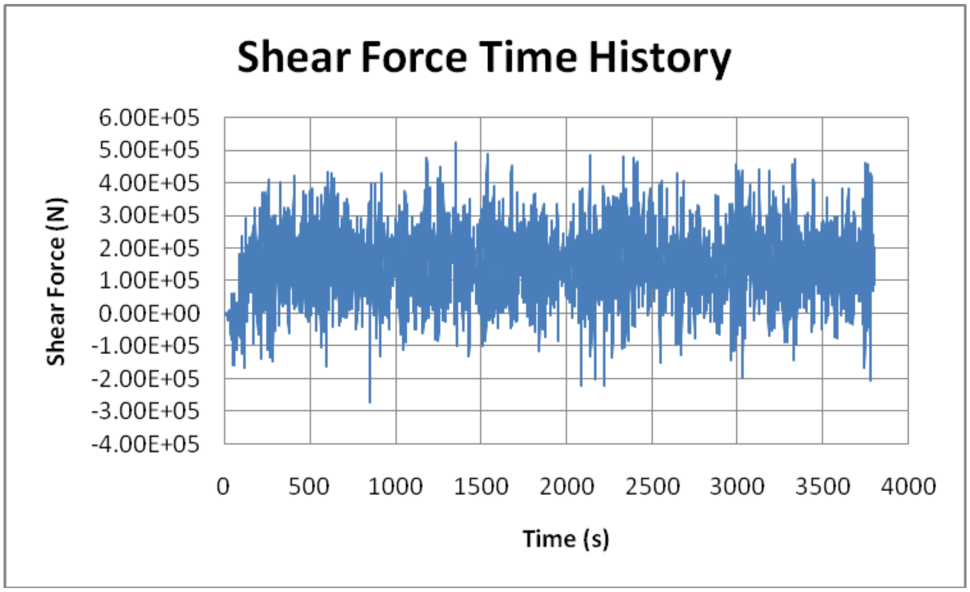


Figure 4.1.1-1 : Shear Force Time History at Top Of Fixed Pipe

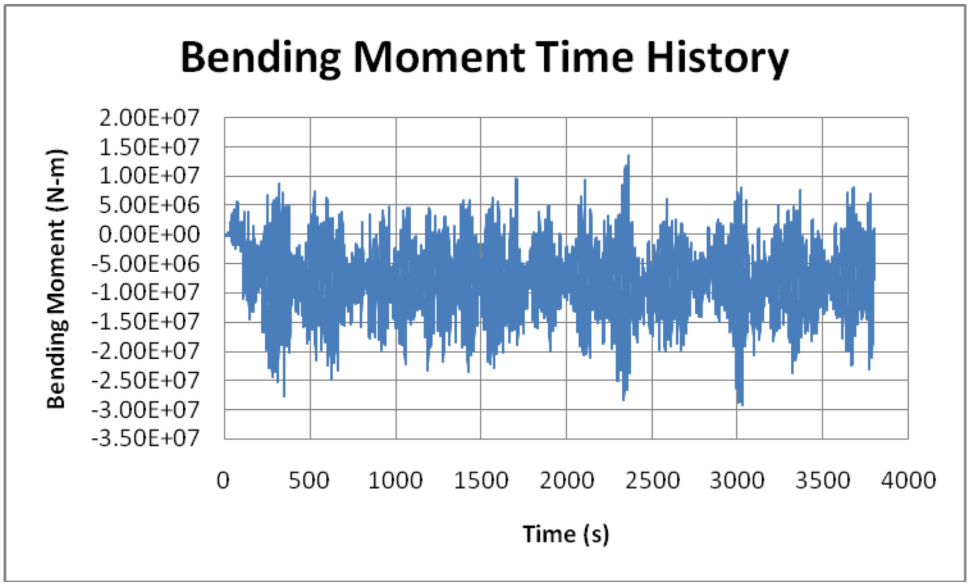


Figure 4.1.1-2 : Bending Moment Time History at Top Of Pipe

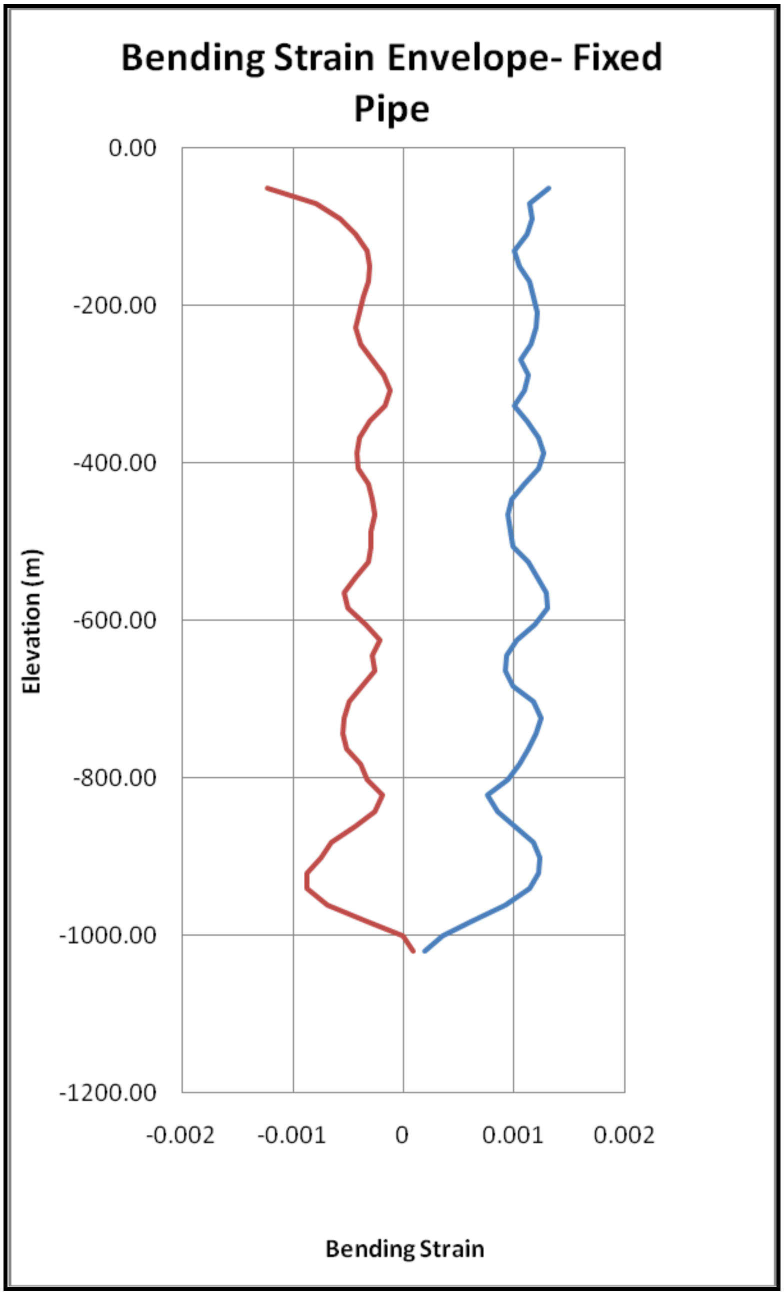


Figure 4.1.1-3: Bending Strain Envelope for Fixed Pipe

4.1.2 4 M PIPE WITH FIXED TOP CONNECTION - 100 YEAR CYCLONE

Table 4.1.2-1 : Force and Moment Statistics at Top Of Fixed Pipe

	Shear Force at Top	Bending Moment at Top
	N	N-m
Maximum	1.22E+06	4.26E+07
Minimum	-1.21E+06	-4.41E+07
Mean	1.19E+05	-5.07E+06
Std Dev	3.10E+05	1.34E+07

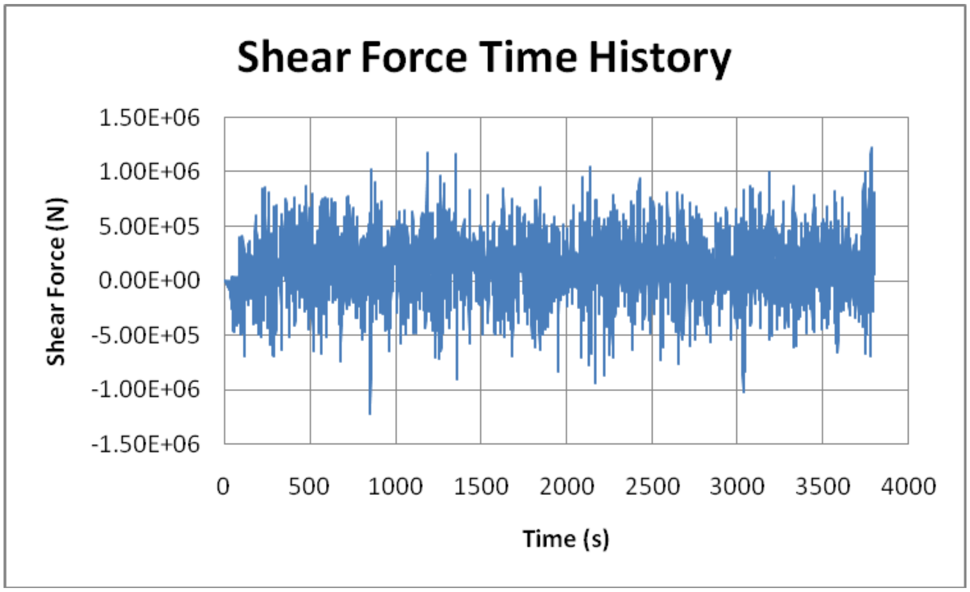


Figure 4.1.2-1 : Shear Force Time History at Top Of Fixed Pipe

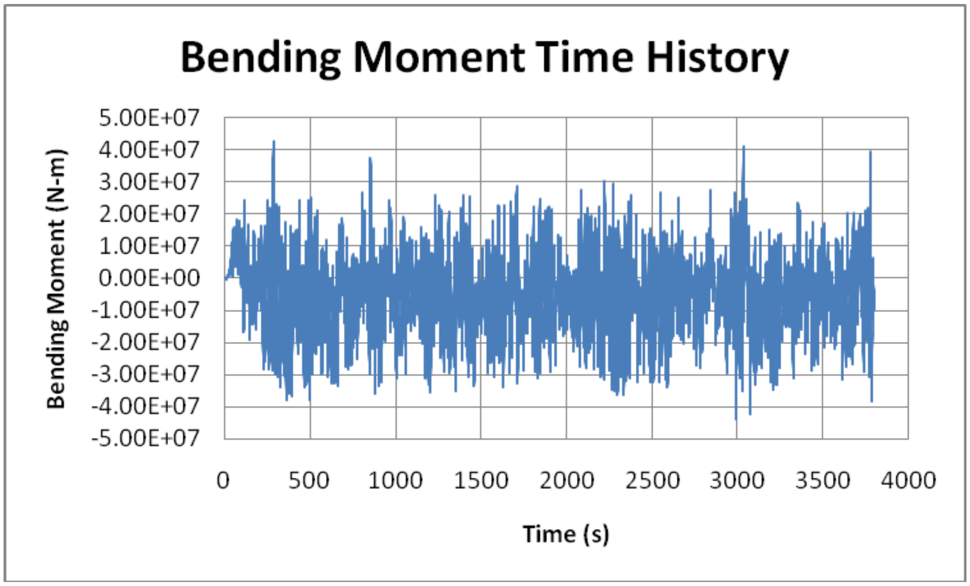


Figure 4.1.2-2 : Bending Moment Time History at Top Of Fixed Pipe

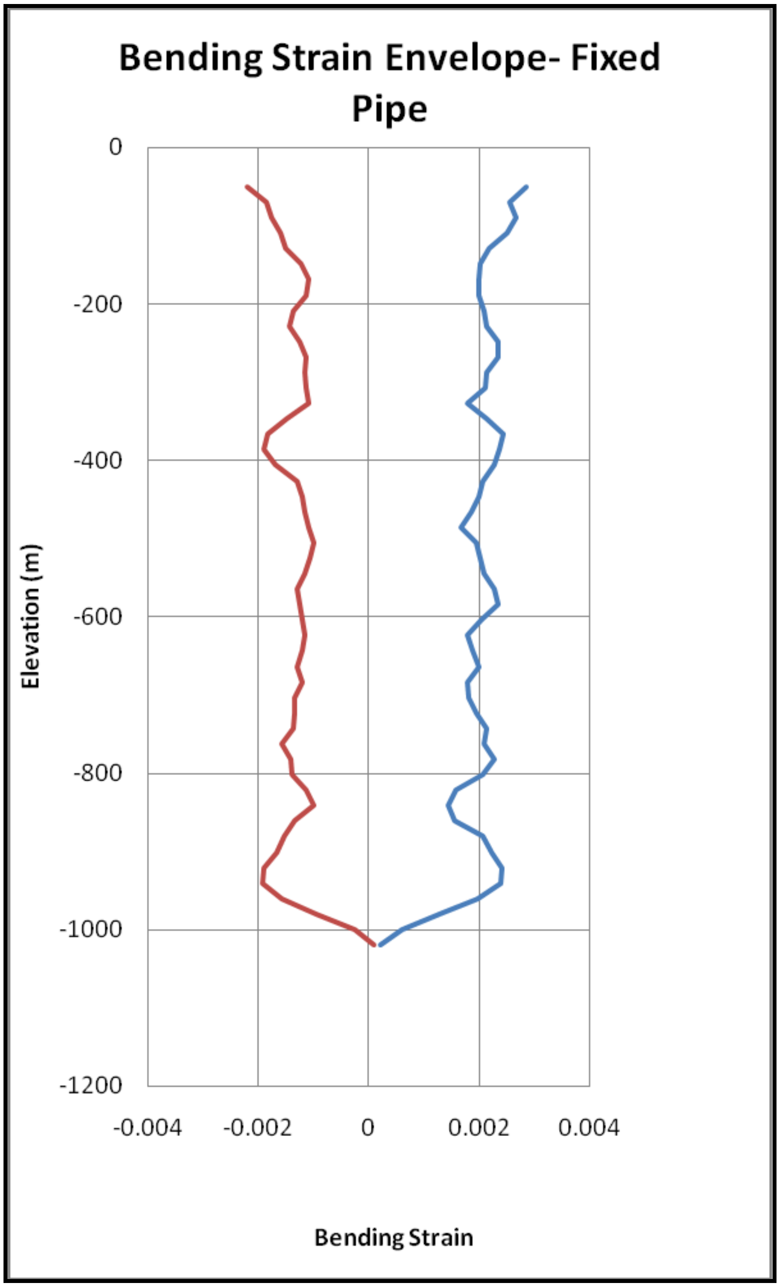


Figure 4.1.2-3: Bending Strain Envelope for Fixed Pipe

4.1.3 4 M TAPERED PIPE WITH FIXED TOP CONNECTION - 25 YEAR SWELL

Table 4.1.3-1 : Force and Moment Statistics at Top Of Tapered Pipe

	Shear Force at Top	Bending Moment at Top
	N	N-m
Maximum	1.26E+06	4.15E+07
Minimum	-6.31E+05	-7.83E+07
Mean	2.19E+05	-1.33E+07
Std Dev	2.28E+05	1.34E+07

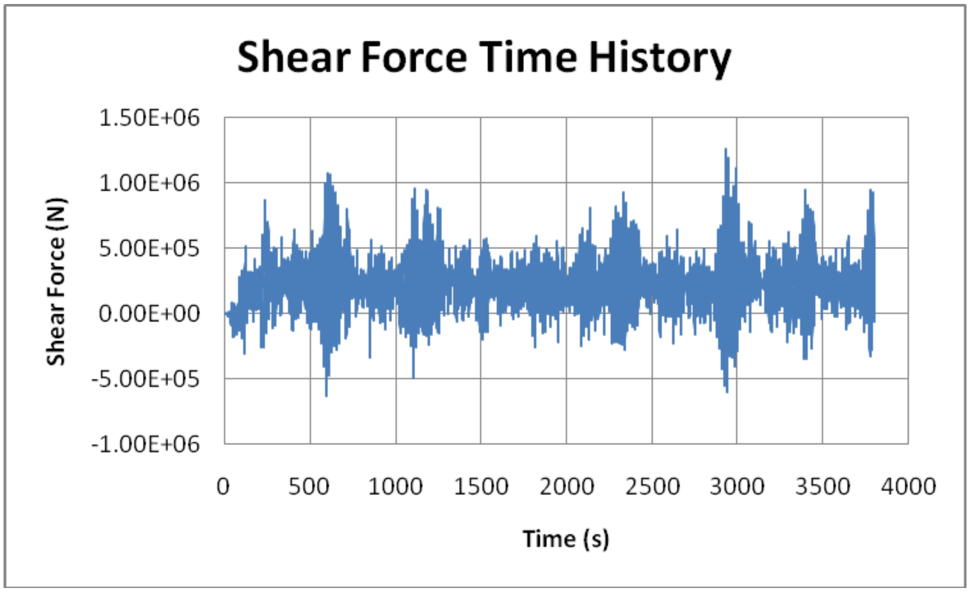


Figure 4.1.3-1 : Shear Force Time History at Top Of Tapered Pipe

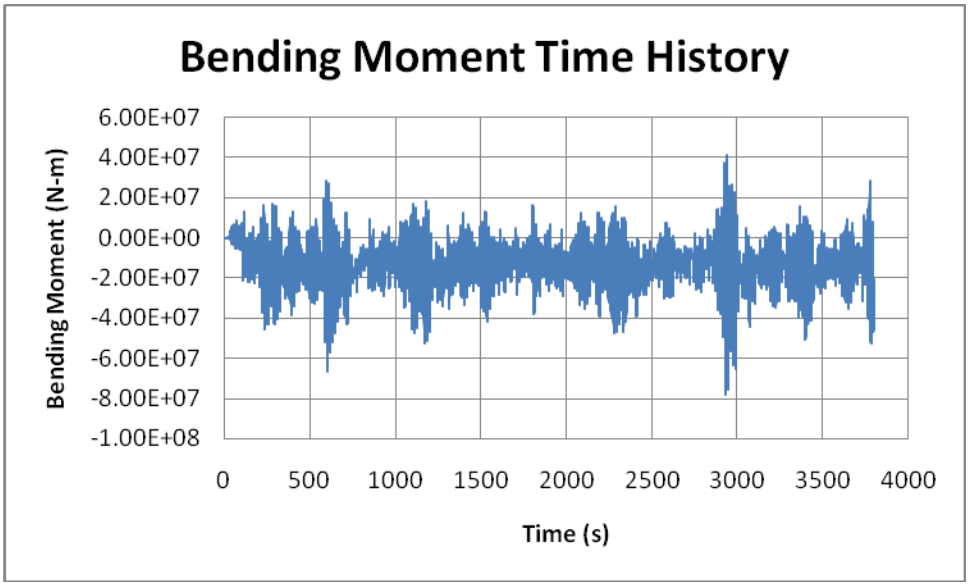


Figure 4.1.3-2 : Bending Moment Time History at Top Of Tapered Pipe

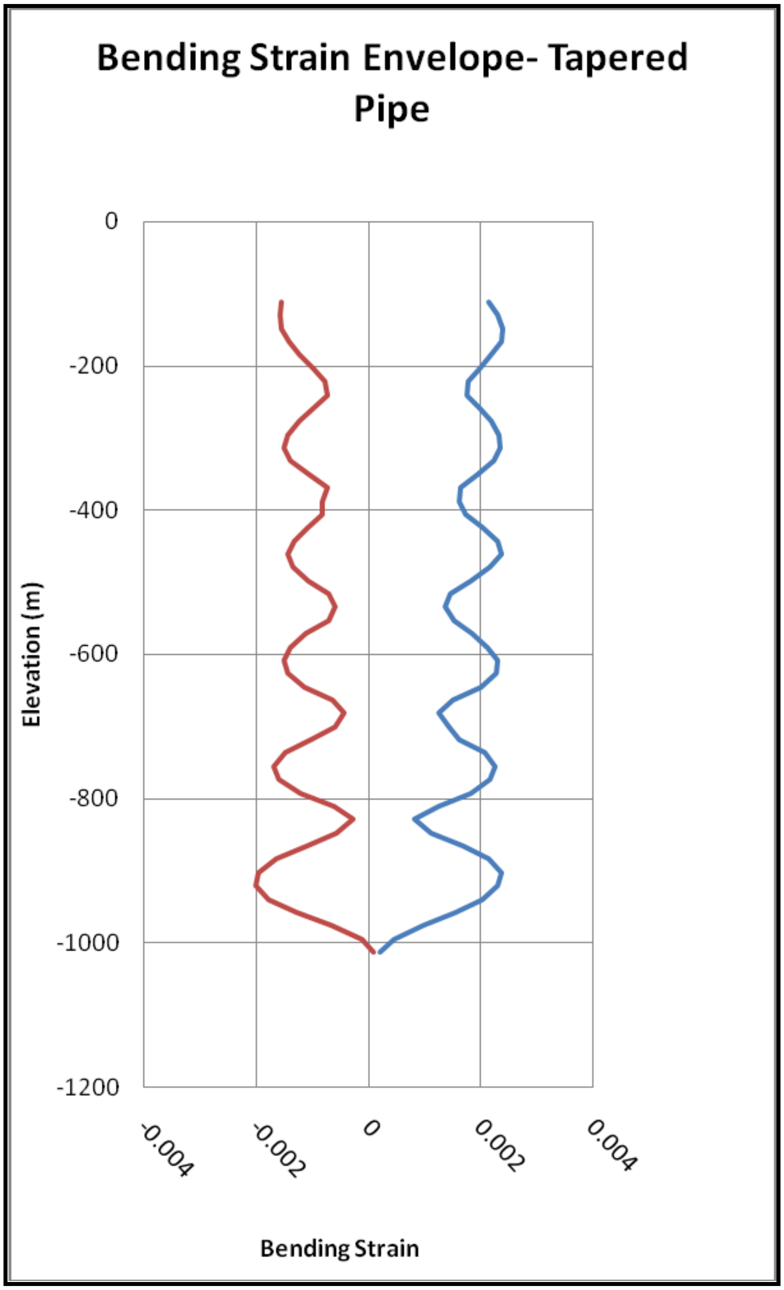


Figure 4.1.3-3: Bending Strain Envelope for Tapered Pipe

4.1.4 4 M TAPERED PIPE WITH FIXED TOP CONNECTION - 100 YEAR CYCLONE

Table 4.1.4-1 : Force and Moment Statistics at Top Of Tapered Pipe

	Shear Force at Top	Bending Moment at Top
	N	N-m
Maximum	2.13E+06	7.89E+07
Minimum	-1.45E+06	-1.25E+08
Mean	3.99E+05	-2.23E+07
Std Dev	5.63E+05	3.11E+07

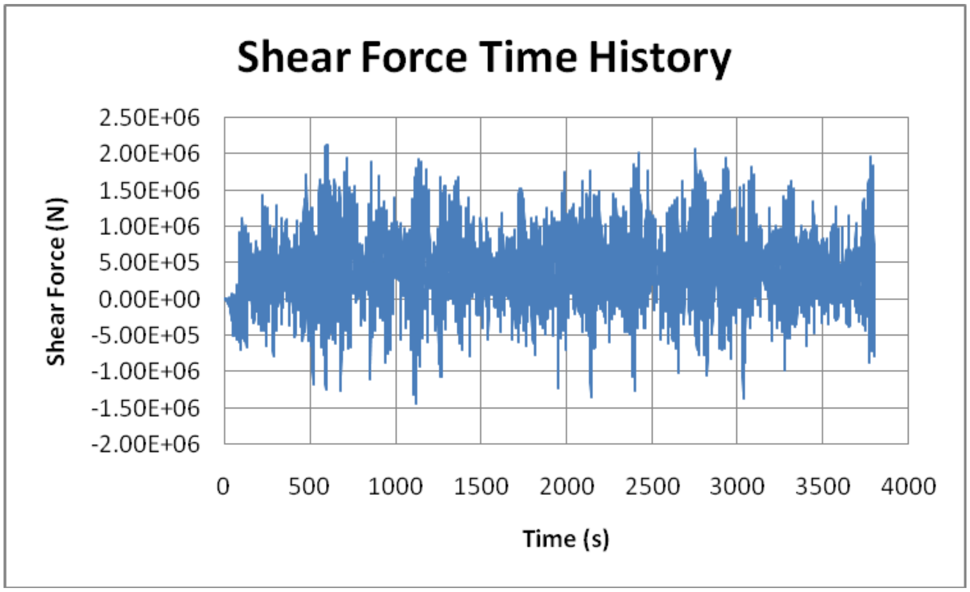


Figure 4.1.4-1 : Shear Force Time History at Top Of Tapered Pipe

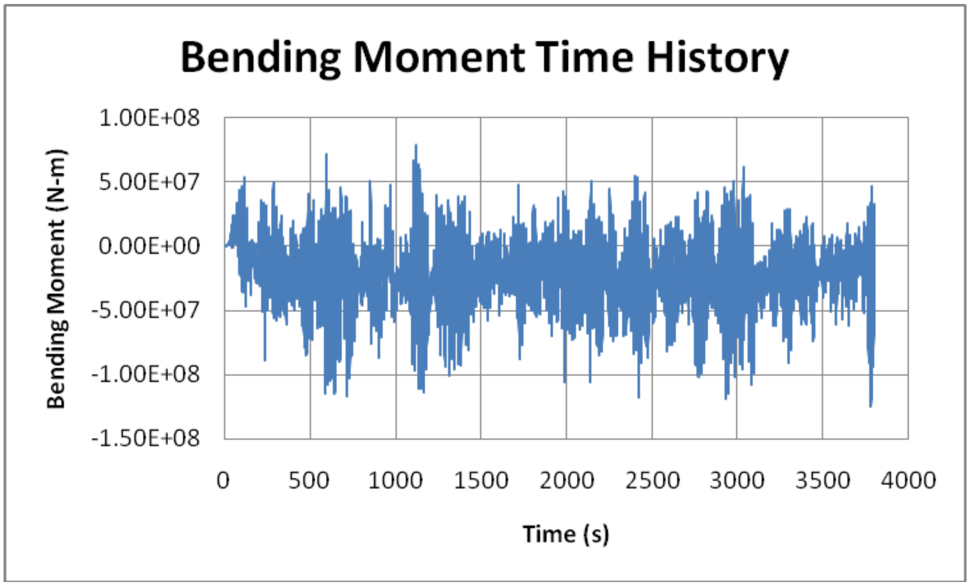


Figure 4.1.4-2 : Bending Moment Time History at Top Of Tapered Pipe

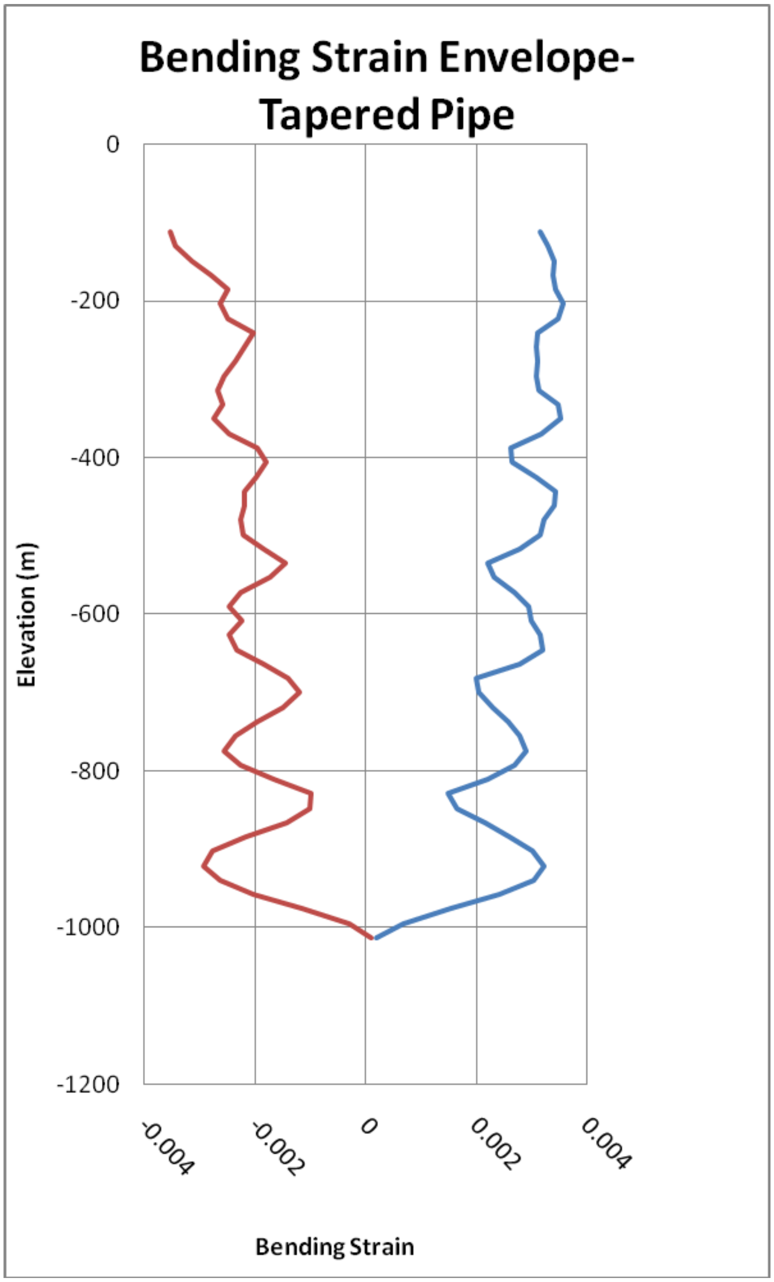


Figure 4.1.4-3: Bending Strain Envelope for Tapered Pipe

4.1.5 4 M PIPE WITH GIMBALED TOP CONNECTION - 25 YEAR SWELL

Table 4.1.5-1 : Force and Moment Statistics at Top Of Gimbaled Pipe

	Shear Force at Top	Bending Moment at Top	Rotation at Top
	N	N-m	deg
Maximum	3.90E+05	1.49E+05	0.85
Minimum	-1.53E+05	-5.70E+05	-3.26
Mean	1.33E+05	-1.99E+05	-1.14
Std Dev	8.02E+04	1.34E+05	0.77

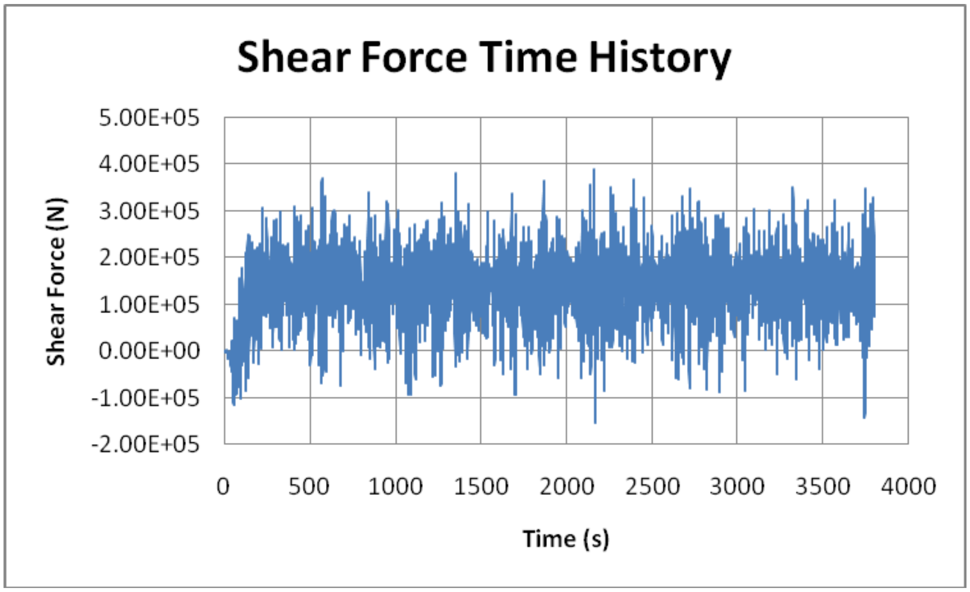


Figure 4.1.5-1 : Shear Force Time History at Top Of Gimbaled Pipe

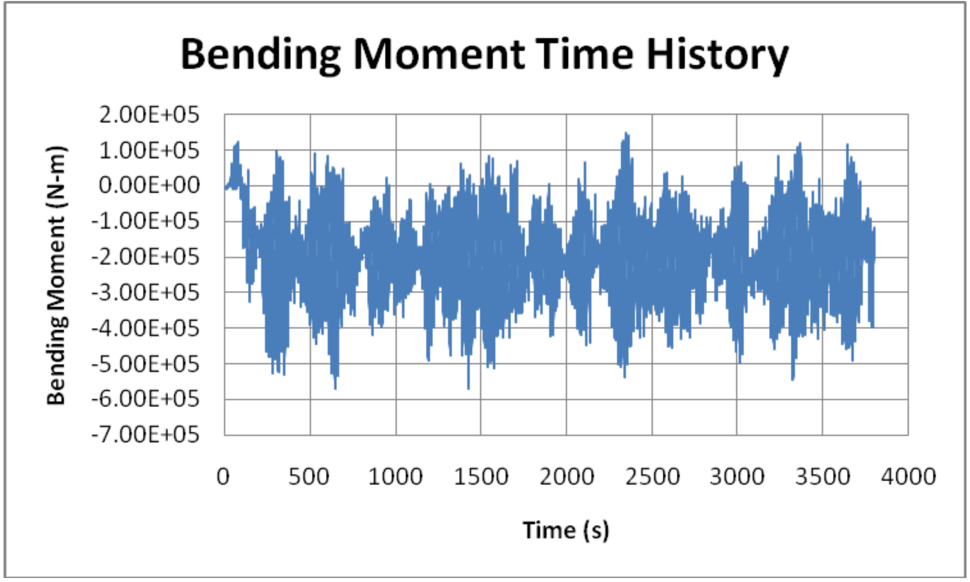


Figure 4.1.5-2 : Bending Moment Time History at Top Of Gimbaled Pipe

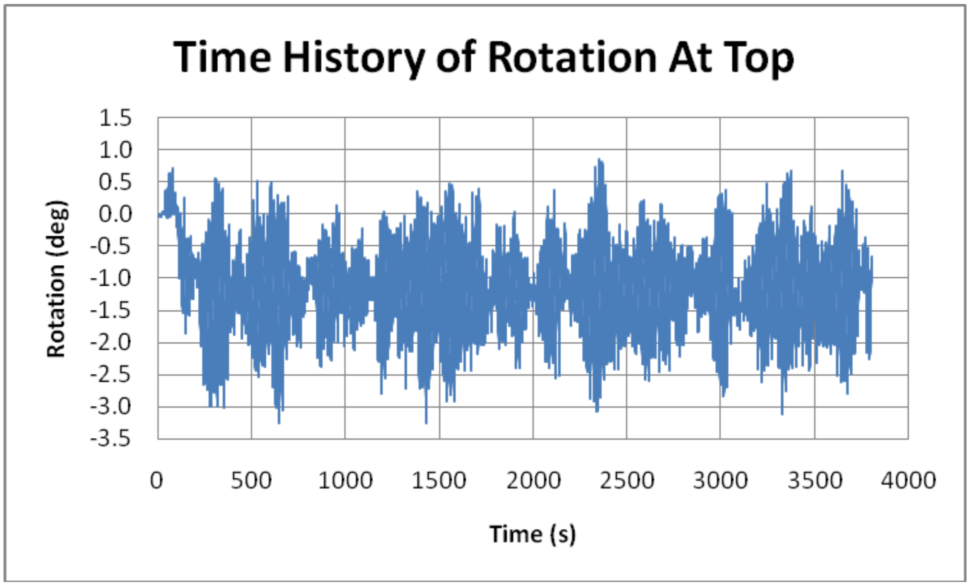


Figure 4.1.5-3 : Time History of Rotation at Top Of Gimbaled Pipe

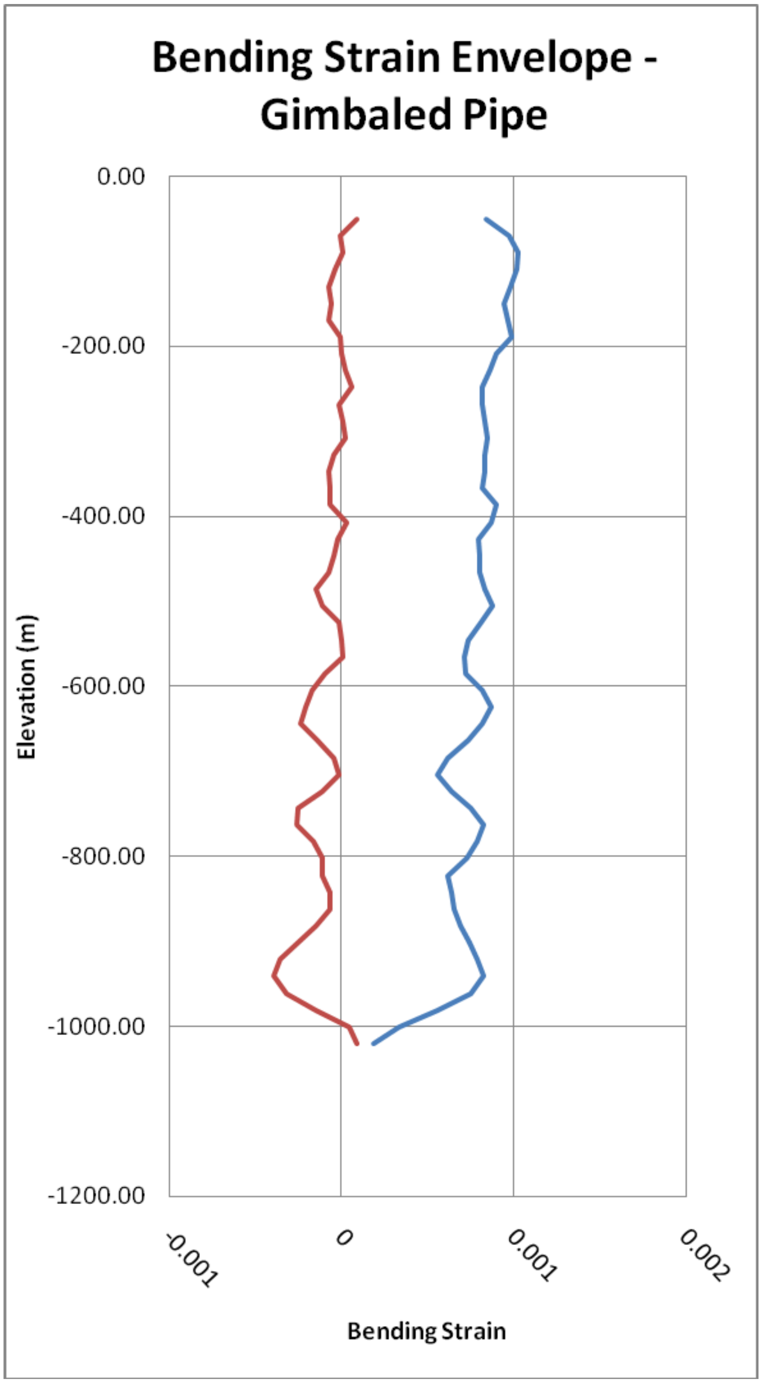


Figure 4.1.5-4: Bending Strain Envelope for Gimballed Pipe

4.1.6 4 M PIPE WITH GIMBALED TOP CONNECTION - 100 YEAR CYCLONE

Table 4.1.6-1 : Force and Moment Statistics at Top Of Gimbaled Pipe

	Shear Force at Top	Bending Moment at Top	Rotation at Top
	N	N-m	deg
Maximum	9.45E+05	4.12E+05	2.36
Minimum	-7.93E+05	-9.72E+05	-5.57
Mean	2.04E+05	-2.67E+05	-1.53
Std Dev	2.25E+05	2.34E+05	1.34

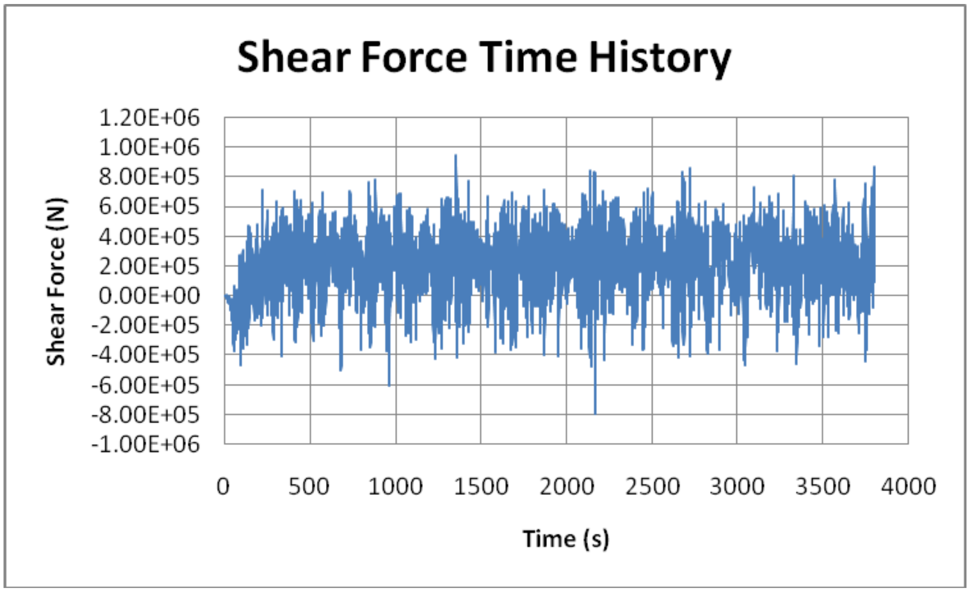


Figure 4.1.6-1 : Shear Force Time History at Top Of Gimbaled Pipe

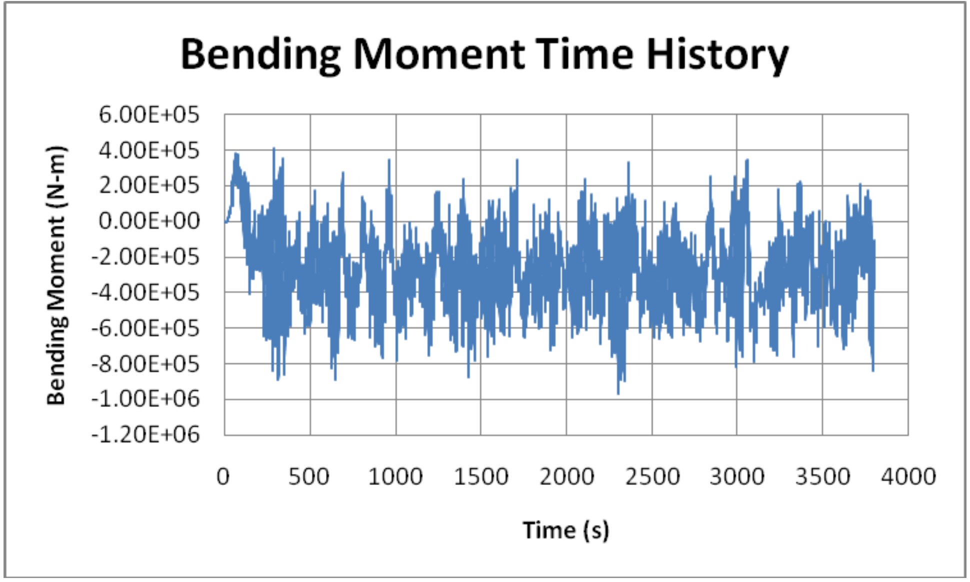


Figure 4.1.6-2 : Bending Moment Time History at Top Of Gimbaled Pipe

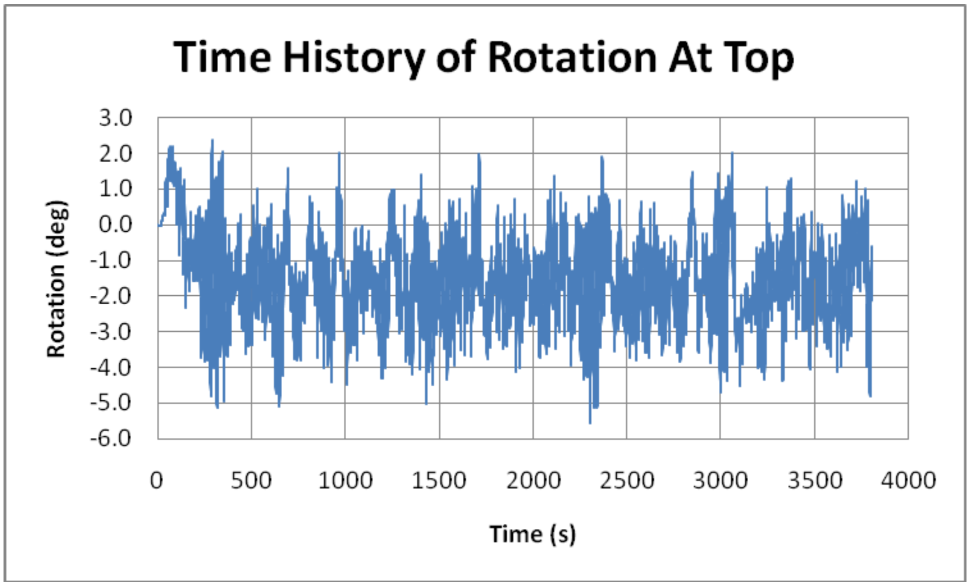


Figure 4.1.6-3 : Time History of Rotation at Top Of Gimbaled Pipe

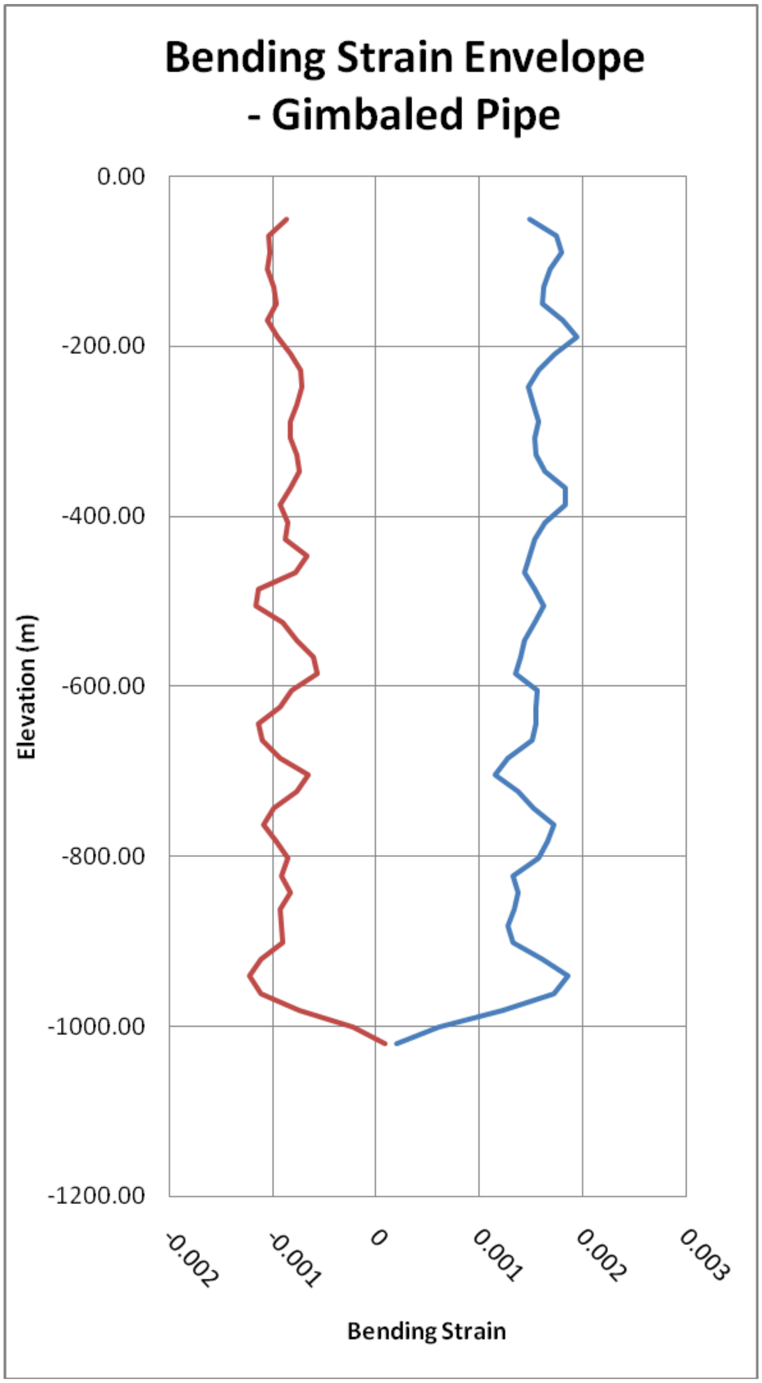


Figure 4.1.6-4: Bending Strain Envelope for Gimballed Pipe

4.2 10 m OD CWP FOR 100 MW OTEC PLANT

4.2.1 CASE 1: GIMBAL SPRING STIFFNESS = 1.0E07 N-m/rad

Table 4.2.1-1 : Force and Moment Statistics at Top Of Gimbaled Pipe

	Shear Force at Top	Bending Moment at Top	Rotation at Top
	N	N-m	deg
Maximum	6.37E+06	6.87E+05	3.94
Minimum	-5.25E+06	-8.57E+05	-4.91
Mean	5.41E+05	-2.11E+05	-1.21
Std Dev	1.75E+06	2.38E+05	1.37

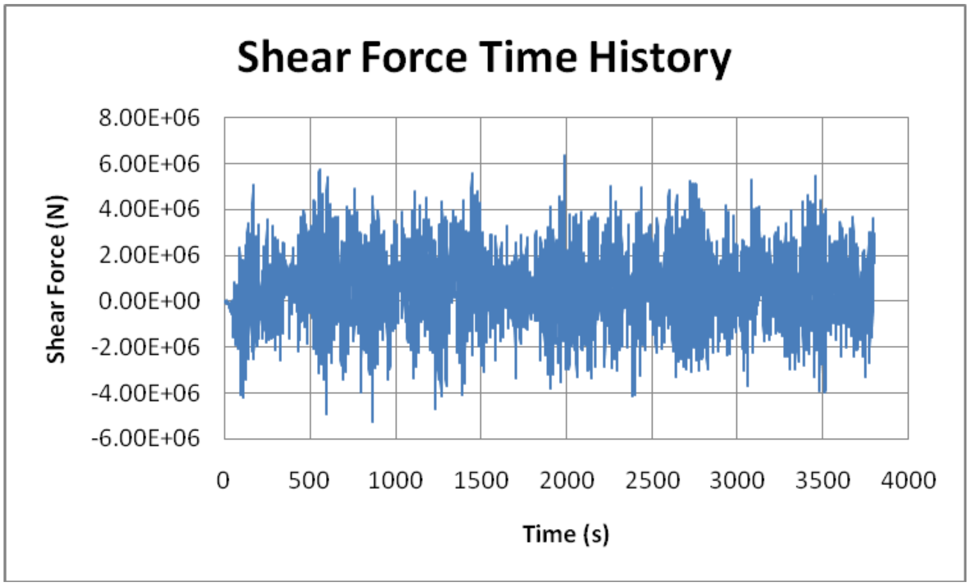


Figure 4.2.1-1 : Shear Force Time History at Top Of Gimbaled Pipe

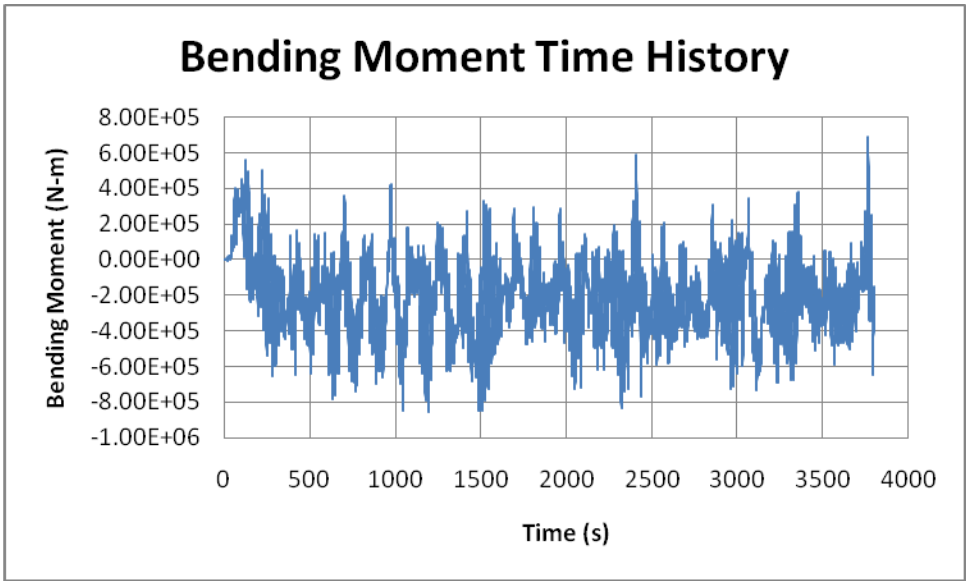


Figure 4.2.1-2 : Bending Moment Time History at Top Of Gimbaled Pipe

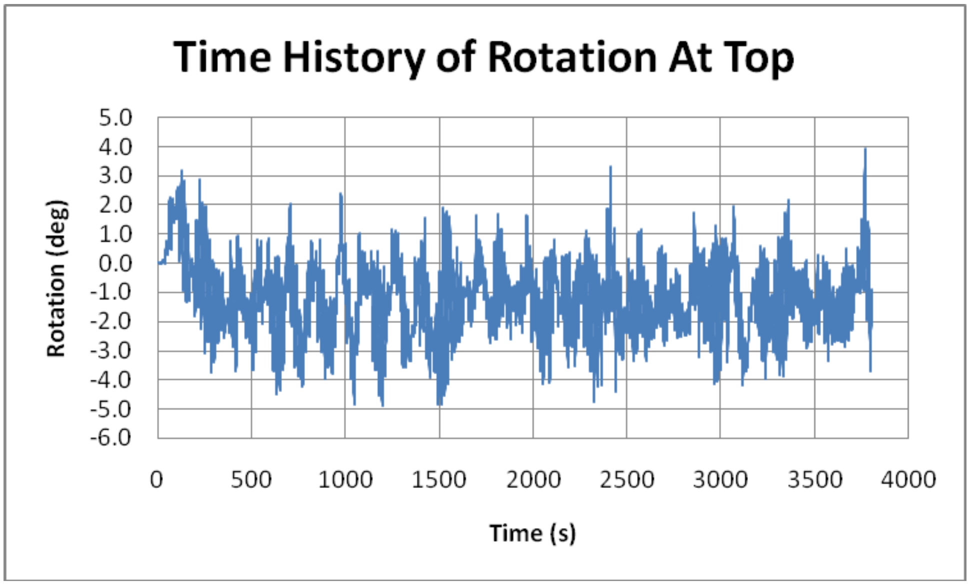


Figure 4.2.1-3 : Time History of Rotation at Top Of Gimbaled Pipe

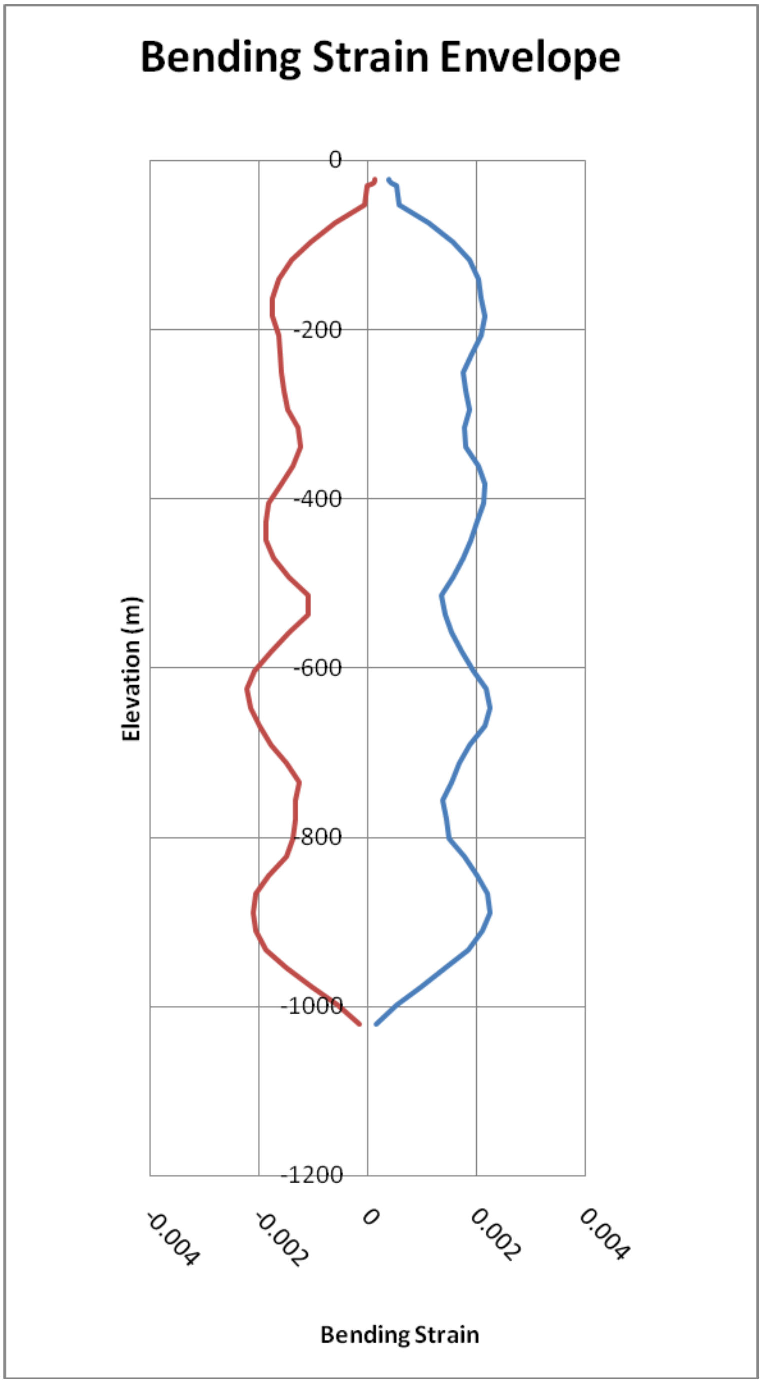


Figure 4.2.1-4: Bending Strain Envelope for Gimballed Pipe

4.2.2 CASE 1: GIMBAL SPRING STIFFNESS = 1.0E09 N-m/rad

Table 4.2.2-1 : Force and Moment Statistics at Top Of Gimbaled Pipe

	Shear Force at Top	Bending Moment at Top	Rotation at Top
	N	N-m	deg
Maximum	6.32E+06	6.29E+07	3.60
Minimum	-4.77E+06	-7.40E+07	-4.24
Mean	5.24E+05	-1.55E+07	-0.89
Std Dev	1.71E+06	2.17E+07	1.24

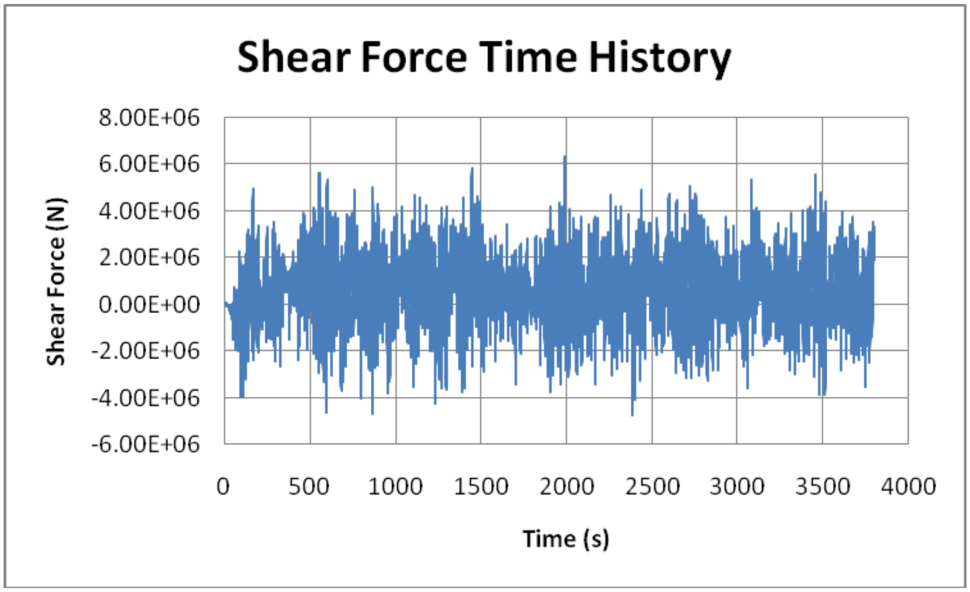


Figure 4.2.2-1 : Shear Force Time History at Top Of Gimbaled Pipe

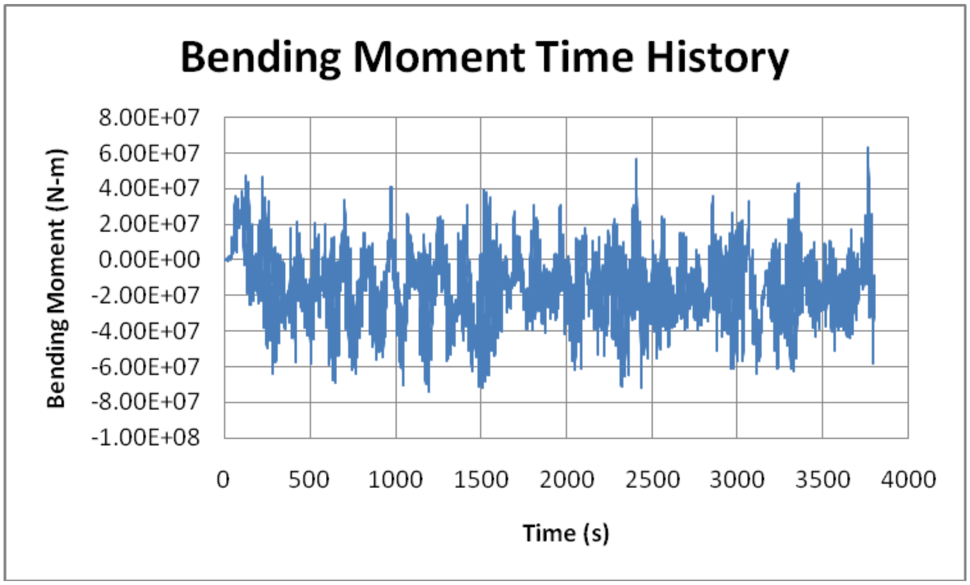


Figure 4.2.2-2 : Bending Moment Time History at Top Of Gimbaled Pipe

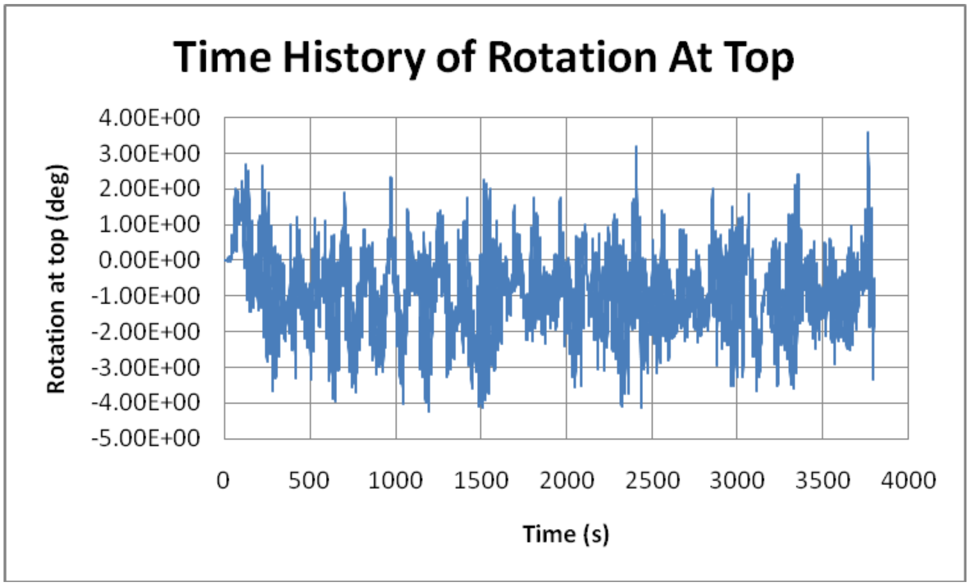


Figure 4.2.2-3 : Time History of Rotation at Top Of Gimbaled Pipe

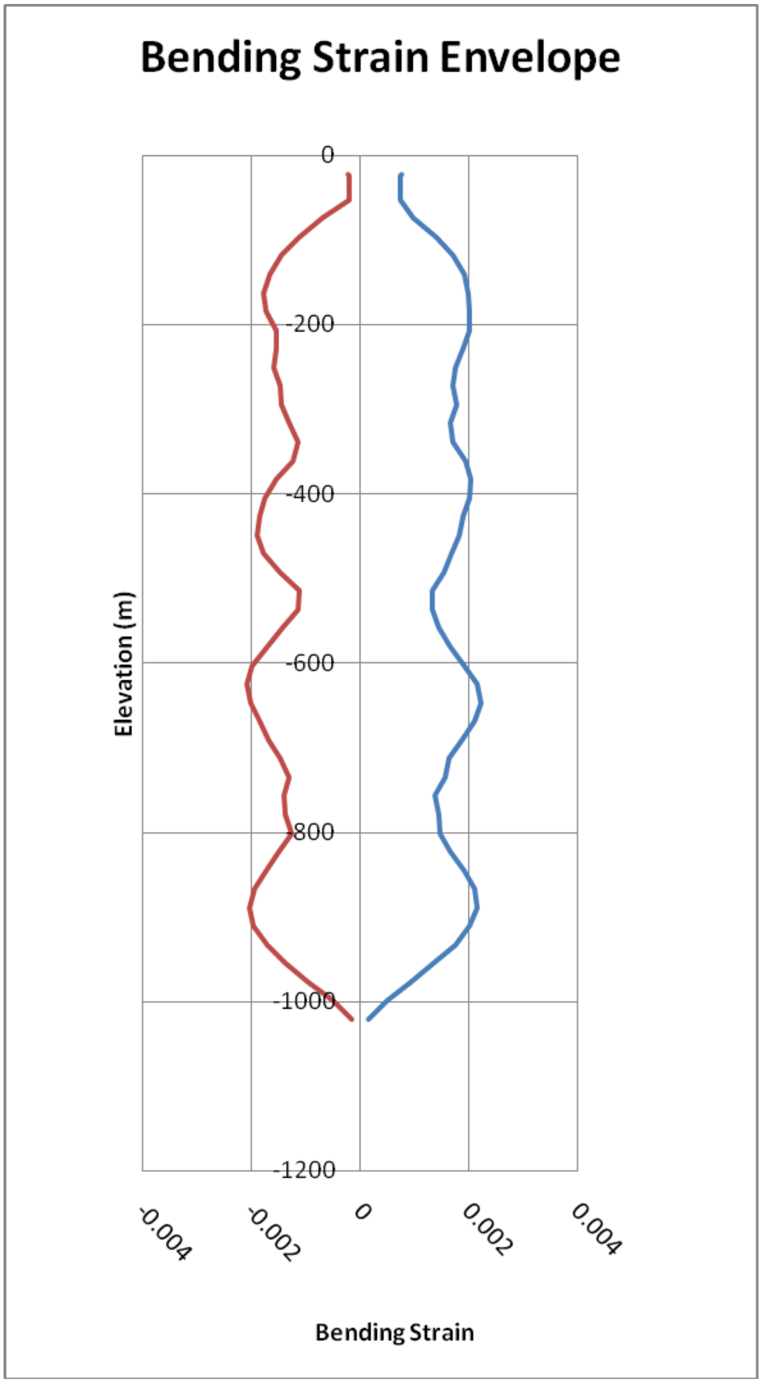


Figure 4.2.2-4: Bending Strain Envelope for Gimballed Pipe

4.1 10 m OD CWP FOR 100 MW OTEC PLANT - FATIGUE ANALYSIS

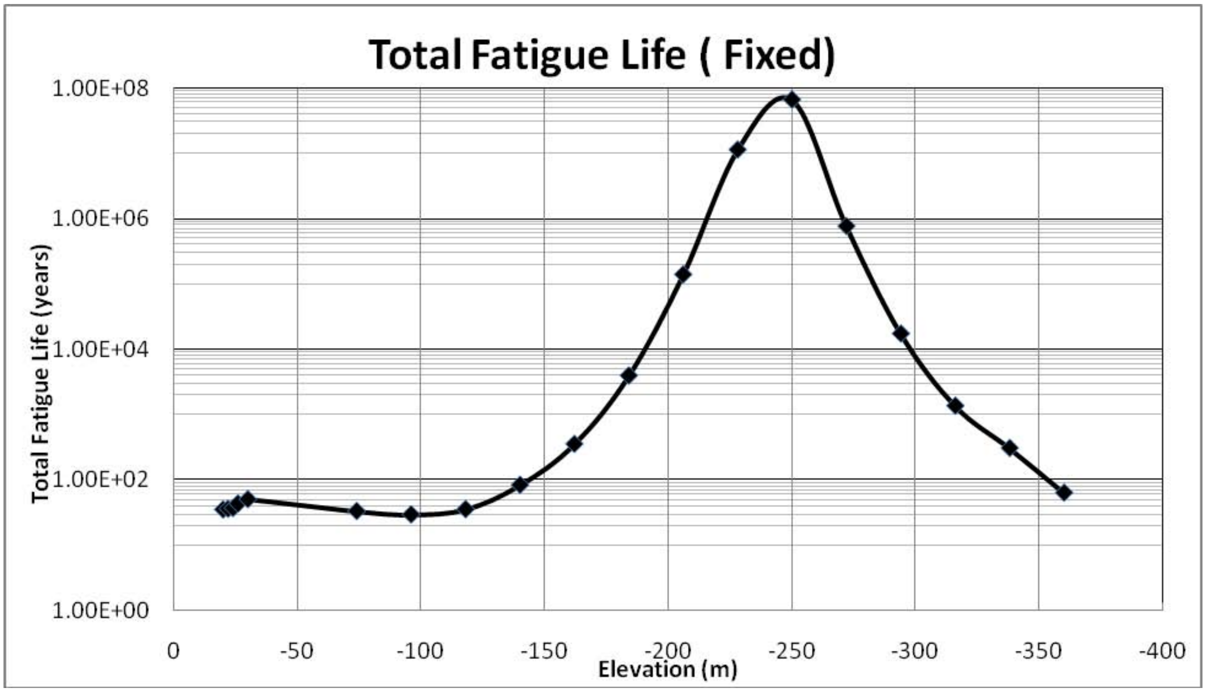


Figure 4.3-1: Total Fatigue Life for Fixed Pipe

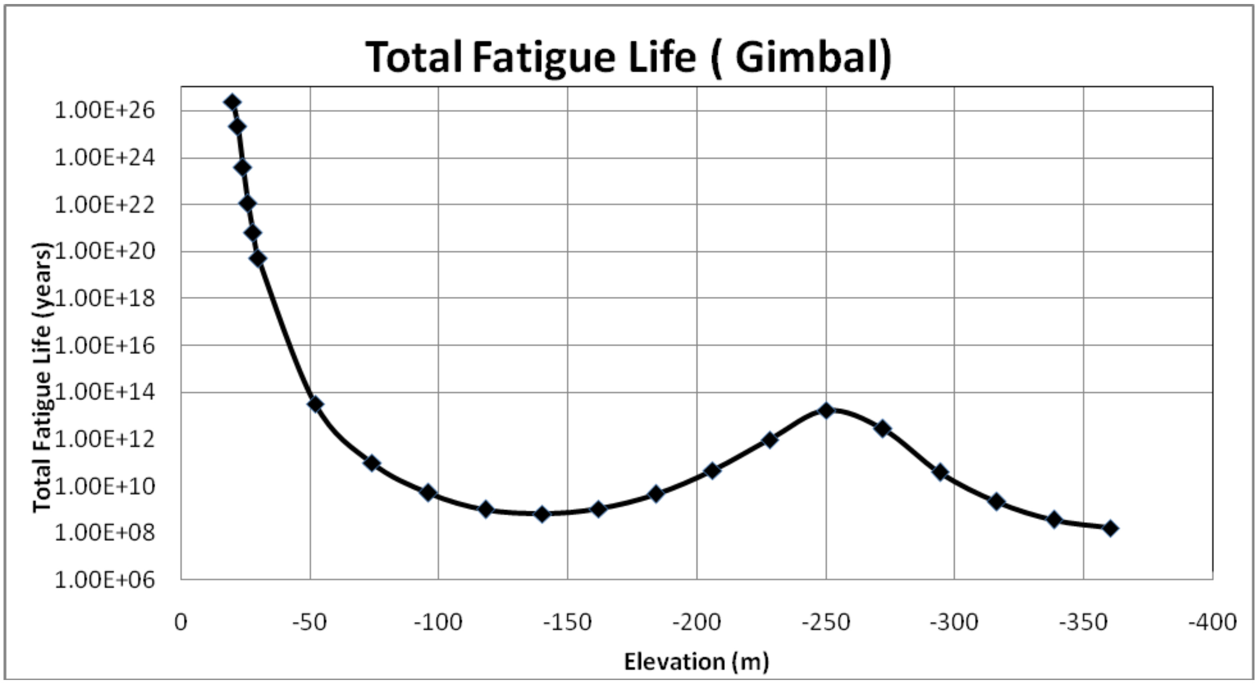
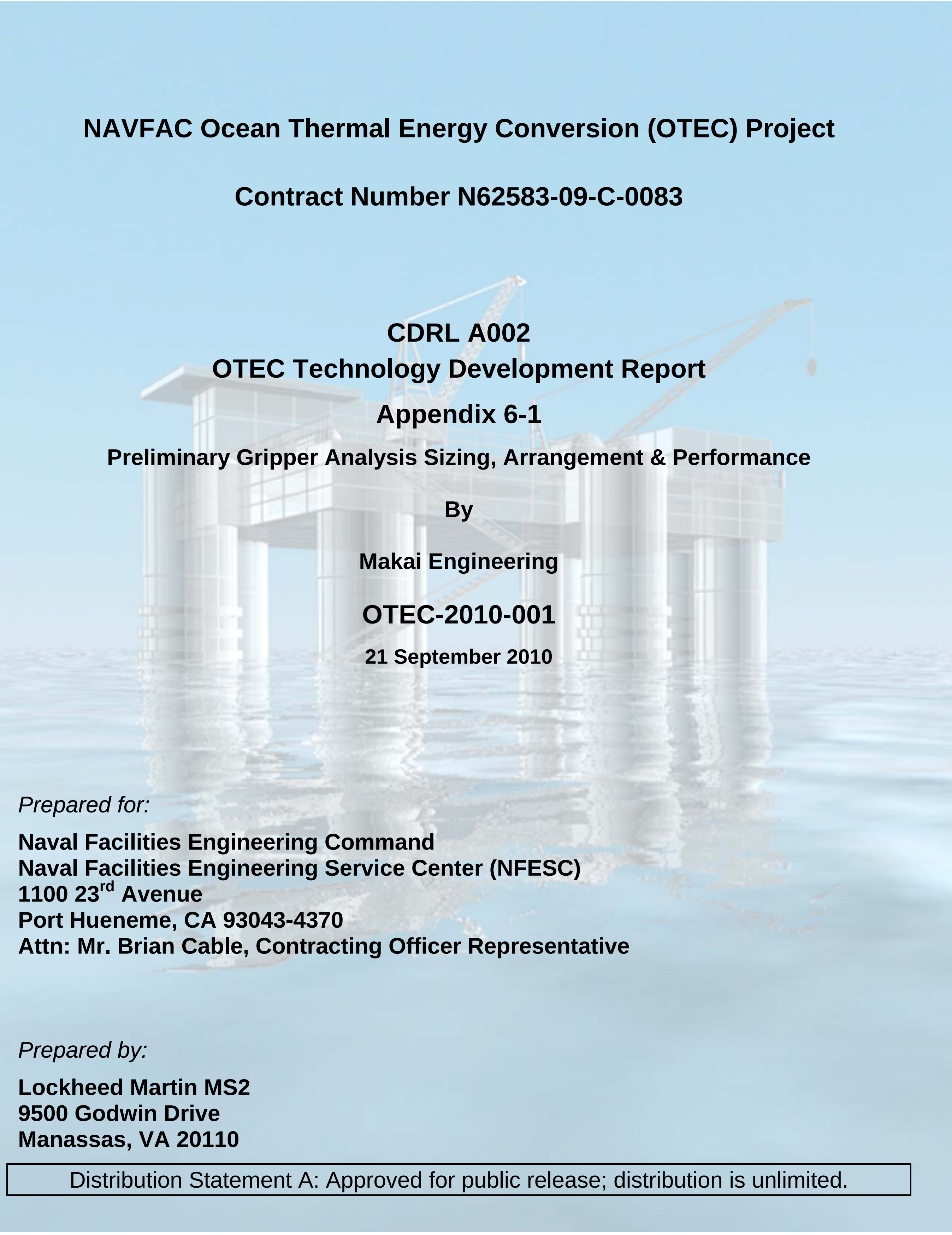


Figure 4.3-1: Total Fatigue Life for Gimbaled Pipe



NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report

Appendix 6-1

Preliminary Gripper Analysis Sizing, Arrangement & Performance

By

Makai Engineering

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
Naval Facilities Engineering Service Center (NFESC)
1100 23rd Avenue
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Distribution Statement A: Approved for public release; distribution is unlimited.

Preliminary Gripper Analysis

Sizing, Arrangement & Performance

Prepared By

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November 2, 2009

Contents

Executive Summary

Background Information

The cold water pipe (CWP) for the 100MW OTEC plant is to be fabricated at sea in 11m segments on a semi-submersible platform. The pipe will be fabricated in a vertical position and lowered down after each segment is cured, at which point the subsequent segment is fabricated. While the pipe is being fabricated, it must be supported vertically to hold its weight and laterally to limit the horizontal movement of the pipe. The vertical support will be provided by two "grippers," which squeeze the outside of the pipe and utilize friction to hold the pipe's weight. Additionally, the grippers are also responsible for lowering each segment of the pipe. To do this, one gripper must disengage while the other gripper is lowered. Once the segment is lowered, the first gripper reengages and the second gripper disengages to return to its original position. The lowering sequence necessitates that each gripper be capable of holding the entire weight of the CWP individually. Lateral support to the pipe is provided by two "guides," which limit the horizontal movement of the pipe. Unlike the grippers, which squeeze and hold on to the CWP, the guides must allow the pipe to slide through while each segment is being lowered. In addition, both the grippers and the guides will use some sort of pad to engage the CWP that will not damage the pipe.

Scope of Report

The purpose of this report is to document the conceptual design of the CWP support system utilized during fabrication of the pipe. The present study has focused on analyzing the global behavior of the CWP and its support system under the loads imparted by ocean currents. The study only considers the static response of the CWP and does not go in to the dynamics associated with oscillating currents and ocean waves. The work done in this study set out to define several critical design factors, namely:

- the arrangement and locations of the grippers/guides
- the dimensions of the grippers/guides (length and thickness)
- the stiffness of the grippers/guides (radial, shear and rotational)
- the allowed degrees of motion of the grippers/guides

The goal of the study was to optimize the above design factors such that they reduce the motion of CWP as much as possible while ensuring that the pipe would not slip in the grippers and that the pressure on the CWP did not surpass a prescribed nominal value.

Analysis

The primary tool used in analyzing the grippers and guides was a finite element (FE) model that represents the CWP as several beam elements and the grippers/guides as spring elements (Figure 3). The FE model was developed specifically for the purpose of analyzing the grippers and guides and calculates overall reaction forces, peak pressures on the pipe, shear and normal forces in each pad and displacements of the CWP at any point along its length. The loads applied in the model are based on the weight of the pipe and the static forces/moments imparted by ocean currents on the CWP. The locations, dimensions and material properties of the grippers/guides are all inputs in the model. The stiffness of the spring elements representing the grippers and guides are derived from the dimensions and material properties of the pads assuming the rest of the platform structure to be rigid.

The FE model was used to perform a sensitivity study that examined the impact each input has the performance of the system. In the study, a baseline design was specified and then each input parameter was varied individually. The study showed which parameters were most influential and helped in optimizing the design of the grippers and guides. A second study was done in order to assess the benefit of allowing the pads three different degrees of freedom: pivoting, tilting and floating (see pg. 15 for a detailed explanation.) Like the sensitivity study, the characteristic comparison study examined the effect of each characteristic against a baseline design.

Results

After many iterations of the sensitivity and characteristics comparison studies, a final baseline design was established. The final baseline design has two grippers located near the platform deck and two guides located below the grippers. The exact dimensions of the final baseline design are shown in Figure 1.

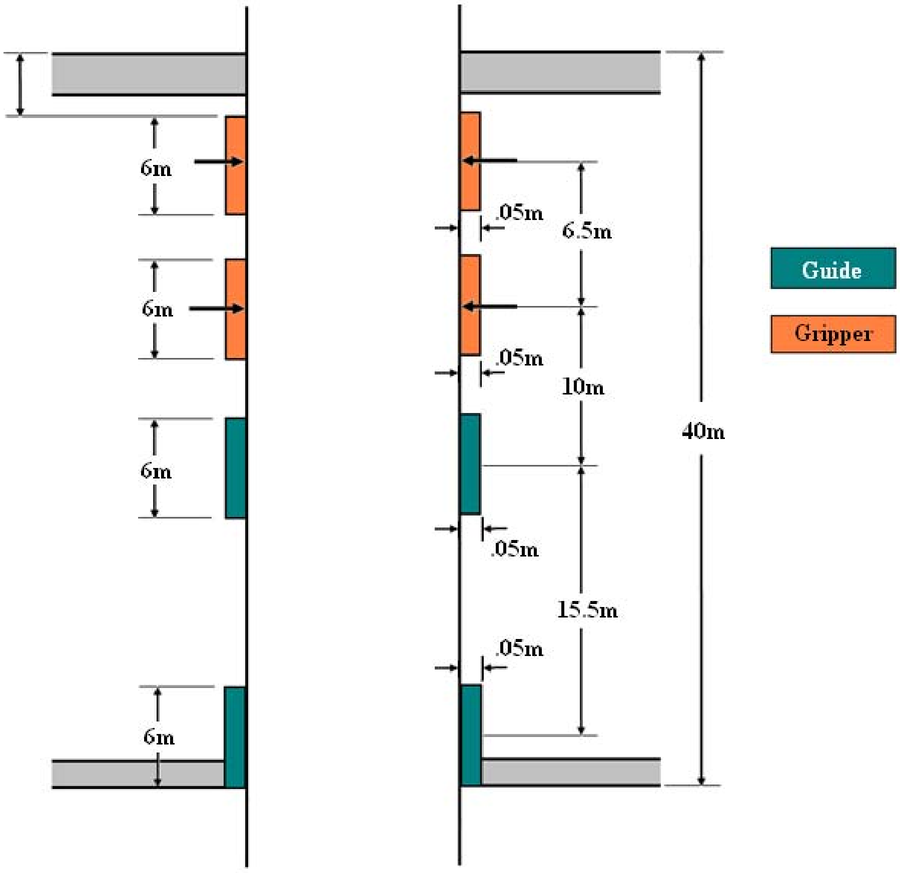


Figure 1 - Baseline Design

Other key properties of the baseline design are:

- Young’s modulus of all pads: 6 MPa
- Shear modulus of all pads: 2 MPa
- All pads can pivot
- Gripper 2 floats

The displacements of the CWP with the final baseline design employed are shown in the table below.

Table 1 – Final Baseline Design Results

		Horizontal Displacement		Axial Displacement (mm)	Rotation (degrees)
		Top of Fab (mm)	Deck Level (mm)		
Mean Current Load	Gripper 1 - Engaged Gripper 2 -Engaged	0.02	0.05	0.67	0.0006
	Gripper 1 - Disengaged Gripper 2 -Engaged	0.55	0.27	1.95	0.0014
Maximum Current Load	Gripper 1 - Engaged Gripper 2 -Engaged	2.73	0.91	0.67	0.0095
	Gripper 1 - Disengaged Gripper 2 -Engaged	9.27	4.65	1.95	0.024

One major limitation to the results in Table 1 is that the FE code assumes that the platform structure is perfectly rigid when in fact the platform must be somewhat elastic. Some basic calculations were made in order to estimate the platform elasticity at the various gripper/guide locations, and the estimates were incorporated into the FE code by reducing the stiffness of the grippers/guides (see Figure 24 for details.) The results incorporating the platform elasticity estimates are shown in the table below.

Table 2 – Final Baseline Design Results including platform stiffness estimates

		Horizontal Displacement		Axial Displacement (mm)	Rotation (degrees)
		Top of Fab (mm)	Deck Level (mm)		
Mean Current Load	Gripper 1 - Engaged Gripper 2 -Engaged	0.90	0.24	1.60	0.0034
	Gripper 1 - Disengaged Gripper 2 -Engaged	4.66	3.61	3.91	0.0055
Maximum Current Load	Gripper 1 - Engaged Gripper 2 -Engaged	15.15	4.13	1.60	0.0574
	Gripper 1 - Disengaged Gripper 2 -Engaged	78.68	60.97	3.91	0.0923

Design Overview

The CWP support structure is composed of two grippers and two guides that are responsible for supporting the CWP during the fabrication process. The grippers are capable of applying a squeezing pressure to the CWP and are responsible for supporting the weight of the CWP. The guides provide lateral support to the CWP but do not help support the weight of the pipe.

Performance Goals

The performance goals define the desired limits for the:

- Maximum horizontal displacement at top of CWP
- Maximum axial displacement at top of CWP
- Maximum CWP rotation from vertical
- Allowable pressure on the CWP

The first three performance goals from above are illustrated in Figure 2. Additionally, the design must also ensure that the CWP does no slip in the grippers and that the pipe is able to slide through the guides when being lowered.

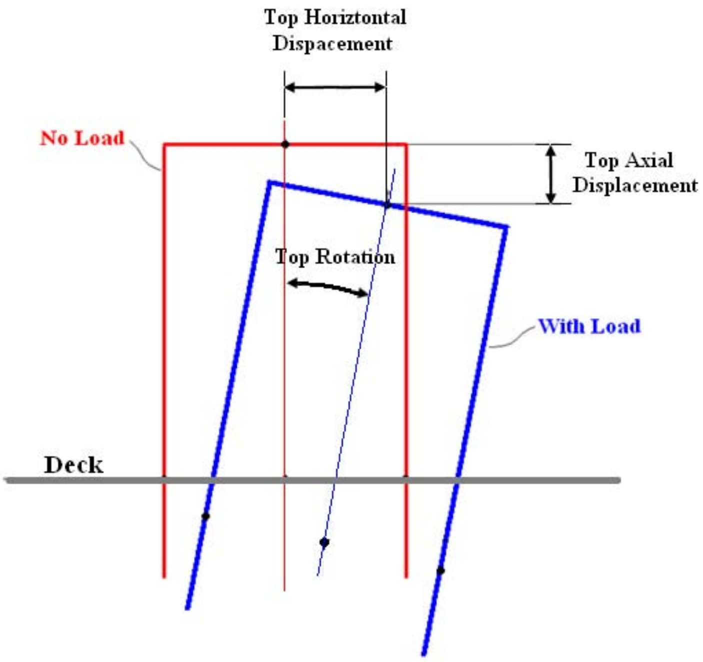


Figure 2 - Performance Goals

Finite Element Model

A finite element model of the CWP in the platform area was created to determine the behavior of the CWP under current loads. The model is designed to investigate the movement of the pipe under the static load imposed by ocean currents. The model consists of three frame elements (beam elements that also have an axial degree of freedom) representing the CWP and several spring elements that represent the stiffnesses of the guides and the grippers. A drawing of the FE model is shown in Figure 3. The model has 15 total elements and 12 active degrees of freedom. The grippers/guides in the figure are all generically represented as supports, each of which has axial, lateral and rotational stiffness.

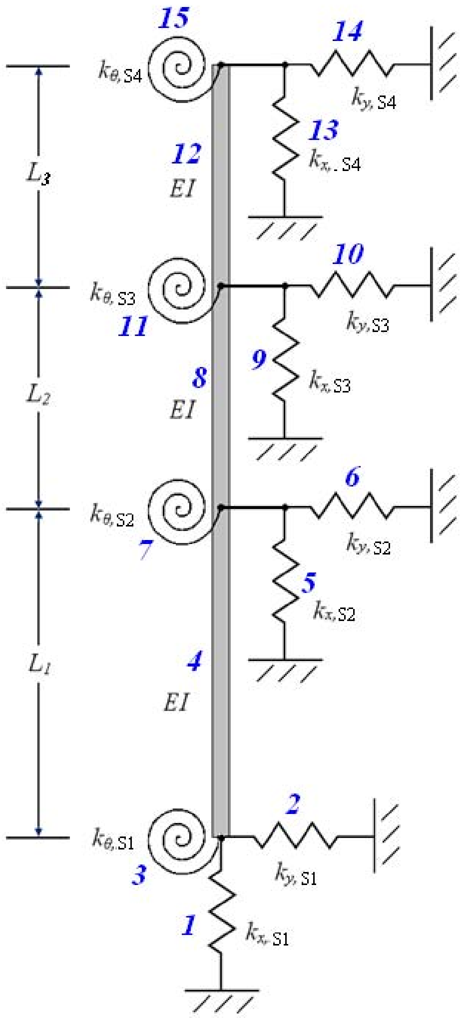


Figure 3 - Finite Element Model

Assumptions

The assumptions made in the FE model are:

- Guides/grippers are assumed to be infinitely rigid except for their respective pads. The stiffness of the spring elements are calculated based on the material properties and geometry of the pads.
- Gripper preload squeeze is applied with no load, i.e. the grippers squeeze the CWP while it is centered and vertical.
- The sharing of the axial load from CWP weight in the grippers is calculated assuming both grippers are first engaged with no weight load and then the entire weight load is applied at once.
- Dynamic motions of platform or pipe are not considered

Element Stiffness Derivations

The stiffness of each gripper and guide in the model is derived from the material properties and geometry of the pad. As stated above, the stiffness's are found assuming the entire structure is rigid except for the gripper/guide pads.

Lateral Stiffness

When the CWP is moved laterally within the rubber pad, only half of the pad resists the pipe's motion. Additionally, the apparent thickness of the rubber pad varies causing different strains at different locations. The highest strain (and consequently the highest pressure) occurs where the apparent thickness of the rubber is minimum; the center of the CWP. The lowest strain occurs at the edge of the CWP. This phenomenon is illustrated in Figure 4.

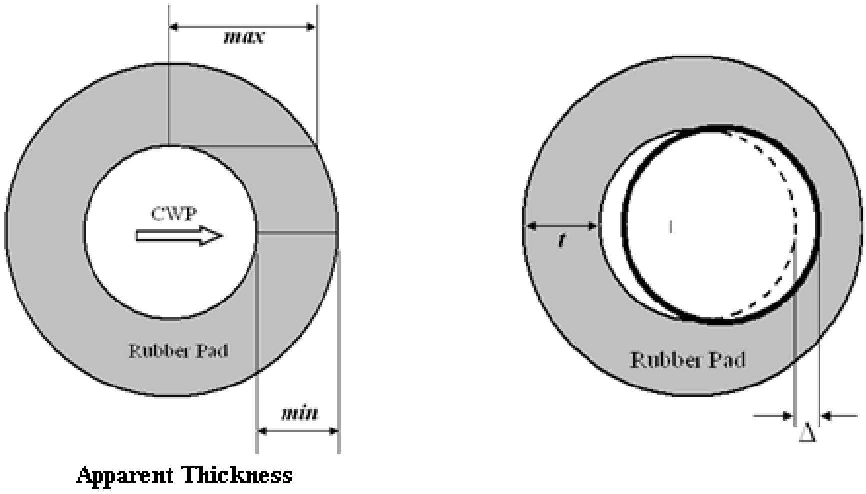


Figure 4 - Lateral Movement in Rubber Sleeve

Solving for the equivalent stiffness for this case can be simplified by finding the average thickness of the portion of the pad being displaced. The simplest way to find the average thickness is to divide the displaced area by the diameter of the CWP, as shown in Figure 5.

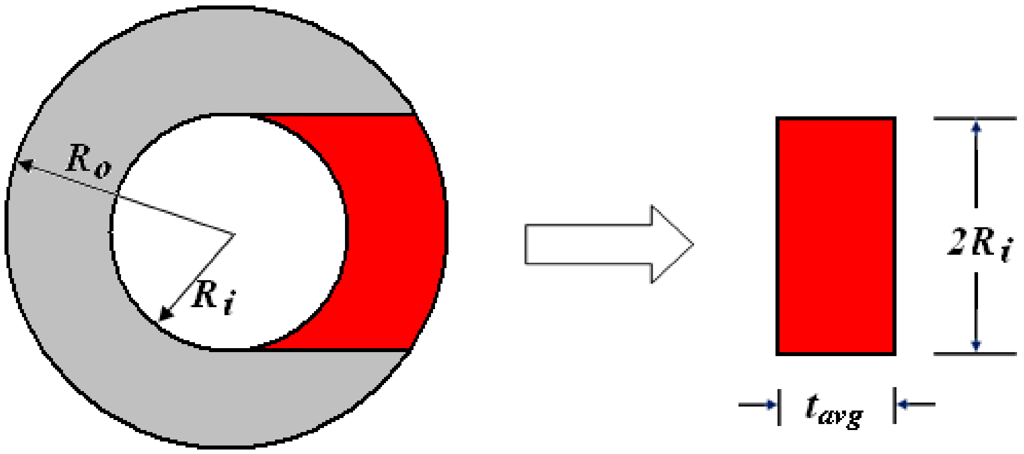


Figure 5 - Average Pad Thickness

The average thickness is found from:

$$t_{avg} = \frac{\frac{\pi\left(R_o^2 - R_i^2\right)}{2} - \frac{R_o^2}{2}\left[2cos^{-1}\left(\frac{R_o}{R_i}\right) - sin\left(2cos^{-1}\left(\frac{R_o}{R_i}\right)\right)\right]}{2R_i}$$

Additionally, since the grippers will apply a preload to hold the CWP, the effect of this preload must be taken into account. The effect on the equivalent stiffness of the system can be deduced by considering two identical spring elements connected in series. If the elements are each compressed by an initial amount Δ_1, and then subjected to a second displacement Δ_2 at the connection point, the force required to displace the springs by Δ_2 is found by:

$$F = k(\Delta_1 + \Delta_2) - k(\Delta_1 - \Delta_2) = 2k\Delta_2$$

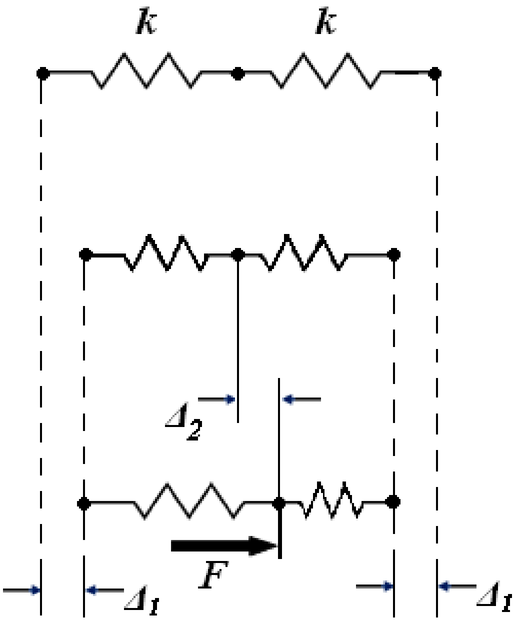


Figure 6 - Spring Stiffness of Preloaded Springs

The apparent stiffness of the system is then:

$$k_{eq=}\frac{F}{\Delta_2} = 2k$$

It should be noted that in the case of the grippers, the expressions above only holds for the case in which both sides of the gripper are still in contact with the CWP (i.e. $\Delta_1 > \Delta_2$) since the gripper pads must be in compression to apply a force. The expression does not appy to the guides because they do not apply a clamping pressure.

The lateral stiffness of the gripper pads is then given by:

$$k_y = \frac{2E_y DL}{t_{avg}}$$

Axial Stiffness

The axial stiffness is found simply by considering the shear of the pad:

$$k_z = \frac{\pi DlG}{t}$$

Rotational Stiffness

The rotational stiffness is found by considering the moment induced when the CWP is rotated by an angle θ. There will be two contributions to the moment: one results from the lateral stiffness and the other from the shear stiffness.

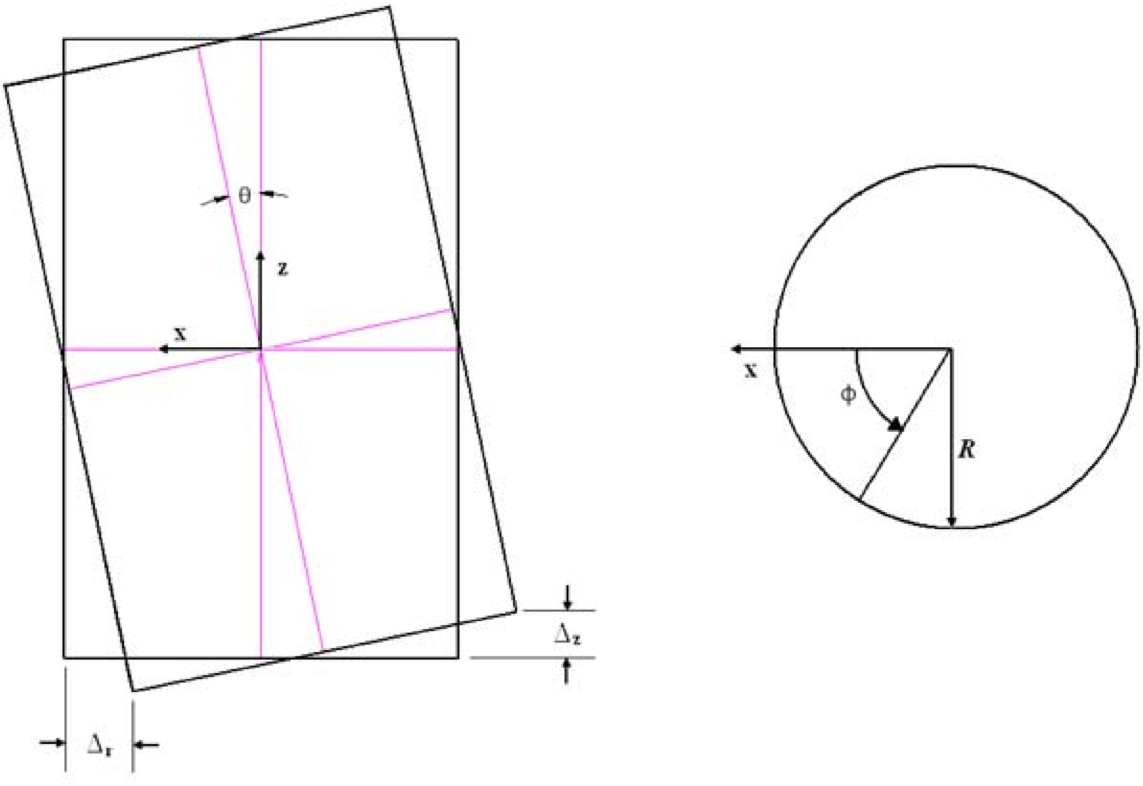


Figure 7 - CWP Rotation

The displacements at the edge of the CWP when it is rotated by an angle θ are:

$$\Delta_y = z(\sin\theta) - R(\cos\theta - 1)\cos\phi$$

$$\Delta_z = z(\cos\theta - 1) - R(\sin\theta)\cos\phi$$

For small angles of θ the displacements can be simplified to:

$$\Delta_y = z(\sin\theta)$$
$$\Delta_z = -R(\sin\theta)\cos\phi$$

The reaction force of the gripper pads due to the axial displacements is found by integrating the strains over the area of the pads and multiplying by the shear modulus. Similarly, the reaction moment can be found by integrating the strain times the moment arm $Rcos\phi$ and then multiplying the quantity by the shear modulus, as shown below.

$$M = G\int_{-\frac{L}{2}}^{\frac{L}{2}}\int_{0}^{2\pi} Rcos\phi\,\frac{(Rsin\theta cos\phi)}{t}R d\phi\, dz = \frac{G\pi R^3 L}{t}sin\theta$$

For small angles the rotational stiffness due to the axial displacements is then:

$$k_{\theta,shear} = \frac{G\pi R^3 L}{t}$$

The stiffness due to horizontal displacements is found by considering the lateral forces acting on the CWP as it rotates. A diagram of these forces is shown in Figure 8.

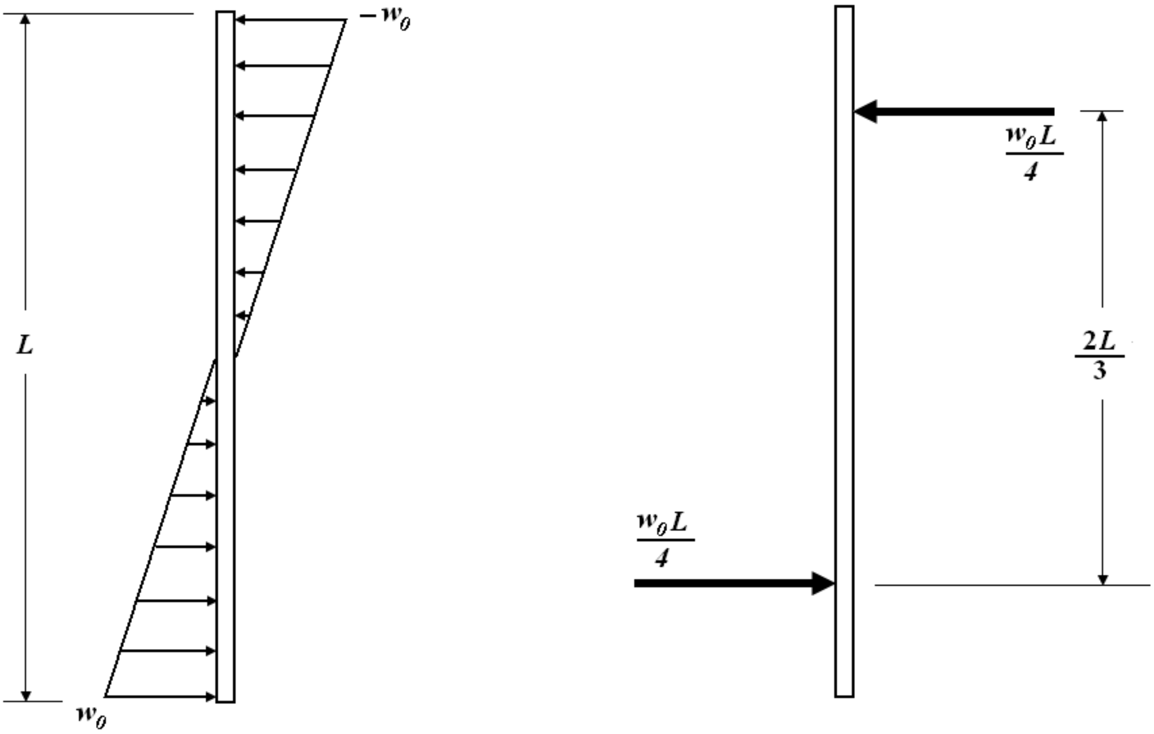


Figure 8 - Reaction Forces due to Rotation

The magnitude of w_0 is:

$$w_0 = \frac{E_r D L sin\theta}{2t_{avg}}$$

The reaction moment is then given by:

$$M = \left(\frac{w_0 L}{4}\right)\left(\frac{2L}{3}\right) = \frac{E_r D L^3 sin\theta}{12t_{avg}}$$

$$k_{\theta,lateral} = \frac{2M}{\theta} = \frac{E_r D L^3}{6t_{avg}}$$

Note that this spring constant is doubled for the because the gripper pads as two springs in series. Again, this only hold true when both sides of the gripper pad remain in contact and does not apply for the guide pads.

Finally, the total rotational stiffness is:

$$k_\theta = k_{\theta,shear} + k_{\theta,lateral} = \frac{E_r D L^3}{6t_{avg}} + \frac{G\pi R^3 L}{t}$$

Where,

E = Young’s modulus of rubber pad

G = Shear modulus of rubber pad

D = Outer diameter of the CWP

t = thickness of rubber pad

l = length of rubber pad

Stiffnesses from Literature

The lateral, axial and rotational stiffness of a cylinder inside a rubber annulus have also been derived by Alan Gent in *Engineering with Rubber*. The formulae given by Gent are:

$$k_y = \frac{2E_r D l}{t}$$

$$k_z = \frac{4\pi G l}{\ln\left(\frac{a_2}{a_1}\right)}$$

$$k_\theta = \frac{4\pi G l}{a_1^{-2} - a_2^{-2}}$$

The stiffnesses given by Gent were compared to those derived in the previous section. A comparison between the two is shown in Table 1. The values in the table are calculated using the dimensions and material properties of the baseline design (discussed later.)

Table 1 – Stiffness Comparison

	Lateral	Axial	Rotational
Derived Value	1.02E+10	7.95E+09	1.41E+11
From Gent	1.52E+10	7.99E+09	7.47E+10
% difference	19.6	0.2	30.8

Gripper/Guide Characteristics

Allowing the guides and grippers to move and rotate with the CWP can improve the performance of the grippers. As such, three pad characteristics that allow the supports to move/rotate with the CWP were investigated. The three pad characteristics and their benefits are discussed below.

Pivoting: Gripper/guide pad rotates with the CWP.

- Allows pad to apply a uniform pressure to the CWP
- The uniform pressure grips the CWP better and reduces the peak pressure on the CWP

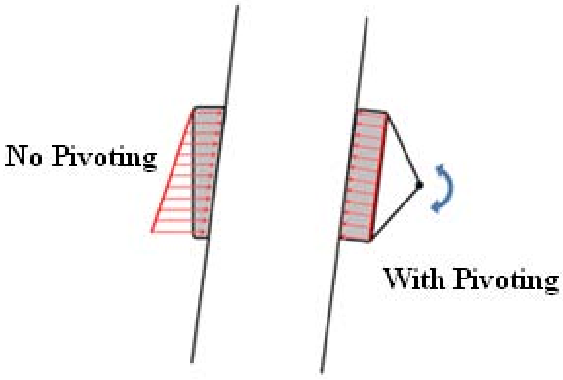


Figure 9 – Gripper/Guide Pivoting

Tilting: Gripper/guide pads can move vertically and rotate with the pipe.

- Creates a uniform shear load around circumference of CWP in addition to the same benefits as pivoting.
- The uniform shear load improves gripping ability.

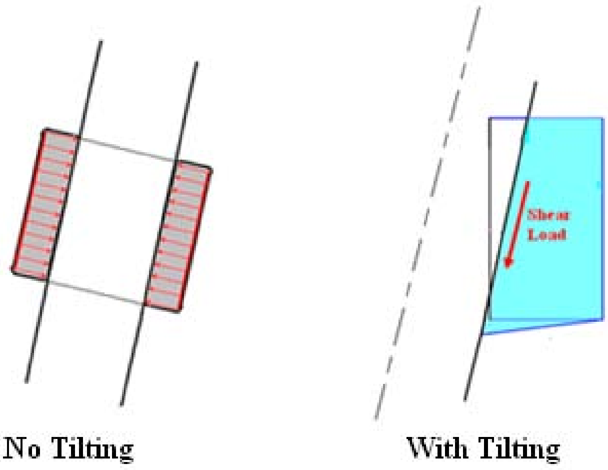


Figure 10 - Gripper/Guide Tilting

Floating: Gripper pads are free to move horizontally.

- Creates uniform normal load on CWP
- The uniform normal load leads to uniform friction forces around CWP which improves gripping ability

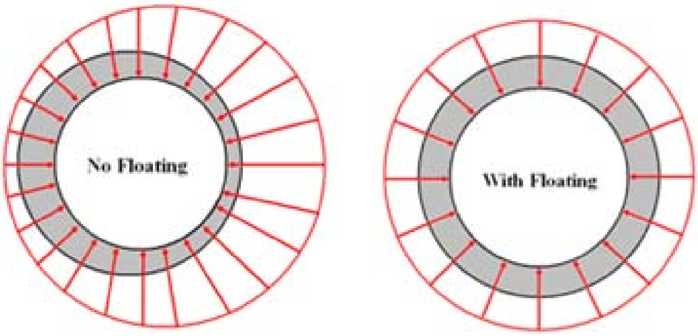


Figure 11 - Gripper/Guide Floating

Loading

The loads on the CWP considered in the FE analysis are caused by ocean currents acting on the CWP. The data used for the currents was taken from the Noda report which was measured at Kahe Pt. The current profiles are shown in Figure 12. Both the mean current profile and the maximum (worst case) current profile are utilized in the FE code in order to examine how the CWP moves under different loads.

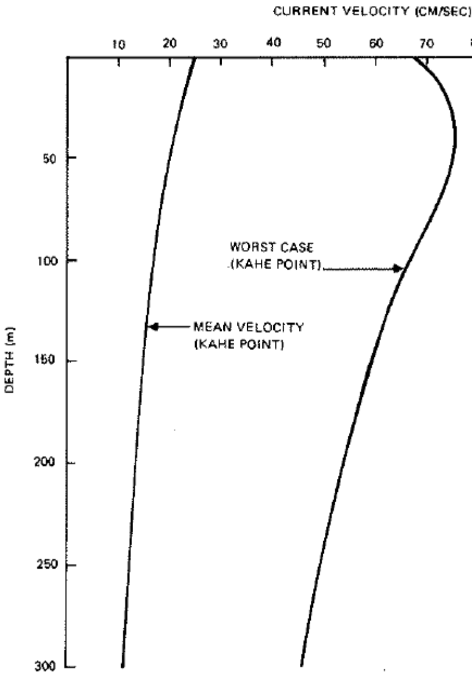
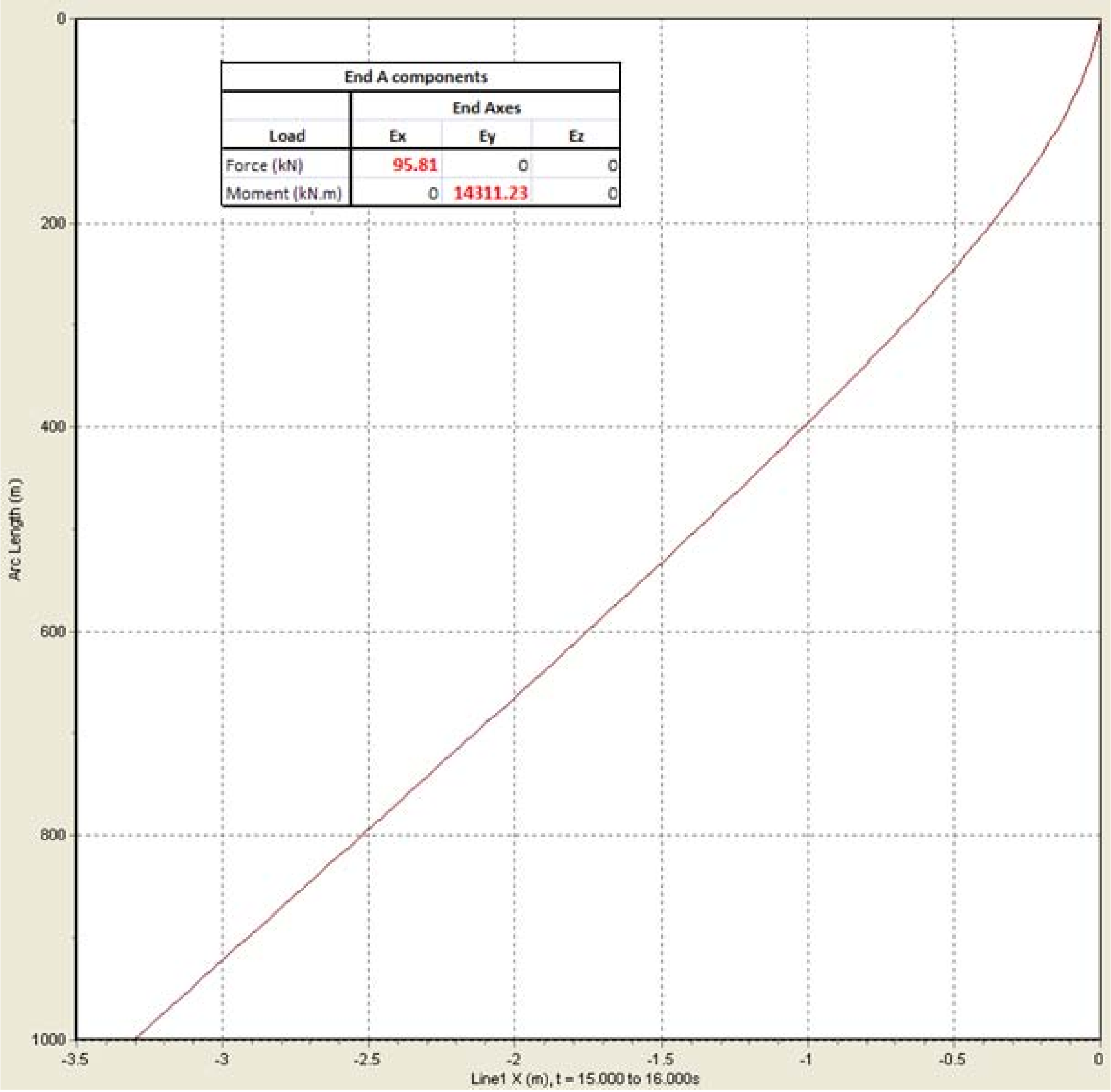


Figure 12 - Kahe Pt. Current Profile

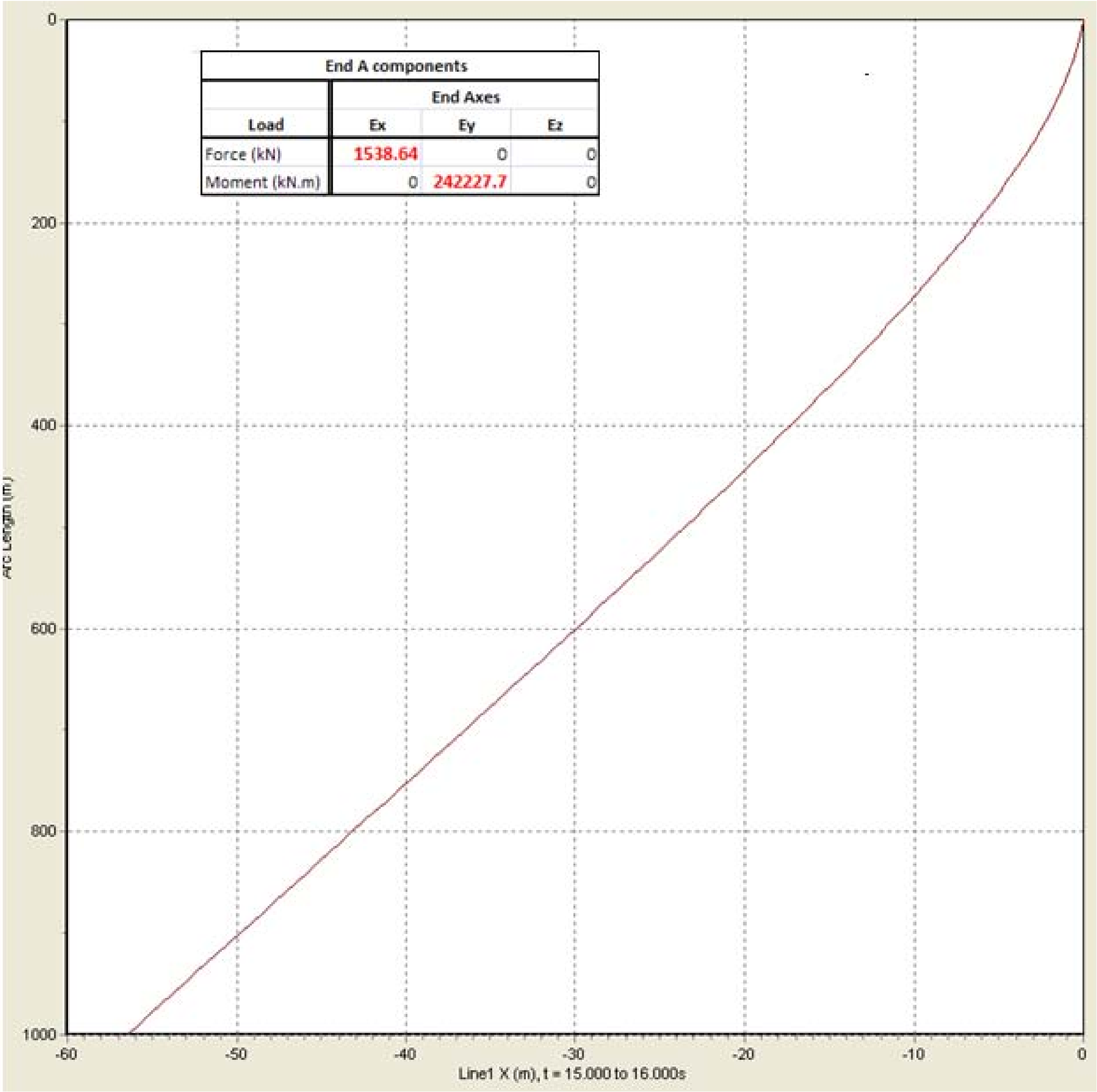
The reaction forces at the keel of the platform were calculated using Orcaflex software. Orcaflex is used in lieu of hand calculations to account for the reduction in moment due to the bending of the CWP under the current loads. The displacement of the fully deployed (1000m long) CWP under the mean and maximum current conditions is shown in Figure 13 and Figure 14. The magnitude of the reaction shear force and moments are also included in the figures.



End A components

Load	End Axes		
	Ex	Ey	Ez
Force (kN)	95.81	0	0
Moment (kN.m)	0	14311.23	0

Figure 13 – Orcaflex Results: Mean Current Load on CWP



End A components			
	End Axes		
Load	Ex	Ey	Ez
Force (kN)	1538.64	0	0
Moment (kN.m)	0	242227.7	0

Figure 14 - Orcaflex Results: Maximum Current Loads

Finite Element Code Input Parameters

The parameters that define the CWP support structure are listed below and shown in Figure 15. These parameters, along with the CWP properties and loads, are inputs in the finite element program. The performance goals for the CWP support structure are also inputs and utilized in the post-processing phase.

- 1-4: Support Length
- 5-8: Support Thickness
- 9: Distance from support 1 to support 2
- 10: Distance from support 2 to support 3

- 11: Distance from support 3 to support 4
- 12: Distance from top of support 4 to platform deck
- 13: Height of Platform
- 14: Preload squeezing pressure applied by grippers
- 15-18: Young’s modulus of pads
- 19-22: Shear modulus of pads

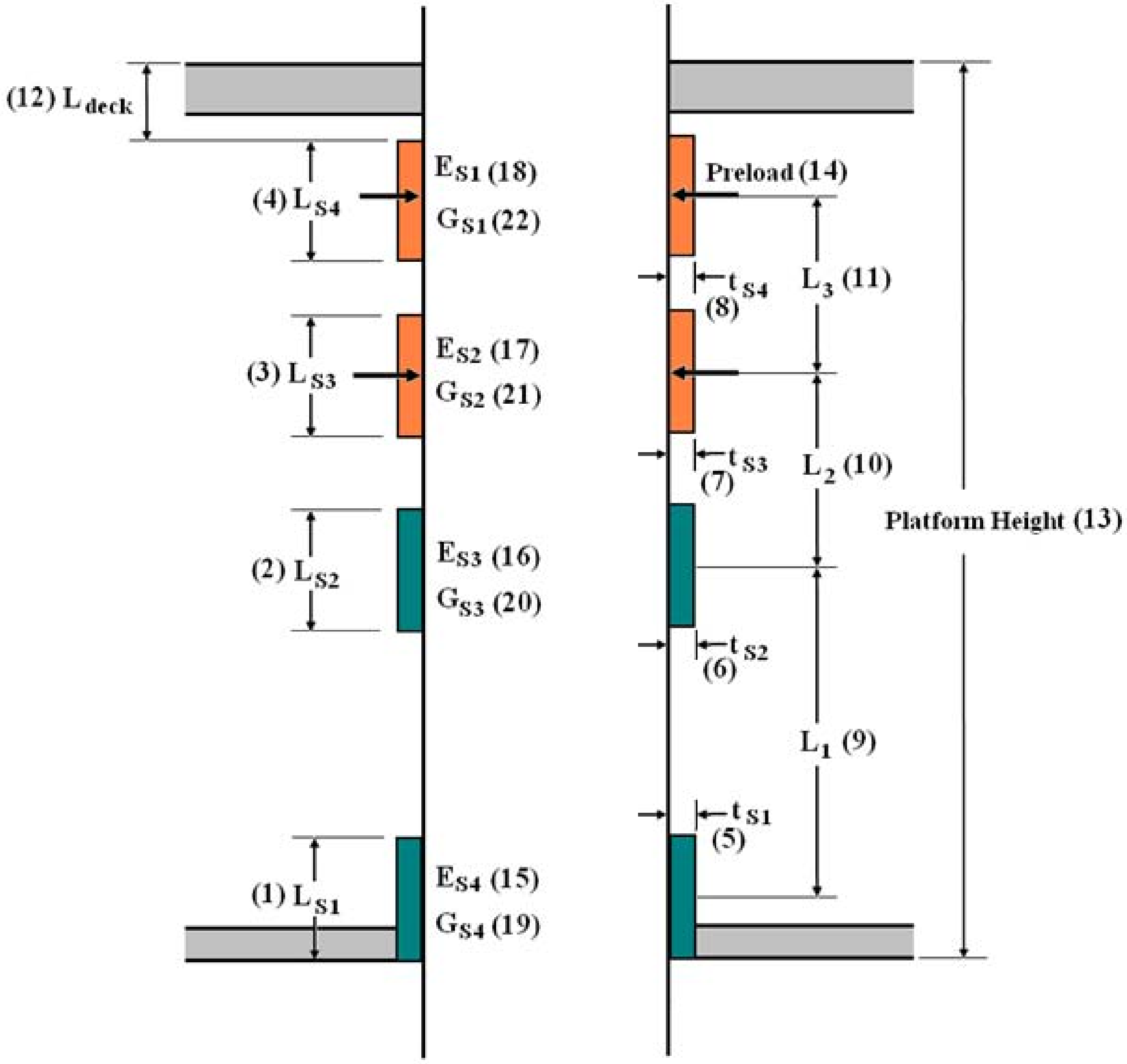


Figure 15 - Input Parameters

Finite Element Code Output

As with all FE codes, the raw output of the code is the displacements and reaction forces at each node (the nodes located at the center of the grippers and guides.) From this raw output, LaGrange shape functions are used to find the deflection of the CWP along its length. Additionally, the code calculates the normal and shear forces on theoretical gripper/guide pads assuming that the there are 8 pads around the circumference. The reaction forces at the nodes, the normal and shear forces on the pads and the deflection are plotted together to deliver a concise depiction of the grippers performance. An example of an output plot is shown in Figure 16.

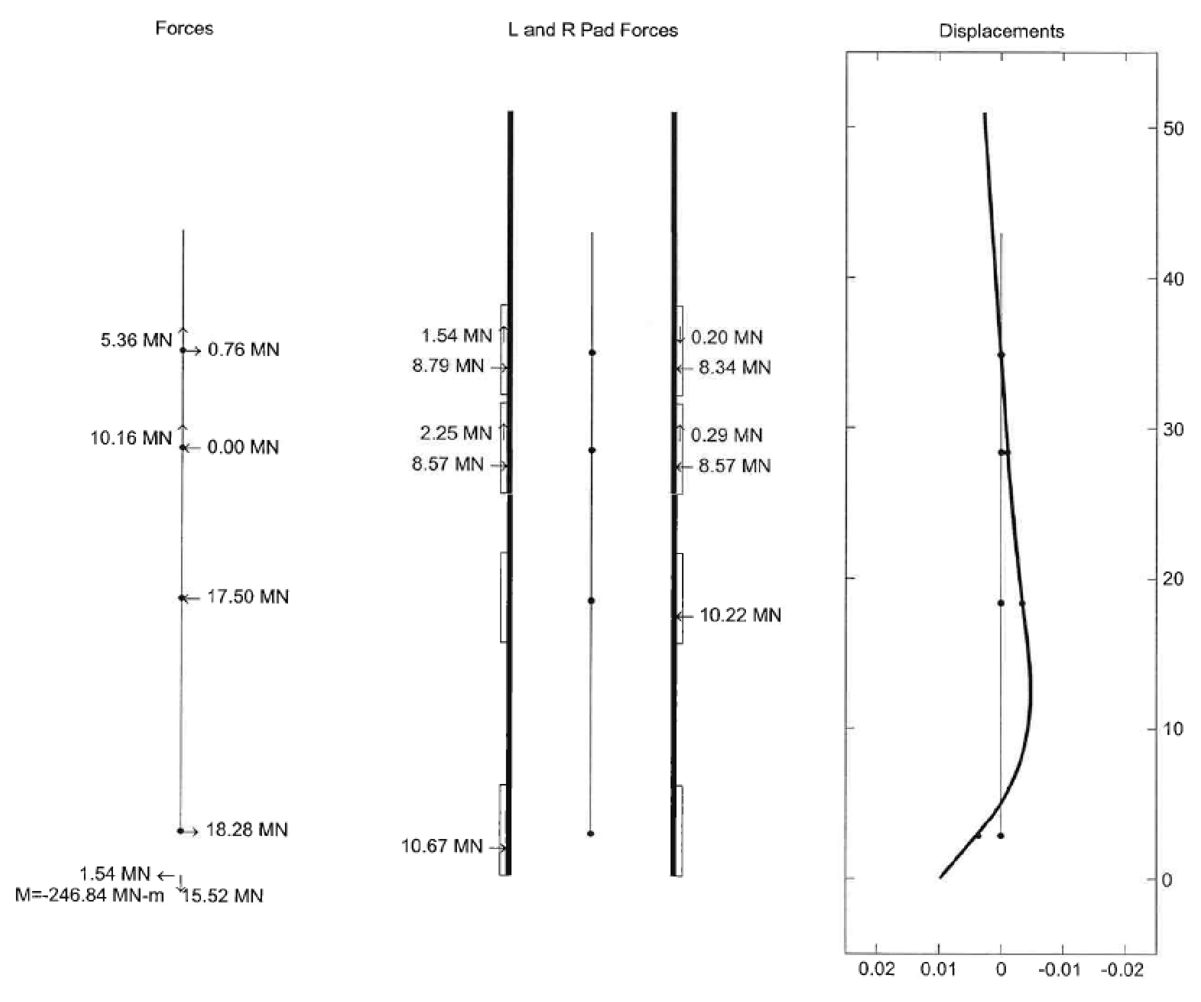


Figure 16 - Finite Element Code Output Plot

In addition to the plotted results, the FE code also compares the results to the performance goals. By dividing a given output by its corresponding performance goal value, the code calculates a safety factor for each performance goal. Safety factors are computed for the:

- Horizontal displacement at top of fabrication
- Axial displacement at top of fabrication
- Rotation at top of fabrication
- Pressure in all pads
- Slip in gripper pads

- Slide in guide pads

When calculating the safety factor for pressure on the CWP, the code compares the pressure at the location where it is maximum to the allowable pressure. The maximum pressure on the CWP occurs due to a combination of horizontal movement and rotation of the pipe within the gripper/guide pads. An illustration of the location of maximum pressure is shown in Figure 17.

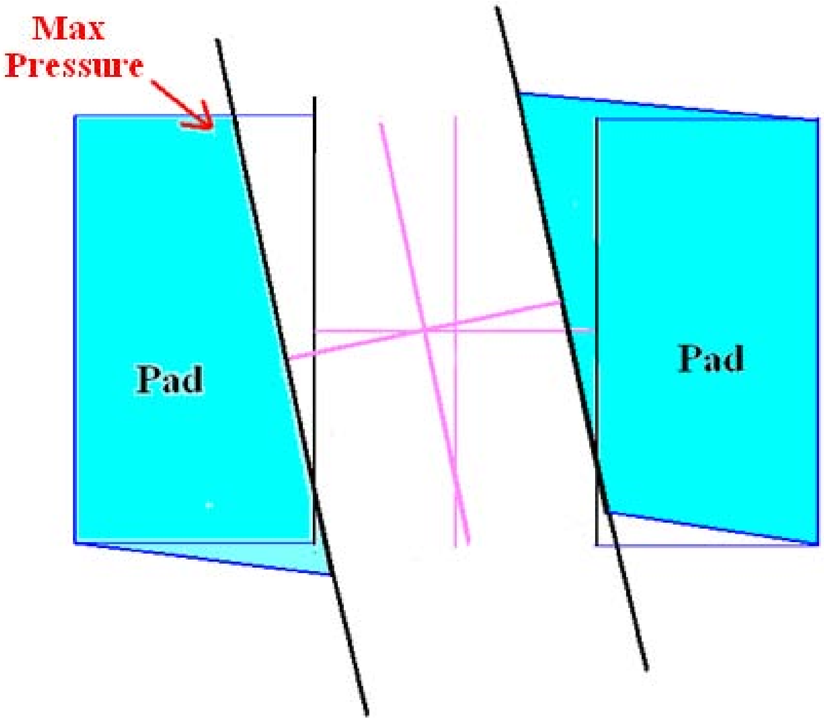


Figure 17 - Maximum Pressure Location

The safety factor guarding against slipping is found by dividing the maximum friction force (normal force x COF) by the shear force on the gripper pad. The safety factor for sliding in the guide pads is the inverse of the equation used to calculate the safety factor for slipping.

Design Analysis

Sensitivity Study

The FE model was utilized to conduct a sensitivity study on several design parameters. The parameters investigated in the study were:

- Length of support 1
- Length of support 2
- Length of support 3

- Length of support 4
- Young’s modulus of gripper pads
- Shear modulus of gripper pads
- Young’s modulus of guide pads
- Young’s modulus of all pads
- Preload pressure

The study started with a baseline design and then varied each parameter to investigate its effect on the performance of the structure. The outputs of the sensitivity study were the safety factors for each performance goal. Using the safety factors in the sensitivity study allowed the results to be plotted together and also enabled problem areas to be easily identified when safety factors were less than one. The sensitivity study was used in an iterative process to find an efficient design that satisfied all the performance goals of the support structure. In total, approximately a dozen iterations were done before arriving at the current baseline design. The final iteration design is discussed in the ‘Baseline Design’ section of the report. The complete results of the sensitivity study for the final iteration are shown in Appendix A.

Characteristics Comparison Study

A second study was done in order to identify the desired characteristics (pivoting, tilting, floating) of the grippers and guides. The methods used to incorporate the different pad characteristics into the FE code are discussed below:

- Pivoting – rotational stiffness of pad set to zero, horizontal pressure in pad made uniform.
- Tilting – rotational stiffness of pad set to zero, shear stress in pads made uniform
- Floating – horizontal stiffness of pad set to zero, normal force in pads made uniform

As with the sensitivity study, the characteristic comparison study used the performance goal safety factors to compare the various characteristics.

The major findings from the characteristic comparison study were:

- Pivoting in all pads is beneficial because it keeps the pressure in each pad uniform which lowers the maximum pressure on the pipe.
- Allowing gripper 2 to float is advantageous because it keeps the normal force in the pads uniform which helps to keep the pipe from slipping. Note that having gripper 2 float should also help reduce the cost of the structure because it eliminates the need for a lateral support system for the gripper.
- Allowing gripper 2 to tilt would also improve the gripping ability. However, this would be difficult and possibly expensive to implement. As such, tilting was not included in the baseline design.

Baseline Design

The dimensions of the baseline design are shown in Figure 18.

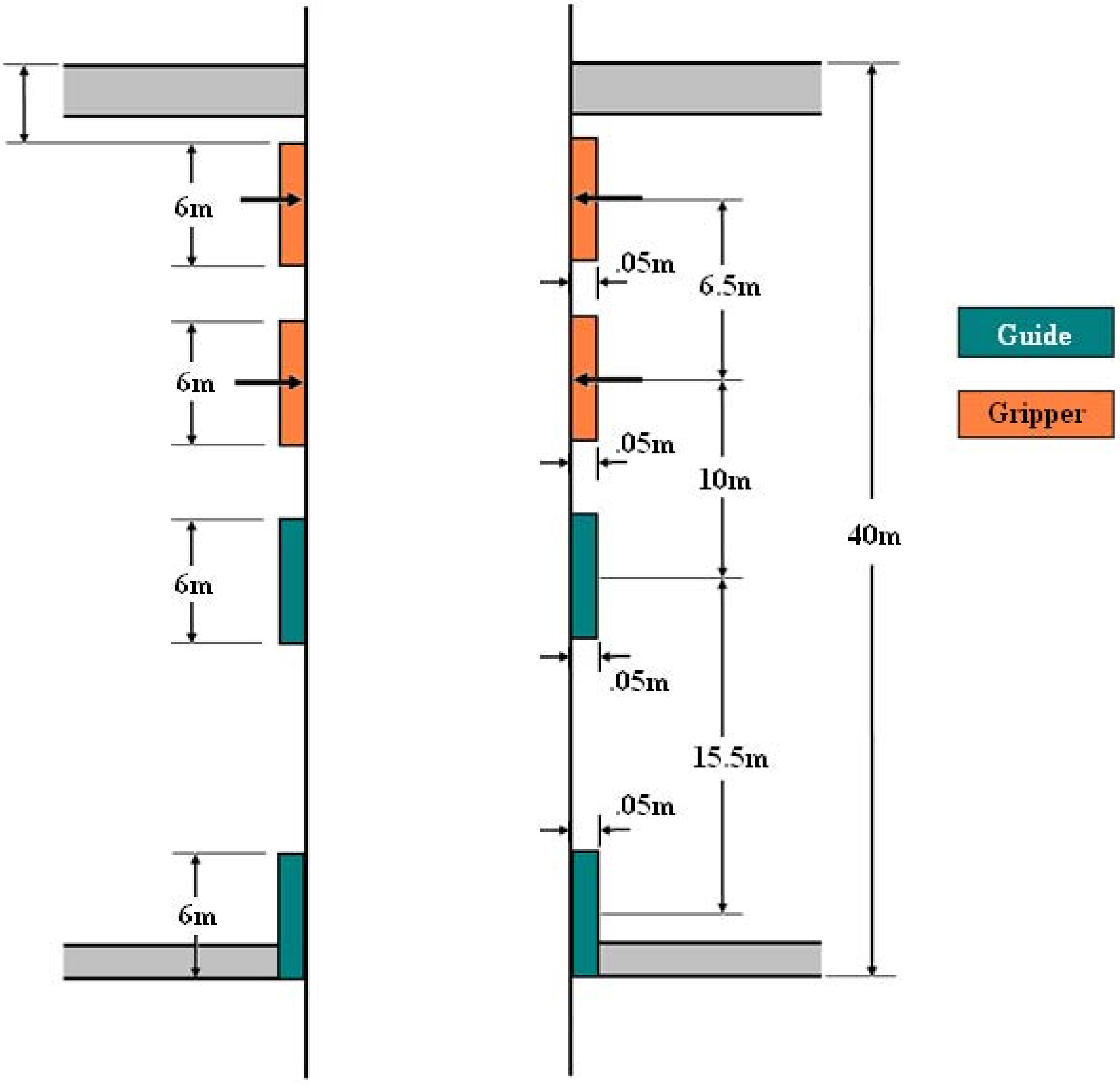


Figure 18 - Baseline Design

Other properties of the baseline design are shown below.

- Young’s modulus of all pads: 6 MPa*
- Shear modulus of all pads: 2 MPa*
- All pads can pivot
- Gripper 2 floats

* equivalent to rubber used in automobile tires.

The equivalent spring stiffnesses of used in the FE code are shown in Figure 19.

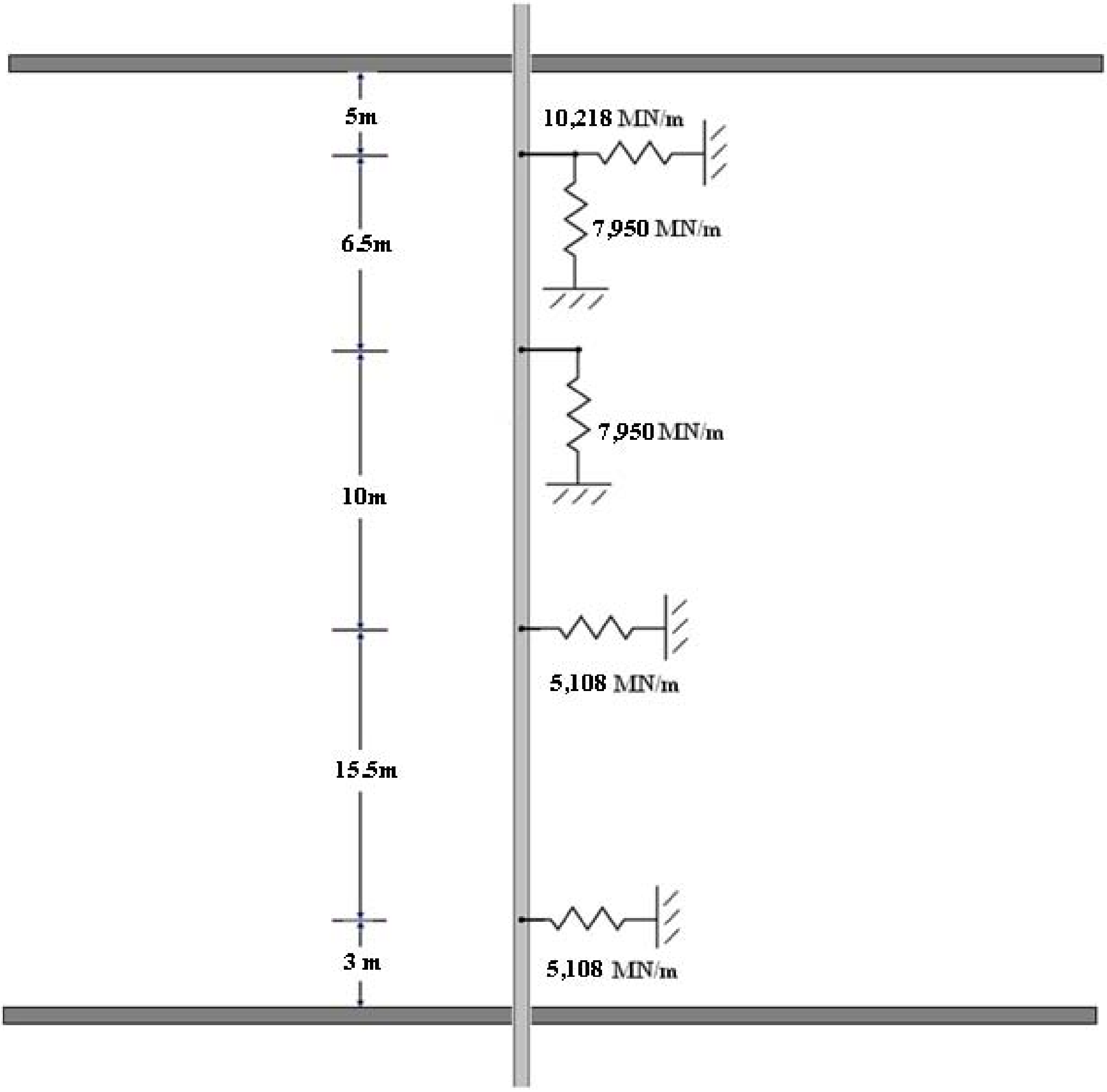


Figure 19 - Gripper and Guide Stiffnesses

Rationale for Baseline Design

Gripper Lengths

The lengths of the grippers are dictated by the need to hold the weight of the CWP. Assuming a clamping pressure of 50 psi and a COF of 0.25, the minimum length needed to hold the weight is 5.5m. The additional 0.5m of gripper length is added to ensure the pipe does not slip when current loads are applied.

Guide Lengths

The lengths of the guides are a function of the reaction forces in the guides and the maximum pressure applied to the pipe. The lateral loads on the guides are large in order to counteract the moment caused by the current on the pipe. Thus, the guides must be long enough to distribute the force over a large area in order to keep the pressure on the CWP under the allowable limit. 6m guides are the minimum length needed to keep the pressure on the pipe below the allowable limit of 75 psi.

Gripper/Guide Order

Having the guides in the two lowest positions allows the guides to counteract the majority of the current loads (see Figure 20). When the grippers do not need to provide as much lateral support the normal forces in the grippers are more uniform improving the gripping ability. Additionally, by placing the grippers closer to the deck they are not submerged in the water. This will make any maintenance that must be done on the grippers much easier.

Distance between Supports

The distance between the supports is driven by the need to separate the guides as much as possible. Having a large distance between the guides is beneficial because it increases the length of the moment arm used to counteract the moment caused by the current. The longer moment arm reduces the reaction forces on the guides allowing for shorter guide pads.

The distance between gripper 2 and the upper guide determines how many lowering cycles must be done in order to lower each 11m segment of CWP. The current baseline design has 4m of space between the gripper and guide, meaning each segment can be lowered in three cycles. A larger spacing could be beneficial and reduce the number of cycles needed, however this would also reduce the spacing between the guides, which, as discussed above, would cause the reaction forces in the guides to become larger.

Results of Baseline Design

Output plots for the baseline design are shown for the following loading scenarios:

- Maximum current loads - both grippers engaged (Figure 20)
- Maximum current loads - gripper 1 disengaged (Figure 21)
- Mean current loads - both grippers engaged (Figure 22)
- Mean current loads – gripper 1 disengaged (Figure 23)

The values for the displacement and rotations for each scenario are shown in Table 2.

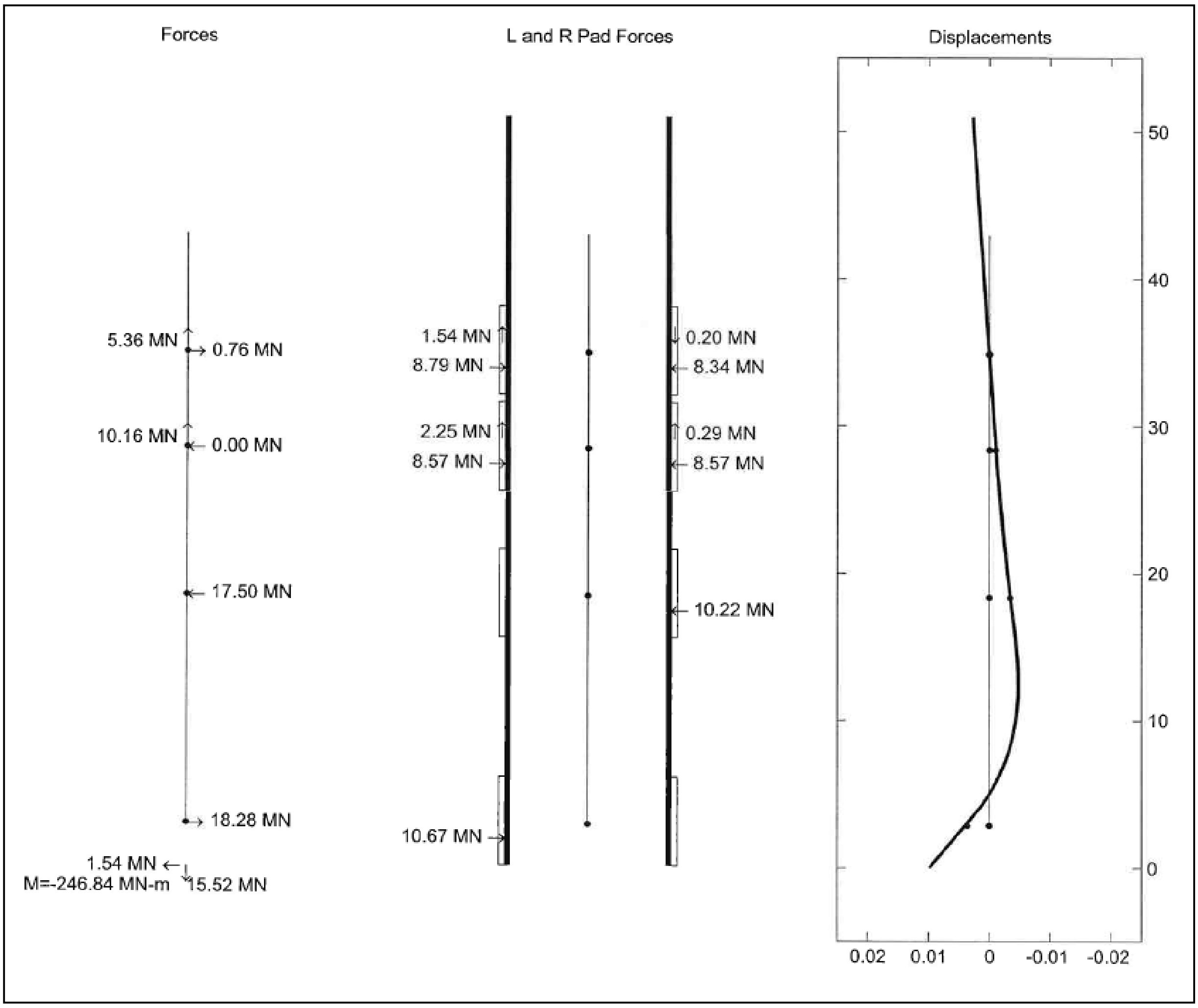


Figure 20 - Maximum Current Load -Both Grippers Engaged

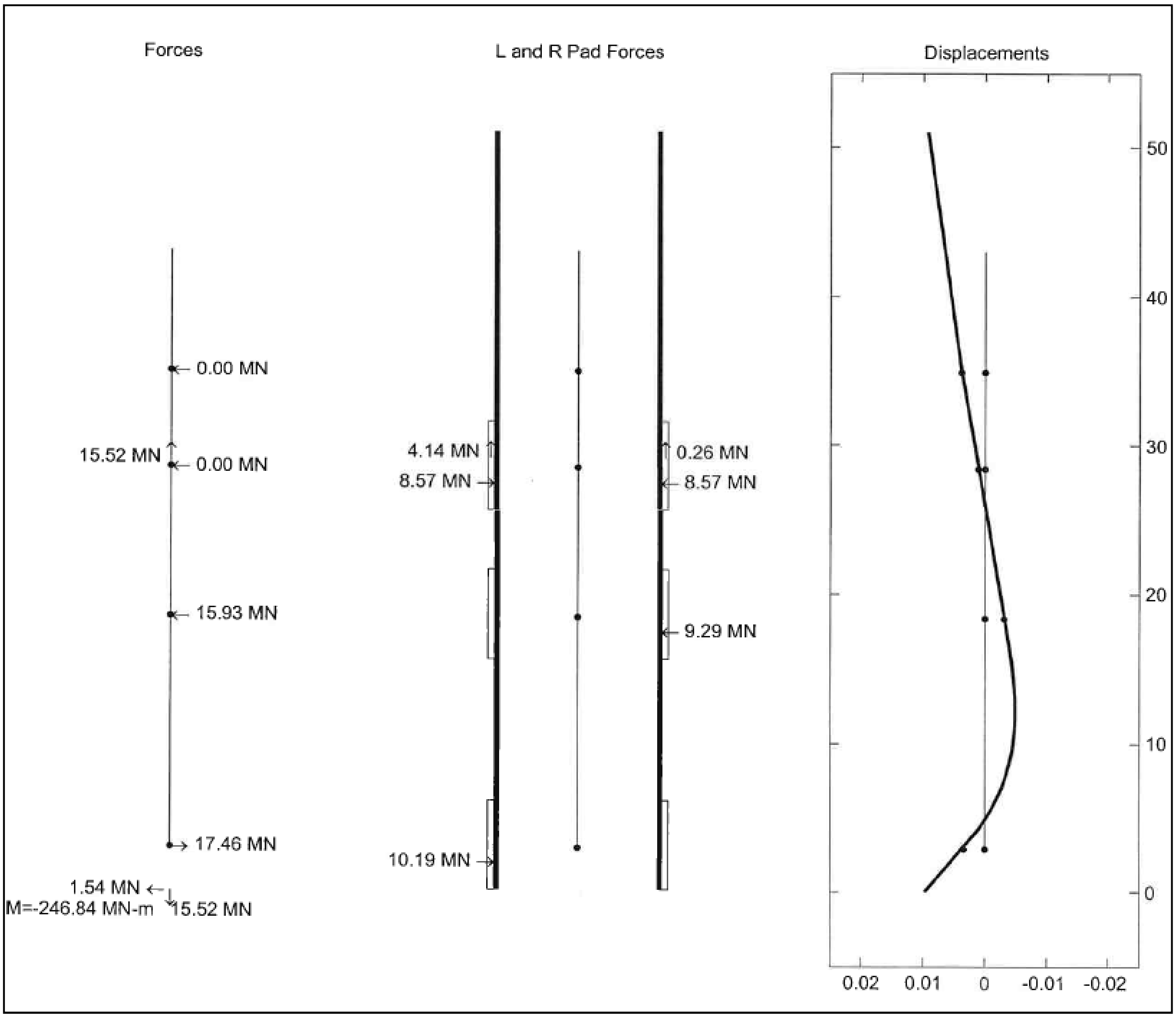


Figure 21 - Maximum Current Load - Gripper 1 Disengaged

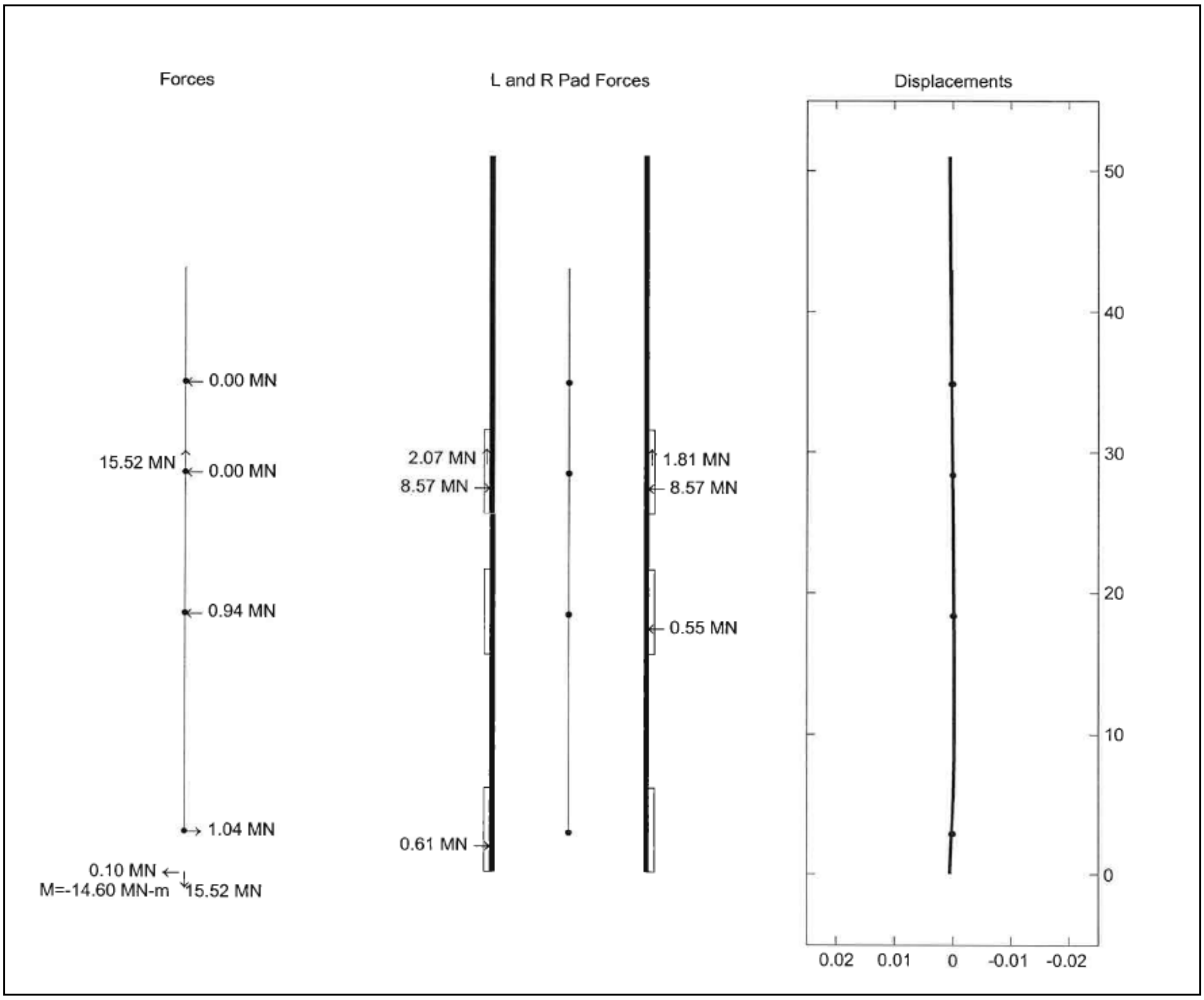


Figure 22 - Mean Current Load - Gripper 1 Disengaged

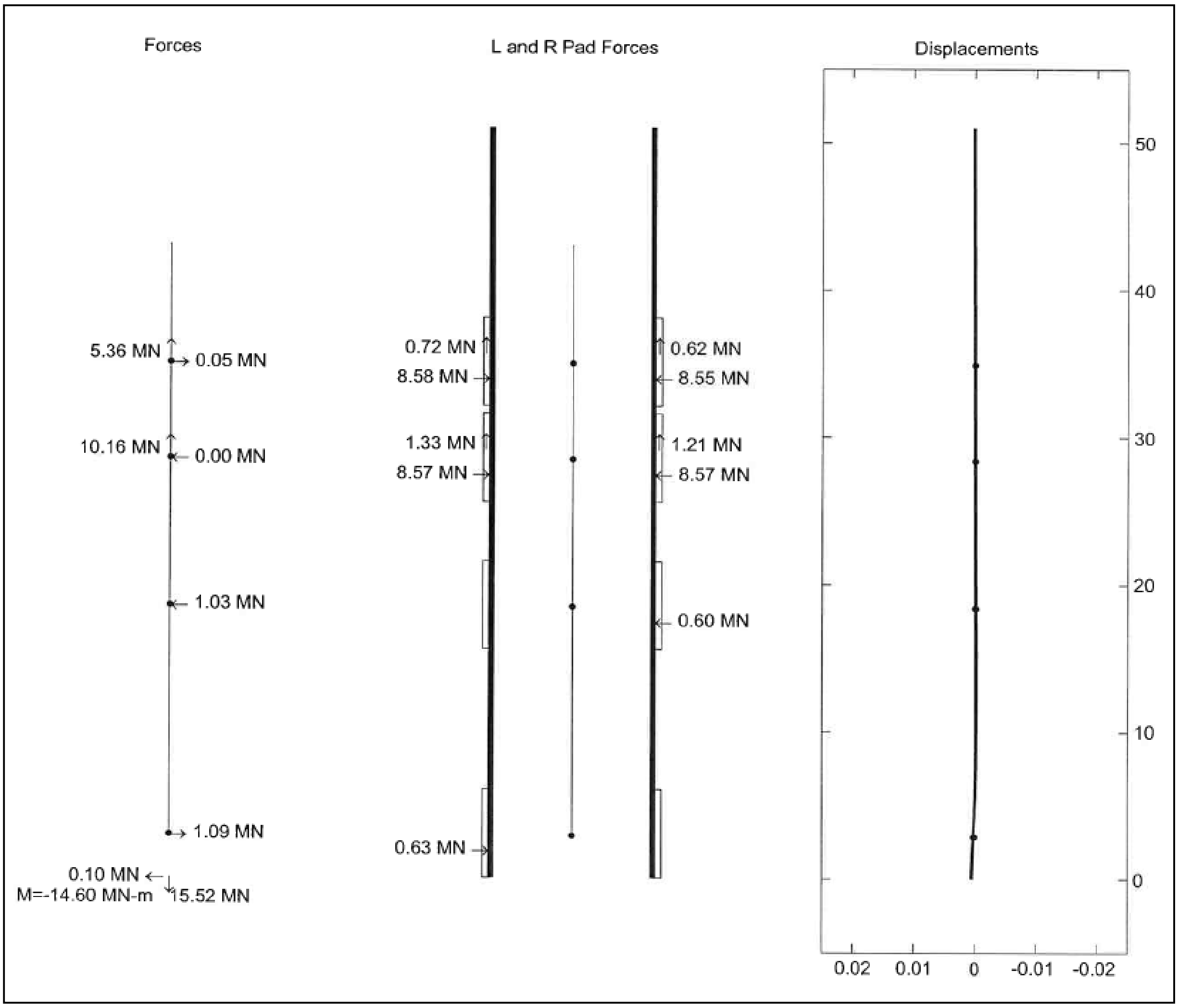


Figure 23 - Mean Current Load - Both Grippers Engaged

Table 2 – Baseline Results

		Horizontal Displacement		Axial Displacement (mm)	Rotation (degrees)
		Top of Fab (mm)	Deck Level (mm)		
Mean Current Load	Gripper 1 - Engaged Gripper 2 -Engaged	0.02	0.05	0.67	0.0006
	Gripper 1 - Disengaged Gripper 2 -Engaged	0.55	0.27	1.95	0.0014
Maximum Current Load	Gripper 1 - Engaged Gripper 2 -Engaged	2.73	0.91	0.67	0.0095
	Gripper 1 - Disengaged Gripper 2 -Engaged	9.27	4.65	1.95	0.024

Platform Stiffness

One major limitation in the FE code is the assumption that the platform structure is perfectly rigid. Clearly, the platform structure must be somewhat elastic and the magnitude of this elasticity could have a large effect on the movement of the CWP. A few basic calculations were carried out in order to get an idea of how the of the elasticity of the platform compares to that of the rubber pads.

First, the dimensions and properties of the pads (from the baseline design) were used to find the deflection of the pad subjected to a 25 psi pressure. 25 psi was chosen because it is the maximum amount the pressure on the CWP can increase if there is a 50 psi preload and the allowable pressure on the pipe is 75 psi, as is assumed in the baseline design. Consequently, a 25 psi increase in pressure produces the largest deflection that can occur in the rubber pad.

To approximate the deflections of the steel platform structure, an average stress and length scale were estimated for the platform at each support location. This allowed an estimated deflection to be calculated for the steel platform. The estimated values are shown in Table 3 along with the calculated deflections. Note that the location of support 3 is not included in the calculations because it is assumed to float and therefore has no platform support.

Table 3 – Estimated Deflections of Steel Structure

	Support 1	Support 2	Support 4
Estimated average stress on steel structure (psi)	5000	20000	5000
Estimated length scale (m)	5	20	5
Deflection of steel structure (mm)	0.86	13.79	0.86
Deflection of rubber pads under 25 psi (mm)	1.46	1.46	1.46

The estimations showed that the displacement of the steel structure at supports 1 and 4 were roughly the same magnitude as the deflection of the rubber pad, while the deflection at support 2 was nearly 10 times that of the rubber pad. Clearly these estimates indicate that the platform elasticity will have an effect on the movement of the CWP.

Results of Baseline Design Including Platform Stiffness Estimates

The platform stiffness estimates were incorporated in to the FE code to get an understanding of how an elastic platform structure will effect the movement of the CWP. The easiest way to include the platform elasticity into the code was to reduce the stiffness of the supports. As such, the stiffness of each support was reduced by a specific amount based on the estimates from Table 3. The adjustments to the support stiffnesses are shown in Figure 24.

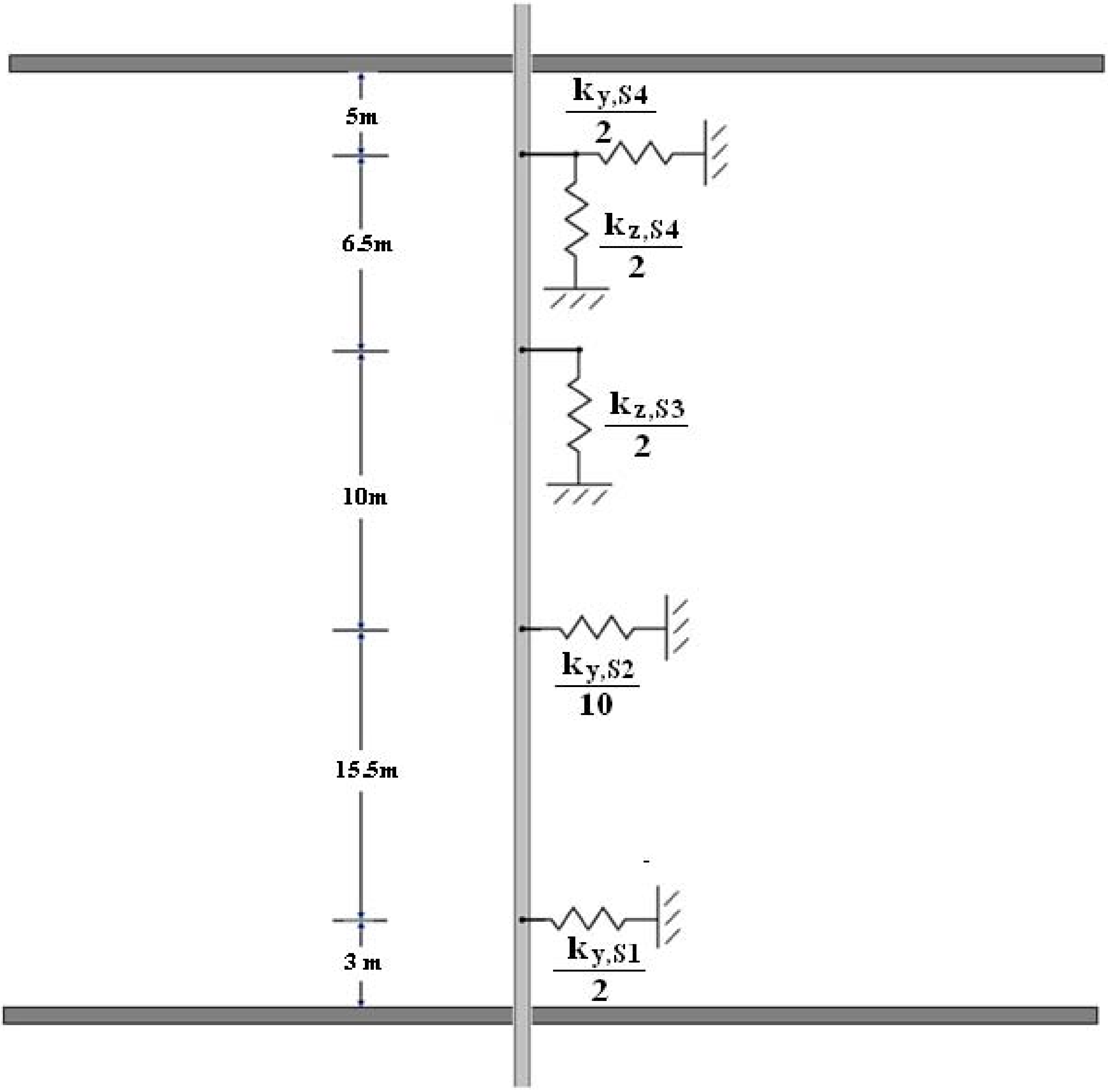


Figure 24 - Adjustments to Support Stiffnesses to Account for Platform Elasticity

The results from the FE code are shown in Figures 24-27 and Table 4. The results indicate that including the elasticity of the platform has a dramatic impact on the performance of the gripper. The horizontal displacements are nearly an order of magnitude larger when the elasticity of the platform is considered. However, it should be reiterated that these results are very rough estimates of the elasticity of the platform and a much more detailed analysis must be performed in the future.

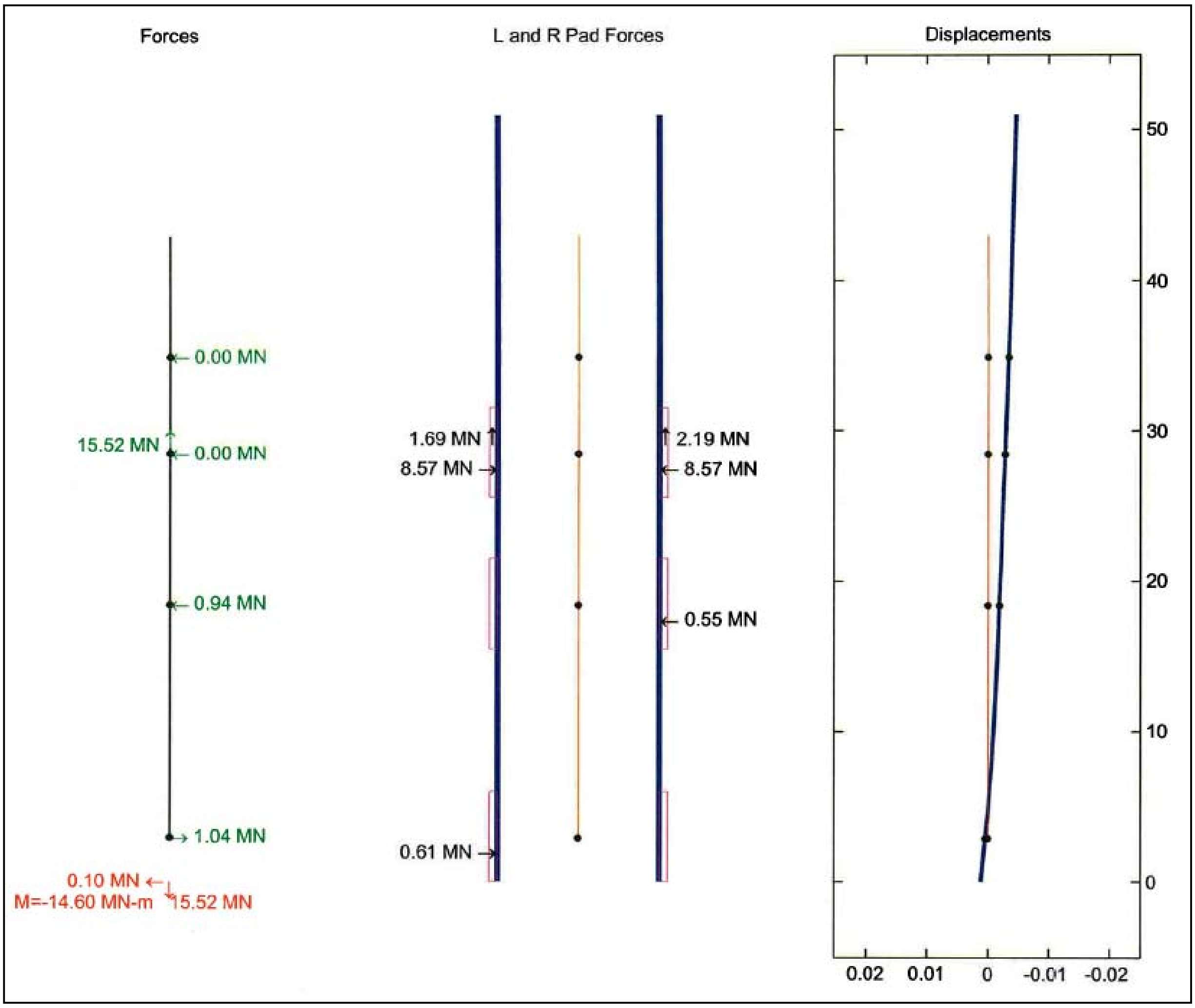


Figure 25 – Mean Current Loads with Elastic Platform - Gripper 1 Disengaged

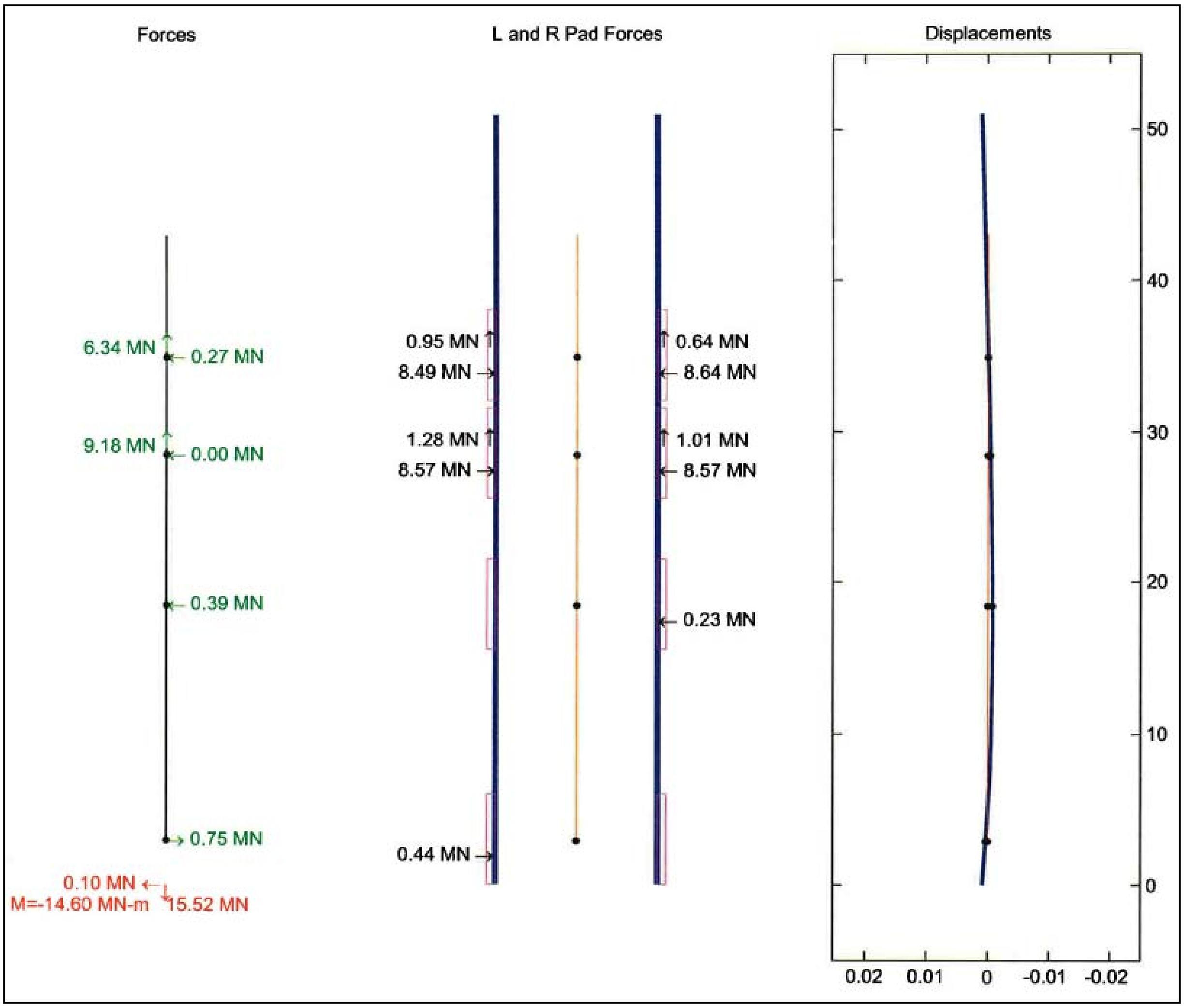


Figure 26 – Mean Current Loads with Elastic Platform – Both Grippers Engaged

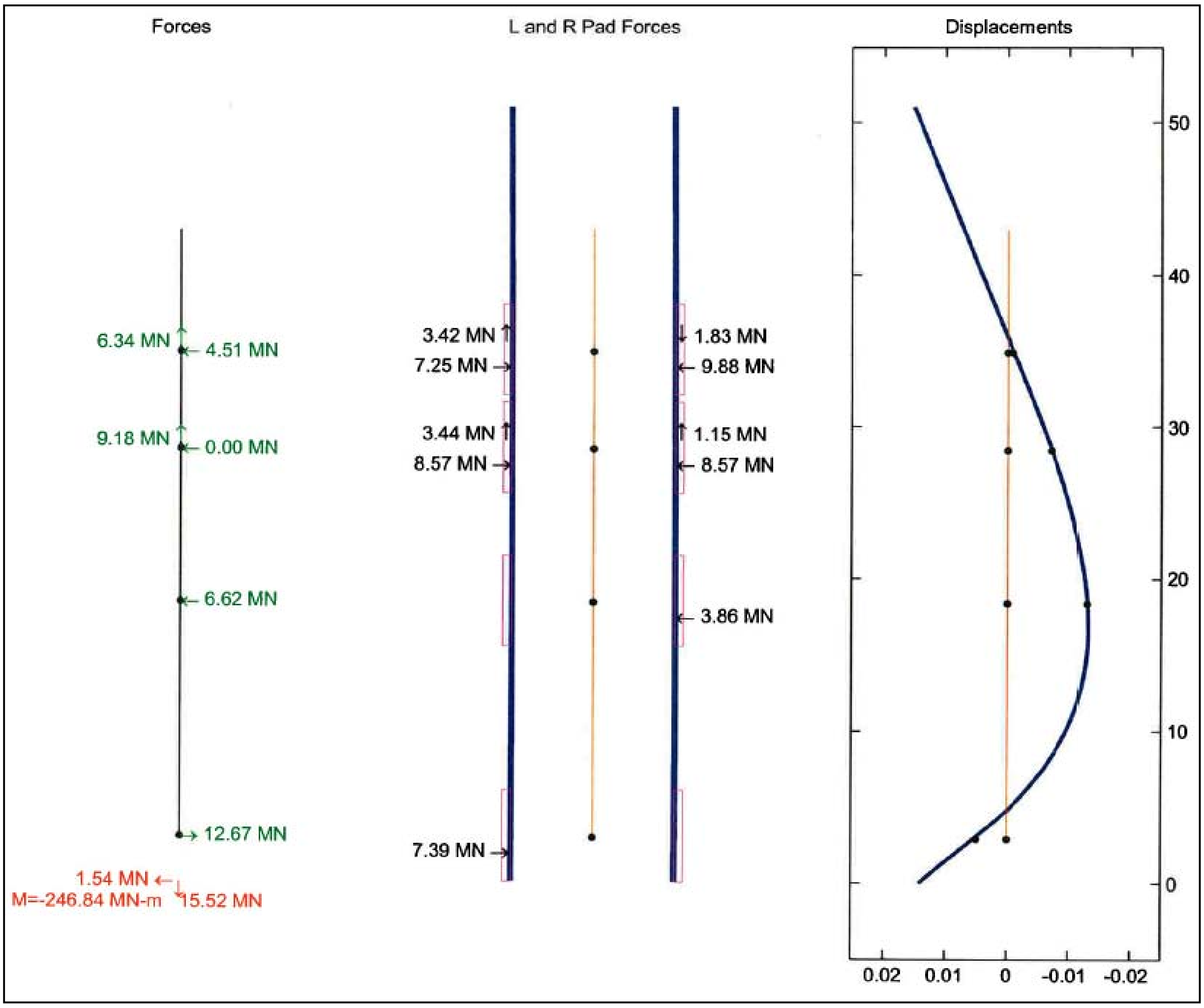


Figure 27 - Maximum Current Loads with Elastic Platform – Both Grippers Engaged

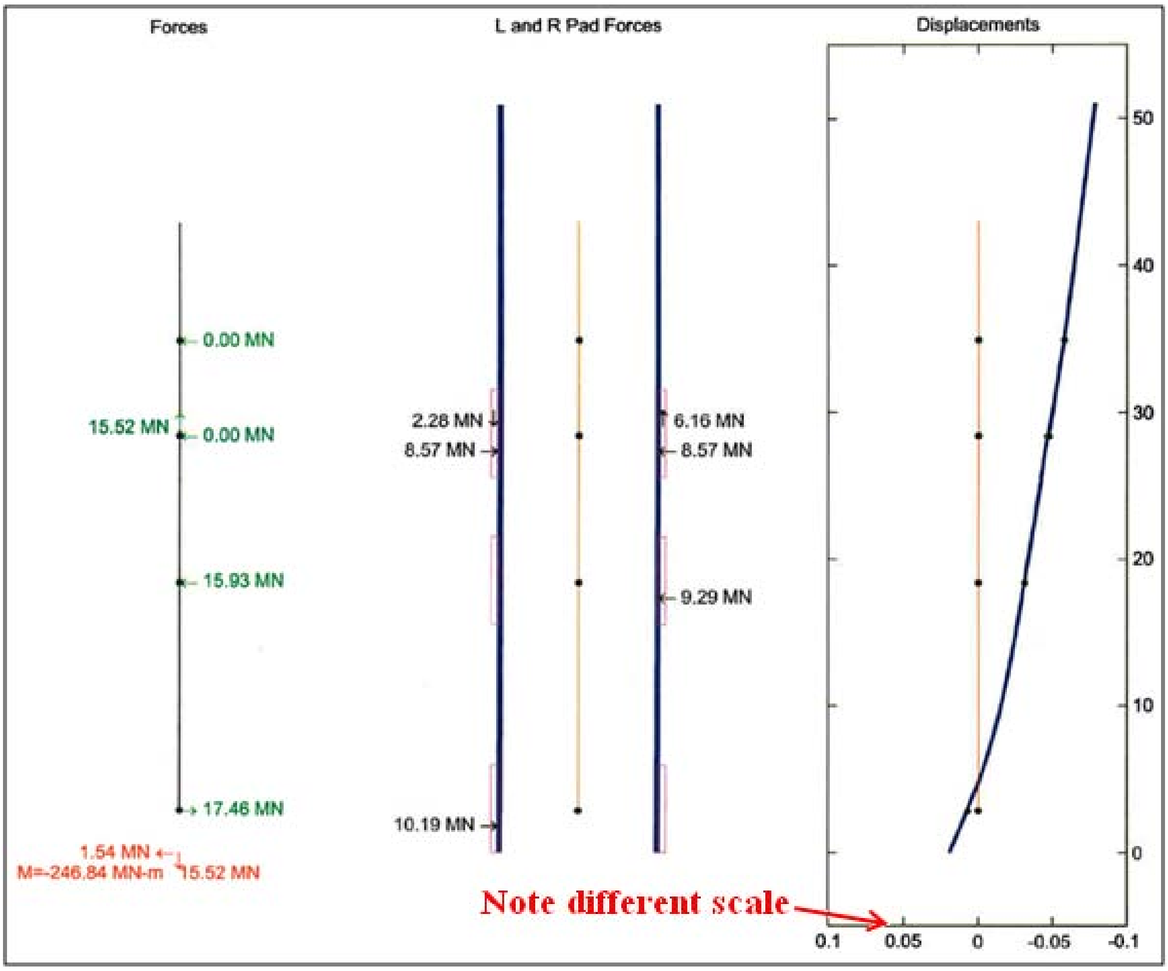
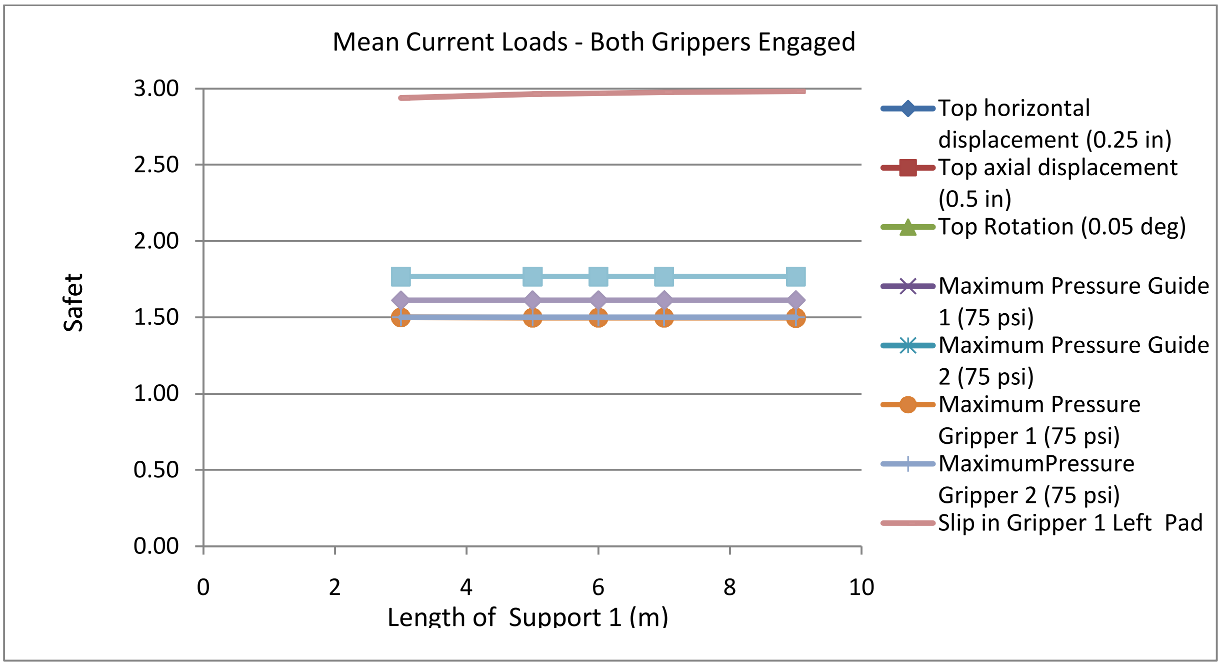


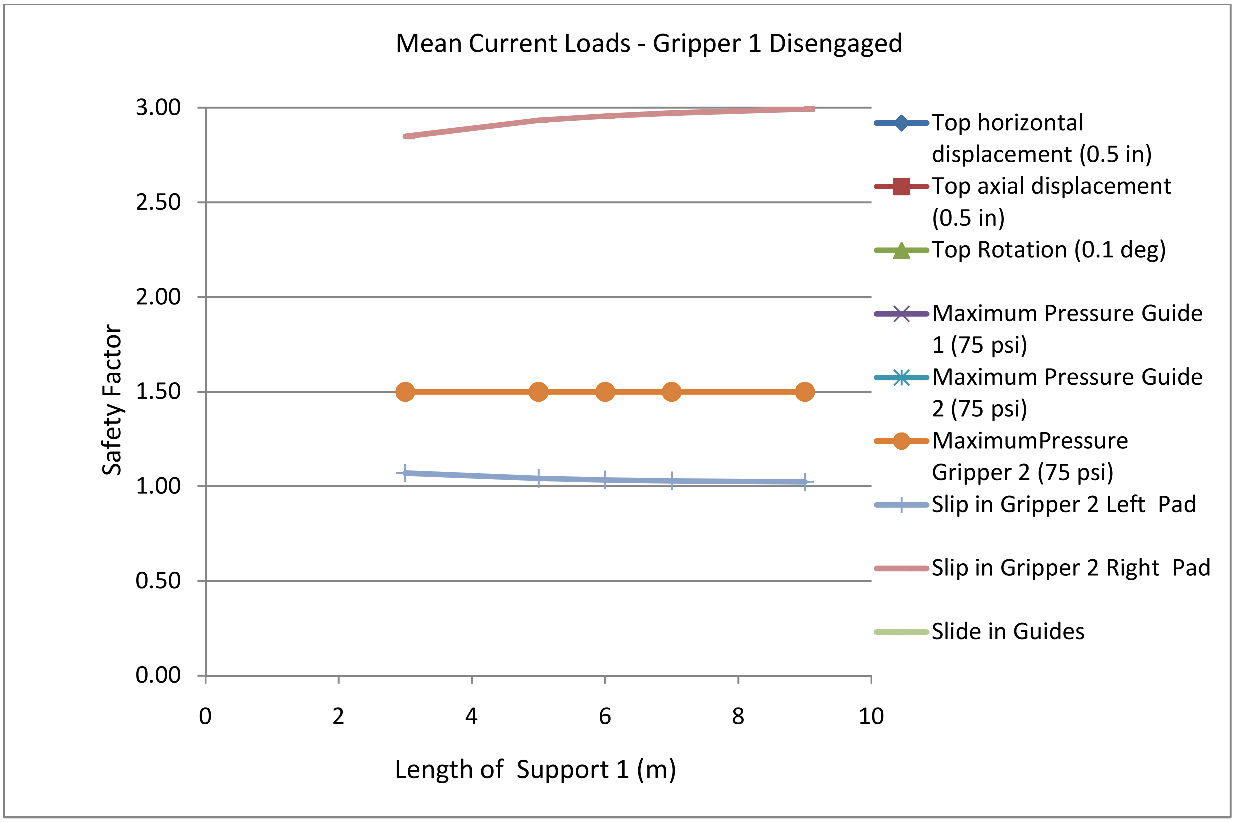
Figure 28 - Maximum Current Loads with Elastic Platform - Gripper 1 Disengaged

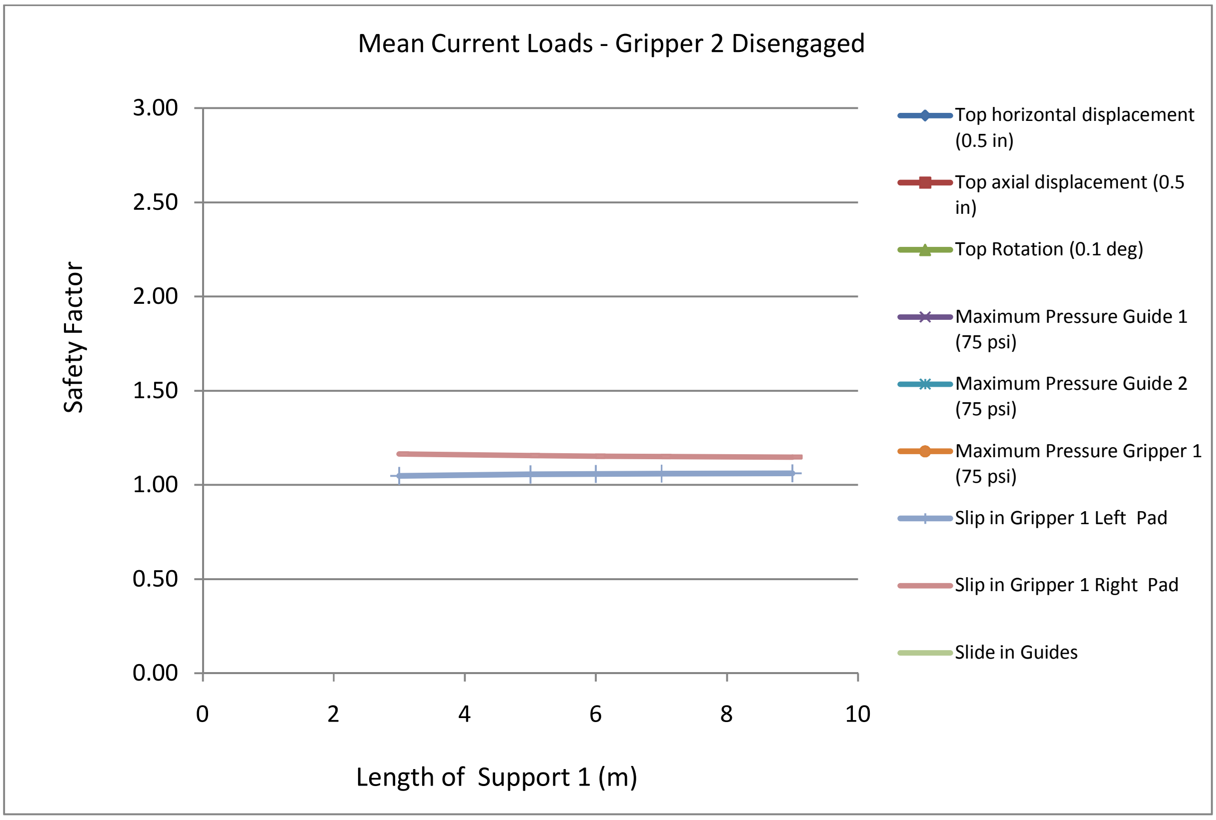
Table 4 - Baseline Results with Elastic Platform

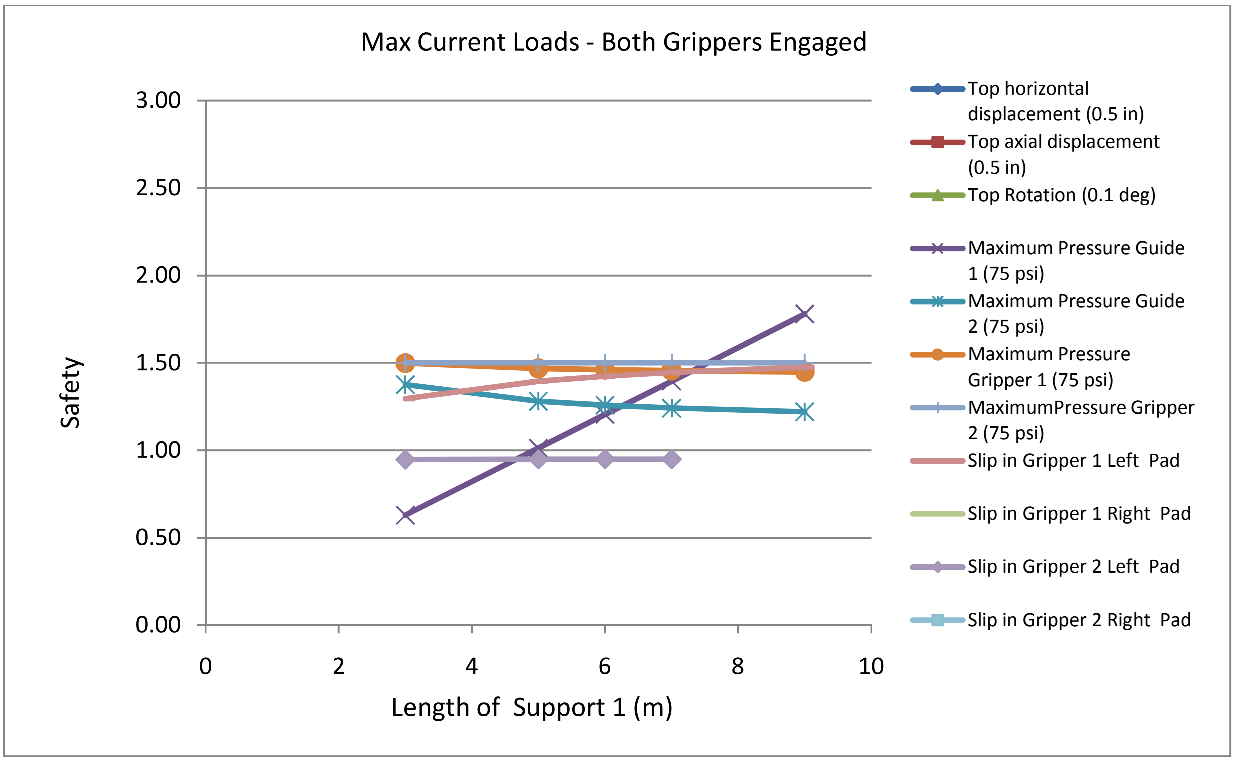
		Horizontal Displacement		Axial Displacement (mm)	Rotation (degrees)
		Top of Fab (mm)	Deck Level (mm)		
Mean Current Load	Gripper 1 - Engaged Gripper 2 -Engaged	0.90	0.24	1.60	0.0034
	Gripper 1 - Disengaged Gripper 2 -Engaged	4.66	3.61	3.91	0.0055
Maximum Current Load	Gripper 1 - Engaged Gripper 2 -Engaged	15.15	4.13	1.60	0.0574
	Gripper 1 - Disengaged Gripper 2 -Engaged	78.68	60.97	3.91	0.0923

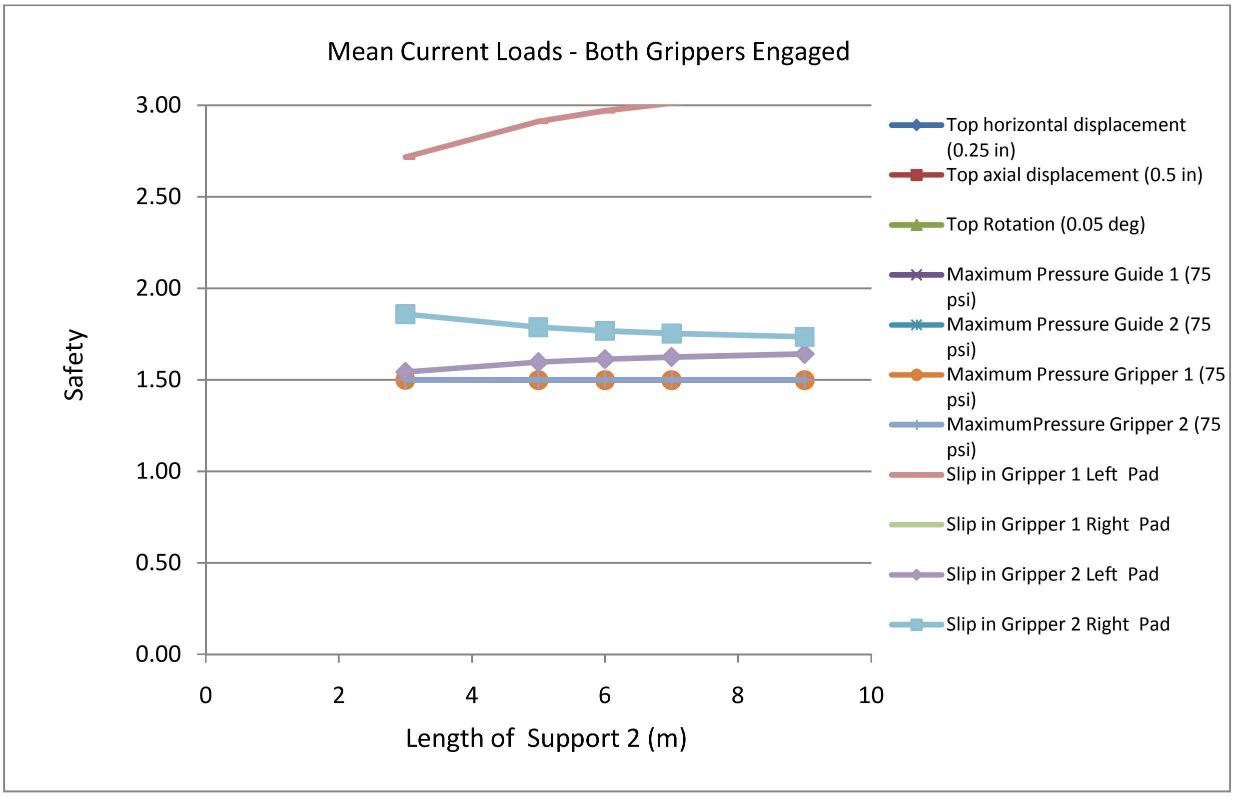
Appendix A – Sensitivity Study Results

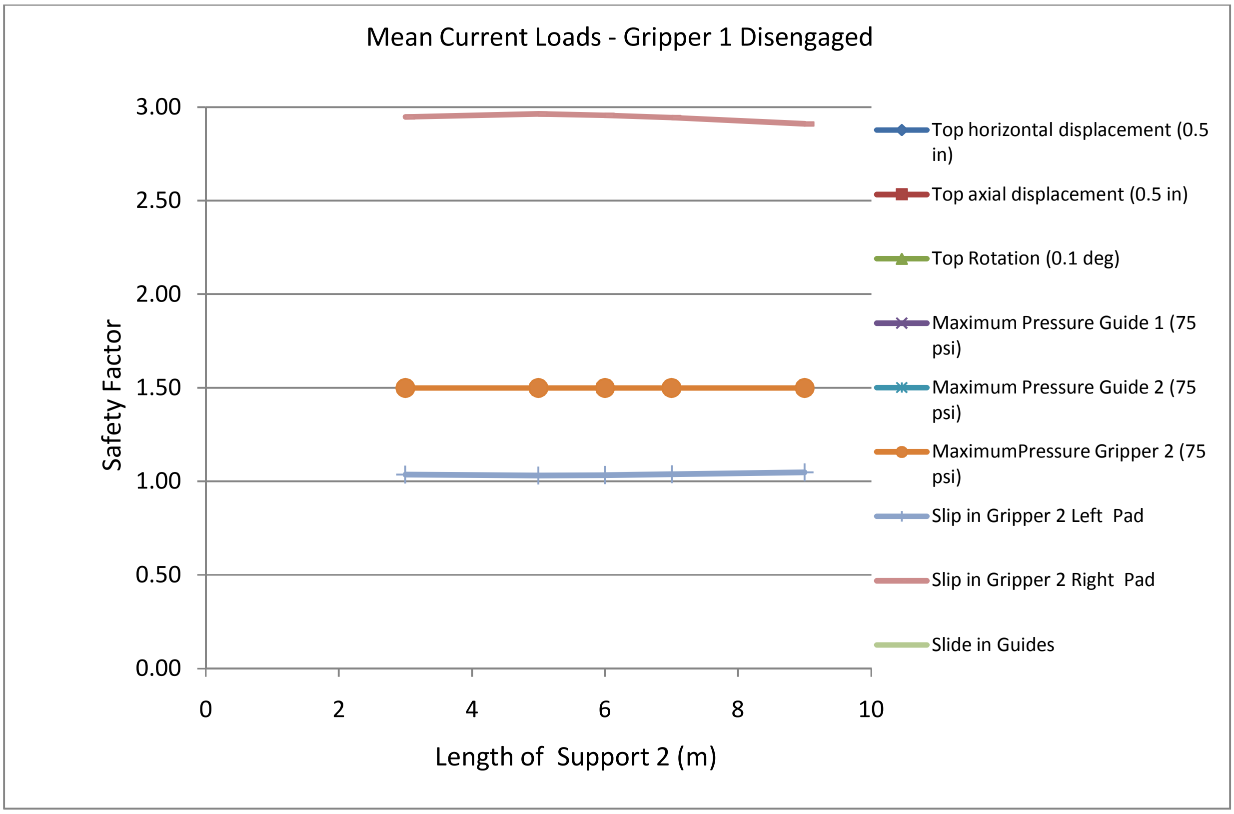


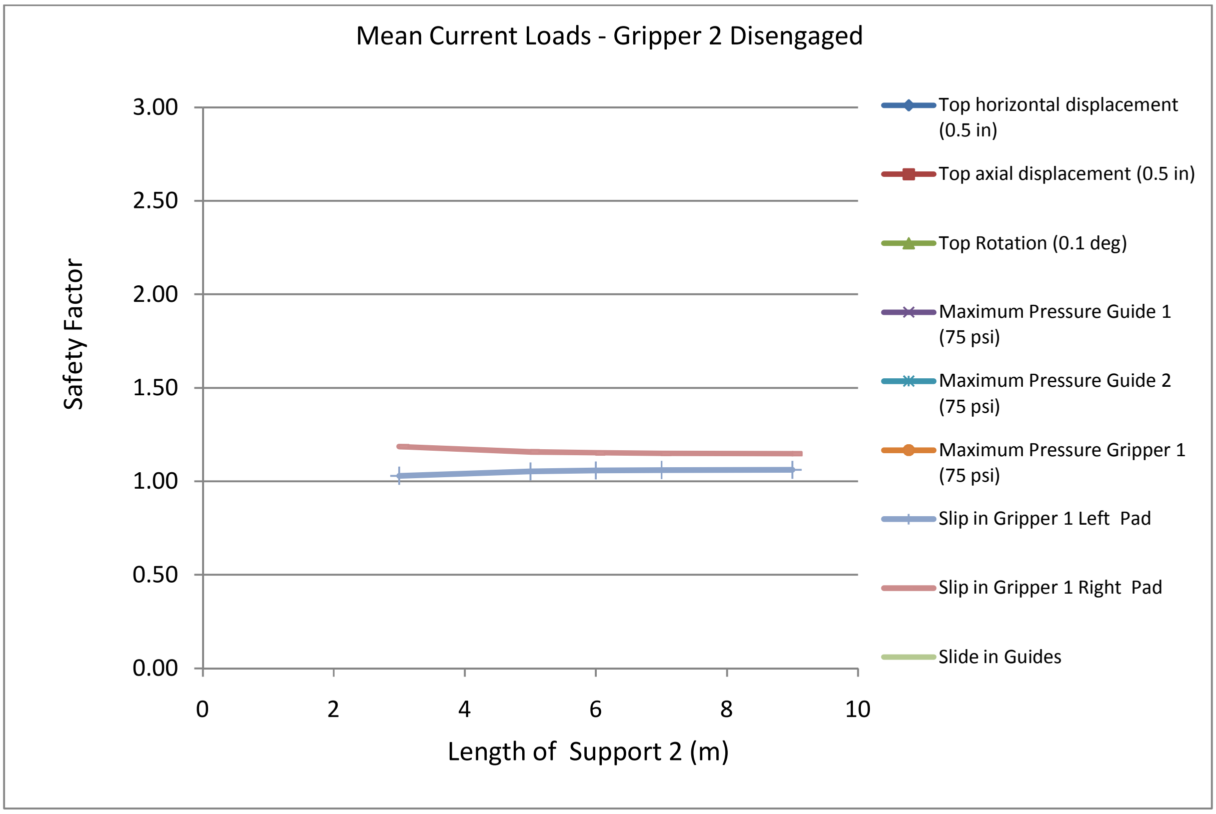


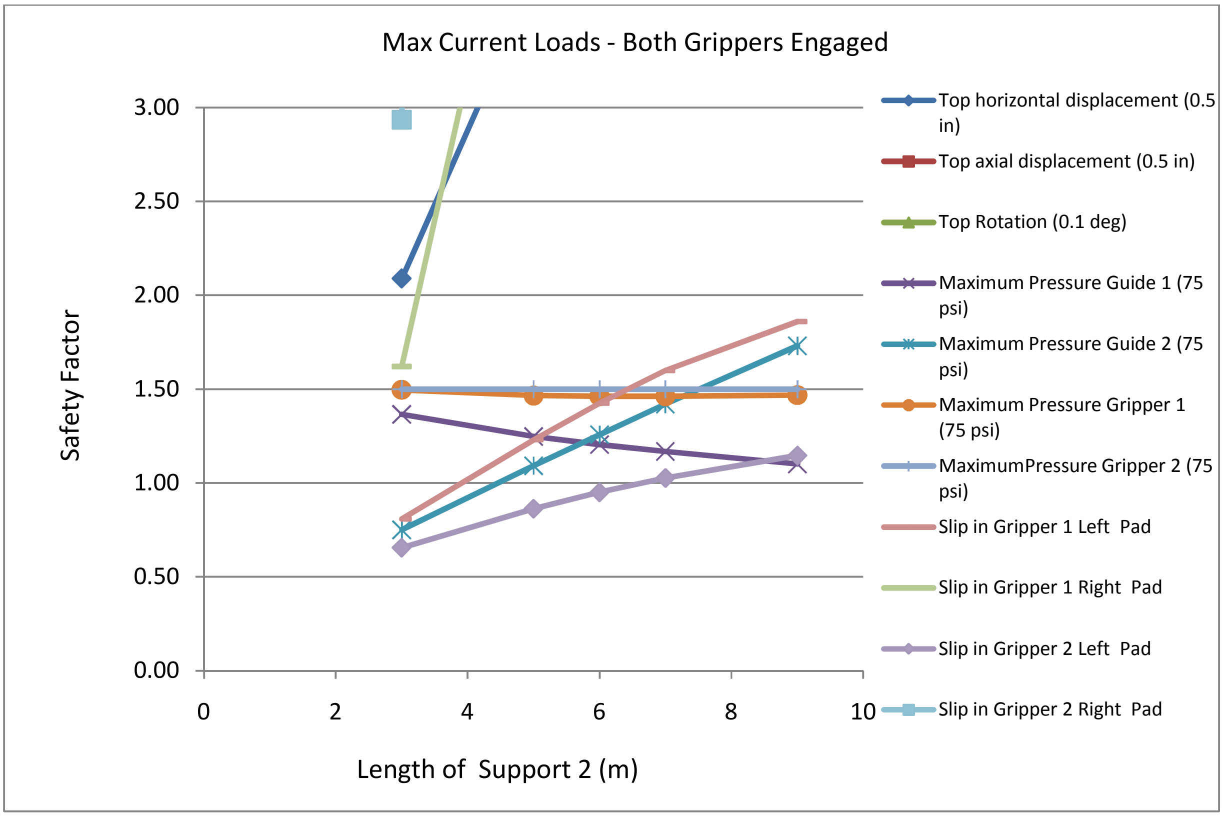

Mean Current Loads - Gripper 2 Disengaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 1 (m)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slide in Guides

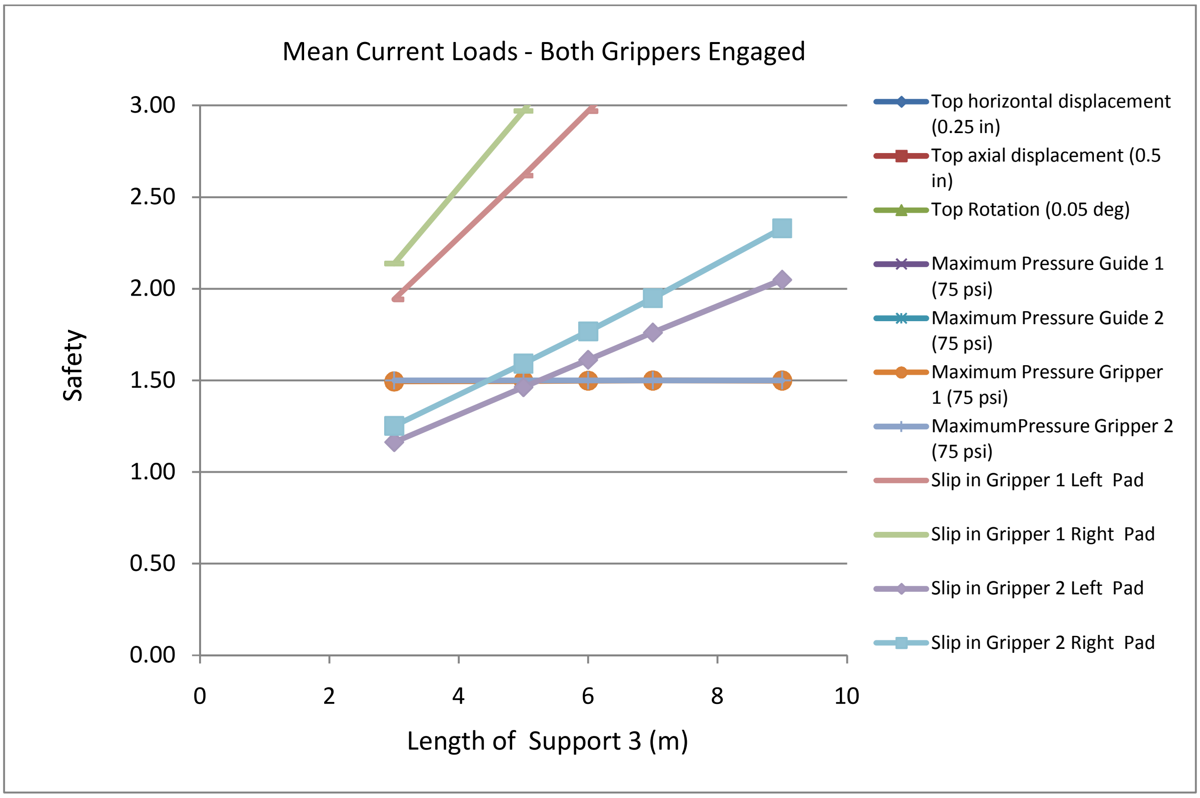

Max Current Loads - Both Grippers Engaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 1 (m)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

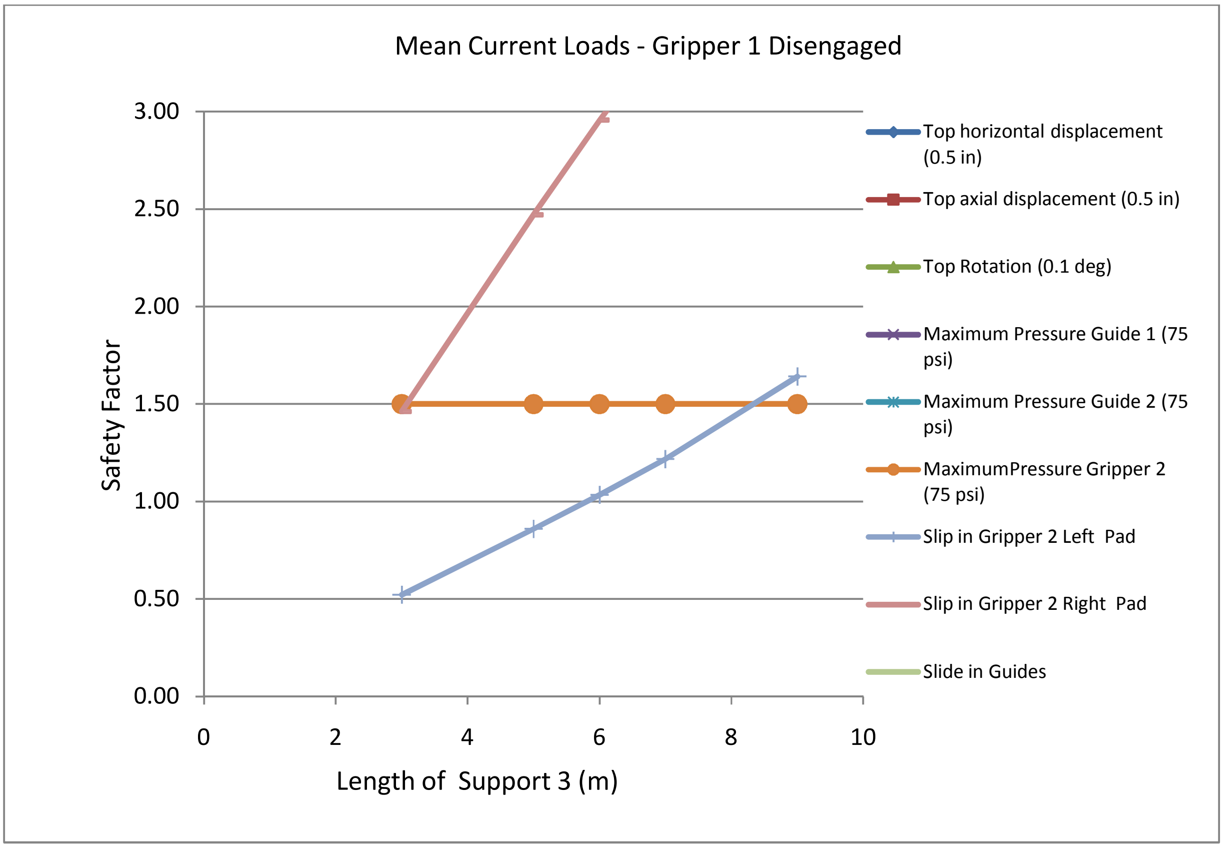

Mean Current Loads - Both Grippers Engaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 2 (m)
Top horizontal displacement (0.25 in)
Top axial displacement (0.5 in)
Top Rotation (0.05 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

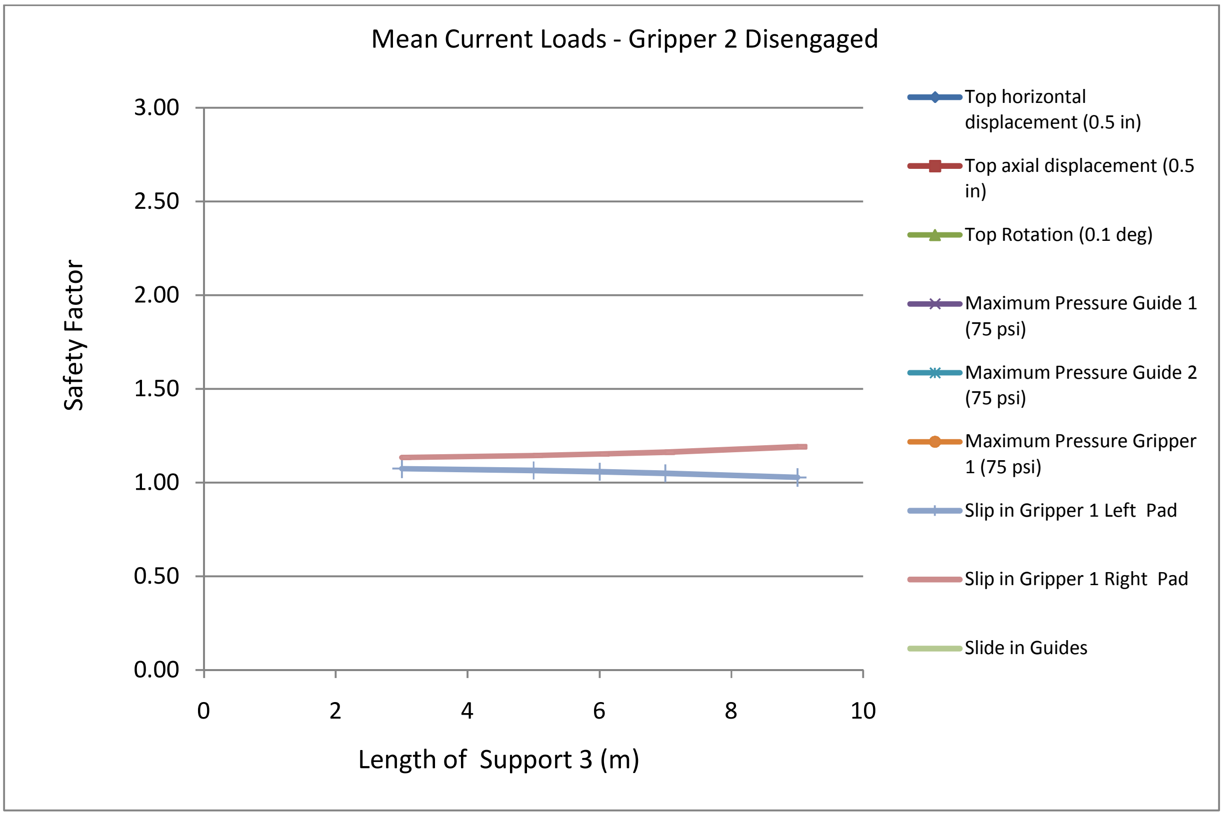

Mean Current Loads - Gripper 1 Disengaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 2 (m)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad
Slide in Guides

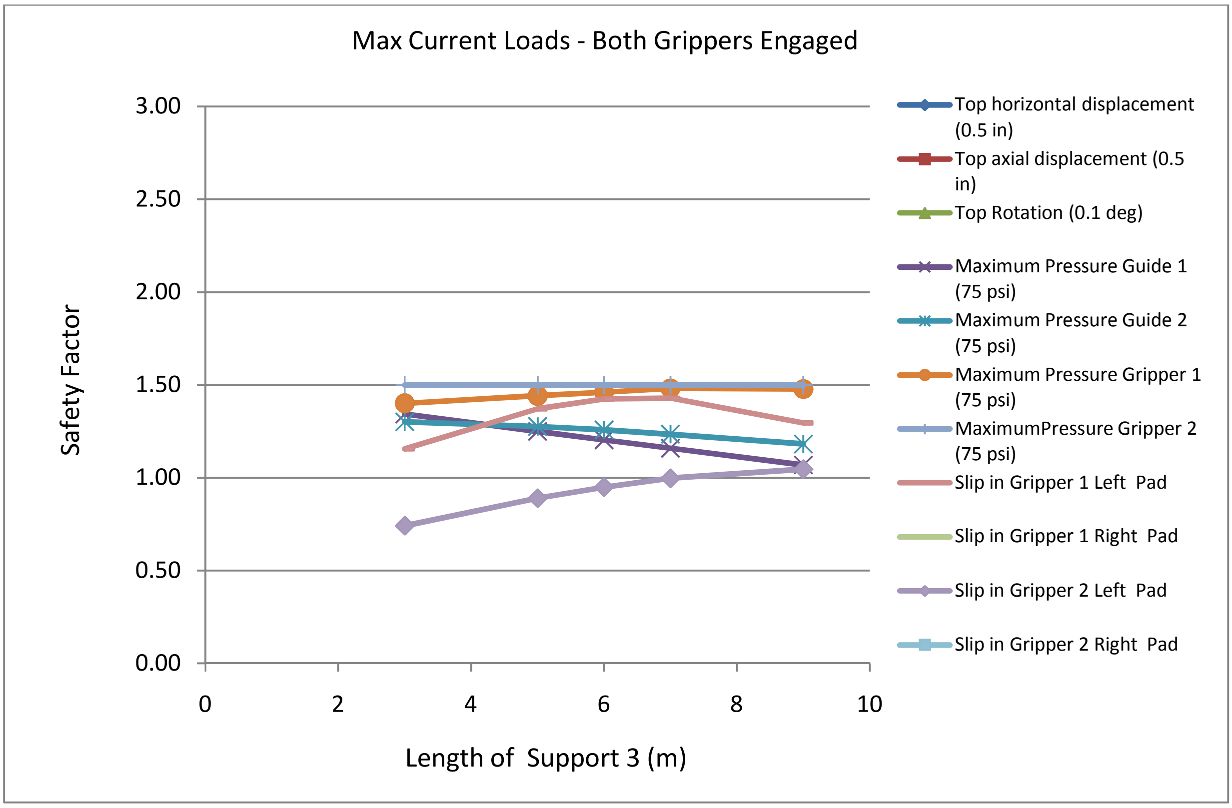

Mean Current Loads - Gripper 2 Disengaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 2 (m)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slide in Guides

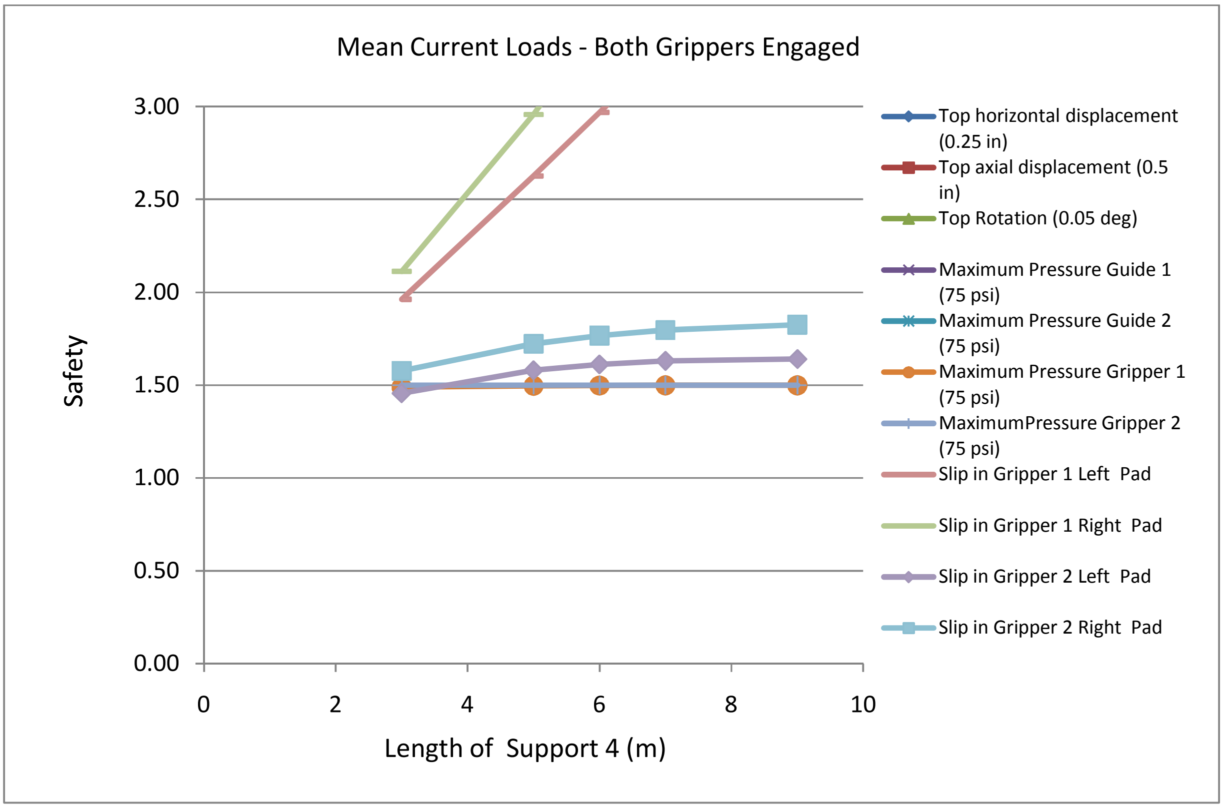

Max Current Loads - Both Grippers Engaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 2 (m)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

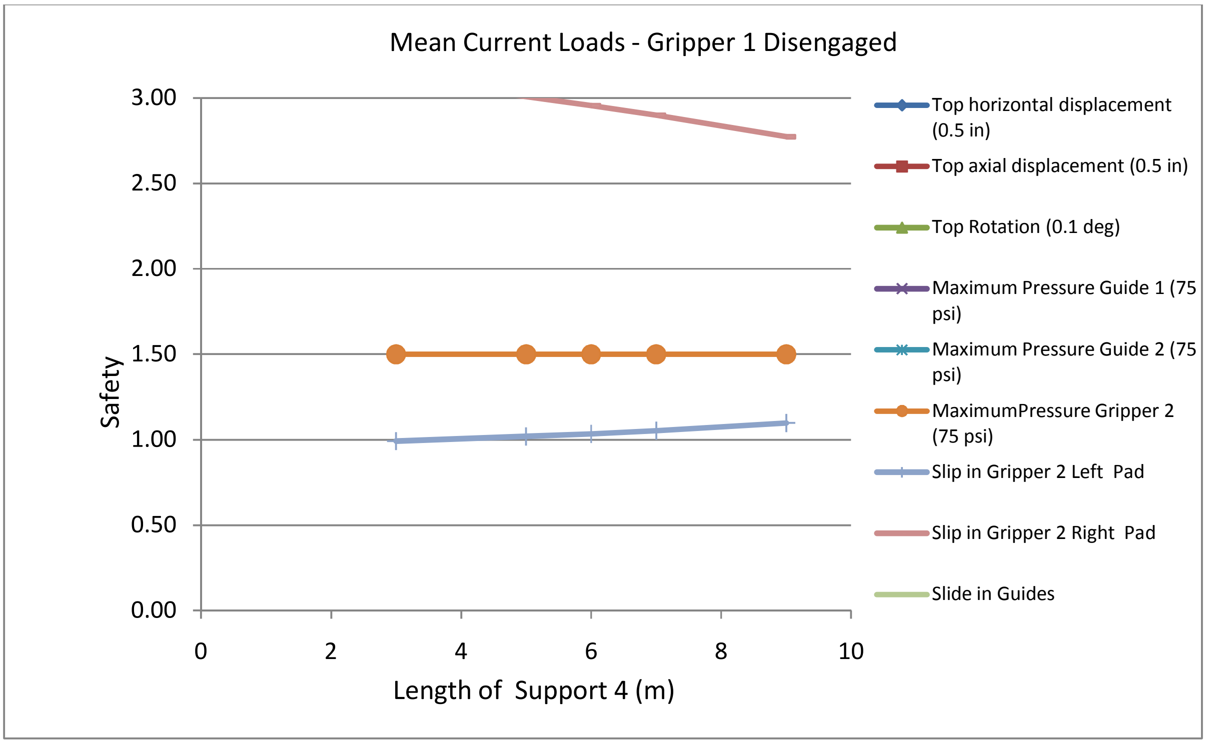

Mean Current Loads - Both Grippers Engaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 3 (m)
Top horizontal displacement (0.25 in)
Top axial displacement (0.5 in)
Top Rotation (0.05 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

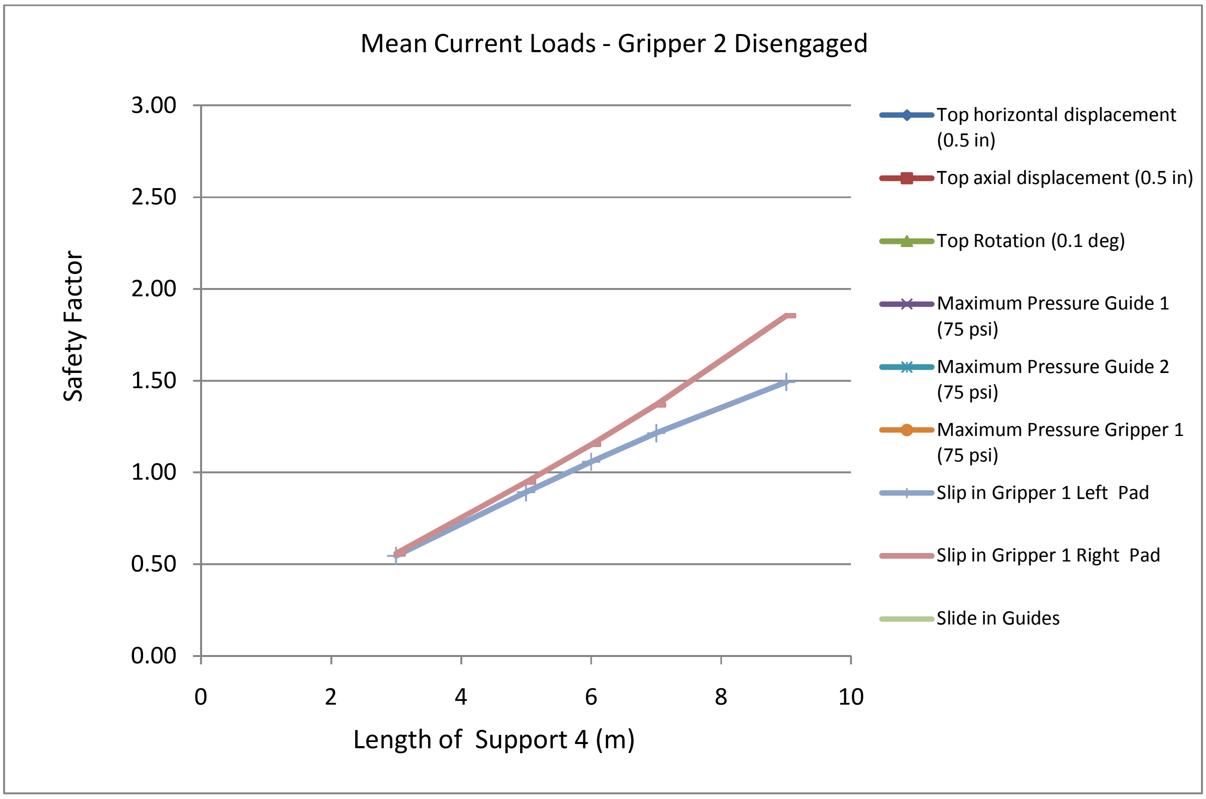

Mean Current Loads - Gripper 1 Disengaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 3 (m)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad
Slide in Guides

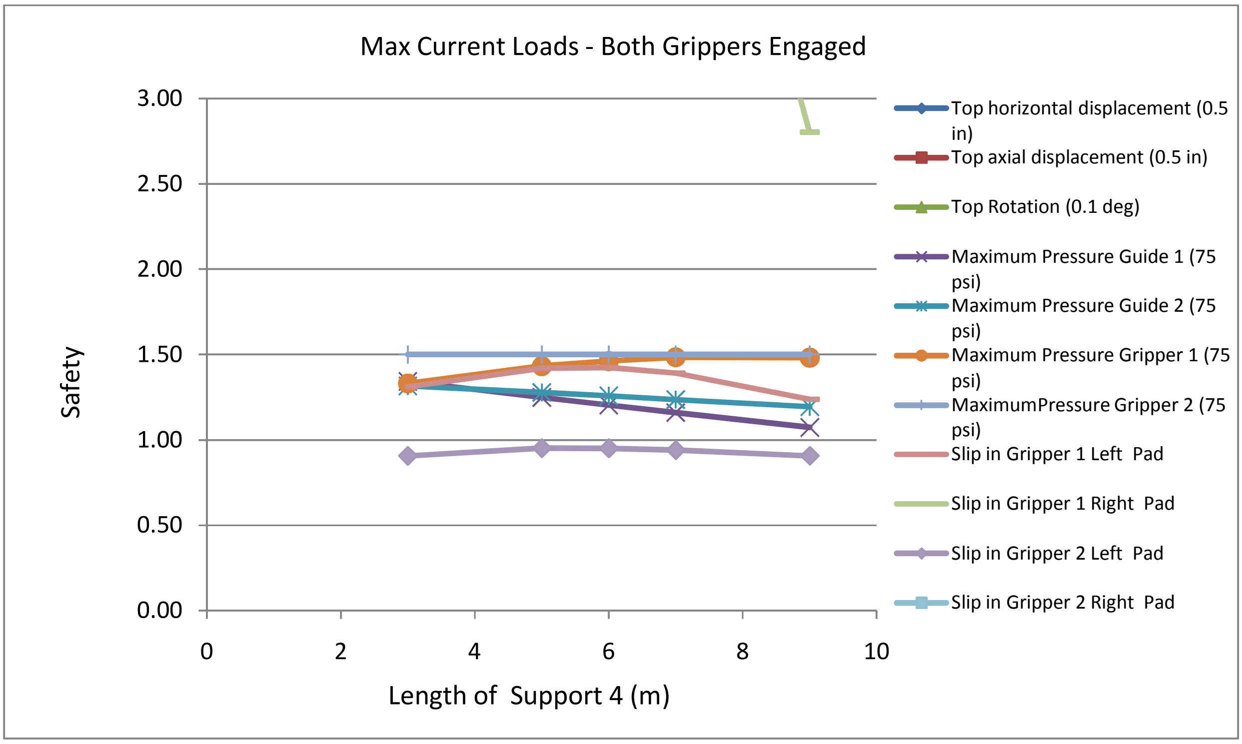

Mean Current Loads - Gripper 2 Disengaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 3 (m)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slide in Guides

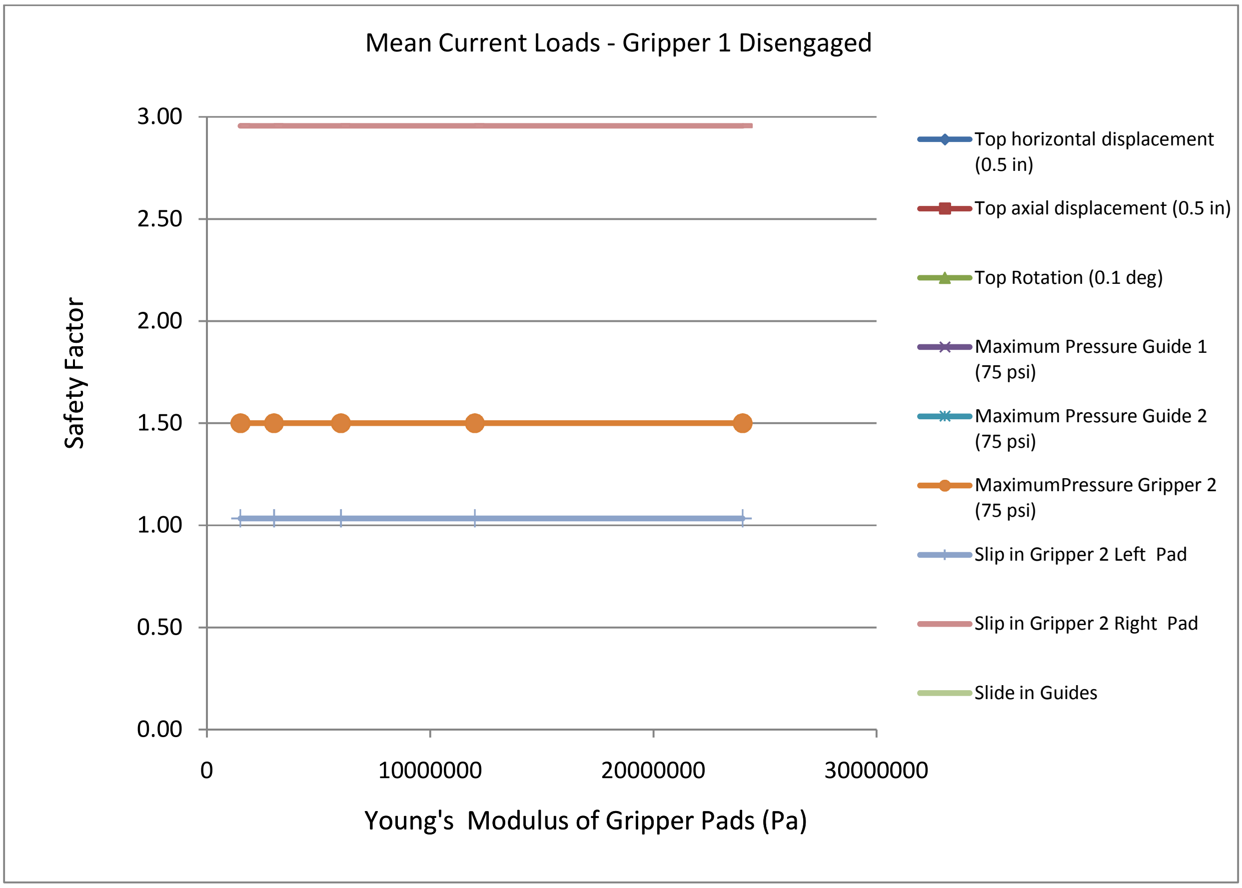

Max Current Loads - Both Grippers Engaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 3 (m)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

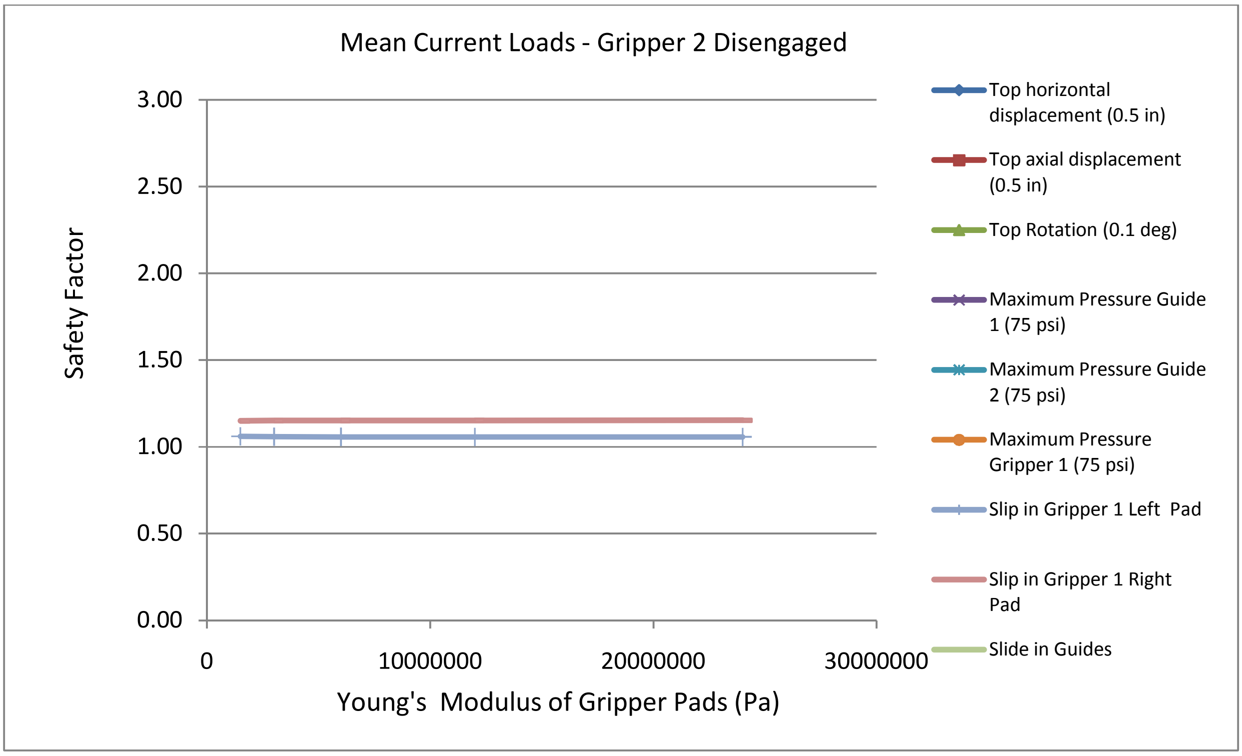

Mean Current Loads - Both Grippers Engaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 4 (m)
Top horizontal displacement (0.25 in)
Top axial displacement (0.5 in)
Top Rotation (0.05 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

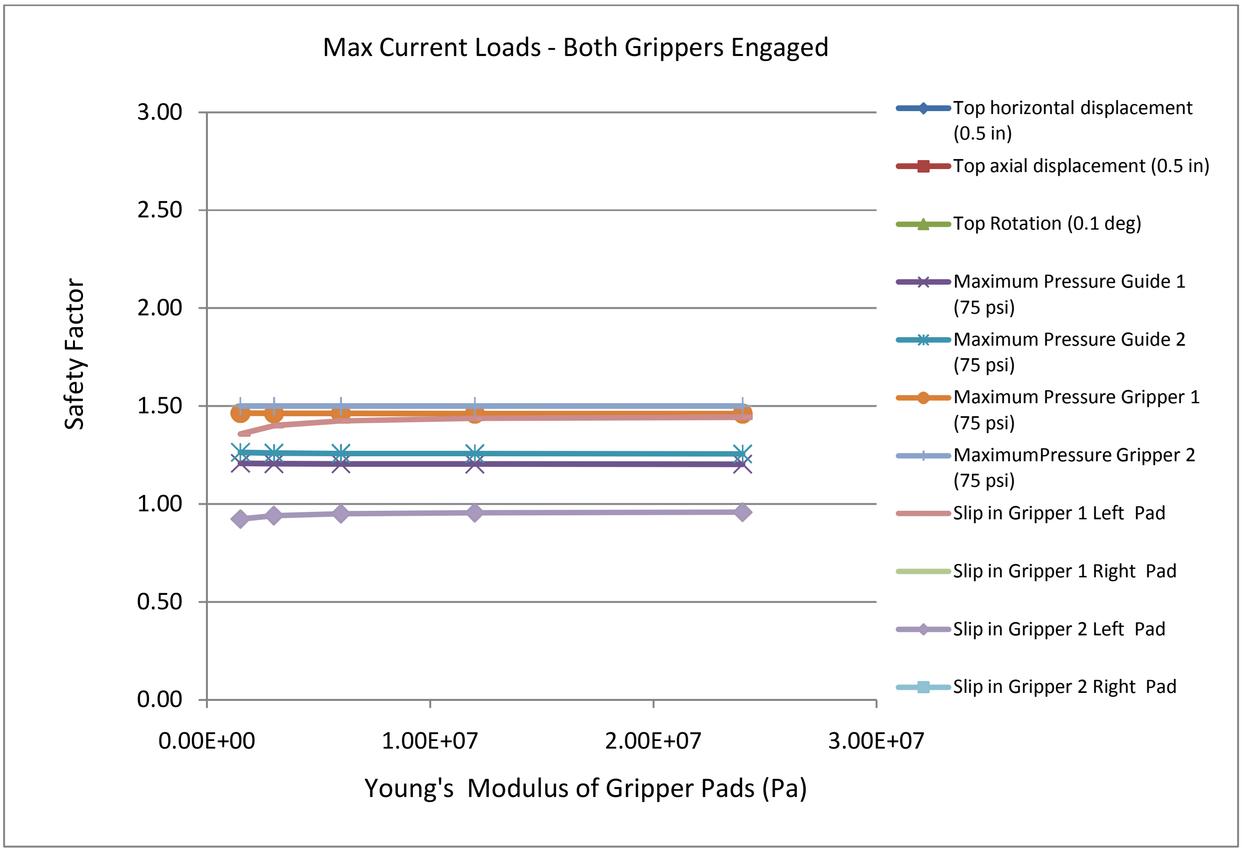

Mean Current Loads - Gripper 1 Disengaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 4 (m)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad
Slide in Guides

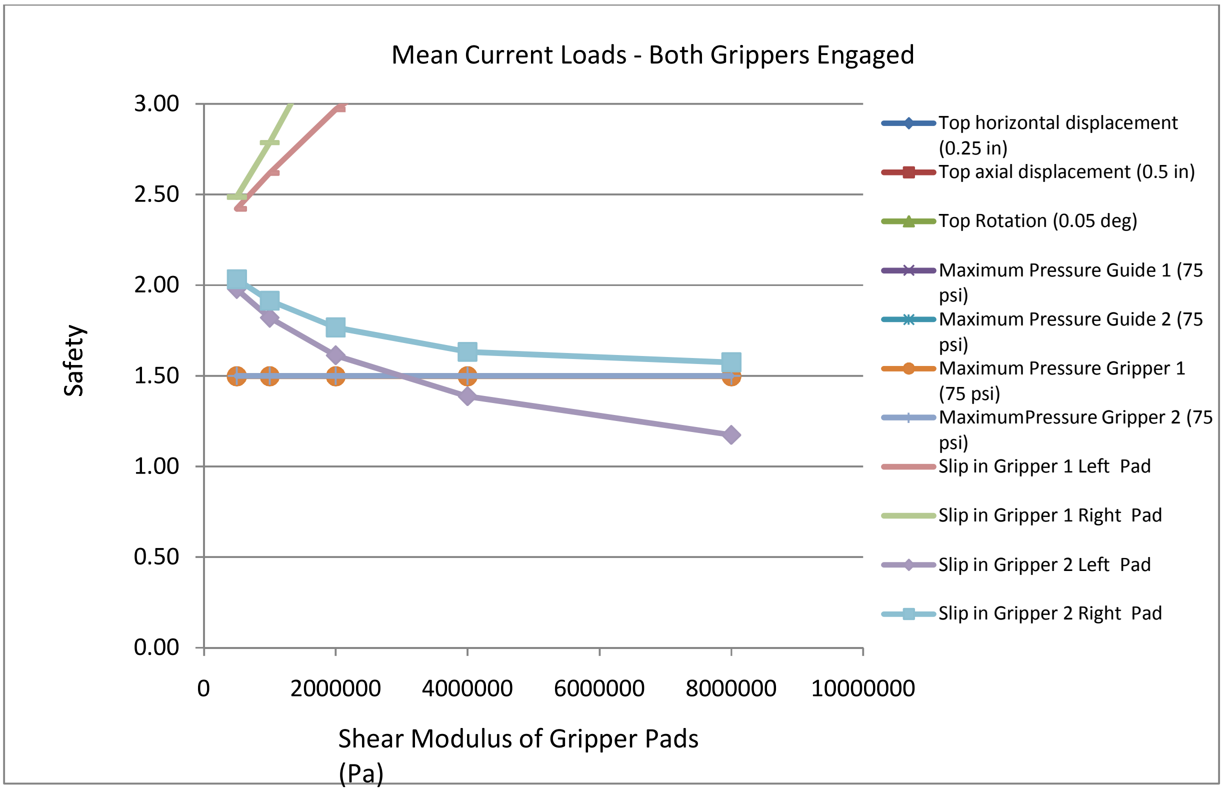

Mean Current Loads - Gripper 2 Disengaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 4 (m)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slide in Guides

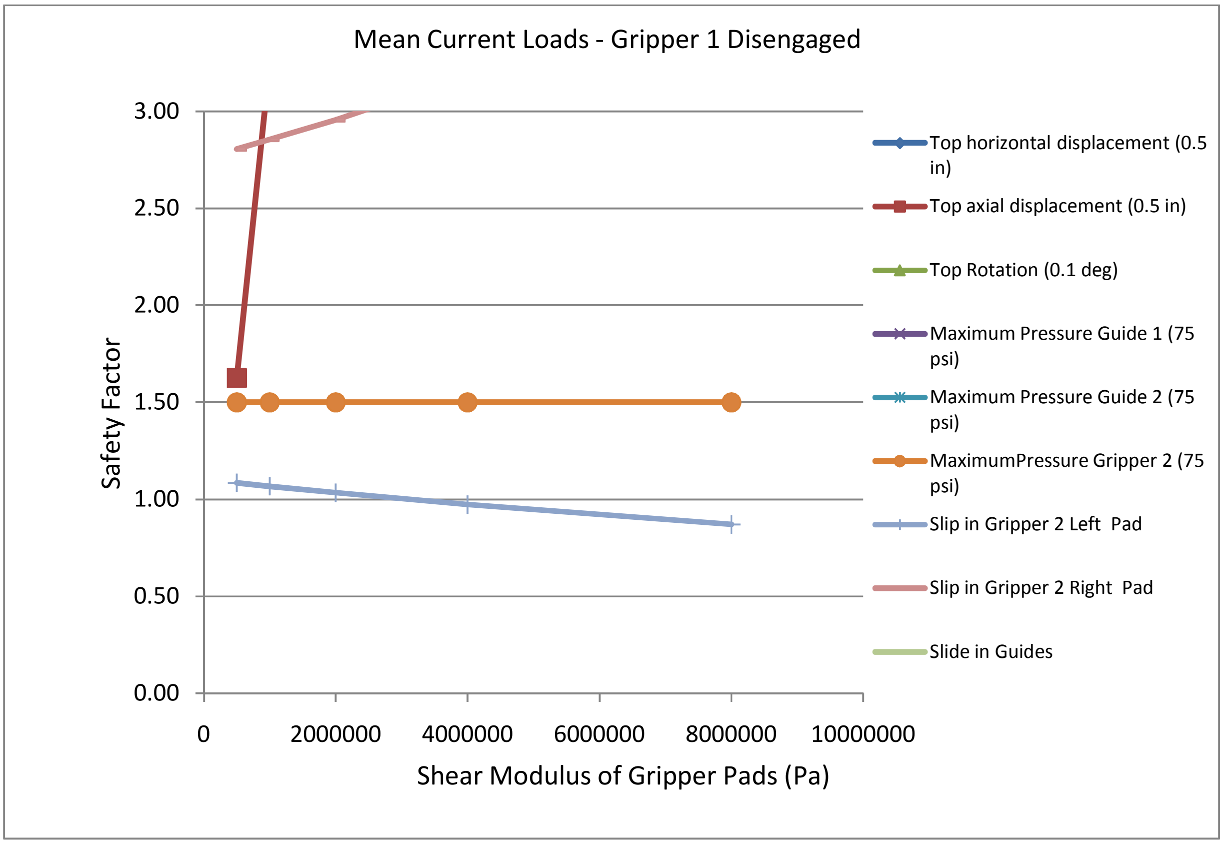

Max Current Loads - Both Grippers Engaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
Length of Support 4 (m)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

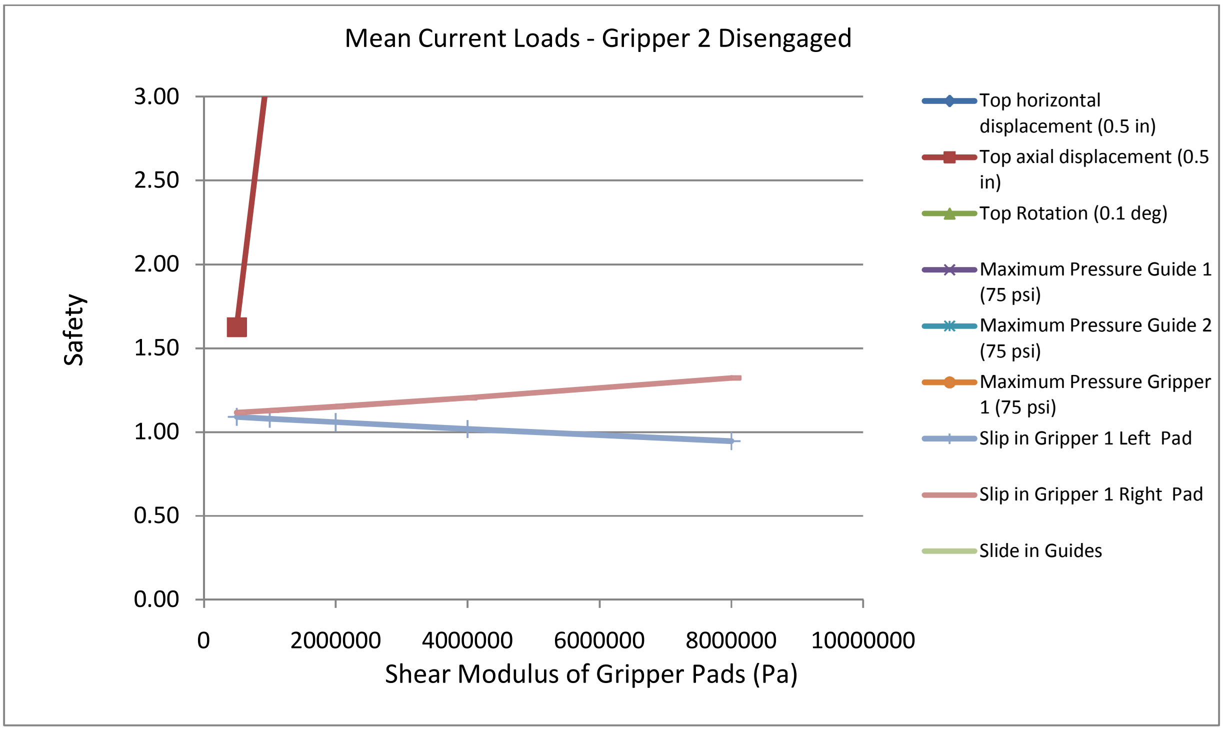

Mean Current Loads - Gripper 1 Disengaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
10000000
20000000
30000000
Young's Modulus of Gripper Pads (Pa)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad
Slide in Guides

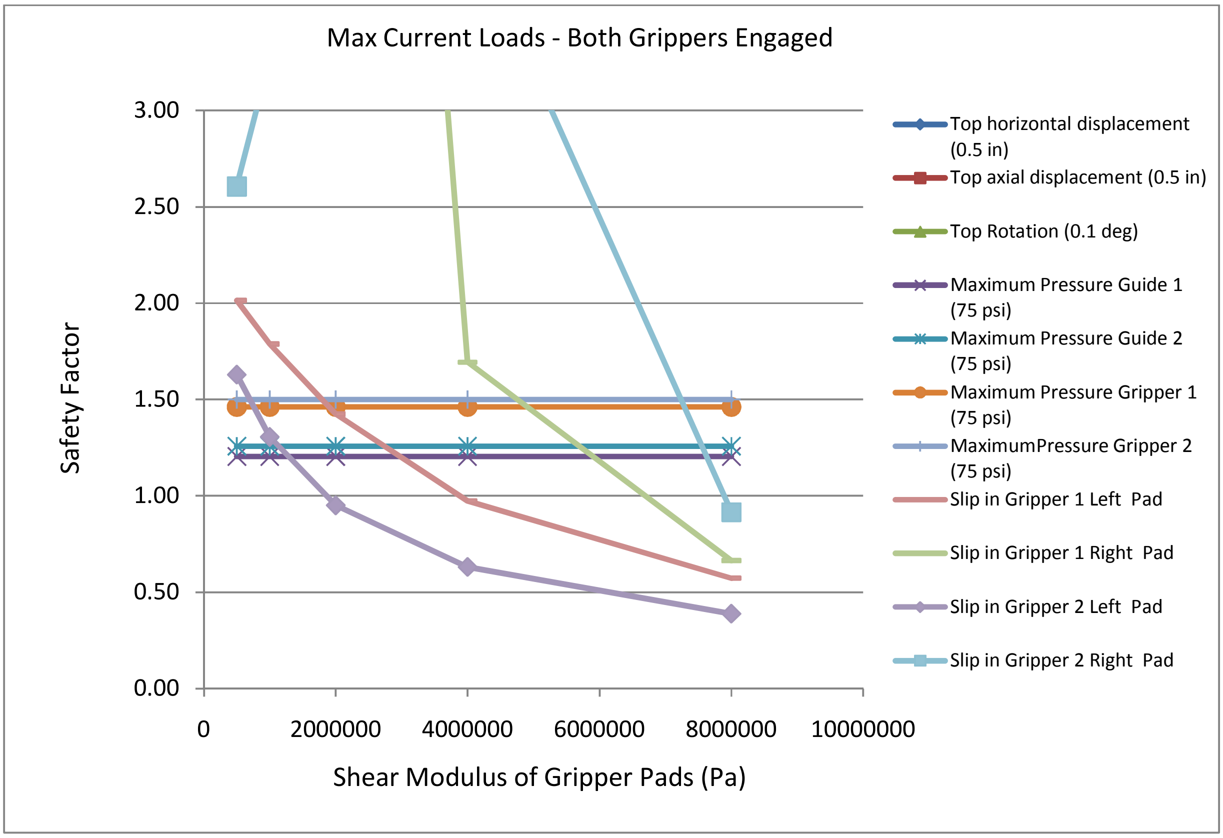

Mean Current Loads - Gripper 2 Disengaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
10000000
20000000
30000000
Young's Modulus of Gripper Pads (Pa)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slide in Guides


Max Current Loads - Both Grippers Engaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00E+00
1.00E+07
2.00E+07
3.00E+07
Young's Modulus of Gripper Pads (Pa)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

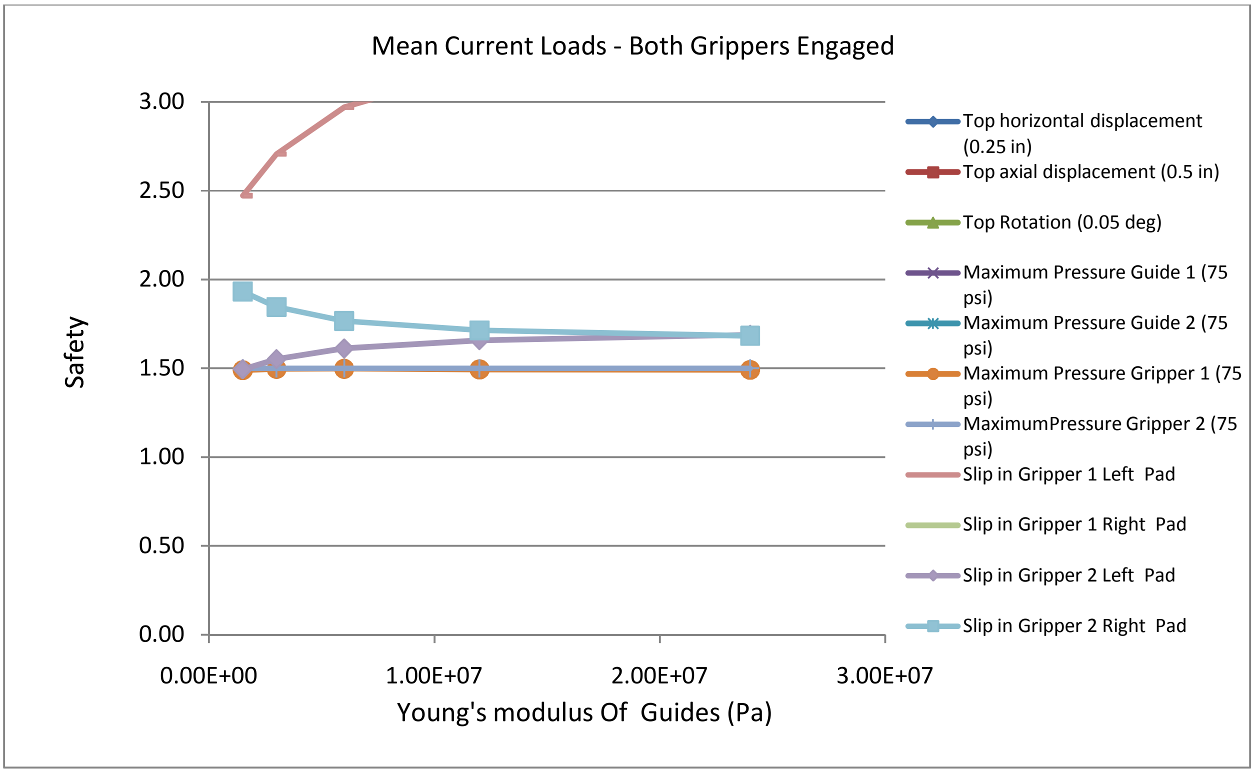

Mean Current Loads - Both Grippers Engaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2000000
4000000
6000000
8000000
10000000
Shear Modulus of Gripper Pads (Pa)
Top horizontal displacement (0.25 in)
Top axial displacement (0.5 in)
Top Rotation (0.05 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad


Mean Current Loads - Gripper 1 Disengaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2000000
4000000
6000000
8000000
10000000
Shear Modulus of Gripper Pads (Pa)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad
Slide in Guides

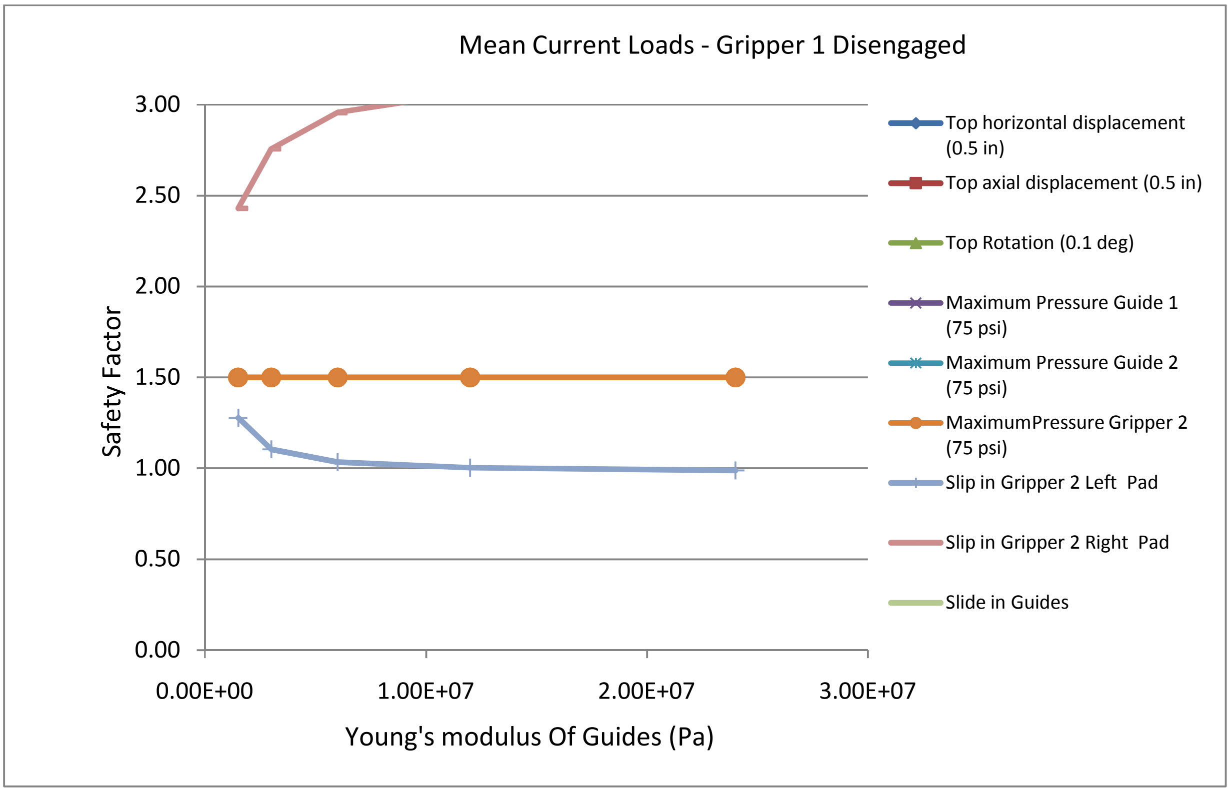

Mean Current Loads - Gripper 2 Disengaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2000000
4000000
6000000
8000000
10000000
Shear Modulus of Gripper Pads (Pa)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slide in Guides



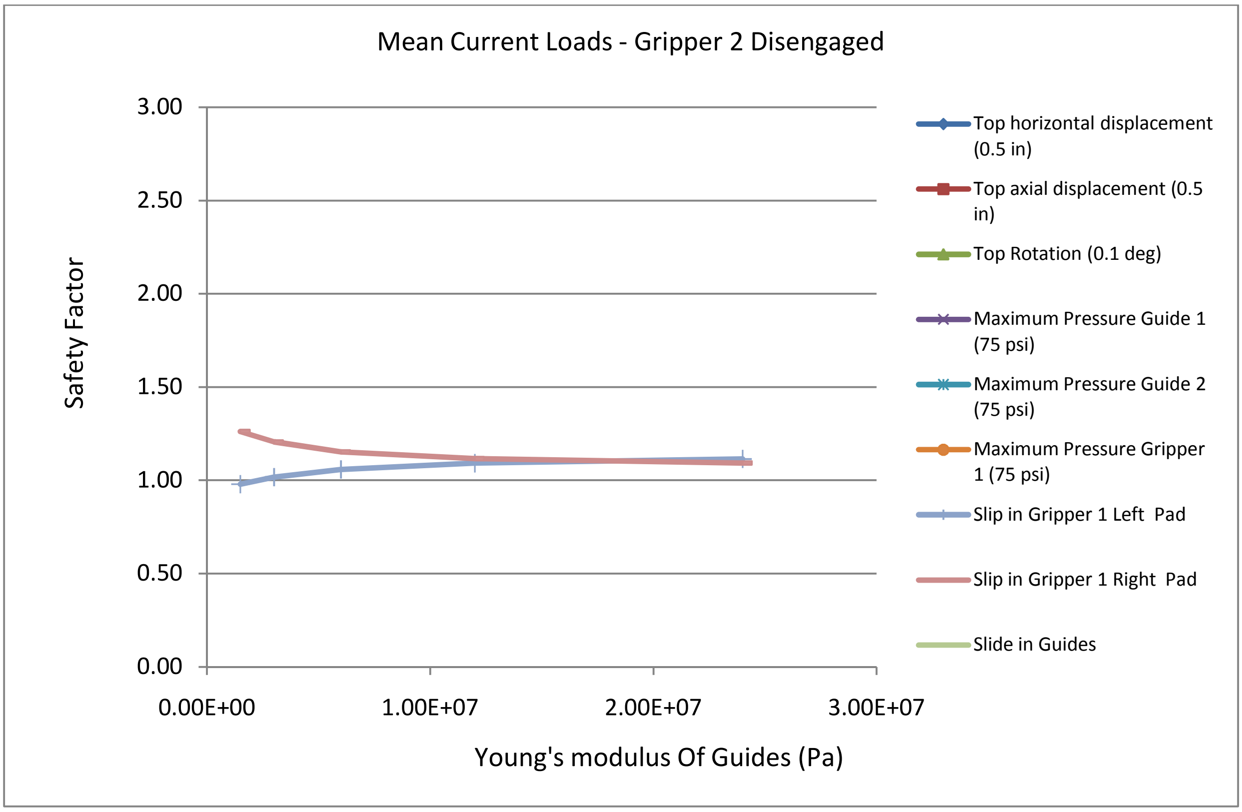
Max Current Loads - Both Grippers Engaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2000000
4000000
6000000
8000000
10000000
Shear Modulus of Gripper Pads (Pa)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad



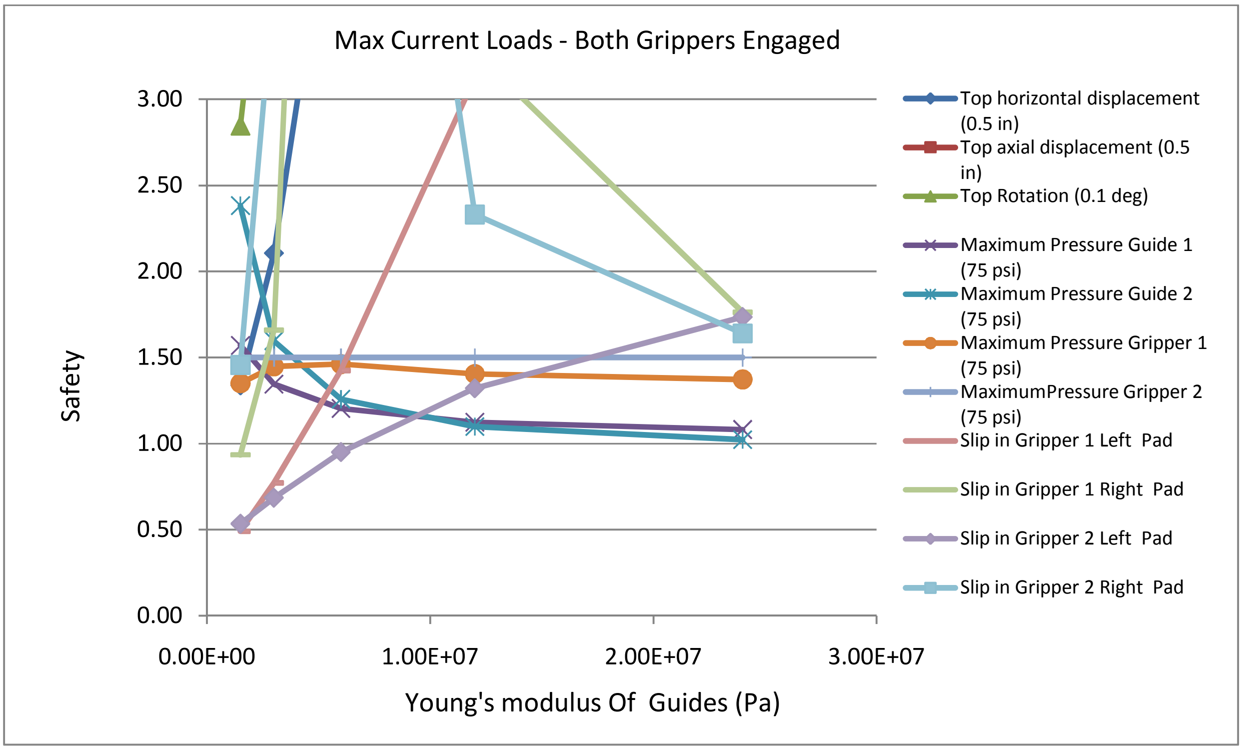
Mean Current Loads - Both Grippers Engaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00E+00
1.00E+07
2.00E+07
3.00E+07
Young's modulus Of Guides (Pa)
Top horizontal displacement (0.25 in)
Top axial displacement (0.5 in)
Top Rotation (0.05 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

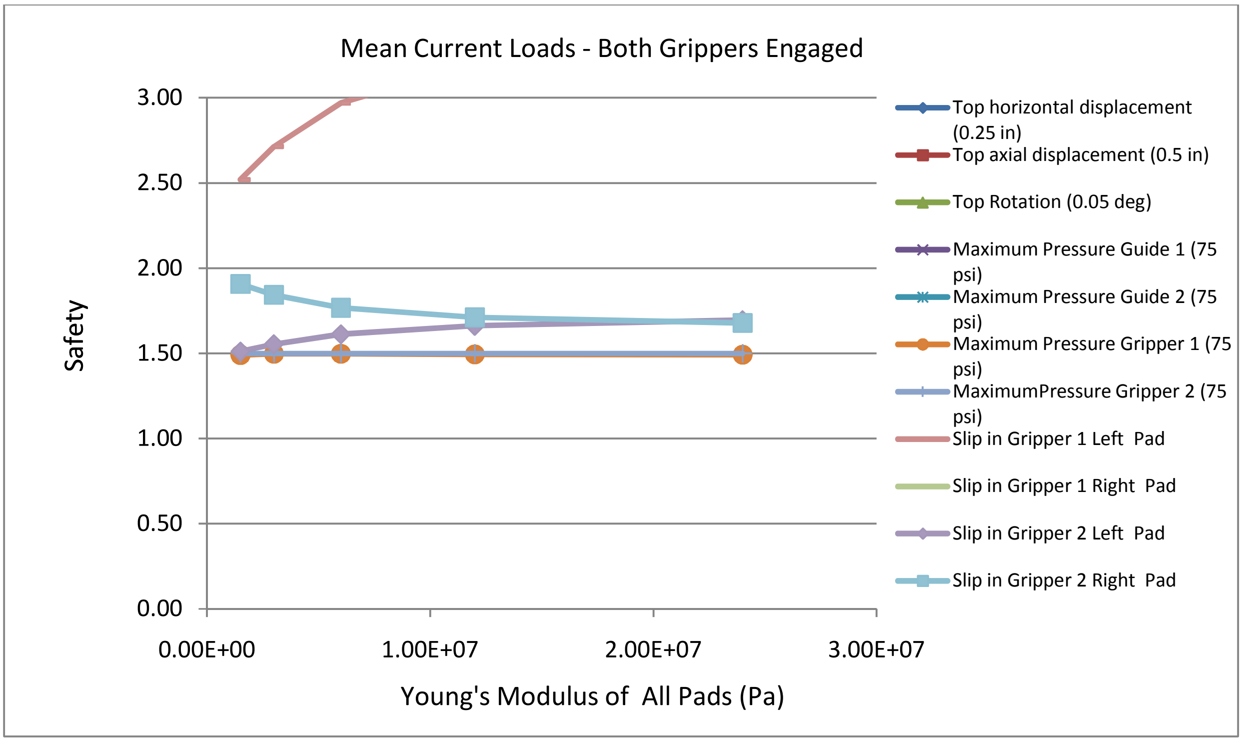


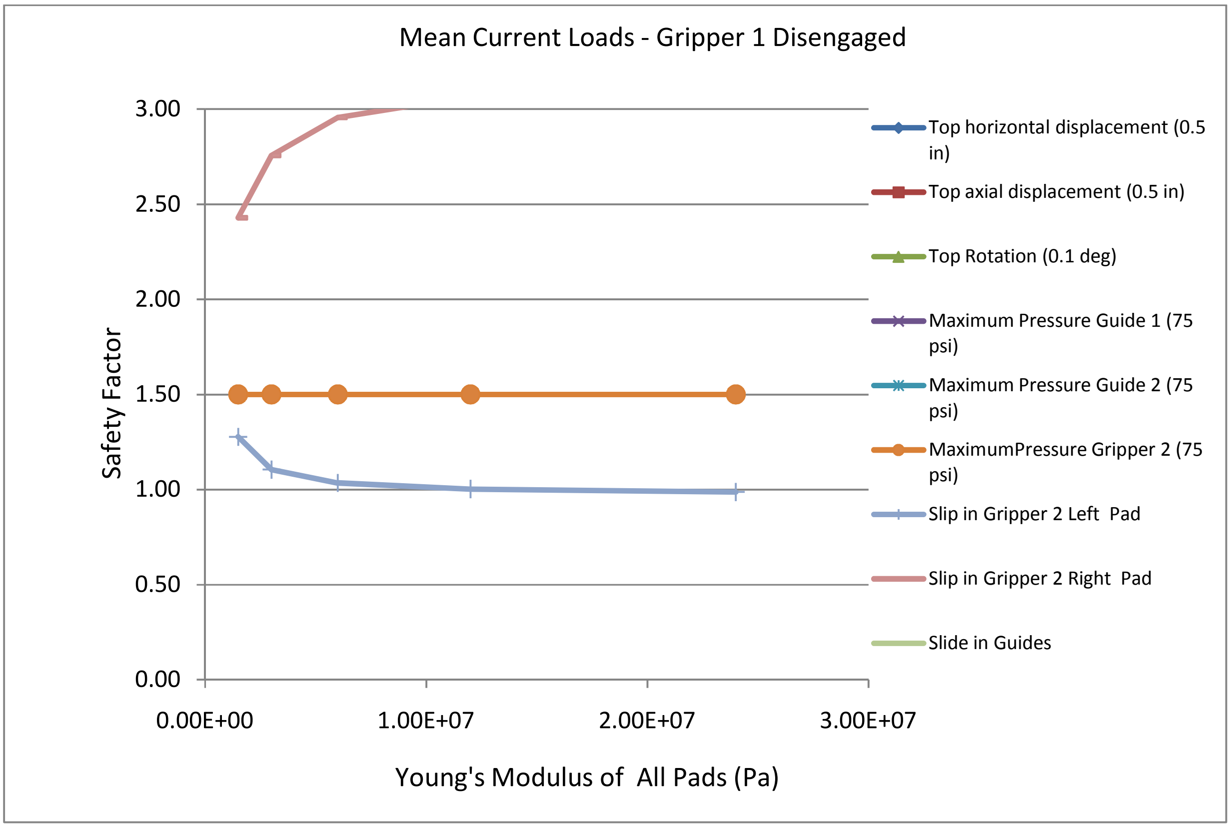
Mean Current Loads - Gripper 1 Disengaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00E+00
1.00E+07
2.00E+07
3.00E+07
Young's modulus Of Guides (Pa)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad
Slide in Guides

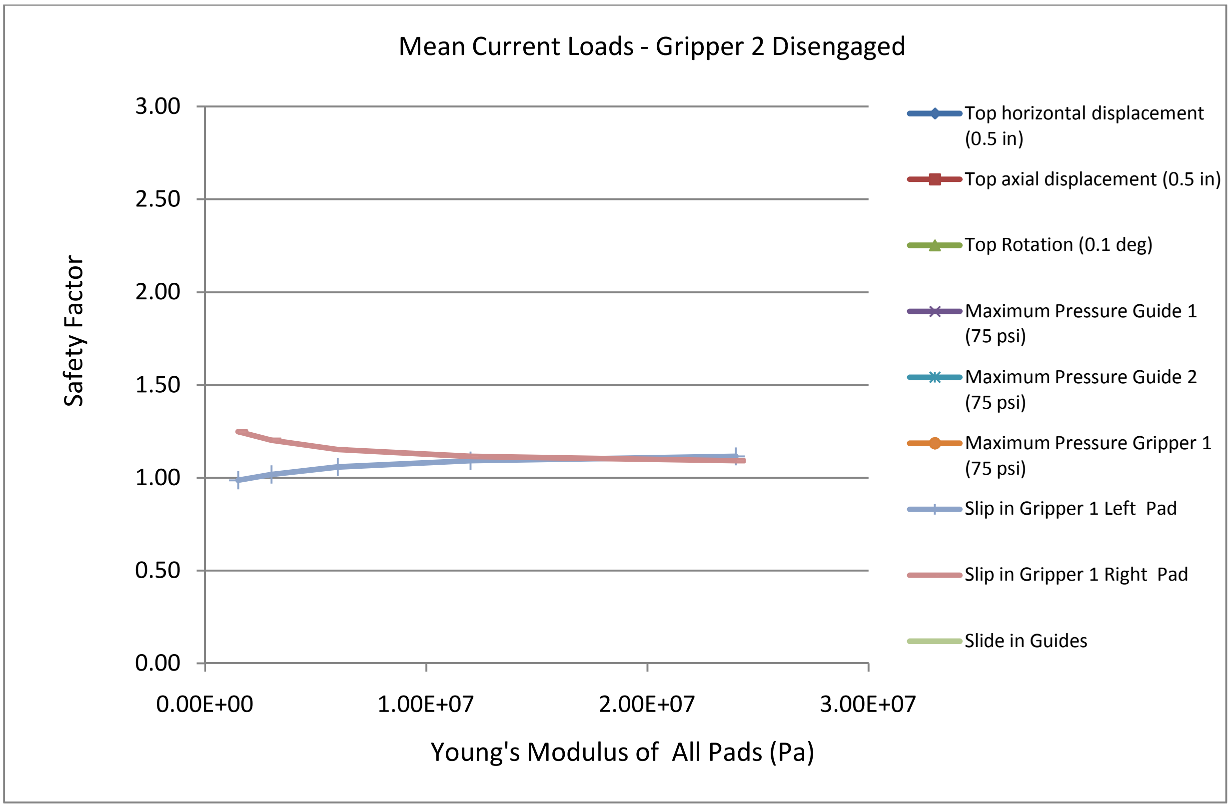


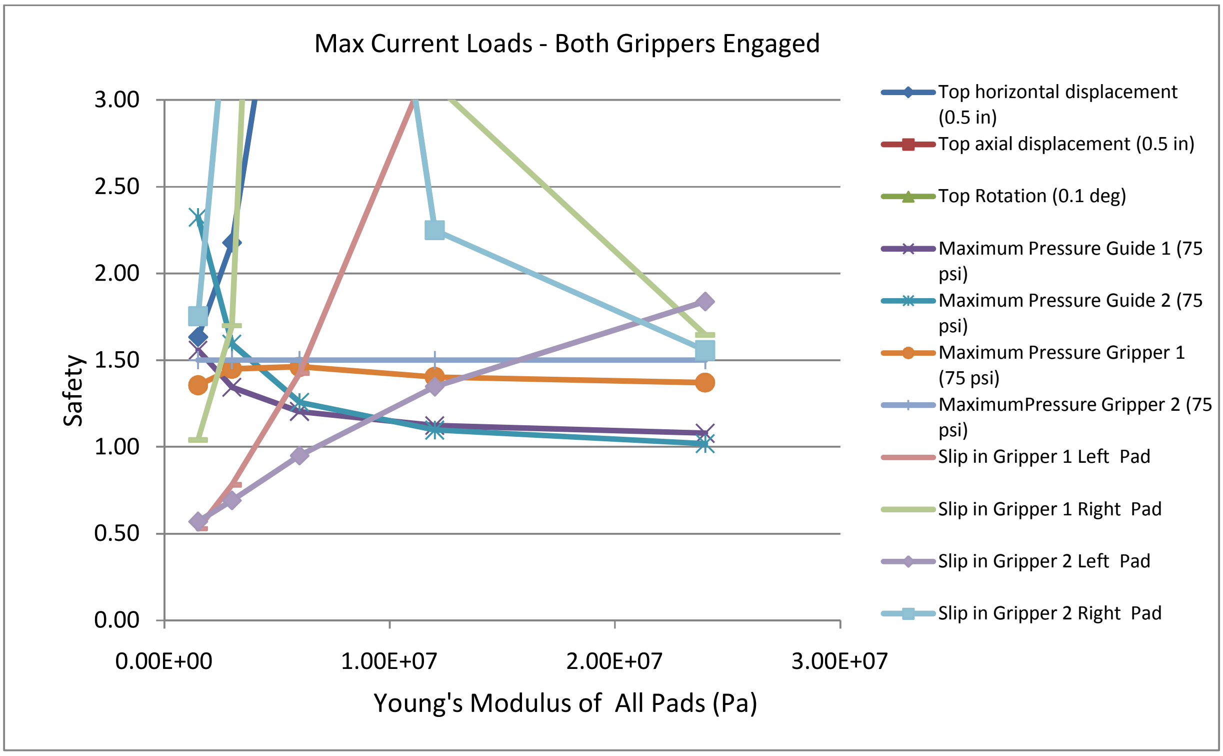
Mean Current Loads - Gripper 2 Disengaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00E+00
1.00E+07
2.00E+07
3.00E+07
Young's modulus Of Guides (Pa)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slide in Guides

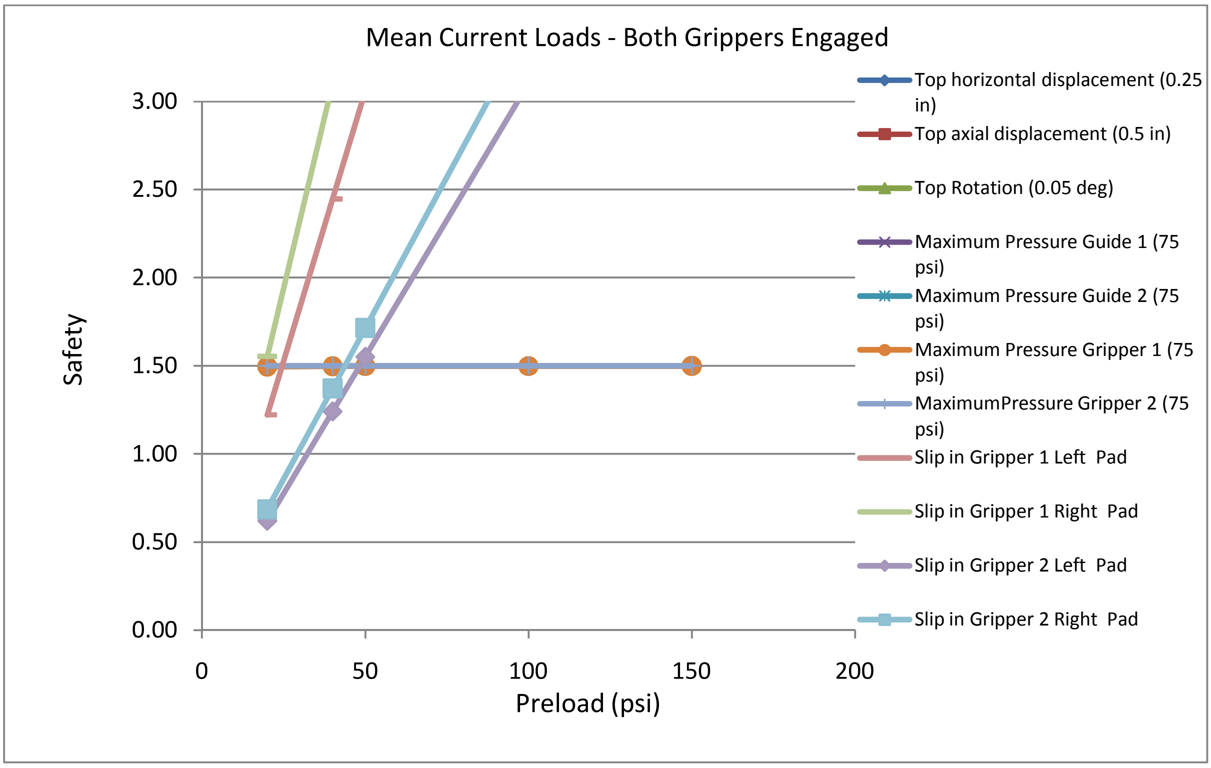

Max Current Loads - Both Grippers Engaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00E+00
1.00E+07
2.00E+07
3.00E+07
Young's modulus Of Guides (Pa)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

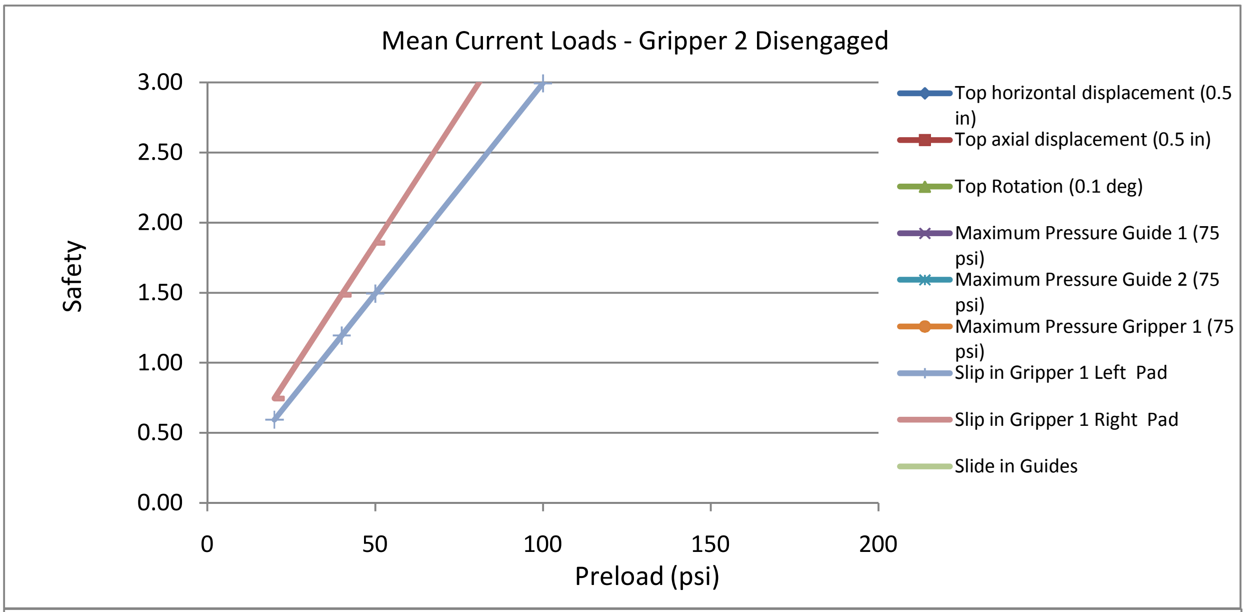

Mean Current Loads - Both Grippers Engaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00E+00
1.00E+07
2.00E+07
3.00E+07
Young's Modulus of All Pads (Pa)
Top horizontal displacement (0.25 in)
Top axial displacement (0.5 in)
Top Rotation (0.05 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

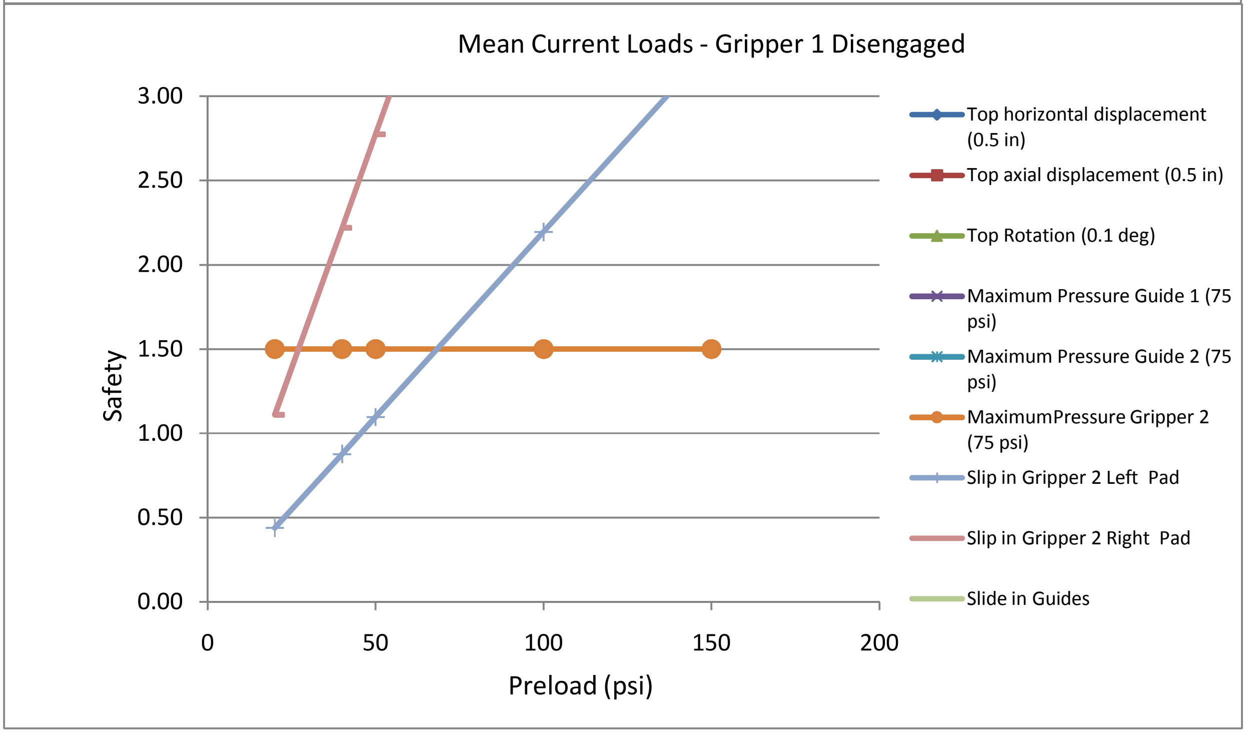

Mean Current Loads - Gripper 1 Disengaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00E+00
1.00E+07
2.00E+07
3.00E+07
Young's Modulus of All Pads (Pa)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad
Slide in Guides

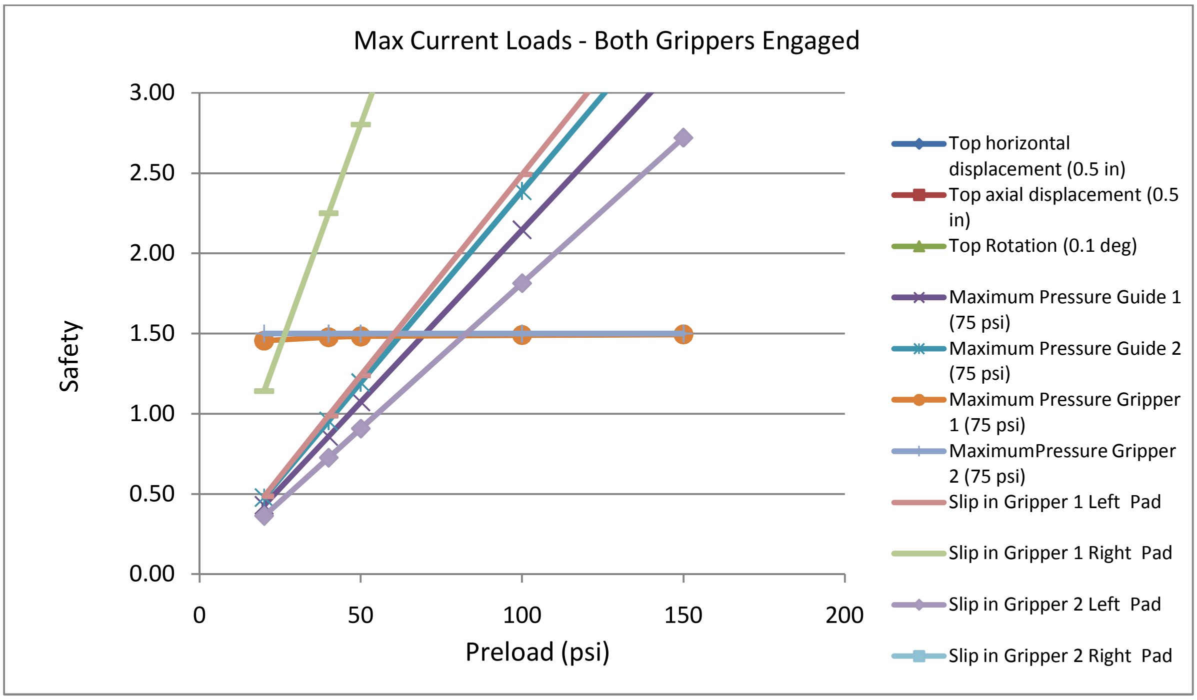

Mean Current Loads - Gripper 2 Disengaged
Safety Factor
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00E+00
1.00E+07
2.00E+07
3.00E+07
Young's Modulus of All Pads (Pa)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slide in Guides


Max Current Loads - Both Grippers Engaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00E+00
1.00E+07
2.00E+07
3.00E+07
Young's Modulus of All Pads (Pa)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

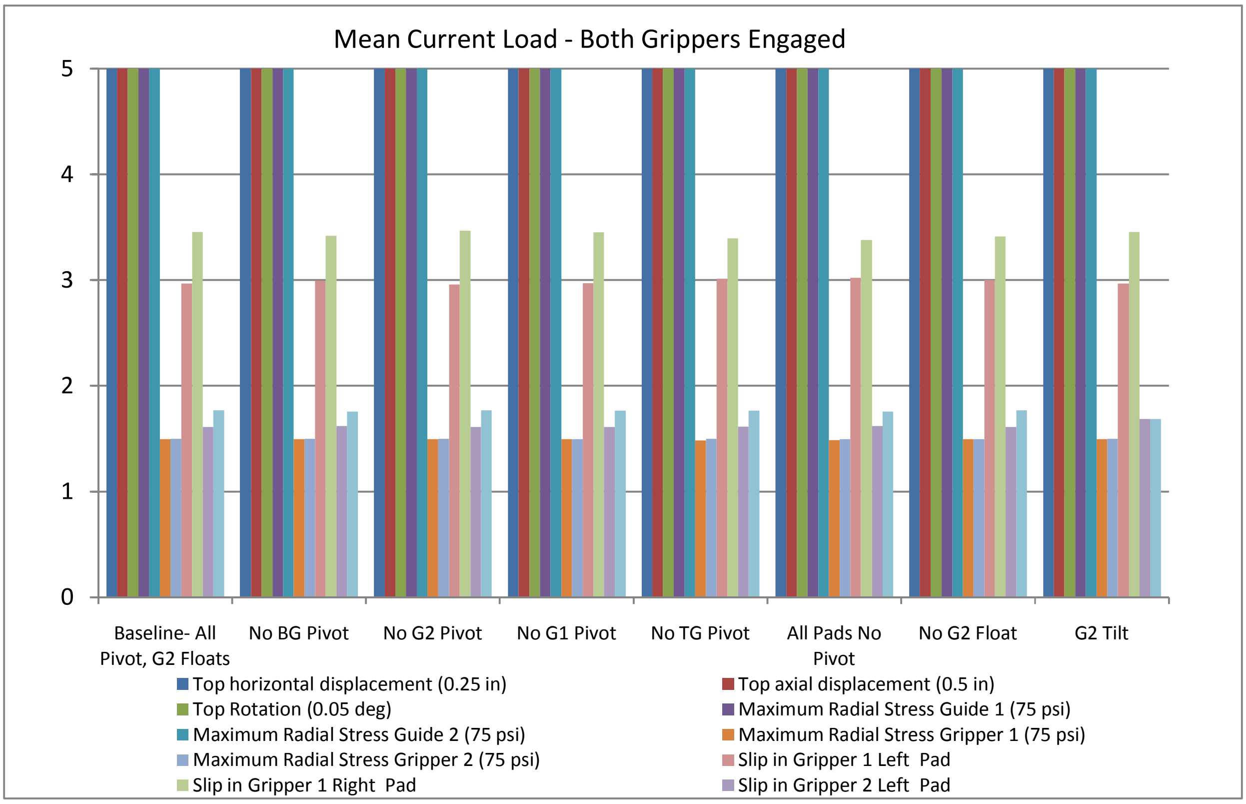

Mean Current Loads - Both Grippers Engaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
Preload (psi)
Top horizontal displacement (0.25 in)
Top axial displacement (0.5 in)
Top Rotation (0.05 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

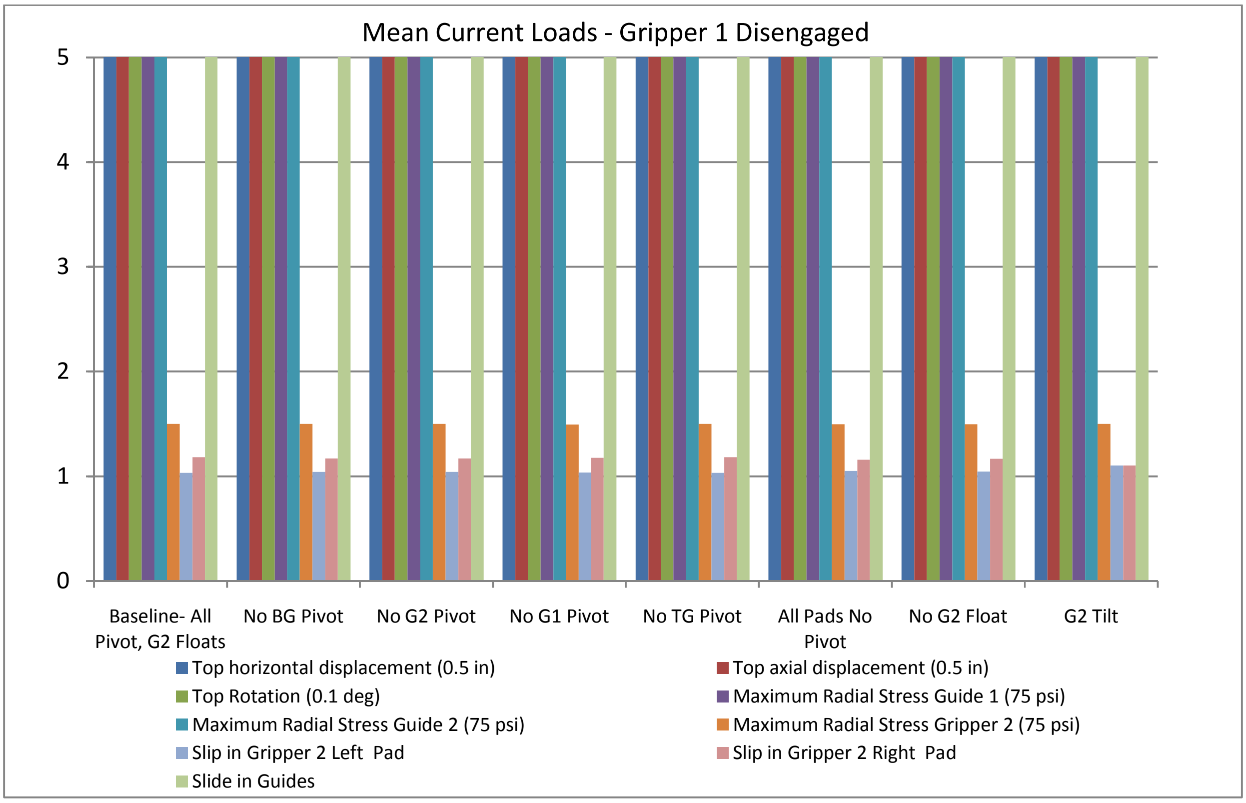

Mean Current Loads - Gripper 2 Disengaged
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Safety
0
50
100
150
200
Preload (psi)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slide in Guides

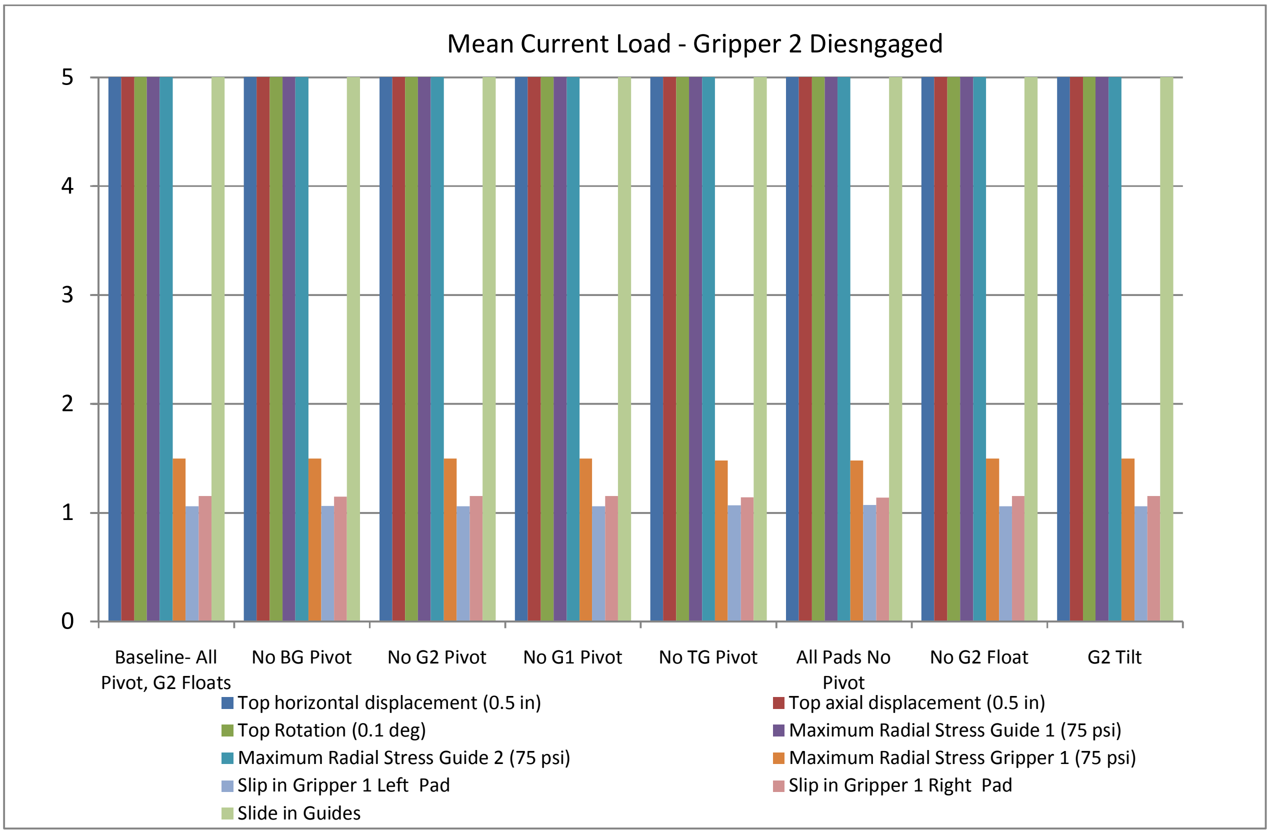

Mean Current Loads - Gripper 1 Disengaged
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Safety
0
50
100
150
200
Preload (psi)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad
Slide in Guides

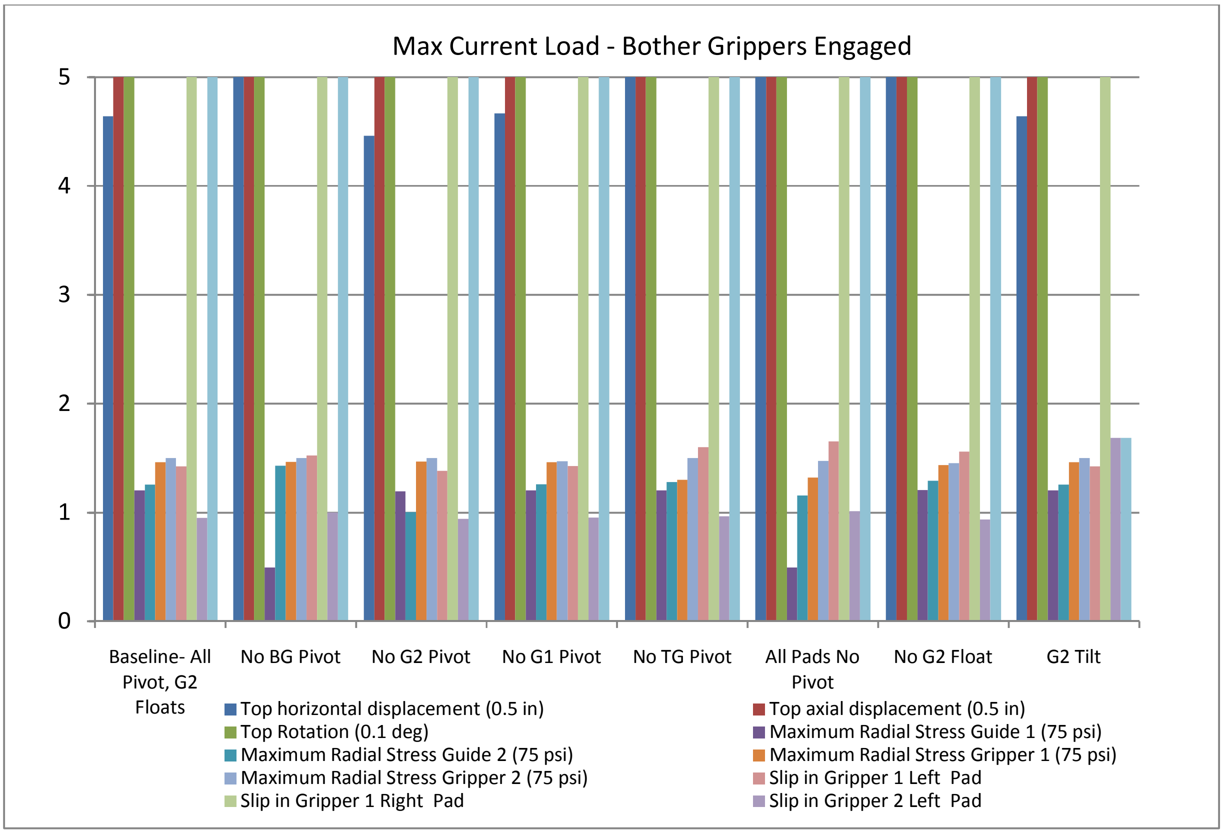

Max Current Loads - Both Grippers Engaged
Safety
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
Preload (psi)
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Pressure Guide 1 (75 psi)
Maximum Pressure Guide 2 (75 psi)
Maximum Pressure Gripper 1 (75 psi)
MaximumPressure Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad
Slip in Gripper 2 Right Pad

Appendix B – Characteristics Comparison Study Results






Mean Current Load - Gripper 2 Diesngaged
5
4
3
2
1
0
Baseline- All Pivot, G2 Floats
No BG Pivot
No G2 Pivot
No G1 Pivot
No TG Pivot
All Pads No Pivot
No G2 Float
G2 Tilt
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Radial Stress Guide 1 (75 psi)
Maximum Radial Stress Guide 2 (75 psi)
Maximum Radial Stress Gripper 1 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slide in Guides


Max Current Load - Bother Grippers Engaged
5
4
3
2
1
0
Baseline- All Pivot, G2 Floats
No BG Pivot
No G2 Pivot
No G1 Pivot
No TG Pivot
All Pads No Pivot
No G2 Float
G2 Tilt
Top horizontal displacement (0.5 in)
Top axial displacement (0.5 in)
Top Rotation (0.1 deg)
Maximum Radial Stress Guide 1 (75 psi)
Maximum Radial Stress Guide 2 (75 psi)
Maximum Radial Stress Gripper 1 (75 psi)
Maximum Radial Stress Gripper 2 (75 psi)
Slip in Gripper 1 Left Pad
Slip in Gripper 1 Right Pad
Slip in Gripper 2 Left Pad

NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report

Appendix 6-2

Gripper/Platform Interfacing

By

Makai Engineering

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
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GRIPPER/PLATFROM INTERFACING

Prepared by:

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PO Box 1206, Kailua, Hawaii 96734

Revision	Date	Description of Changes
1	4/6/2010	First draft of document

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GRIPPER/PLATFORM INTERFACING

LIST OF FIGURES

LIST OF TABLES

1. GRIPPERS AND GUIDES

1.1 DESIGN OVERVIEW

The cold water pipe (CWP) for the 10MW OTEC pilot plant is to be fabricated at sea in 11m segments on a semi-submersible platform. The pipe will be fabricated in a vertical position and lowered down after each segment is cured, at which point the subsequent segment is fabricated. While the pipe is being fabricated, it must be supported vertically to hold its weight and laterally to limit the horizontal movement of the pipe. The vertical support will be provided by two "grippers," which squeeze the outside of the pipe and utilize friction to hold the pipe's weight. Additionally, the grippers are also responsible for lowering each segment of the pipe. To do this, one gripper must disengage while the other gripper is lowered. Once the segment is lowered, the first gripper reengages and the second gripper disengages to return to its original position. The lowering sequence necessitates that each gripper be capable of holding the entire weight of the CWP individually. Lateral support to the pipe is provided by two "guides," which limit the horizontal movement of the pipe. Unlike the grippers, which squeeze and hold on to the CWP, the guides must allow the pipe to slide through while each segment is being lowered. In addition, both the grippers and the guides will use some sort of pad to engage the CWP that will not damage the pipe.

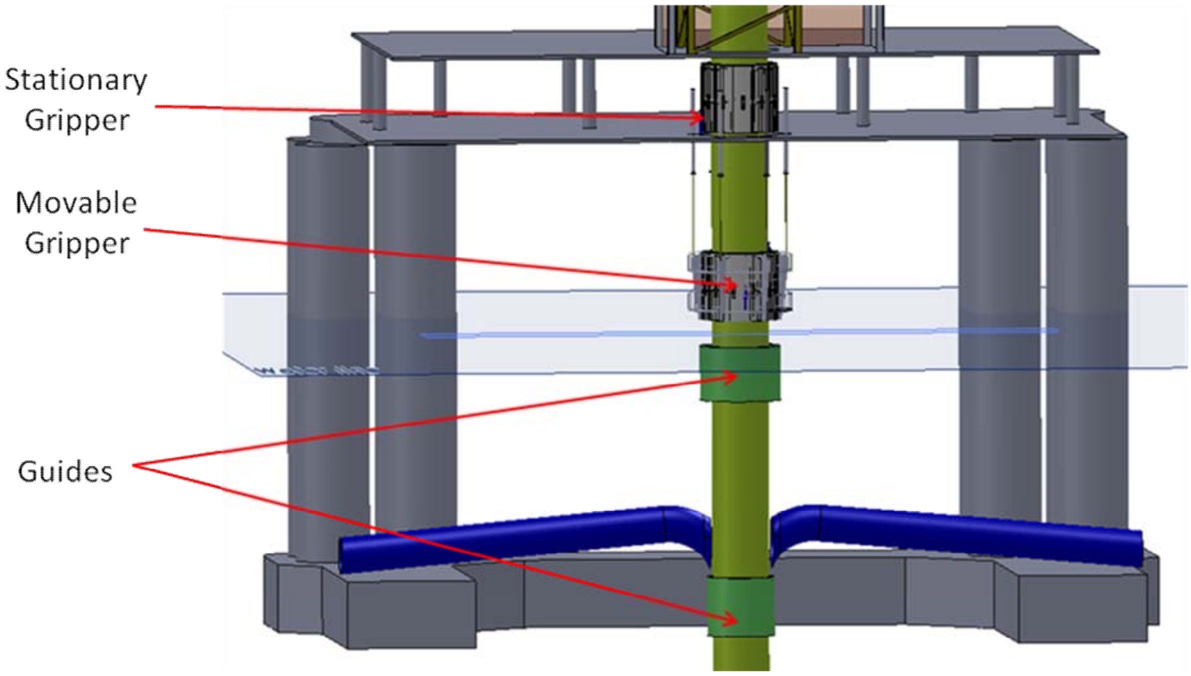


Figure 1- Gripper and Guide Overview

1.2 DIMENSIONS

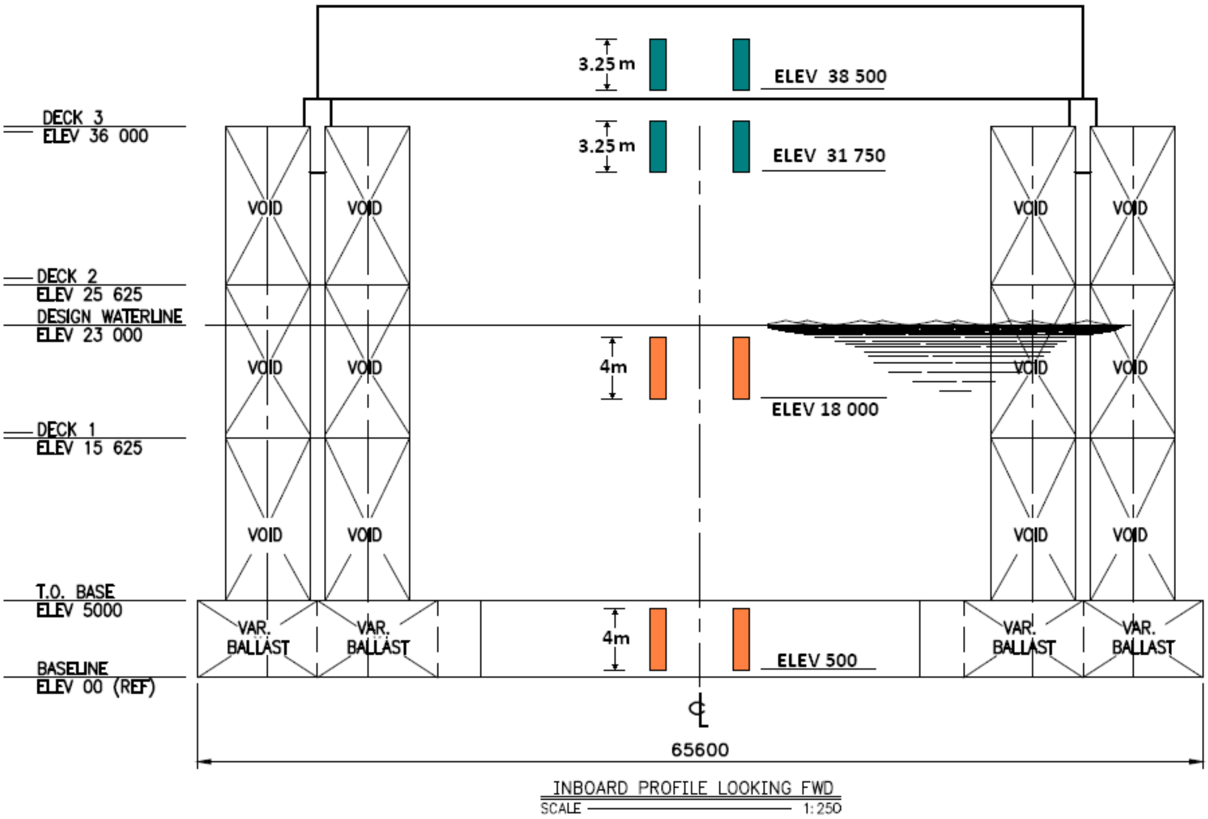


Figure 2 - Gripper and Guide Dimensions

1.3 LOADING

The maximum loads are shown in Table 1. The loads shown are calculated using the 10 yr swell sea states.

Table 1 – Component Loading

Component	Vertical Load (KN)		Lateral Load (KN)	
	Static	Dynamic (+/-)	Static	Dynamic (+/-)
Upper Gripper	2,912	173	39	170
Lower Gripper	2,912	173	-	-
Upper Guide	291	17	566	2,413
Lower Guide	291	17	722	3,078

1.4 WEIGHT OF COMPONENTS

Table 2 - Component Weights

		total, dry weight tonnes	total, wet weight tonnes	Removed /Remain after Fabrication --	sub-merged %	Est Basis	Contin-gency %	~CG relative to pontoon bottom m
Pipe Handling Equipment	Top Griper structure	20	n/a	remain	0%	D	25%	37
	Top Gripper pads	60	n/a	Remove	0%	E	30%	37
	bottom Gripper	20	n/a	Remove	0%	D	25%	29.5-23.5
	bottom gripper pads	60	n/a	Remove	0%	E	30%	29.5-23.5
	Top guide	15	13.1	Optional	100%	D	25%	18
	Top guide pads	50	20.0	Remove	100%	E	30%	18
	Bottom Guide	36	24.0	Remain	100%	D	25%	0
	Winch/ Heave Compensator	4	n/a	Remain	0%	E	30%	+44
	Hydraulic Supply, control	2	n/a	Remove	0%	E	30%	+44
	Blower/compressor	1	n/a	Remove	0%	E	30%	+44
	Top Pipe Pressure Cap	7.5	n/a	Remove	0%	E	30%	+44 to 0
	Allowances	5	n/a	n/a	0%	F	30%	+40
CWP	Water Manifold Completion Cap	2	1.74	Remove	100%	F	30%	4
	Bottom Weight	48	41.3	Remain	finally	D	10%	+40 to -1000
	Bottom Wt handling equipment	5	n/a	Remove	0%	F	30%	n/a
	CWP fabricated	663	320	Remain	100%	D	10%	-500

Estimate Basis:

A	Manufacturer Catalog
B	Final engineering Dwg total
C	80% design Eng Dwg total
D	Preliminary Engineering Dwg total
E	Engineering Estimate
F	Guesstimate

1.5 COST ESTIMATE

The costs shown in Table 3 is a rough order of magnitude preliminary estimation.

Table 3 - Cost Estimate

	Assembly Item	Qty	Qty Confid	Unit	$/unit	Cost Confid	Cost	Tolerance
Steel Work	Outer Wedge	61.3	1.00	MT	$ 11,000	0.90	$ 673,901	$ 67,390
	Inner Wedge	57.2	1.00	MT	$ 11,000	0.90	$ 628,792	$ 62,879
	Outer Sleeve	28.1	1.00	MT	$ 11,000	0.90	$ 308,760	$ 30,876
	Top Gripper Centering Wedge	9.1	1.00	MT	$ 11,000	0.90	$ 99,835	$ 9,984
	Bottom Gripper Support Structure	14.0	1.00	MT	$ 11,000	0.90	$ 154,192	$ 15,419
	Bottom Guide Frame	25.7	1.00	MT	$ 11,000	0.90	$ 282,653	$ 28,265
	SUB TOTAL						**$2,148,133**	**$ 214,813**
Pad	Tension Layer	665	0.90	yds	$ 38	0.90	$ 27,794	$ 2,779
	Gel Encapsulated in Polyurethane	15.4	0.90	m^3	$ 1,290	0.50	$ 21,853	$ 10,926
	Gel Support structure	3.2	1.00	MT	$ 11,000	0.90	$ 35,200	$ 3,520
	Friction Layer	768000	0.80	in^2	$0.12	0.70	$ 110,592	$ 33,178
	Slide layer (Guide)	192000	0.80	in^2	$0.69	0.80	$ 158,976	$ 31,795
	Fabrication	100	0.75	%	-	0.75	$ 354,415	$ 88,604
	SUB TOTAL						**$ 708,829**	**$ 170,802**
Hydralics	Engagging Hydraulics	24	0.90	each	*$ 305*	0.75	$ 8,052	$ 2,013
	Controls	1	0.70	each	*$ 5,000*	0.60	$ 6,500	$ 2,600
	Pump	1	0.80	each	*$ 7,500*	0.60	$ 9,000	$ 3,600
	Lowering Hydralics	4	0.60	each	*$ 20,000*	0.60	$ 112,000	$ 44,800
	Controls	1	0.70	each	*$ 5,000*	0.60	$ 6,500	$ 2,600
	Pump	1	0.80	each	*$ 10,000*	0.60	$ 12,000	$ 4,800
	SUB TOTAL						**$ 154,052**	**$ 60,413**
	GRAND TOTAL						**$3,011,014**	**$ 446,028**

1.6 SUPPORT STRUCTURE STIFFNESS

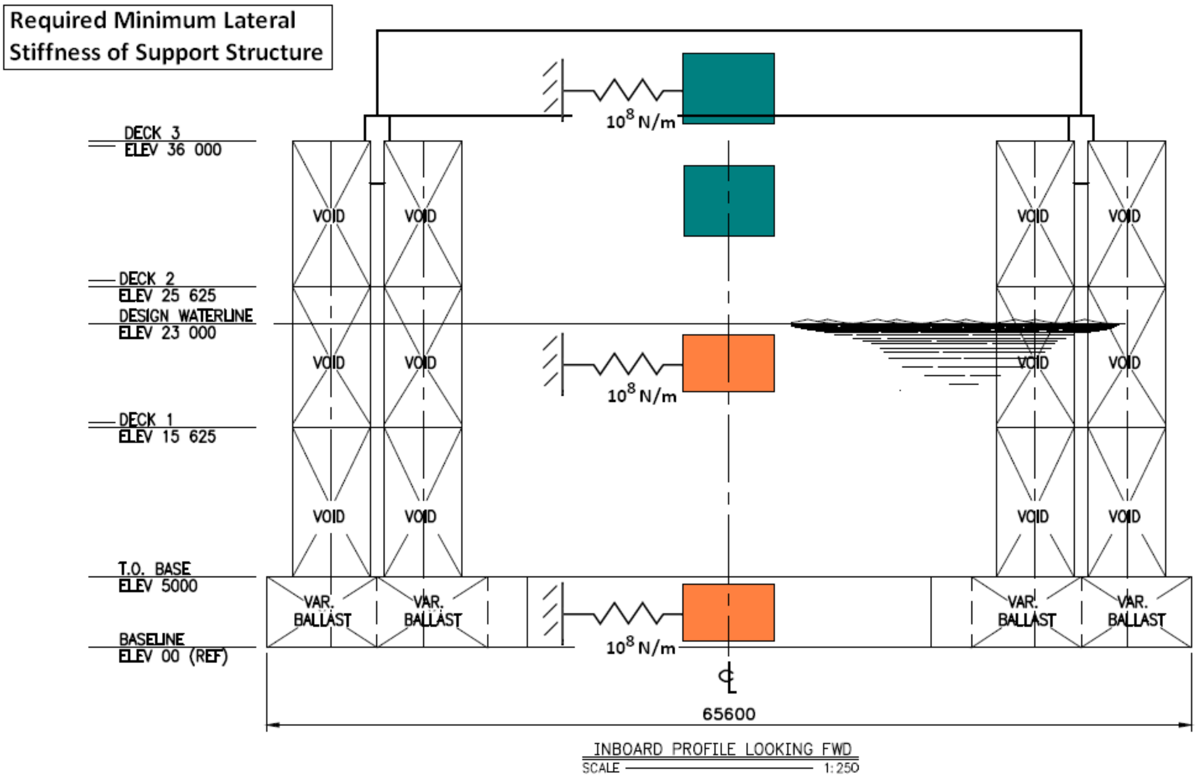


Figure 3 - Required Support Structure Stiffness

1.7 SUPPORT STRUCTURE ENVELOPE

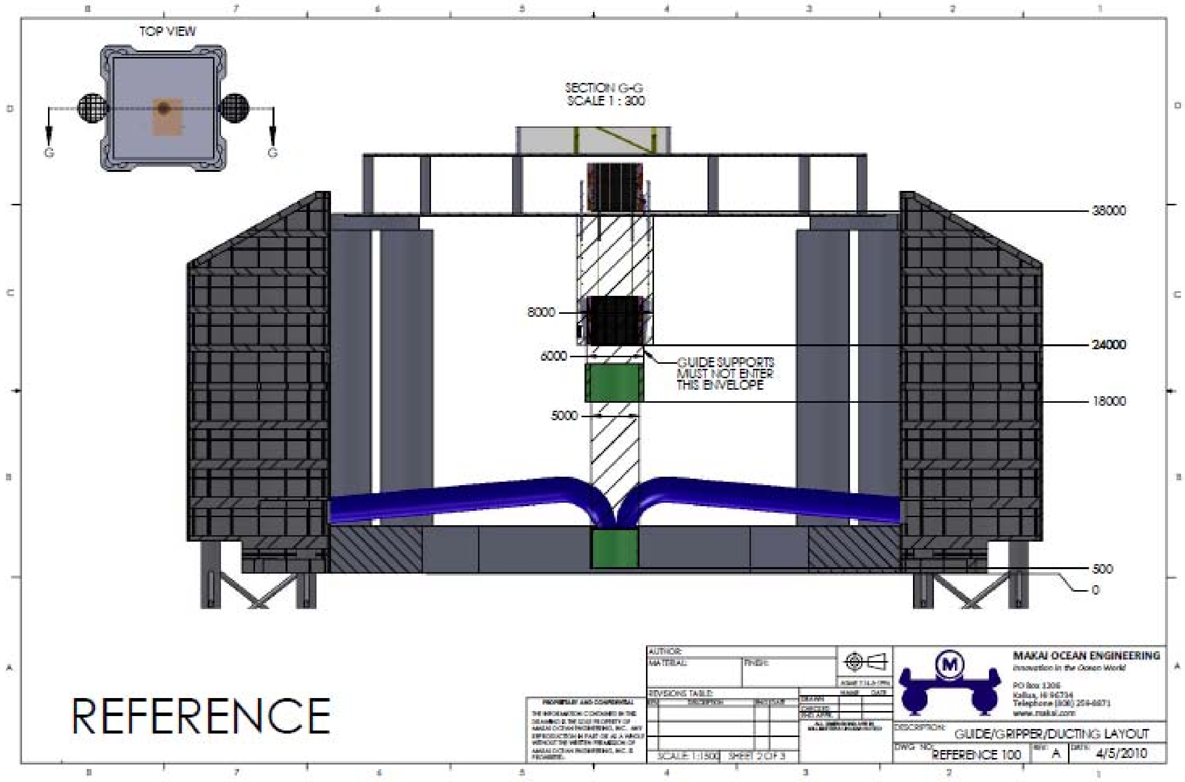


Figure 4 - Support Structure Envelope

2. COLD WATER DUCTS

2.1 DIMENSIONS

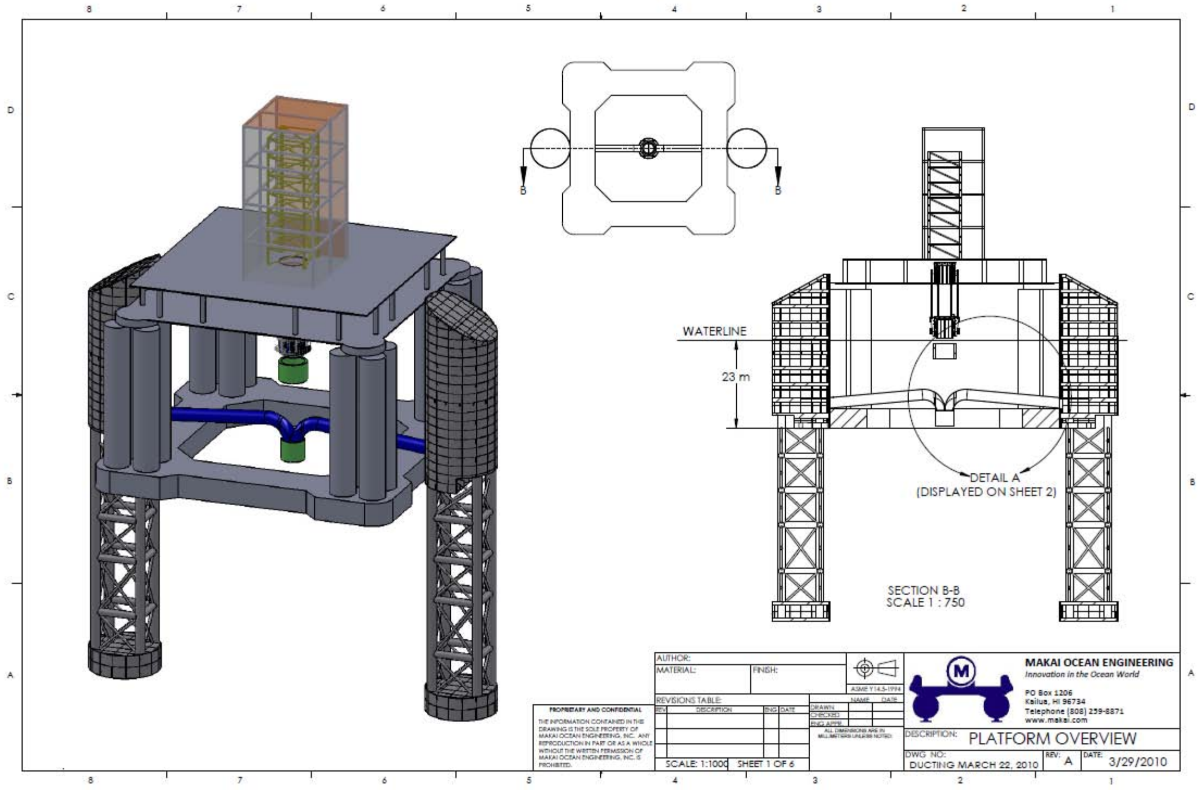


Figure 5 - Cold Water Duct Layout

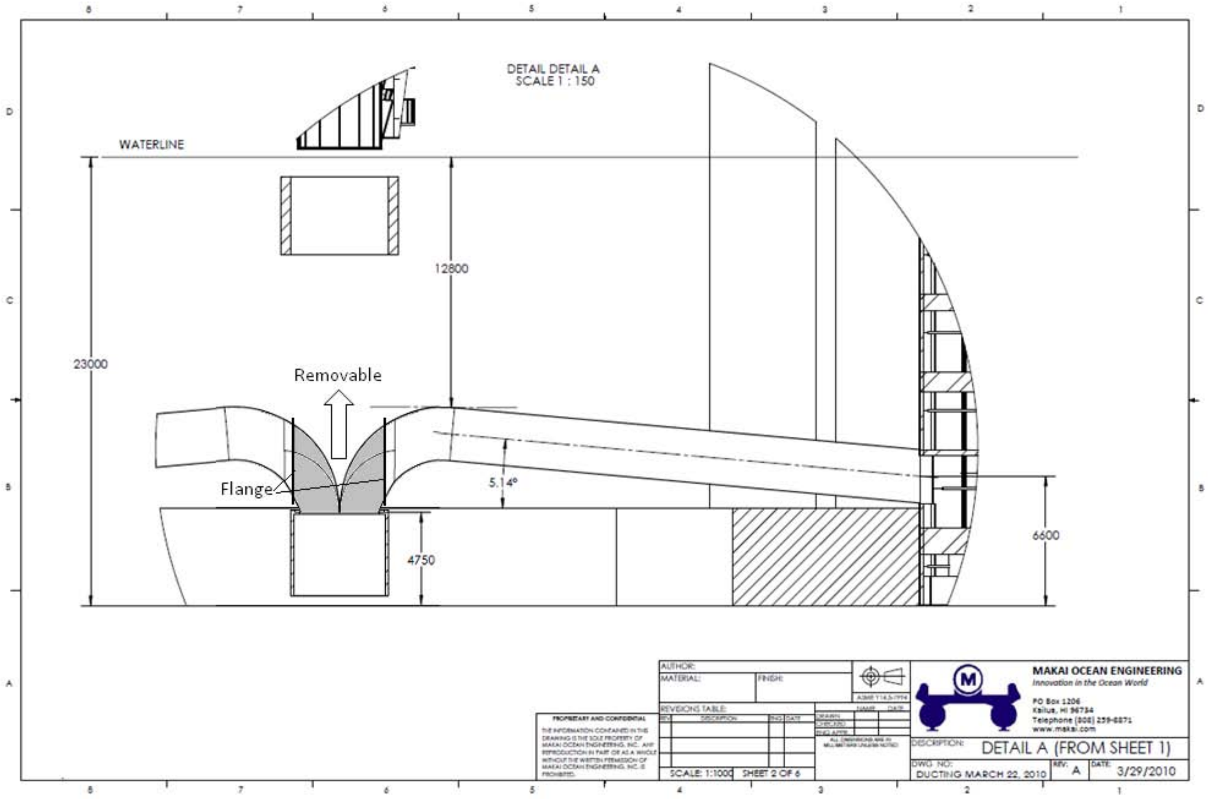


Figure 6 - Cold Water Duct Elevations

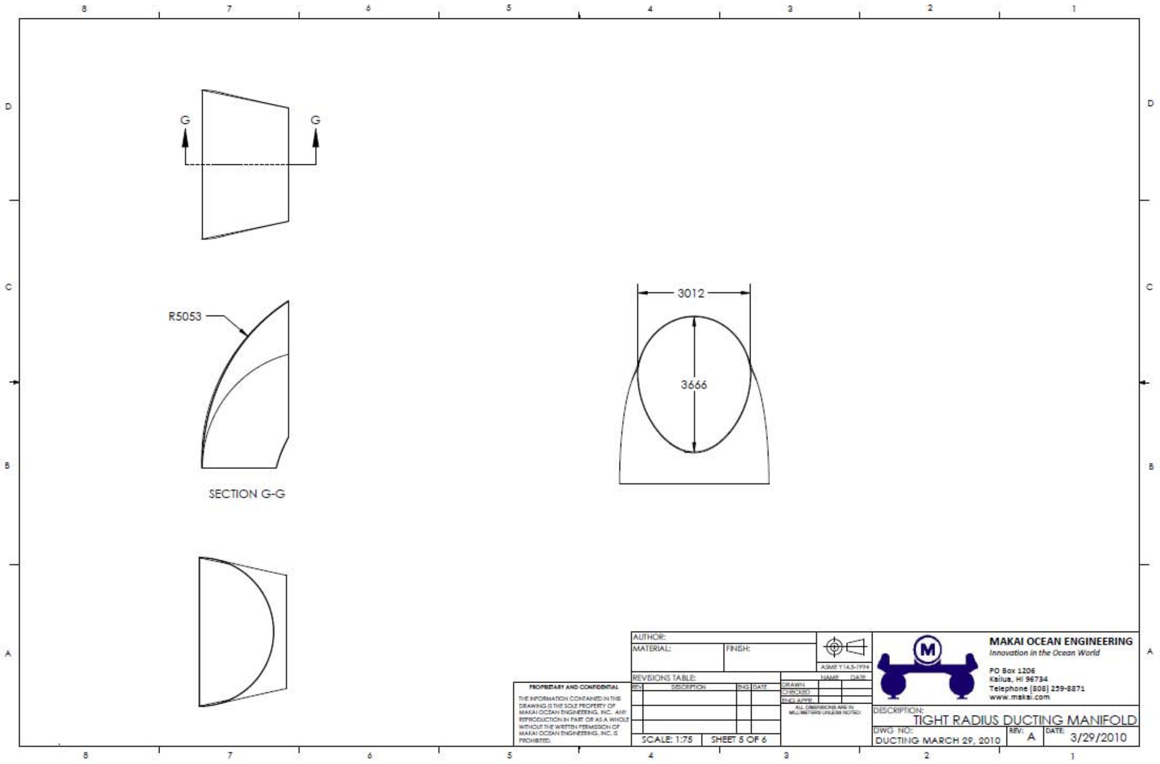


Figure 7 - Manifold Dimensions

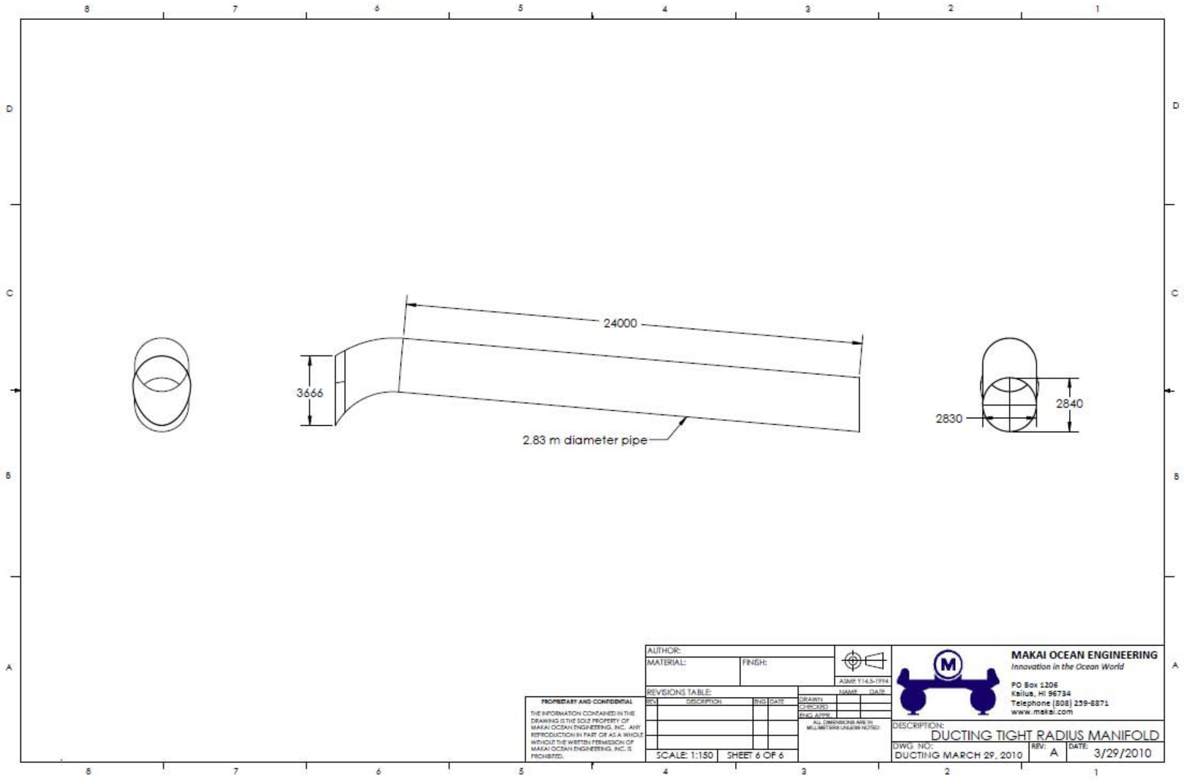


Figure 8 - Cold Water Duct Dimensions

2.2 CONNECTION TO CWP

The manifold cap will be lowered on to the top of the CWP termination flange and bolted in place. A spool piece will then be used to connect the manifold to the two cold water ducts.

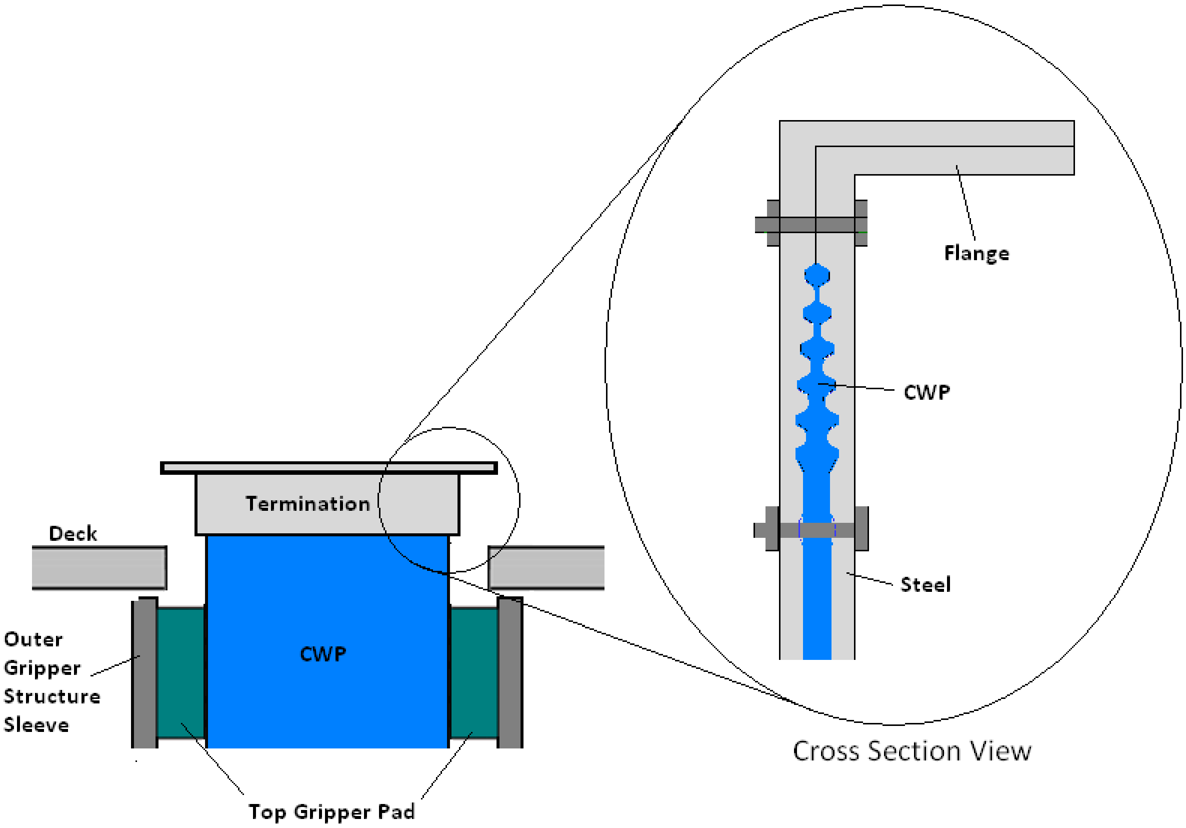
2.3 CONNECTION TO REMORAS

The cold water ducts will be attached to the remoras with a flex joint. The flex joint will be permanently attached to the end of the cold water ducts and capable of being attached/detached from the remoras.

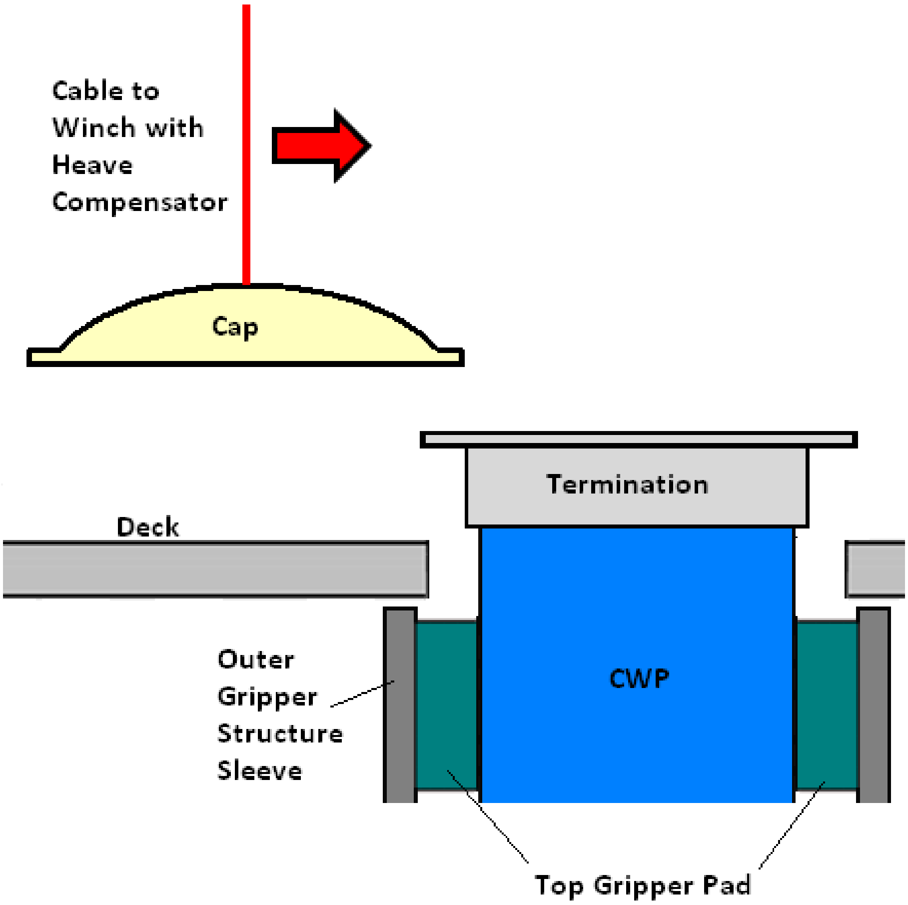
3. CONOPS

3.1 FINAL SEQUENCE

1) Fabrication of CWP complete. CWP held with grippers with end of CWP near deck level.
   a) Attach steel termination to end of CWP with bolts.

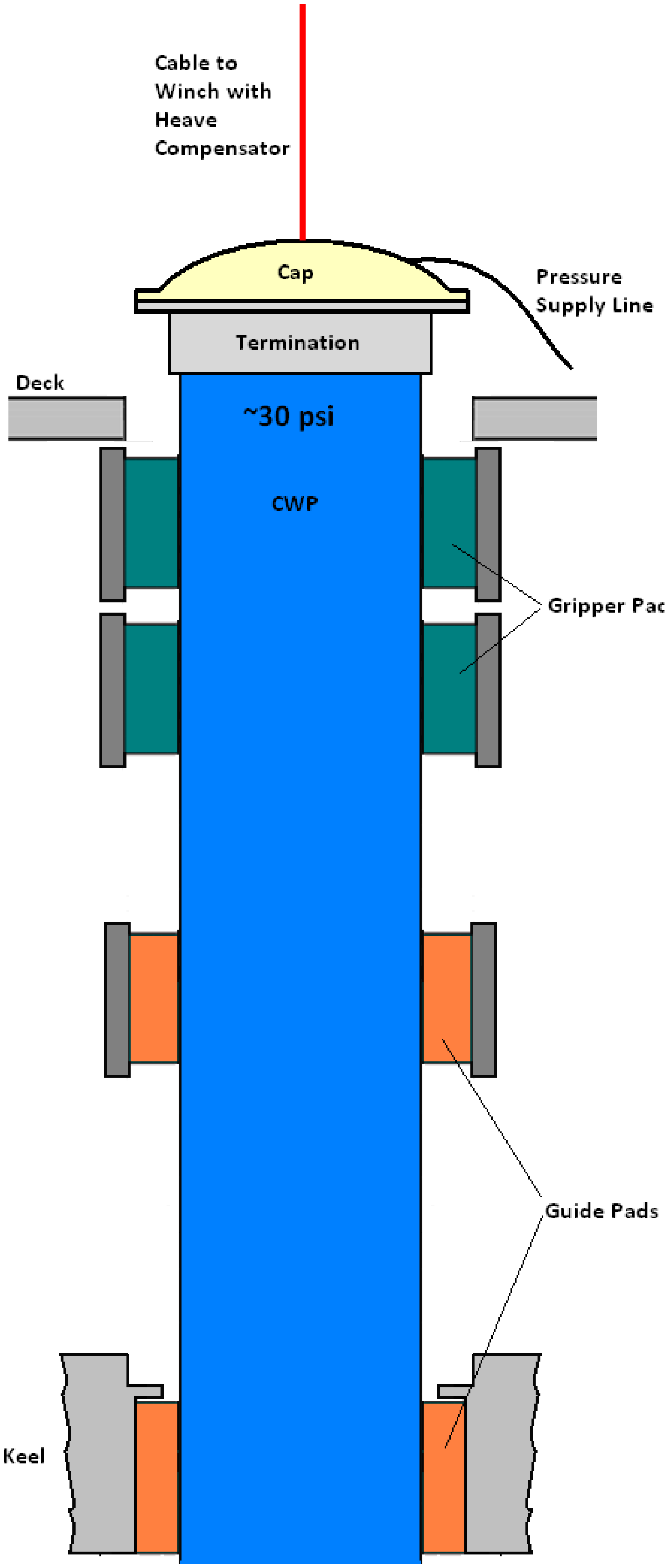


   b) Lift pre-assembled CWP cap with winch and move on top of CWP termination.



c) Blow pipe to ~30 psi.

   i) A large air compressor will be needed to provide the necessary air required for soft ballast control of the CWP.


Cable to
Winch with
Heave
Compensator
Cap
Pressure
Supply Line
Termination
Deck
~30 psi
CWP
Gripper Pac
Guide Pads
Keel

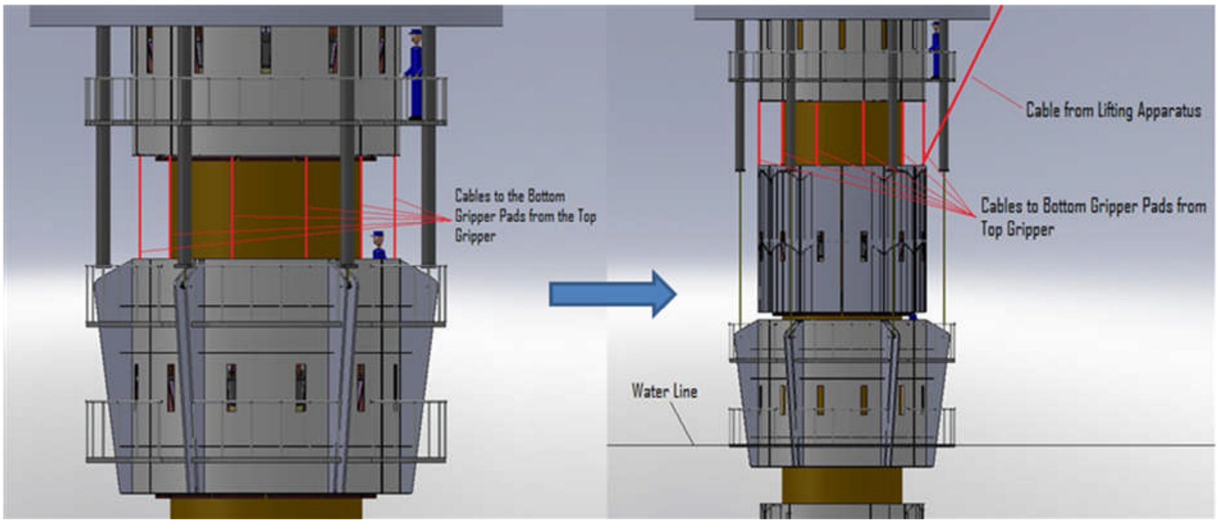
2) Weight of CWP supported by soft ballasting and winch with heave compensator. Both grippers disengaged.

   a) Remove gripper pads.

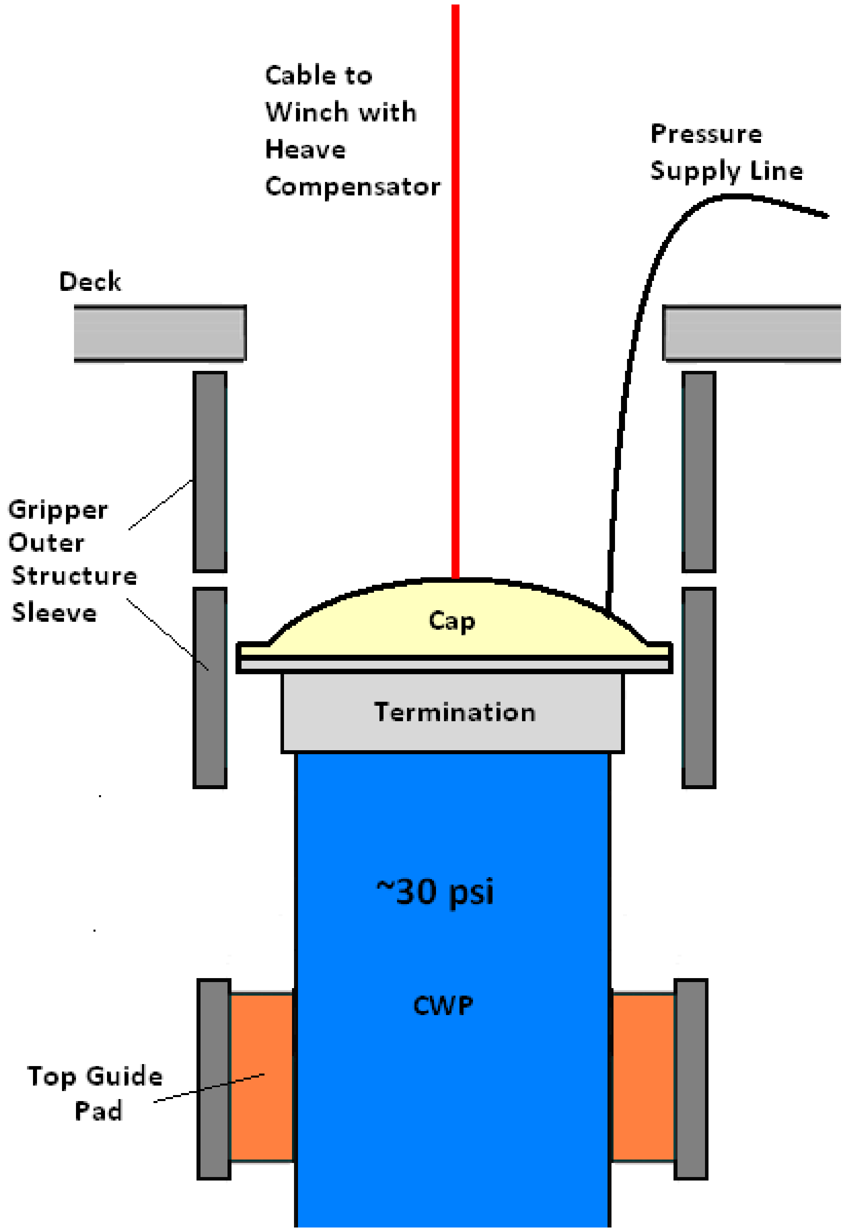
      i) The individual gripper pads must be removed from the outer structure sleeve to allow the flange on the termination to pass through.

      ii) Each gripper pad must be lifted out of the way and up to the deck.

      iii) One method of pulling out the gripper pads is to use the bottom gripper hydraulics to assist in pulling out all the pads at once. This concept is illustrated below.

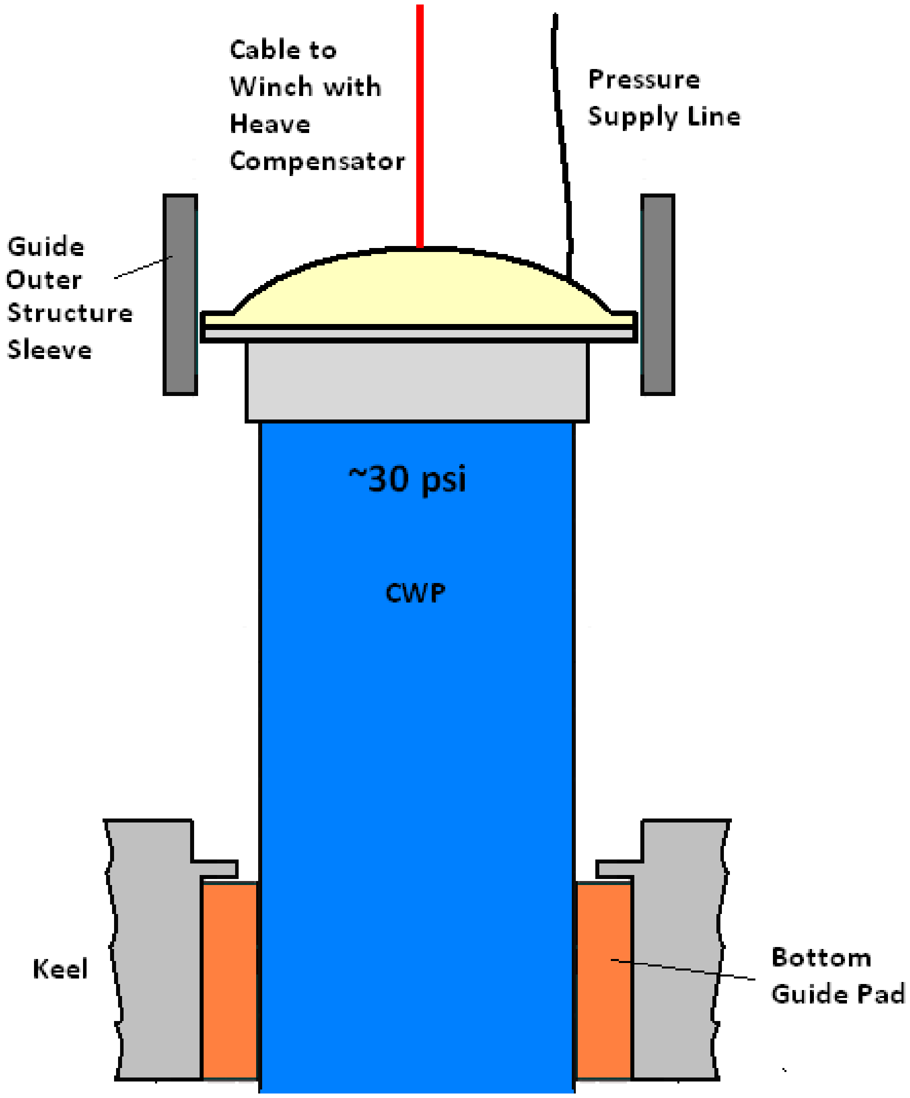


   b) Lower CWP through gripper outer structure sleeve.

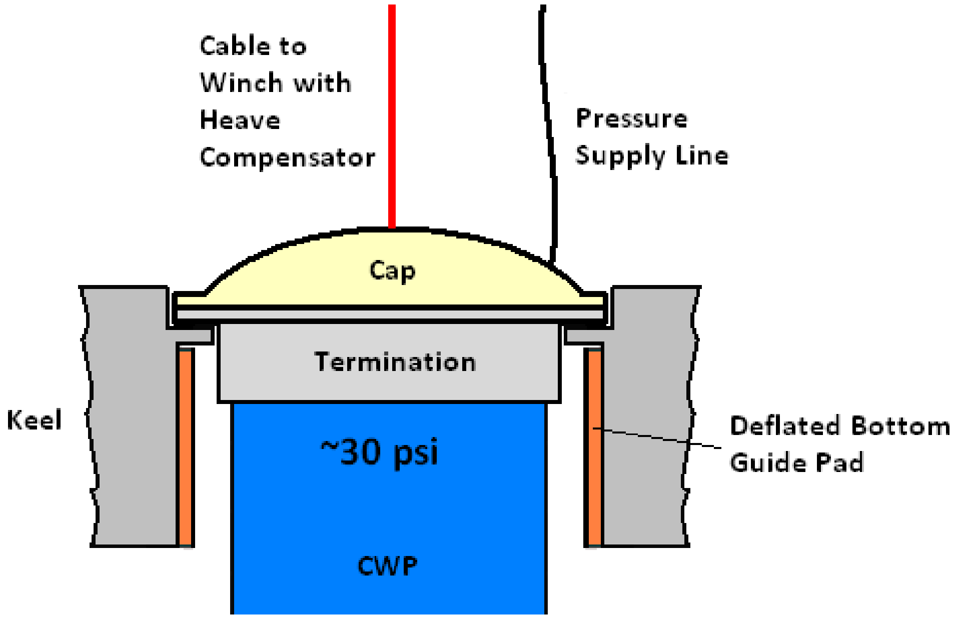


c) Remove top guide pad.

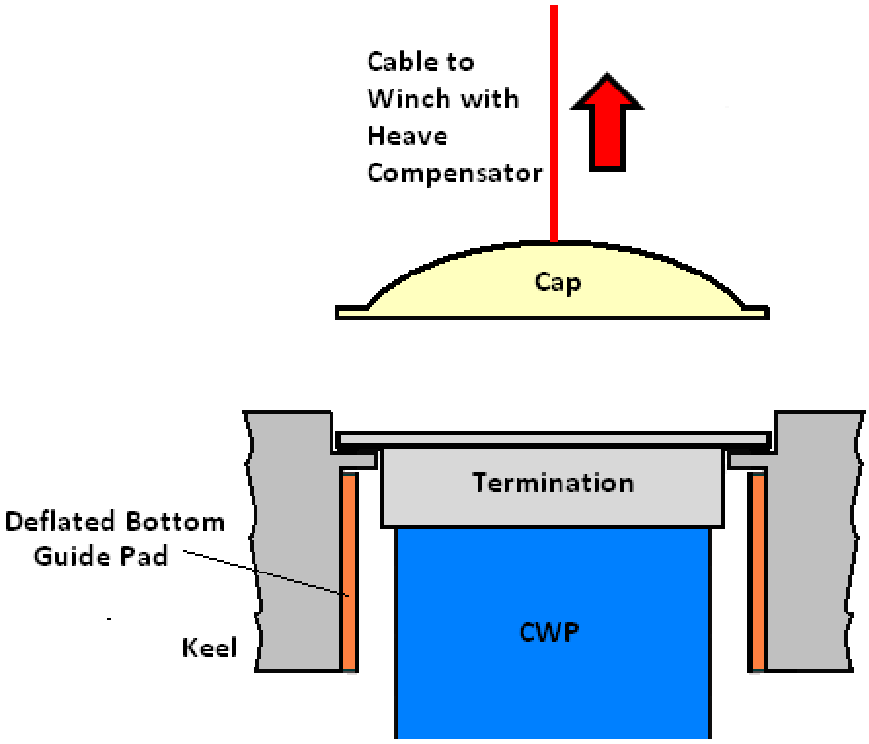
d) Lower CWP through top guide structure.



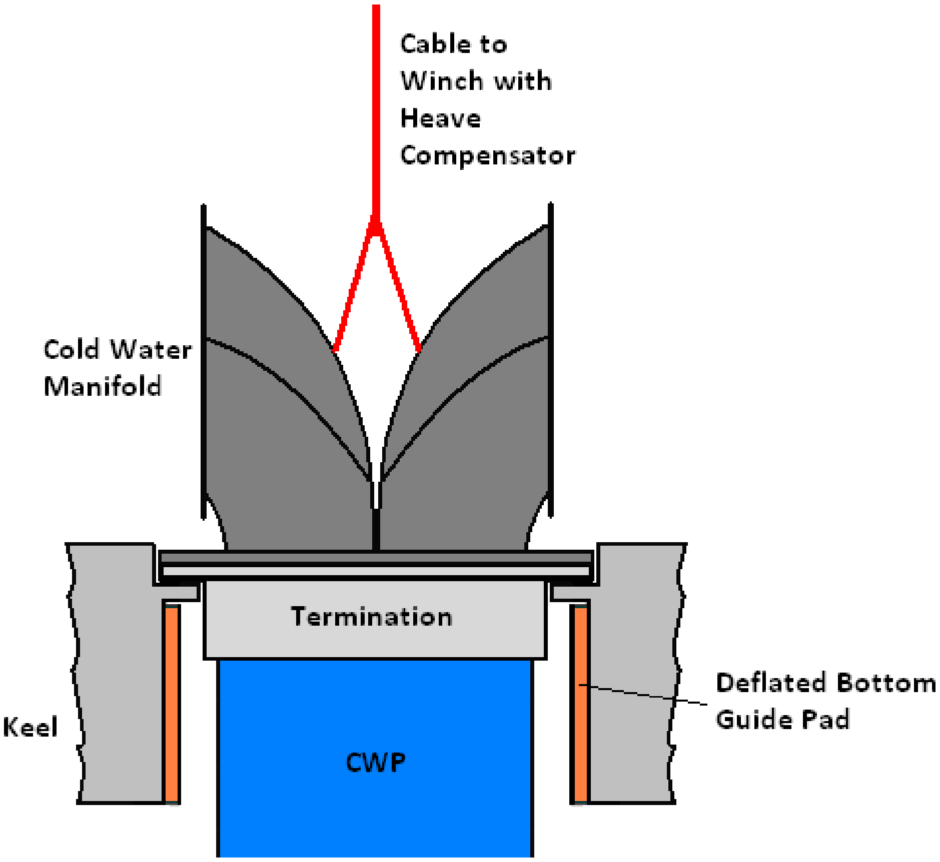
e) Lower CWP on to final position at the platform keel.



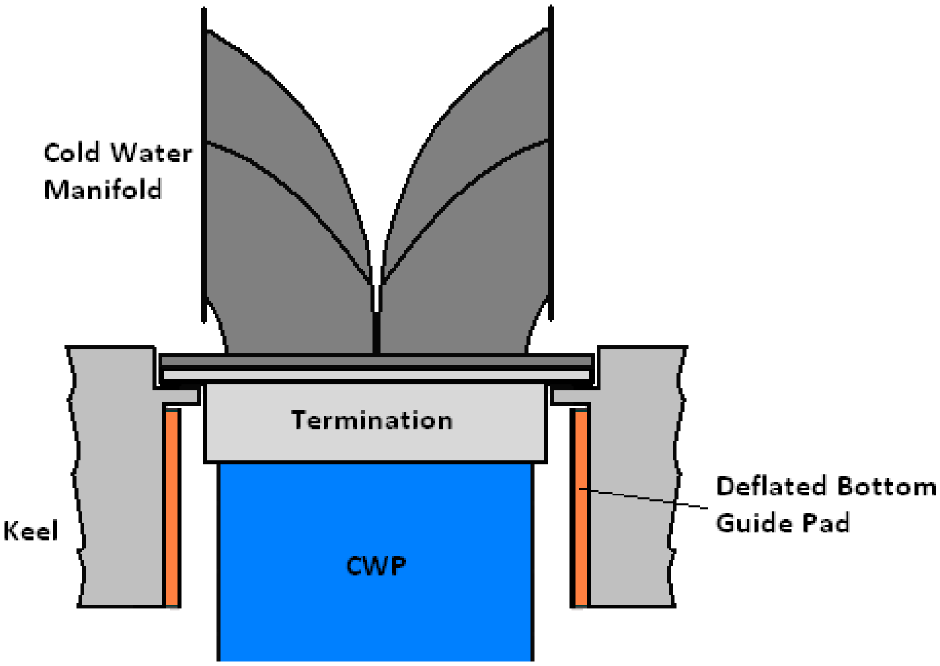
3) Weight of CWP supported by platform.
   a) Depressurize CWP and remove cap.

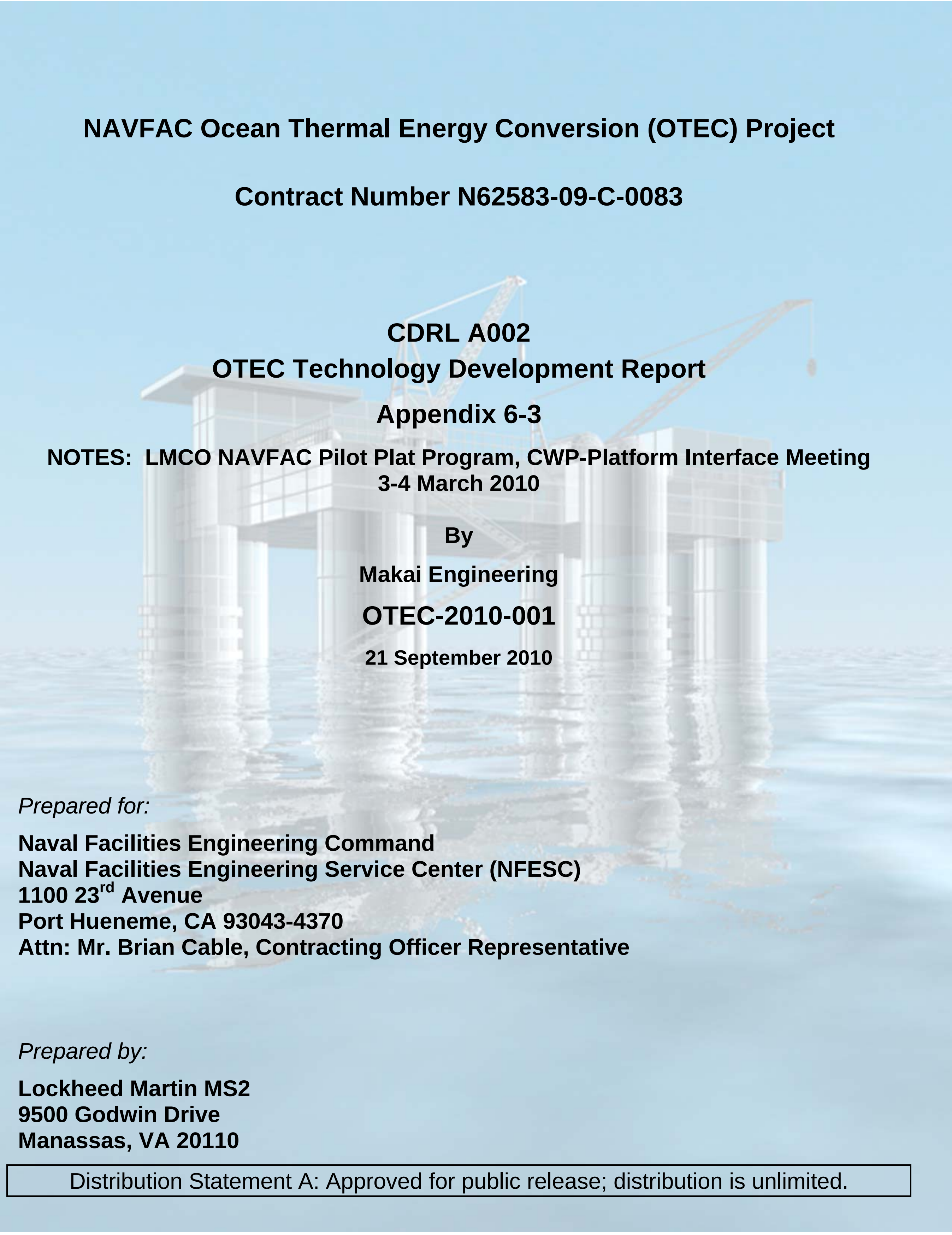


   b) Lower cold water manifold in on top of CWP termination.



c) Bolt cold water manifold in place. Attach manifold to ducts with spool pieces.





NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report

Appendix 6-3

NOTES: LMCO NAVFAC Pilot Plat Program, CWP-Platform Interface Meeting 3-4 March 2010

By

Makai Engineering

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
Naval Facilities Engineering Service Center (NFESC)
1100 23rd Avenue
Port Hueneme, CA 93043-4370
Attn: Mr. Brian Cable, Contracting Officer Representative

Prepared by:

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9500 Godwin Drive
Manassas, VA 20110

Distribution Statement A: Approved for public release; distribution is unlimited.

Notes: LMCO NAVFAC Pilot Plat Program, CWP-Platform Interface Meeting: March 3-4, 2010

Locaton: Houston Offshore Engineering

Joe Van Ryzin, Makai Ocean Engineering.

Day 2: Focus on Hardware Solutions to the CWP/Platform Interface Loads

Attendance:

Joe Van Ryzin, Makai
Nick Reese, Makai
Laurie Meyer, LMCO
Alan Miller, LMCO
Shan Shi, HOE
Ngok Lai, HOE
John Halkyard, Halkyard and Assoc
Garrett Lang (Navy, Bill Seelig associate)
Dennis How, Navfac (Day 2, Friday)
Dave Wilkinson, Navfac (Day 2, Friday)
ArcandraTahar, Horton
Mark Brown, SST

Agenda:

- Overview of the Design issues, likely solutions, logic for the day. Joe VR
- Discussion on 10M OPERATIONAL Mode
  - Review of Rainfall 10M lifetime results
  - Alan Miller discuss fatigue Life
  - Review of Preliminary Taper Results – and plans for future analysis
  - Decision: Gimbal or No Gimbal?
    - Gimbal Types
    - Case for a non-spider gimbal
    - Gimbal/NAVFAC Logic
- Discussion of 10M Fabrication Mode
  - Review of recent analysis for fabrication mode – max moments?
  - Review of Gripper-Guide current design
  - Can Guide re-arrangement solve problem? How much “problem” remains?
  - Level of improvement from weather window?
  - Level of improvement from ballasting down?
  - Level of improvement from deploying with remoras?
  - Step through logic: What is likely implemented?
    - do we need to increase pressure resistance of cwp?
- 4m NAVFAC discussion
  - Recent results: strain better or worse?
  - If Better – no decisions – repeat 10M approach
  - If worse – repeat logic of 10m + include stronger cwp
- Schedule for NAVFAC – when we can deliver:
  - Verification of Analytical solutions:
    - HARP, FLEXCOM, AQWA, AEGIR all agree
    - No funny stiffness solutions
  - Loads for the 4m platform

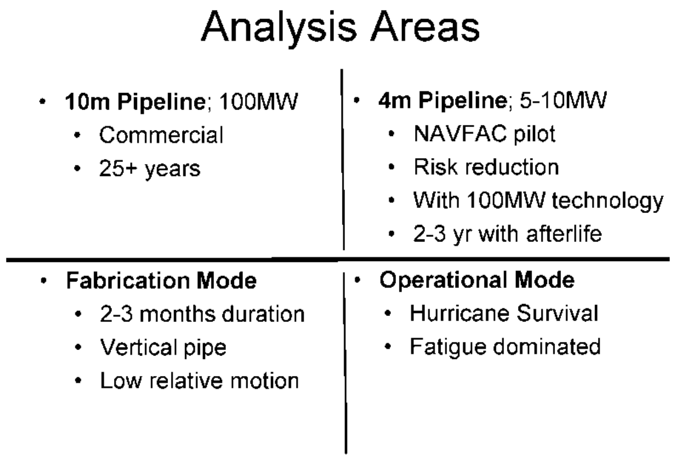
        - RainFlow Analysis
        - Taper Pipe Needed
        - Fabrication Loads
    - Final Decision on Gimbal
    - Decisions on Testing

also

- Navy Vessel of Opportunity
- Test Planning

DISCUSSION

Overview of the Design issues, likely solutions, logic for the day: the following shows the areas of focus: both the 10m and the 4m pipes, both operational and fabrication modes for each pipe.



Analysis Areas

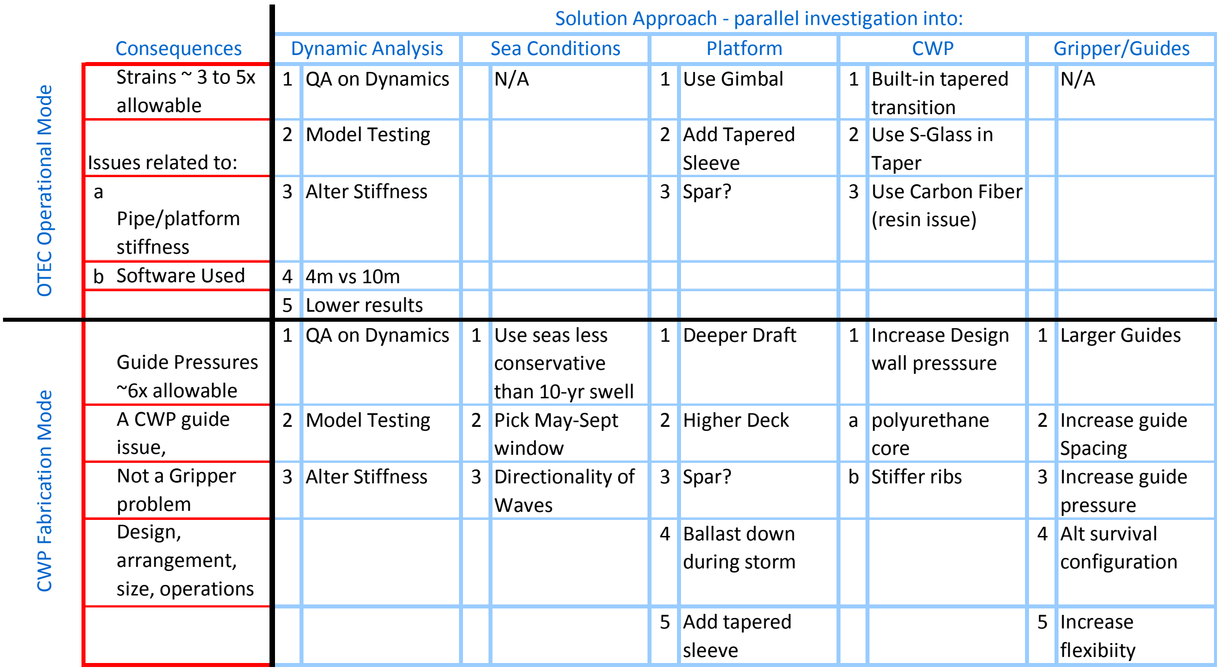
- **10m Pipeline**; 100MW
    - Commercial
    - 25+ years
- **4m Pipeline**; 5-10MW
    - NAVFAC pilot
    - Risk reduction
    - With 100MW technology
    - 2-3 yr with afterlife
- **Fabrication Mode**
    - 2-3 months duration
    - Vertical pipe
    - Low relative motion
- **Operational Mode**
    - Hurricane Survival
    - Fatigue dominated

The prior days review of the software tools for analysis of the CWP/platform interface summary:

- HARP now providing much lower strains – understand error with Jan/Dec runs.
- HARP believed to be best tool for future analysis – will need validation with new FLEXCOM, AQWA, AEGIR and ABACUS (4m) – particularly connection stiffness issues.
- Lots of calibration suggestions: sensitivity testing, including cwp in WAMIT, alternate connection stiffness, etc.
- Probably still have fatigue strain problem with cwp – more runs needed.
- Still have scheduling issues: 10m/4m/fabrication/platform solutions all needed soon.
- Making select set of runs overnight

Going into this week's meetings, the following summarizes the possible issues and the potential solutions that are to be investigated:

Impact and Possible Solutions to higher CWP/Platform Dynamic Loads:



		Solution Approach - parallel investigation into:				
	Consequences	Dynamic Analysis	Sea Conditions	Platform	CWP	Gripper/Guides
OTEC Operational Mode	Strains ~ 3 to 5x allowable	1 QA on Dynamics	N/A	1 Use Gimbal	1 Built-in tapered transition	N/A
	Issues related to:	2 Model Testing		2 Add Tapered Sleeve	2 Use S-Glass in Taper	
	a Pipe/platform stiffness	3 Alter Stiffness		3 Spar?	3 Use Carbon Fiber (resin issue)	
	b Software Used	4 4m vs 10m				
		5 Lower results				
CWP Fabrication Mode	Guide Pressures ~6x allowable	1 QA on Dynamics	1 Use seas less conservative than 10-yr swell	1 Deeper Draft	1 Increase Design wall presssure	1 Larger Guides
	A CWP guide issue,	2 Model Testing	2 Pick May-Sept window	2 Higher Deck	a polyurethane core	2 Increase guide Spacing
	Not a Gripper problem	3 Alter Stiffness	3 Directionality of Waves	3 Spar?	b Stiffer ribs	3 Increase guide pressure
	Design, arrangement, size, operations			4 Ballast down during storm		4 Alt survival configuration
				5 Add tapered sleeve		5 Increase flexibiity

3/3/2010

The agenda Commenced with the 10m pipe (need a solution here such that the pilot plant tests the commercial configuration). The discussion followed the following logic charts for both the 10m pipe in both the operational modes and the fabrication modes – the conclusions and results of the discussion are included in red.

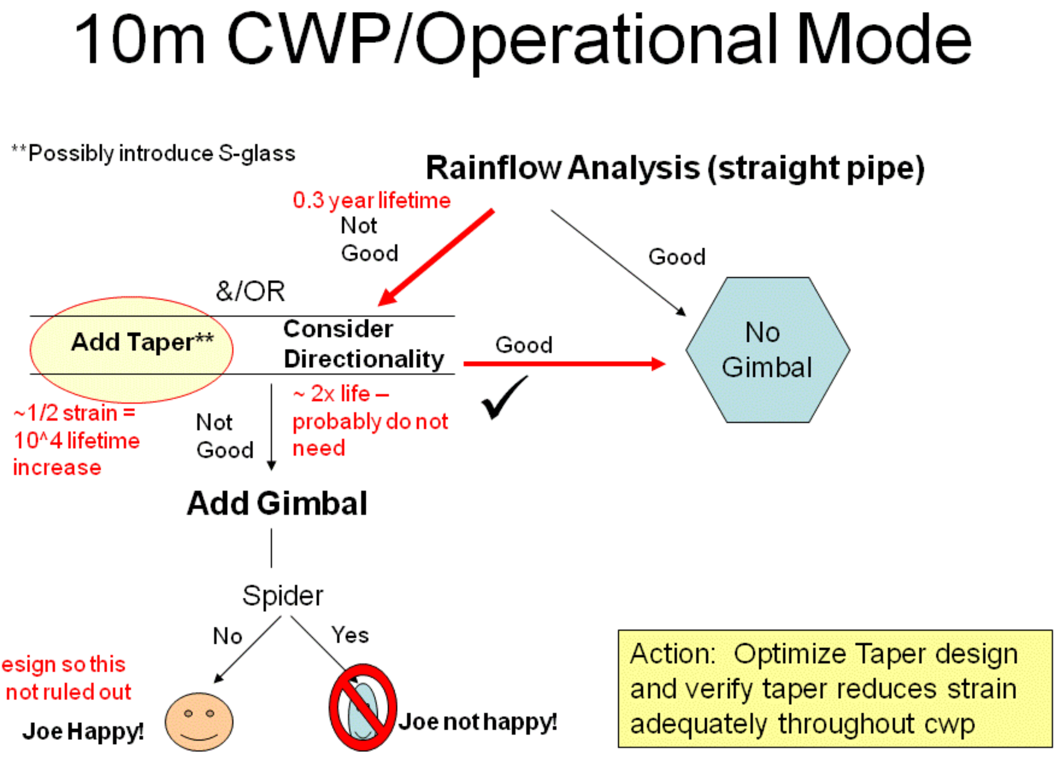
Operational Mode, 10m.

The 100MW platform has 14.25m columns on 58m centers. Moment to trim is 3x the HOE pilot plant platform.

Operational modes are governed by fatigue strength of the CWP. Hence strain is the driving factor. Shan Shi had run a fatigue analysis on the 10m pipeline connected to the original 100MW commercial plant in operational mode. This involved 16 runs for the 16 sea state bins identified by John Halkyard as being representative of a typical year at our site. Alan Miller took the results of these 16 bins (the annual total cycles and strain amplitude bins) and determined the fatigue lifetime of the CWP. This life was very short – a matter of months. Hence the first step in the logic tree – the red arrow pointing toward the Taper. Options then include:

- Adding a tapered section to the CWP at the platform connection can reduce the high strain at the top of the CWP.
- A minor improvement in life can be achieved by taking into the directionality of the waves. The fatigue analysis currently performed assumes that one part of the pipe receives the maximum strain caused by all the waves.

Shan Shi performed one only run on the 10m pipeline with a stiffened taper under bin 16 sea states. The CWP at the platform was given a 3x stiffness and the stiffness was tapered to 1x at a distance of 10 diameters from the platform. Under this analysis, the CWP strain at the platform connection reduced by a factor of 2.



10m CWP/Operational Mode

**Possibly introduce S-glass

Rainflow Analysis (straight pipe)

0.3 year lifetime
Not
Good

Good

&/OR

Add Taper**

Consider Directionality

Good

No
Gimbal

~1/2 strain =
10^4 lifetime
increase

Not
Good

~ 2x life –
probably do not
need

✓

Add Gimbal

Spider

No

Yes

Design so this
is not ruled out

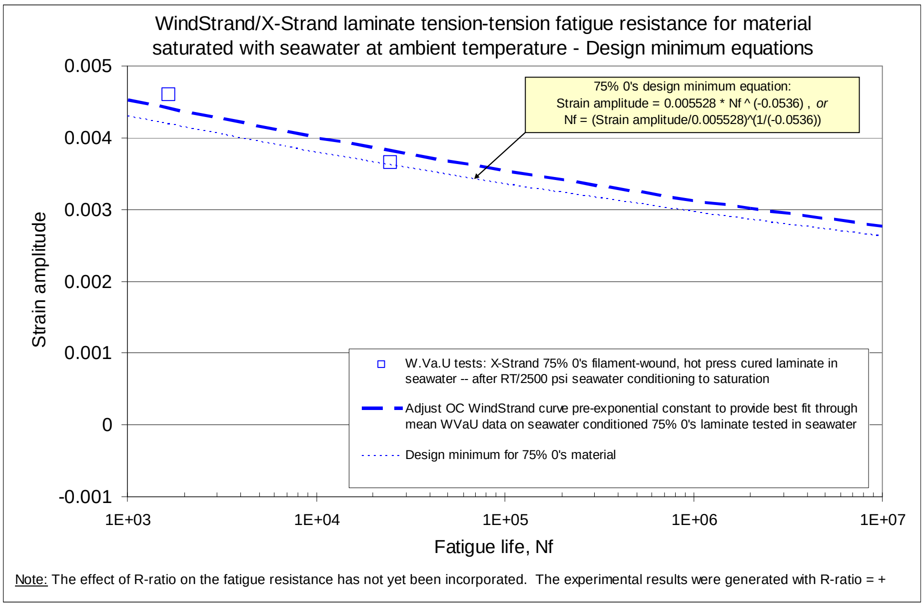
Joe Happy!

Joe not happy!

Action: Optimize Taper design and verify taper reduces strain adequately throughout cwp

Making the assumption that all the bin strains will decrease proportional to the decrease for the bin 16 sample runs, Alan Miller concluded that the lifetime of the CWP was considerably longer than the 30 years desired. The preliminary conclusion is that a gimbal is not needed.

It was observed that the dramatic improvement in lifetime with the taper is due to the very flat fatigue curve. Note that a 50% change in strain is equivalent to a 10^4 change in lifetime (Alan Miller graph):



Thus a gimbal can be avoided for this OTEC plant, assuming that these taper numbers and the dynamic analysis are correct. This needs to be checked carefully. We are vulnerable to:

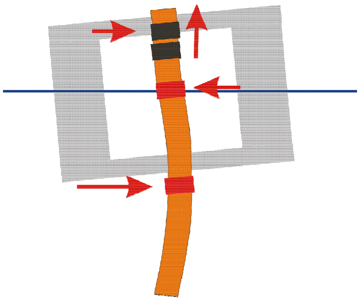
- Errors in the dynamic analysis code being used. This is in the process of being checked.
- The taper results were the result of bin 16 only analysis, not rainflow analysis. Thus we are extrapolating grossly on very sensitive numbers.
- The taper results were for the top of the pipe – there were no checks for other portions of the pipeline.
- This is the first taper analysis ever done on large CWP – overnight run from an over worked Shan Shi.
- Lifetime results are extremely sensitive to slight changes in strain.

If the above analysis is not valid, then a gimbal has to be considered. A gimbal eliminates the moments and strains at the platform connection. We have several design options for a gimbal:

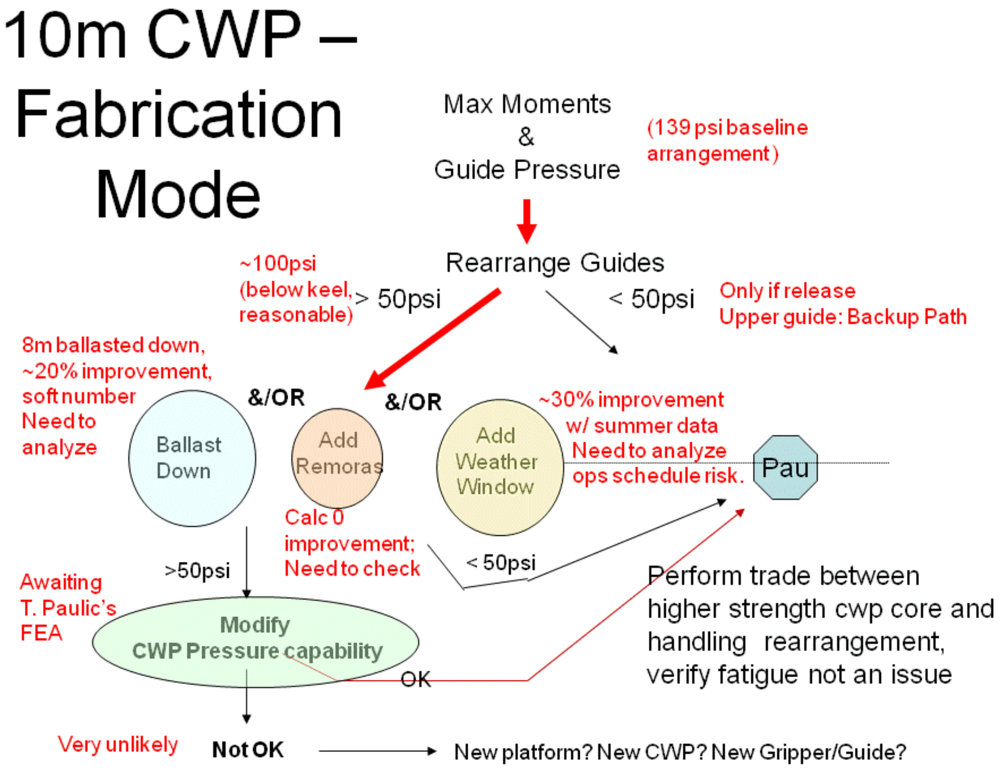
- Halkyard's offshore ball joint gimbal with a spider inside the pipeline.
- Makai's floating hydraulic table without inside pipe obstructions.
- A traditional gimbal with two gimbal rings but small motions – without inside pipe obstructions.

It was emphasized by Makai that a gimbal without internal obstructions is strongly preferred – particularly as a backup, because the CWP can be fabricated through this pre-installed gimbal at the base of the platform. Our overall CWP fabrication procedures and deck layout remain unchanged with or without a gimbal and the overall speed and reliability of the CWP fabrication would be improved. Hence, the backup gimbal would be one without internal obstructions. Of the two candidates, there was no decision.

Fabrication Mode, 10m.



The Fabrication process is driven by the peak forces imposed on the CWP from the two guides (red rectangles on the right). At present, the CWP is designed to withstand a working external clamping pressure of 50 psi (100 psi failure). The pads are fluid filled to provide a uniform pressure over the contact surface of the CWP.



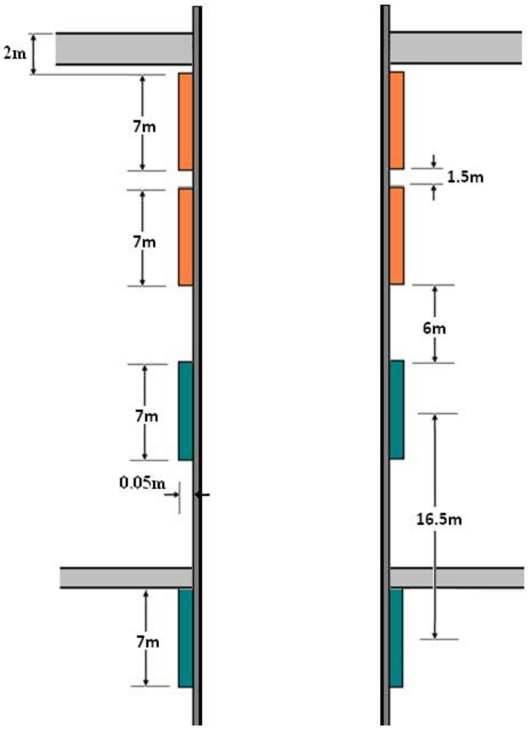
Shan Shi provided loads for further fabrication analysis:

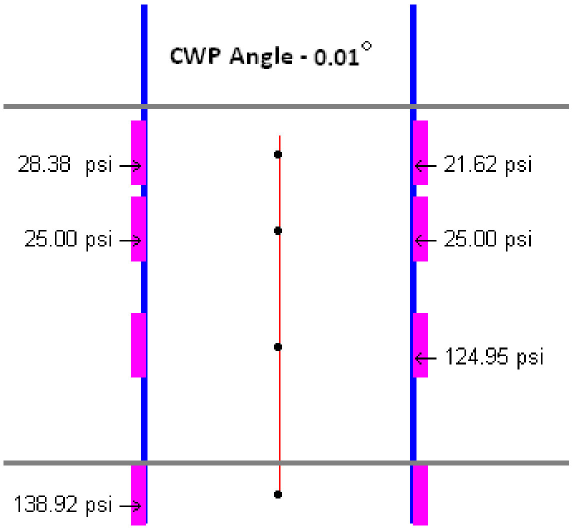
- Pipe Size: 10m
- Pipe Length: 500m
- Loading: 10 yr Swell
- Connection Stiffness: 1.3 x 10^{11} N-m/rad (Stiffness of gripper/guide baseline design)

<u>Output from Dynamic Analysis</u>

- Max Moment at Bottom Guide: 6.2 x 10^{8} N-m
- Max Shear Force at Bottom Guide: 7.1 x 10^{6} N-m

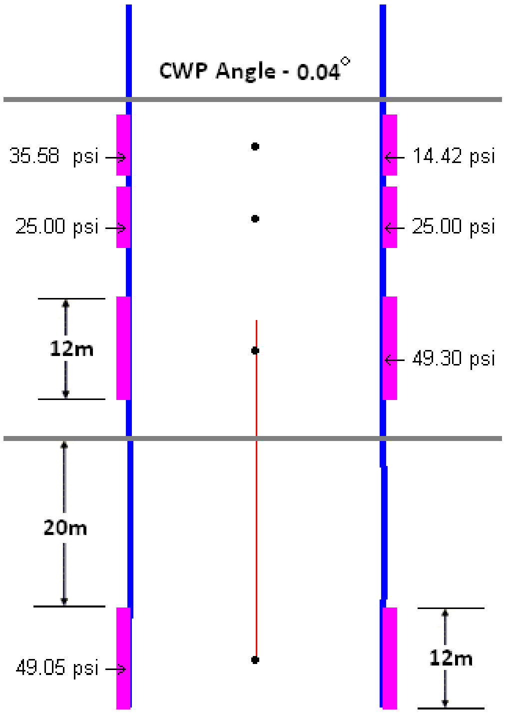
With the December/January arrangement of the guides in the handling system, the peak pressure in the guides is 139 psi (shown below). This is too high for the CWP so alternate arrangements need to be considered.





The logic applied to the fabrication mode is shown below – major conclusions and comments are shown in red.

It was first considered what could be achieved by re-arranging the guides and grippers and considering alternate operational procedures of these components during inclement weather. Two cases were developed based on the peak moments and shear developed during an analysis run from the 10-year max swell and 500m of pipe fabricated (worst case from earlier - admittedly flawed - study).

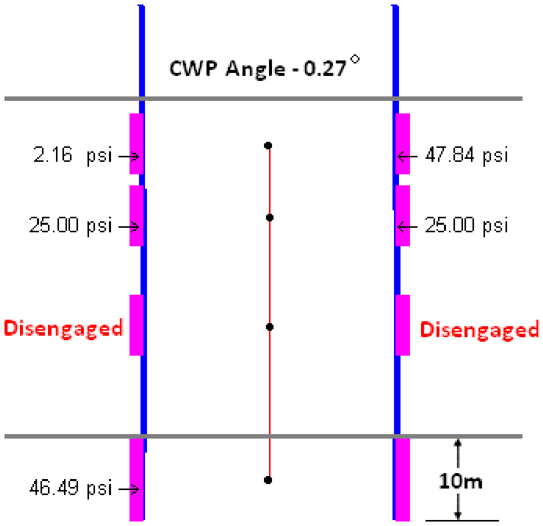


It was first determined what could be achieved by re-arranging the guides and grippers and considering alternate operational procedures of these components during inclement weather.

Design Alternative 3 is a possible gripper and guide arrangement in which the top guide is permanently in place. In order to keep the pressure below 50 psi in the pads, the bottom guide must be lowered 20m below the keel and the length of the guides increased to 12m. All the gripper guide locations and dimensions are identical to the baseline design except for those explicitly shown below. Note that the CWP angle at the deck level (in the upper gripper) is 0.04 degrees. The upper gripper does not need to be gimbaled.

Design Alternative 4 to the right is a possible gripper and guide arrangement in which the top guide is able to be disengaged during inclement weather. The size of the grippers and guides is very similar to the baseline design except that the bottom guide is increased to 10m. All the gripper guide locations and dimensions are identical to the baseline design except for those explicitly shown.

The upper CWP angle in this configuration is 0.27 degrees – sufficient to force the upper gripper to be gimbaled. The gimbaled upper gripper and the retractable upper guide are not insignificant costs for this concept – although pipe pressures can be within the desired 50 psi.



It was concluded that neither option, as shown, is desirable but that some new arrangement could be made to considerably reduce pipe pressures. Hence in the flow diagram, consideration was then given to alternate methods of reducing the loads in the CWP. These include:

- Ballast down the platform.

	Normal	Down
Draft	20m	28m
Air Gap	13m	5m
Heel deg	.08	.06
T pitch sec	30.2	26.2
Max Pitch deg	1.5	0.9

  Conclude that we might improve strains by 40% assuming response is linear to max pitch however problem is much more complex and this was a crude computation of platform characteristics only using a weight for the CWP (no stiffness). Estimated improvement is 20%.

- Add remoras. Shan Shi did a simulation of the 100MW with and without remoras on 10-year swell. Results were similar which was a surprise. Max strains of 0.0035 (stiff 10^{14}) with Remoras and 0.00365 (stiff 10^{12}) without. For now, we have concluded that this is not a viable method of reducing strains.
- Select a narrow weather window. The current design conditions are for 10-year swell and 10-7ear waves for the entire year – these are worst case over a 10-year period. If we look at the best continuous 6 months at the HI site, we can reduce the sea states. John Halkyard has

presented some curves of the statistical mean Hs and standard variation for each month at our HI site. In winter, the mean Hs plus two sigma is 3m while the same value over the 6-month “summer” timeframe is 1.9m. Therefore, there is a ~33% reduction in peak sea state if we pick a narrow window for fabrication. We estimated that the strains are proportional to the Hs (in traditional frequency domain analysis). To verify this, we looked at several cases in the operational mode:

o		Hs	Tp sec	Strain
o	Bin 16	2.4	16.9	.0033
o	Bin 12	2.3	14.0	.0034
o	Bin 9	0.9	13.6	.0011
o	Bin 11	1.6	13.6	.002

By comparing bins 12 and 16, we have similar results for similar Hs and not a strong influence from period. Bins 9 and 11 show a rough 2:1 relationship supporting the assumption that we might see a ~33% reduction in strains by restricting ourselves to the summer months.

There was some discussion of whether this is practical. Can the CWP fabrication be ready at the beginning of this window – there would be little room for a schedule slip. This needs more discussion.

Another option is the increase the 50psi limit on the pipe pressure. LM has not completed this analysis. It is highly probable that foaming the core of the CWP will provide a larger gripping and guide pressure, but there was some difficulty with the FEA analysis and confirming results were not in.

In conclusion, we did not end up with an obvious path toward a safe fabrication scenario for the 10m pipe but there are sufficient options to conclude that it will be feasible. The possible routes are summarized as:

- Do it completely with the re-arrangement of the grippers. Shown are two possibilities – each of which come with a cost penalty but could be accomplished if needed.
- A combination of the above with either ballasting down or the selection of a weather window. Adding these features may relieve some of the costs of the guide/gripper rearrangement.
- Adding higher pressure capability on the pipe greatly relieves the need for extreme guide and gripper rearrangement.
- Or some combination all of the above.

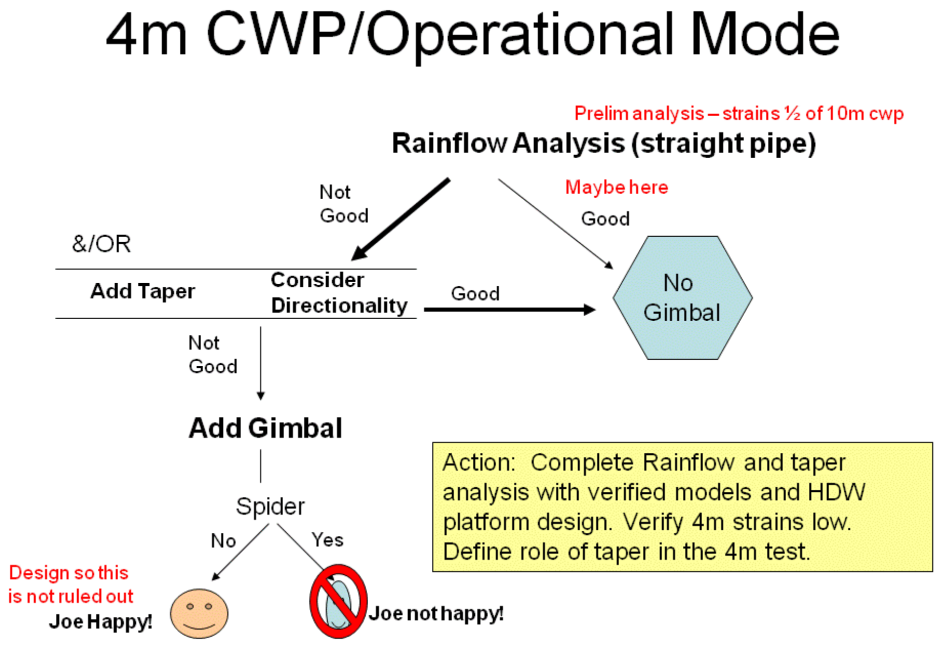
Final conclusion will have to be worked out between Alan and Joe – doing a trade-off between the added costs to the gripper/guide system and the cost of the CWP. Keeping in mind that we are not designing a final 10m pipe and handling system right now – our goal is to be sure we do have one or more paths toward a successful deployment of the 10m and to incorporate whatever methodologies are needed for the 10m into the 4m design if this is a critical technology.

Operational Mode, 4m.

In an analysis of the 4m pipeline, Shan Shi also ran the 2008 pilot plant platform with the version 2 4m CWP on Bin 16 sea states. The stiffness of the connection for both runs was the equivalent of 3m of CWP.

	10m	4m
Bin 16 max strain	.0031	.0017

The conclusion based on these preliminary runs is that we do not have a similar high strain issue with the 4m CWP. In fact, it might be possible to have a greatly reduced taper on the 4m pipeline. This will take further discussion – how much taper is to be added just to gain the practice and confidence of building the taper on the 10m pipeline?



4m CWP/Operational Mode

Action: Complete Rainflow and taper analysis with verified models and HDW platform design. Verify 4m strains low. Define role of taper in the 4m test.

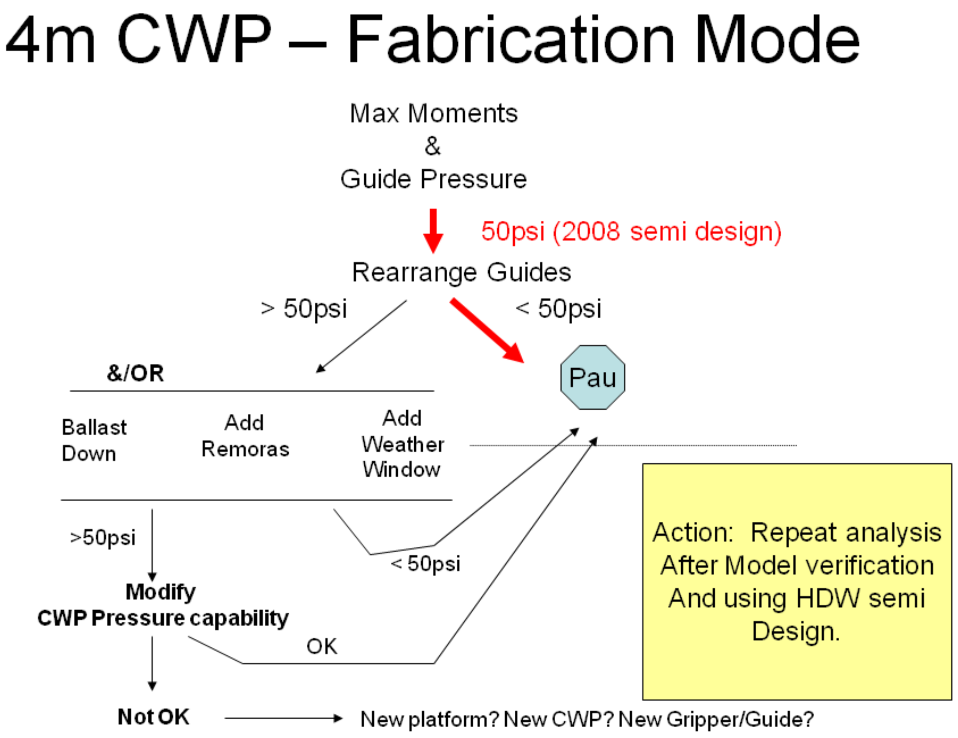
Fabrication Mode, 4m.

Similarly, Shan Shi compared the max strains during fabrication

	10m	4m
10-yr swell	.0045	.0054

This was surprising since we did not see the same relationship as in the operational mode. The above is without remoras. We need to confirm these results and check overall fatigue of the CWP.

1.



4m CWP – Fabrication Mode

Max Moments
&
Guide Pressure

50psi (2008 semi design)

Rearrange Guides

> 50psi

< 50psi

Pau

&/OR

Ballast Down

Add Remoras

Add Weather Window

>50psi

< 50psi

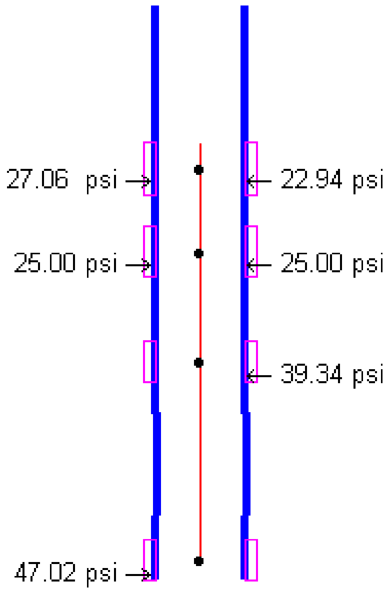
Modify
CWP Pressure capability

OK

Not OK

New platform? New CWP? New Gripper/Guide?

Action: Repeat analysis After Model verification And using HDW semi Design.



Rearrange 4m guides: We analyzed the gripper/guide arrangement with the maximum moment and shear values during fabrication of the 4m pipeline.

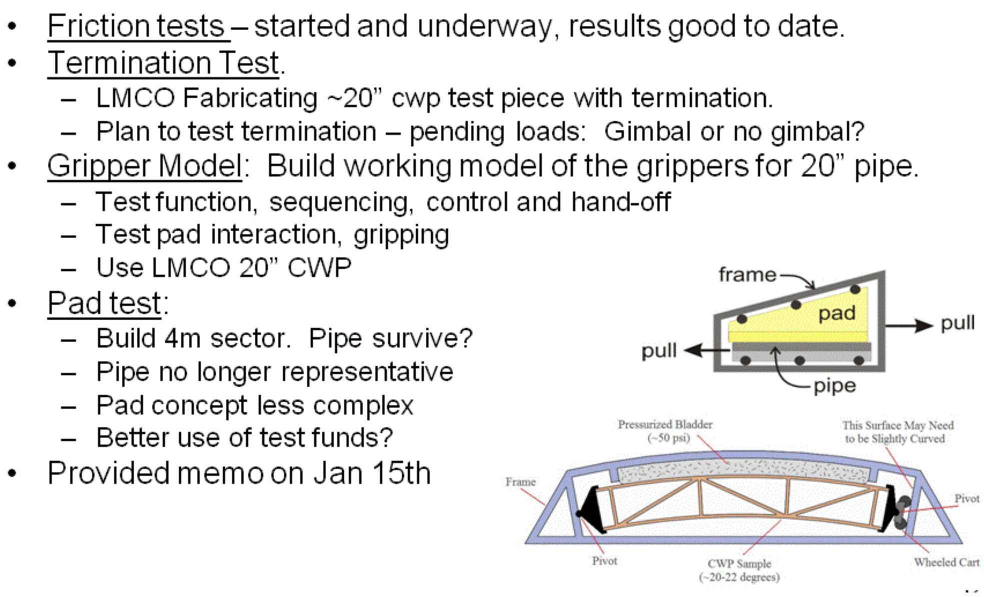
- Pipe Size: 4m
- Pipe Length: 500m
- Loading: 10 yr Swell
- Connection Stiffness: 1.0 x 10^{10} N-m/rad (Stiffness of gripper/guide baseline design)
- Max Moment at Bottom Guide: 4.5 x 107 N-m
- Max Shear Force at Bottom Guide: 1.0 x 106 N-m

Therefore the pressures on the 4m CWP are not excessively high and no rearrangement is necessary. This is probably due to the fact that everything on the 4m pipe scales down except the elevation of the platform – the relative distance between the guides on the pilot plant can be much greater than for the 10m pipeline on a platform of identical overall height. There is not a need to neither gimbal the upper gripper nor open the upper guide during extreme events.

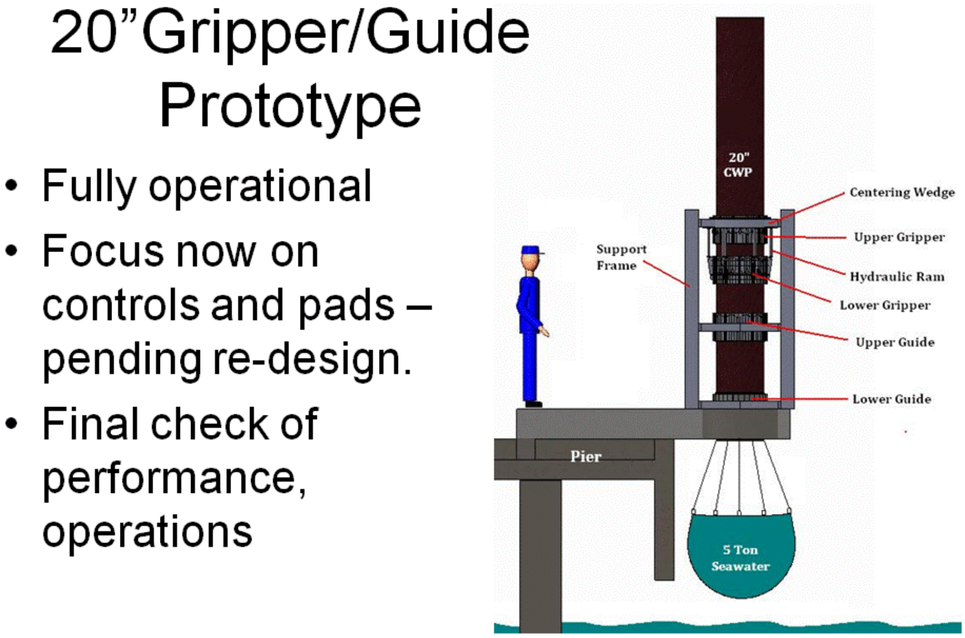
Lowering the strains with weather windows or ballasting down on the 4m cwp were not investigated. It is assumed that the relative value of these techniques would be similar to the 4m pipeline.

TESTING PROGRAM

Under NAVFAC we are planning several tests:



- Friction tests – started and underway, results good to date.
- Termination Test.
  - LMCO Fabricating ~20" cwp test piece with termination.
  - Plan to test termination – pending loads: Gimbal or no gimbal?
- Gripper Model: Build working model of the grippers for 20" pipe.
  - Test function, sequencing, control and hand-off
  - Test pad interaction, gripping
  - Use LMCO 20" CWP
- Pad test:
  - Build 4m sector. Pipe survive?
  - Pipe no longer representative
  - Pad concept less complex
  - Better use of test funds?
- Provided memo on Jan 15th



20"Gripper/Guide Prototype

- Fully operational
- Focus now on controls and pads – pending re-design.
- Final check of performance, operations

The test program can now proceed with some major interface questions being answered; in particular that there is no gimbal. Conclusions are:

- Frictions tests are unchanged – and are underway.

- Termination Test can proceed with plans for a rotary fatigue test. Alan and Joe need to work out details such that the moments on the 20” sample are acceptable for the test machine at Stress engineering and that the time to failure is within the budget for renting the machine.
- Gripper Model can proceed – concepts for the arrangement are adequately defined.
- Pad Test – this test still lacks definition. If increasing the pressure capability of the CWP is a key technology; then this test can test foamed and non-foamed sections of 4m CWP.

Vessel of Opportunity Discussion:

A brief discussion on how difficult it will be for a ship of opportunity to have comparable motions to our platform for the CWP fabrication. One possible approach would be for the vessel to live boat during fabrication and stay bow into the weather. Then move into a mooring once the CWP is completed and protected by a taper.

Discussed whether we would want a gimbal for the ship of opportunity when it is not needed for the SSP. Concluded that this would be a poor test of the CWP.

Proceeding with NAVFAC program:

Gimbal: A gimbal is not needed based on the data provided during the meetings. We proceed without the gimbal but do not rule it out in the future. For the least disruption to the plans and designs that are ongoing, if a future gimbal is needed, we reserve a space at the base of the platform for a gimbal without internal structure. The pipe can be deployed through this gimbal with no changes to the topsides or the fabrication plans. We have two gimbal concepts that could do this.

Termination**:** We need a tapered termination on the CWP to reduce the CWP strains. Shan Shi needs to do an analysis to determine the shape of that taper (minimum length) and Alan Miller needs to incorporate that concept into his CWP fabrication process and into the termination.

Gripper Guide Arrangement: We need to design a 4m gripper/guide that reflects properly the technical issues that are in the 100MW platform and CWP. Do we design a 4m handling system now that includes the added complexity of a gimbaled upper gripper and a releasable upper guide? At present, that is one of several solutions to the 10m handling system based on analysis of a nominal 100MW platform. The final 100MW platform will likely be larger and deeper (as is the pilot plant) and thus more stable. Furthermore, we are likely to be able to take advantage of increased pipe pressure, ballasting down, or weather windows to reduce the loads. Makai is recommending that we proceed forward as follows:

1. We compute a gripper/guide arrangement that minimizes pressure on the 10m CWP without having to release the upper guides and without extending the lower guide an unreasonable distance. That pressure will be higher than 50 psi.
2. We pick a combination of weather windows and ballasting down to limit this pressure to 50 psi. This is then our 10m baseline case. In the future as we complete the 100MW design, this baseline will undoubtedly change.
3. We keep in the option to insert a gimbal at the base of the platform – a internal structure free gimbal that we can push the CWP through.
4. We proceed forward and design the 4m gripper with the March 3-4 4m loads we now have. We do not include a gimbaled upper gripper nor a releasable upper guide. This would add considerably to the cost of the pilot plant, these features are not needed for that plant, and this would be testing components that we most likely will not need and would try to avoid for the commercial OTEC plant.
5. When the 10m dynamic analysis is recomputed, we settle on a configuration and operational procedure that allows us to operate with the baseline gripper/guide arrangement.
6. We build our scale model based on this 10m nominal design.

The above procedure is taking a calculated risk that once we complete the 100MW design details (this level of detail is not part of the NAVFAC contract) that we will need a more complex gripper/guide. Where we now stand, it appears that we can most likely avoid that situation on the 100MW plant but there is a finite risk that we are wrong. This is our proposed approach.

If, on the other hand, we assume a more complex gripper/guide solution for the 4m pipeline, we are adding to the cost of the pilot plant and increasing the complexity for something that is clearly not needed for the 4m pipe and is quite possibly something not needed for the initial Hawaii 100MW OTEC plants.

Post Meeting Recommendations for the next rounds of Dynamic Analysis:

1. Double Check these runs ASAP: The Following runs were input to critical decision points at our March 3-4 meeting but were done quickly and should now be checked carefully. Shan write a short report summarizing results.
    a. Post Analysis of the data from the 10m RainFall analysis from HARP. Double check the totals of the cycles and Alan's evaluation of the total cyclic life that is consumed. No need to repeat the runs of the 16 bins immediately (this comes later). The cumulative cycles and strains are critical – small changes affect very strongly the lifetime, Go over numbers and total count – are they correct? Shan double check his summary spreadsheet and provide results to Alan who will check his analysis.
    b. Confirm that the taper we ran for bin 16 drops the strain by ~50% as we believe (10D taper length, 3X stiffness at platform, stiffness linear), What is the strain curve along the pipe length (no peak strain somewhere else)?
    c. 10m bin 16 with remoras vs. 4m bin 16 with remoras: had .0035 vs. .0017 strains respectively: Is this correct that 4m pipe has about half the strain during operations?
    d. Fabrication w/o remoras 10m 10-year swell vs. 4m 10-year swell w/o remoras. Had strains that were at .0045 and .0054 respectively. Are these correct? They are suspicious because the 4m is worse than the 10m. Also, the values are high and challenge our assumption that fabrication is governed by the pipe pressure and not the fatigue. These are right on the edge of being acceptable for a single low-cycle storm.
        i. Halkyard points out that these worst case swell conditions only occur within a few months – so they can be avoided if needed.
2. Validation (or verification) of codes (assume done before the end of March):
    a. Run HARP & Flexcom and AQWA on same bin 16 sea state condition. Have stiffness in Harp equal to short pipe segment stiffness. Verify that we have similar results in terms of pipe strain at the top and platform motions.
    b. HARP platform motions are unreasonably overly sensitive to CWP/platform stiffness and this is assumed to be a numerical issue. Confirm what the issue is and that future runs will not have similar issues.
    c. Check for sensitivity to number of frequencies used and number of plates used and include the CWP in the WAMIT analysis.
3. The following will be needed to get Makai started on the 4m gripper design completion and the physical modeling of the 10m gripper/guides: moments and shear and axial tension at top of cwp and axial strain. Values vs. time in Excel. All for 500m and 1000m pipe – end of March:
    a. 4m, 2008 platform, w/o remoras. 10-year swell and sea – Stiffness = (Makai to provide)
    b. 4m, 2008 platform, w/o remoras. 90% year swell and sea– Stiffness = (Makai to provide)
    c. 10m, 100MW platform, w/o remoras. 10-year swell and sea – Stiffness = (Makai to provide)
    d. 10m, 100MW platform, w/o remoras. 90% year swell and sea– Stiffness = (Makai to provide)
4. Makai needs RAO's of the 4m platform with the pipe suitable for an ORCAFLEX run under normal operating conditions and under storm conditions. We will use this to compute and iterate on dynamic solutions of the pipe within the gripper pads and guides. – end of March

    a. J Halkyard points out that RAO's may not be best means of interfacing. Makai discuss with Shan Shi to determine best way to get Makai running a dynamic loading of the Grippers and Guides.

5. Perform a tapered pipe analysis and determine a suitable taper. Alan Miller will need this analysis as part of his CWP design and as part of the termination design. All the analysis should include the max strain along the length of the CWP. – mid April??
    a. Repeat the 3:1 stiffness increase and the 10D taper length run with the validated software.
    b. Check that the software is providing reasonable results. Perhaps a comparison to FLEXCOM and a sensitivity test to the number of elements used in the taper?
    c. Perform a sensitivity test to stiffness: try a 10D linear taper with 6x increase in stiffness and another run with 2x stiffness.
    d. Return to the 3:1 stiffness (assuming that we are still getting the strain value decrease, ~50%, that nicely gives us the lifetime desired) and determine the proper shape of the taper that yields a constant strain along the length of the CWP. For CWP fabrication ease, it is preferable to have this length short.
    e.
6. In the long run, we will need the following for the 100MW plant: end of April.
    a. Completion of the two reports from Dec and Jan correcting the high values with the new analytical procedures.
    b. We should check the performance in a 100-year storm to verify that the CWP is not destroyed in this storm. (this could revisit the gimbal decision).
    c. RAO's for Makai on the platform during fabrication for use in OrcaFlex. (Makai and HOE to discuss what is appropriate)
7. In the long run, we will need the following for the NAVFAC pilot plant (with new Horton platform): when new platform data is available.
    a. Operational 16 bins followed by a fatigue analysis. This will need to include the final planned taper of the CWP.
    b. Fabrication for the J Halkyard matrix – 200m, 500m, 1000m lengths under various sea states and swell – 10-year and operational.
    c. Re-look at fatigue during fabrication under the worst case storms/swell. Do rainflow analysis for this event. If severe, take a reduced summer weather window.
    d. Operational run on the 100-year storm. Verify that the CWP survives and compute how much life could be consumed by this one storm.

Note: Official notes for this day provided by John Halkyard. These are Joe Van Ryzin Notes.

Notes: LMCO NAVFAC Pilot Plat Program, CWP-Platform Interface Meeting: March 3-4, 2010

Houston Offshore Engineering

Day 1: Focus on Software and Analysis of the Pipe-Platform Interface

Attendance:

Joe Van Ryzin, Makai
Nick Reese, Makai
Laurie Meyer, LMCO
Alan Miller, LMCO
Shan Shi, HOE
Ngok Lai, HOE
John Halkyard, Halkyard and Assoc
Jim Maher, Horton
David Kring, Navatek
Garrett Lang (Navy, Bill Seelig associate)
Arcandra,Tahar, Horton
Nishu Kurup (HOE)

Agenda:

- Overall Issues and goals – Joe VR
- Analysis basis – John H
- HOE Approach HARP (Coupled) vs. HARP+Flexcom Benchmarking to Date [Shan]
- Effect of pipe connection on motions – John H
- Further Analysis and Benchmarking Options
- ORCA Flex (coupled mode) – Shan?
- Flexcom (coupled mode) – Shan / John H
- Abacus Aqua – Horton
- AEGIR potential – David Kring
- Model Basin Testing – John H (deferred)

Goals:

- Reach a consensus on the analytical approach that is now being implemented: How accurate do we believe we are, where are our deficiencies, what are our strengths?
- Is there a difference between the 4m analytical and the 10m analytical results and challenges?
- What is the path forward for verification of our results?
- Are there other analytical approaches that should be run in parallel. If so, which ones and on what problem?
- What is the best recommendation for the pilot plant and the 4m pipeline for results that can be used ASAP?

Summary:

1. HARP now providing much lower strains – understand error with Jan/Dec runs.

    a. Error due to improper handling of entrapped water inside CWP – mass behaves differently in axial and lateral directions in real cwp but not in program.
        i. HOE has corrected and checked HARP's handling of added mass by re-coding and comparing to ORCAFLEX and FLEXCOM for simple pipe only solutions. Results are identical implying mass now being properly handled.
    b. Error due to large impact of CWP on platform motions, HARP is coupled, Flecom is not – and past numbers were with an uncoupled analysis.
        i. Conclude that we need coupled program only. HARP preferred as it runs faster. Need to compare to two others: AQWA and the new coupled FLEXCOM.

2. HARP believed to be best tool for future analysis – will need validation with new Coupled FLEXCOM, AQUA, and AEGIR – particularly connection stiffness issues.
    a. HOE to run now-modified Flexcom and corrected HARP.
    b. Navy to run AQUA
    c. Navatek to run AEGIR for limited checks.
3. Suggested tests and changes:
    a. Run WAMIT with CWP
    b. Run sensitivity to number of frequencies included
    c. Run sensitivity to number of panels
4. AEGIR program does what WAMIT does but is time domain and can handle non-linearities. Probably identical to WAMIT in our case – but we could use as backup to WAMIT to check force coefficients, etc. It can run with currents which WAMIT can't.
5. Probably still have strain problems with cwp – more runs needed.
    a. Strain values are higher that we would like to see. Will need hardware solutions. (day 2 discussion)
6. Have a nagging cwp/platform stiffness interface issue. HARP requires a spring between the two. If various values used – even if very stiff – we get dramatically different platform pitches but not different cwp strains. It is suggested this is due to numerical errors in matrix solutions with large numbers. This needs to be investigated (by comparing to other programs).
    a. A realistic CWP connection stiffness can be used by taking the stiffness of 3m of cwp and telling HARP this is the connection spring, and start the CWP 3m below the actual connection.
7. HARP is time domain and is fully coupled. WAMIT, a time-domain program is run first to provide force coefficients and other coefficients (similar to RAO's but used to generate forces) and these are inputs into HARP.

NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report

Appendix 6-4

Gripper Hydraulic System Steps

By

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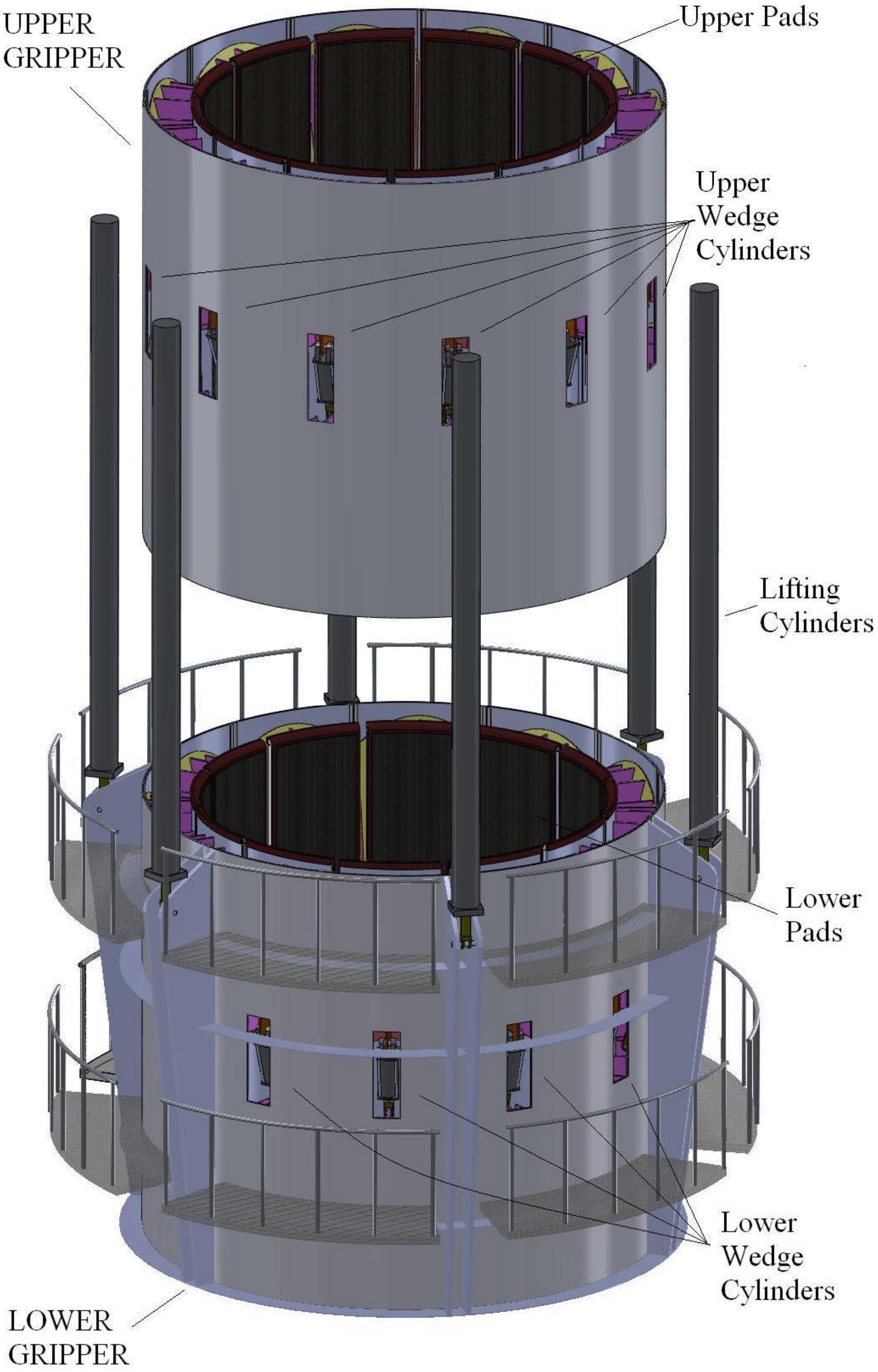

Figure 1: Overview of Gripper Apparatus

Introduction

Makai Ocean Engineering Inc. is designing a system to hold and lower a large diameter fiberglass pipe into the ocean from a floating platform, section by section. The pipe will be held and lowered by two Grippers. The Grippers squeeze the pipe with 12 identical pads, which support the weight of the pipe using friction. The Upper Gripper is fixed to the platform and cannot move up and down, whereas the Lower Gripper can be lifted and lowered by 6 Lifting Cylinders.

A hand-over-hand method of lowering the pipe is used, which is described as follows. The Lower Gripper will squeeze and lower the pipe a given distance. The Upper Gripper then squeezes and holds the pipe while the Lower Gripper lets go of the pipe and raises itself back up to the top of its stroke. The Lower Gripper then squeezes the pipe, the Upper Gripper releases the pipe, and the cycle repeats. The following Figure 2 shows one cycle of the lowering process.

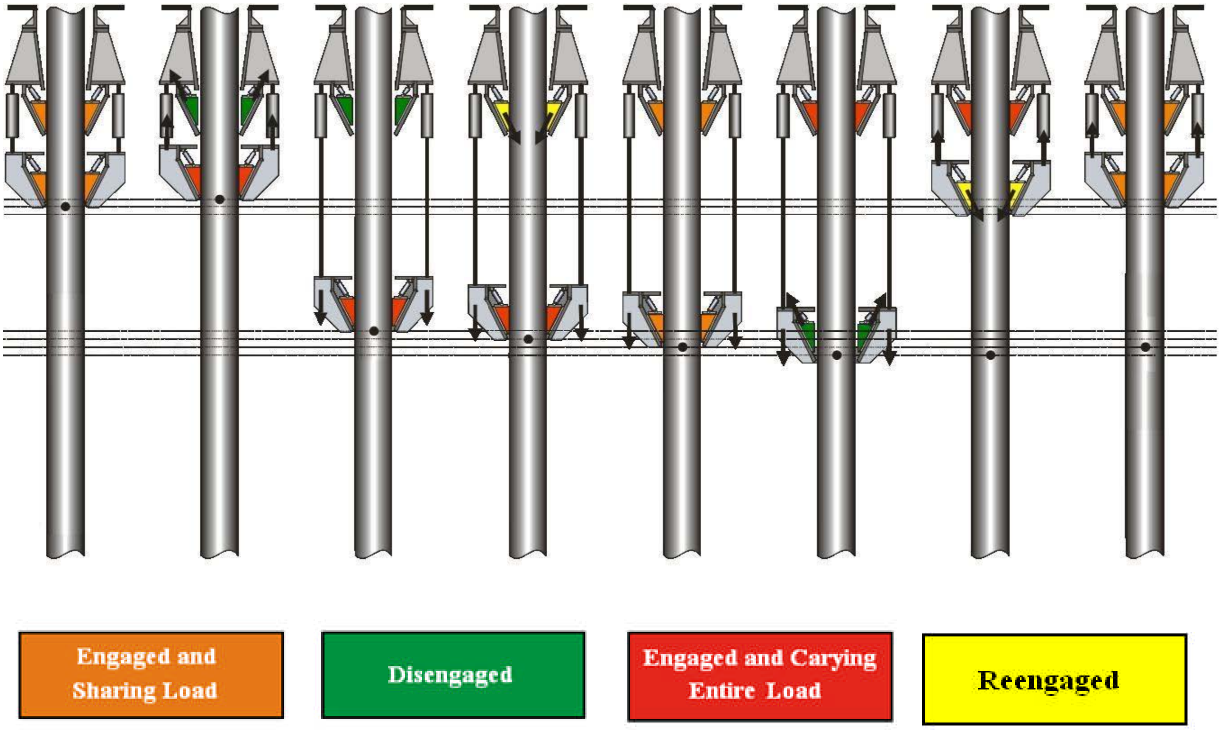

Figure 2: Basic lowering sequence

In this way 1000 meters of pipe will be lowered, section by section, into the ocean. This is an introduction only, and detail about each step will be provided in the body of this document.

The purpose of this document is to describe the action and control modes of the hydraulic system used to lower the pipe. Terminologies used in this report are given in Appendix A.

Components

Shown below is a cross-section view of the Gripper Apparatus.

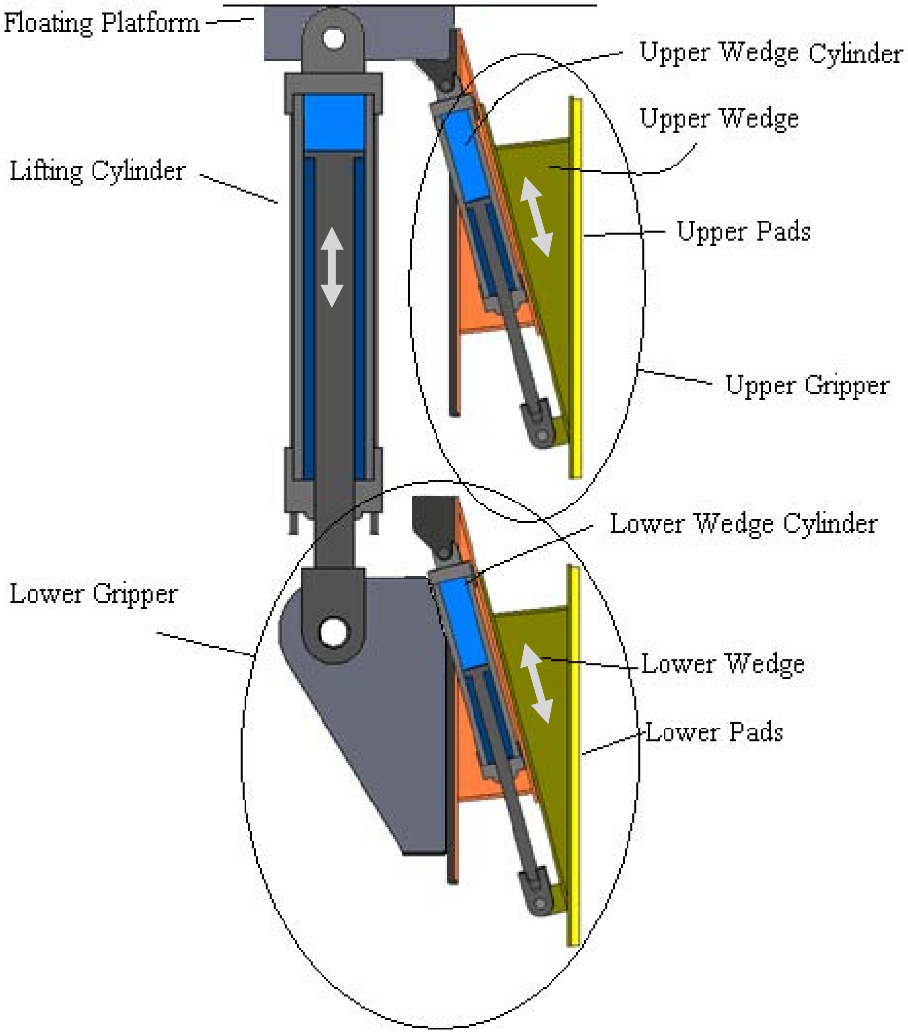

Figure 3: Cross-section of the Gripper apparatusThere are three sub-systems of hydraulic cylinders (see Figure 3):

1. The Upper Gripper: is attached to the floating platform. It squeezes the pipe using 12 hydraulic cylinders. These cylinders are positioned parallel to the wedge faces which are at a 14° angle from vertical. These 12 cylinders are synchronized and always move together equal distances.
2. The Lower Gripper: is identical to the Upper Gripper, but is able to move vertically by way of the Lifting Cylinders, which attach the Lower Gripper to the floating platform.

3. The Lifting Cylinders: 4 cylinders used to raise and lower the Lower Gripper and to control the sharing and transfer of the pipe weight between the two grippers. This set of cylinders acts in the vertical direction. When the Lower Gripper is bearing the pipe weight, these rams share the total lifting load and have a common cylinder pressure – the actuation distance may be slightly different depending upon the angle of tilt of the Lower Gripper

Actuator Positions

Both the Upper and Lower Wedge Cylinders have only three possible positions: fully retracted, minimum clearance and engaged on the pipe.

1. Fully Retracted: when they are fully retracted, the wedges have the maximum radial clearance from the pipe.

2. Minimum Clearance: when at the minimum clearance, the wedges all have the same radial displacement inward toward the pipe. This displacement is defined by a circular envelope which will contain the pipe even at the max pipe tilt.

3. Engaged on Pipe: when engaged on the pipe, the wedges are always applying the full Engagement Pressure.

The Lifting Cylinders have a total of 9 distinct positions required to lower the pipe. For the sake of simplicity, these positions are labeled by their respective step numbers in the section labeled “A. Normal Lowering Sequence.” Whenever the Lower Gripper is in contact with the pipe, all Lifting Cylinders should share a common pressure in order to be able to tilt with the pipe (called “gimballing”). This means that each of the Lifting Cylinders will have a slightly different displacement, depending on the tilt of the Lower Gripper. Further explanation of the Lifting Cylinders positions is given in the Appendix B.

Controls

The following are several control modes that are desired for the hydraulic system:

1. Synchronize displacement of multiple cylinders:
The ability to move cylinders within a subsystem in unison, despite varying loads/pressures on each cylinder.

2. Synchronize displacement of cylinders in different subsystems:
The ability to move cylinders in separate subsystems at some fixed motion ratio, despite varying loads/pressures. For example: the Lifting Cylinders extend in unison at a rate of 10cm/min while the Upper Wedge Cylinders extend in unison at a rate of 5 cm/min (a fixed motion ratio of 2:1).

3. Share pressure between multiple cylinders:
The ability to maintain all the Lifting Cylinders at a given pressure, and share working fluid. Presumably this would give the Lifting Cylinders the ability to “gimbal”, or tilt, with the pipe as lateral current loads affect it. This would also require individual cylinders to extend different displacements. (See Figure 20: Lifting Cylinder Gimbal, in Appendix B)

4. Incorporate and respond to signals from sensors:
The ability of the system to react to feedback from pressure and displacement sensors both within and outside the hydraulic cylinders. For example: the Wedge Cylinders extend slowly until pressure sensors on the pipe register the Engagement Pressure, which brings the cylinders to an immediate stop.

5. Re-phase cylinders that become misaligned:
The ability of the cylinders to become realigned after going out of alignment. For example: The Lifting Cylinders are on a common pressure manifold which causes each cylinder to be at a different actuation length. These must be re-phased for the next step.

Fabrication Mode

A. Normal Lowering Sequence:

Initial State:
The initial states of the hydraulic cylinders are as follows.

1. Upper Wedges
    - Position: Engaged on pipe
    - Pipe Load: Bearing half weight of pipe
2. Lower Wedges
    - Position: Engaged on pipe
    - Pipe Load: Bearing half weight of pipe
3. Lifting Cylinders
    - Position: #1
    - Pipe load: Bearing half pipe weight

A schematic of the initial state is shown below in
Figure 4.

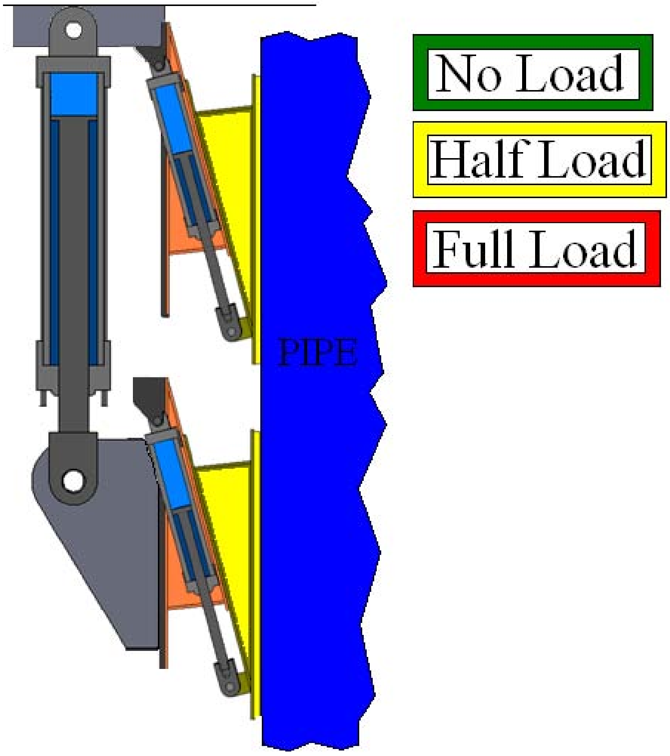

Figure 4: Initial holding position of the Gripper

1. Step 1: Unloading Upper Pads

The pipe load has to be removed from the Upper Wedges before they can be retracted. The Lifting Cylinders lift the Lower Gripper until all the pipe load is carried by the Lower Gripper. See Table 1 and Figure 5.

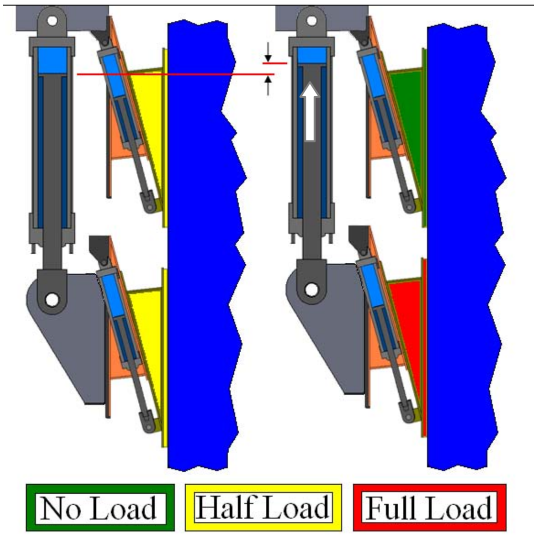

Figure 5: Step 1: Unloading Upper Pads

Table 1: Step 1: Unloading Upper Pads

Cylinders:	Upper Wedge	Lower Wedge	Lifting
Initial Position	Engaged on pipe	Engaged on pipe	#1- See Appendix B
Initial Pipe Load	Half	Half	Half
Action	Locked	Locked	Lift
Controlled by	Displacement = constant	Displacement = constant	Average pressure
Feedback	verify pressure shows engagement.	verify pressure shows engagement.	Av. pressure: Stop when lifting cylinders carry full wt of pipe + lower gripper.
Fixed Motion Ratio	---	---	-1
Final Position	Engaged on pipe	Engaged on pipe	#2- See Appendix B
Final Pipe Load	None	Full	Full
Speed	0	0	Very slow & smooth

Discussion: The Lifting Cylinders will raise the Lower Gripper slightly more than is necessary to transfer all the weight from the Upper Wedges to the Lower Wedges. This lifting distance will be very small (on the order of 1 – 2 centimeters). The load seen by the Lifting Cylinders will be the weight of the Lower Gripper (known) + the weight of the pipe (roughly known). The Lower Wedge Cylinder will see a decreased push force, due to the additional shear force applied to the Lower Wedges, as they bear the full pipe load. Conversely, the Upper Wedge Cylinder will see an increased push force in order to maintain Engagement Pressure, due to the decrease in shear force applied to the Upper Wedges. The wedges should stay stationary despite this change in force, due to having their cylinders hydraulically “locked”.

2. Step 2: Disengaging Upper Wedges

The Upper Wedges retract. The Lifting Cylinders lift the Lower Gripper (and pipe) while the Upper Wedges are retracting so that no relative motion occurs between the Upper Pad face and the pipe. The ratio of the displacement for Lifting Cylinder to Upper Wedge Cylinder is cos(14°):1. See Table 2 and Figure 6.

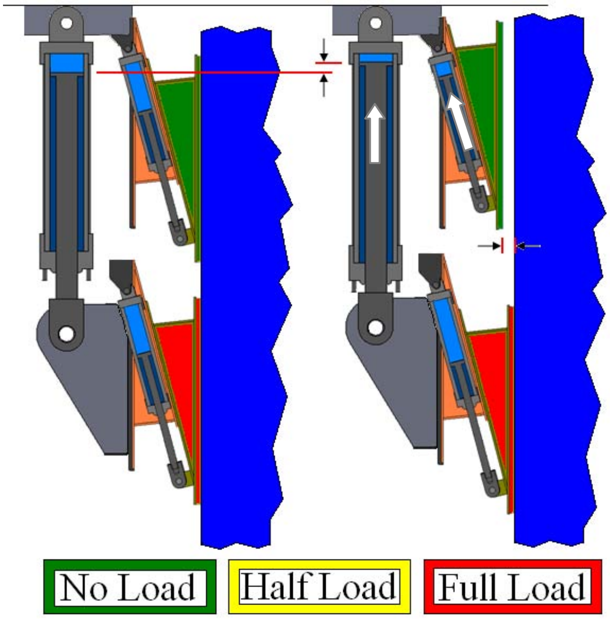

Figure 6: Step 2: Disengaging Upper Wedges

Table 2: Step 2: Retracting Upper Wedges

Hydraulics:	Upper Wedge	Lower Wedge	Lifting
Initial Position	Engaged on pipe	Engaged on pipe	#2- See Appendix B
Initial Pipe Load	None	Full	Full
Action	Retract	Locked	Lift
Controlled by	Synchronized Displacement	Displacement = constant	Average pressure
Feedback	Displacement: Stop when UW are at minimum clearance.	verify pressure shows engagement.	Displacement: keep average vertical displacement in line with UW.
Fixed Motion Ratio	-1	---	-0.97
Final Position	Minimum Clearance	Engaged on pipe	#3- See Appendix B
Final Pipe Load	None	Full	Full
Speed	Slow and smooth	0	Slow and smooth

Discussion: It is necessary to move the Upper Wedges in unison with the Lifting Cylinders until it is certain that the Upper Wedges will not touch the pipe. The Lifting Cylinders will be lifted with pressure control, thus it is critical to ensure that the average displacement of the Lifting Cylinders is equal to the vertical displacement of the Upper Wedges. The Lower Gripper cannot keep the pipe from tipping in any direction, thus there may be slight relative motion between the Upper Wedges and the pipe. The current assumption is that this motion will be insignificant. In the next step the Upper Wedges can be retracted unilaterally, without the Lifting Cylinders.

3. Step 3: Retracting Upper Wedges
The Upper Wedges retract. There is now sufficient clearance between the Upper Wedges and the pipe to enable the wedges to retract without lifting the pipe. The Lower Wedges and Lifting Hydraulics remain locked during this step. See Table 3 and Figure 7.

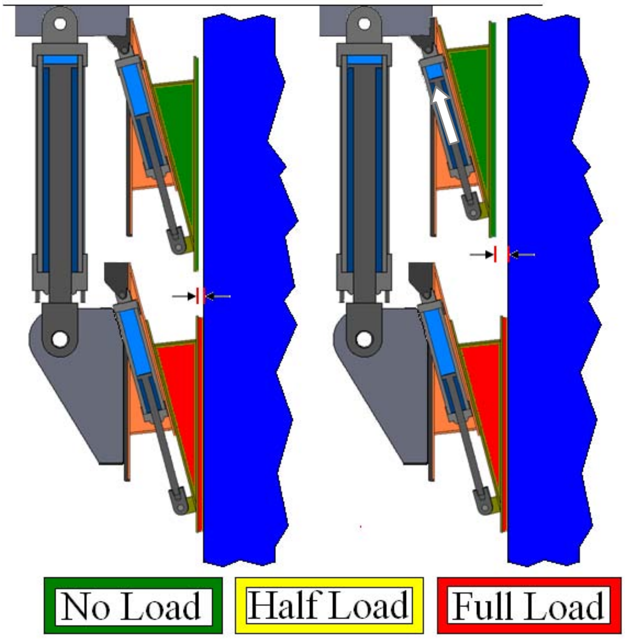

Figure 7: Step 3: Retracting Upper Wedges

Table 3: Step 3: Retracting Upper Wedge Normal Force

Hydraulics:	**Upper Wedge**	**Lower Wedge**	**Lifting**
Initial Position	Minimum clearance	Engaged on pipe	#3- See Appendix B
Initial Pipe Load	None	Full	Full
Action	Retract	Locked	Locked
Controlled by	Synchronized Displacement	Displacement = constant	Average pressure = constant
Feedback	Displacement: Stop when UW are at max clearance	verify pressure shows engagement.	---
Fixed Motion Ratio	-1	---	---
Final Position	Fully Retracted	Engaged on pipe	#4- See Appendix B
Final Pipe Load	None	Full	Full
Speed	Slow and smooth	0	0

Discussion: Once the Upper Wedges have a minimum clearance, they will be retracted by themselves. This leaves a margin of safety in how much clearance they give the pipe when it is lowered (in the next step).

4. Step 4: Lowering Pipe

The pipe is lowered while being held by the Lower Gripper. The Lower Wedge remains engaged on the pipe and the Lifting Cylinders lower at a slow pace with gradual ramp up and slow down on speed. See Table 4 and Figure 8.

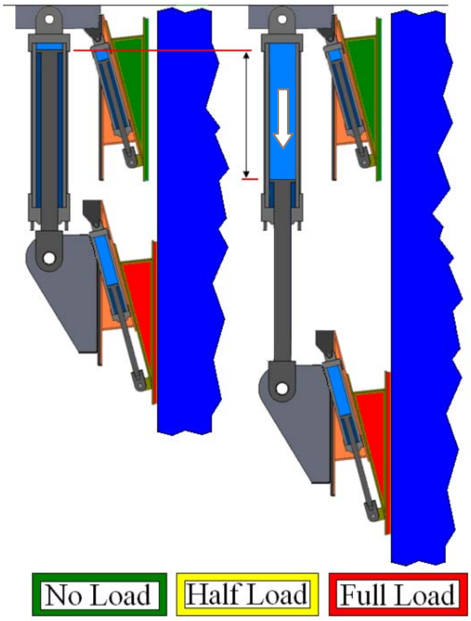

Figure 8: Step 4: Lower Pipe

Table 4: Step 4: Lowering Pipe

Hydraulics:	**Upper Wedge**	**Lower Wedge**	**Lifting**
Initial Position	Fully Retracted	Engaged on pipe	#4- See Appendix B
Initial Pipe Load	None	Full	Full
Action	Locked	Locked	Lower
Controlled by	Displacement = constant	Displacement = constant	Average pressure
Feedback	verify no pressure	verify pressure shows engagement.	Displacement: Stop when pipe is at mean displacement = #5
Fixed Motion Ratio	---	---	1
Final Position	Fully Retracted	Engaged on pipe	#5- See Appendix B
Final Pipe Load	None	Full	Full
Speed	0	0	~10cps ramp up and down

Discussion:

It is desirable to know whether the pipe is slipping as the pipe is lowered. Currently there is no method for detecting slip.

Also, it is desirable to have the Lifting Cylinders on a common hydraulic manifold in order to allow the Lower Gripper to tilt with the pipe as current loads affect it (this ability is known as gimballing). This may cause the pipe to be tilted at the bottom of the lowering stroke.

5. Step 5: Extending Upper Wedges
The Upper Wedges extend from being fully retracted to the minimum clearance. The Lifting Cylinders and Lower Wedges remain locked in place. See Table 5 and

Figure 9.

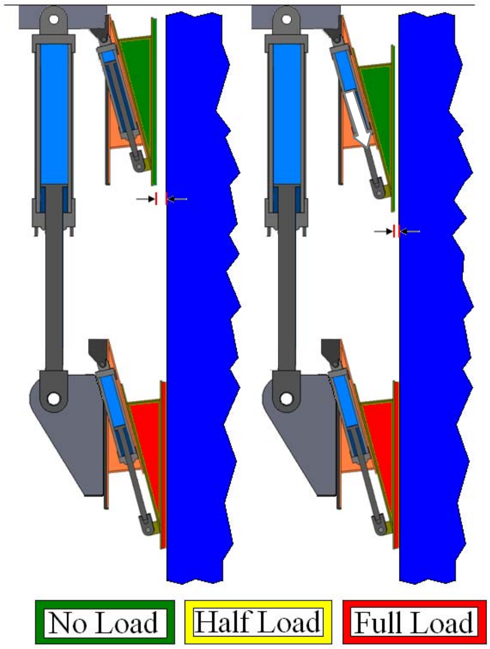

Figure 9: Step 5: Extending Upper Wedges

Table 5: Step 5: Extending Upper Wedges

Hydraulics:	**Upper Wedge**	**Lower Wedge**	**Lifting**
Initial Position	Fully Retracted	Engaged on pipe	#5- See Appendix B
Initial Pipe Load	None	Full	Full
Action	Extend	Locked	Locked
Controlled by	Synchronized Displacement	Displacement = constant	Average pressure = constant
Feedback	Verify no pressure	verify pressure shows engagement.	---
Fixed Motion Ratio	1	---	---
Final Position	Minimum clearance	Engaged on pipe	#6- See Appendix B
Final Pipe Load	None	Full	Full
Speed	Slow and smooth	0	0

Discussion: The Upper Wedges extend in unison to the defined minimum clearance.

6. Step 6: Engaging Upper Wedges

The Upper Wedges press on the pipe. The Lifting Cylinders lower the Lower Gripper (and pipe) while the Upper Wedges are extending so that no relative vertical motion occurs between the pad face and the pipe. The ratio of the displacement for Lifting Hydraulic to Upper Wedge Hydraulic is cos(14°):1. See Table 6 and

Figure 10.

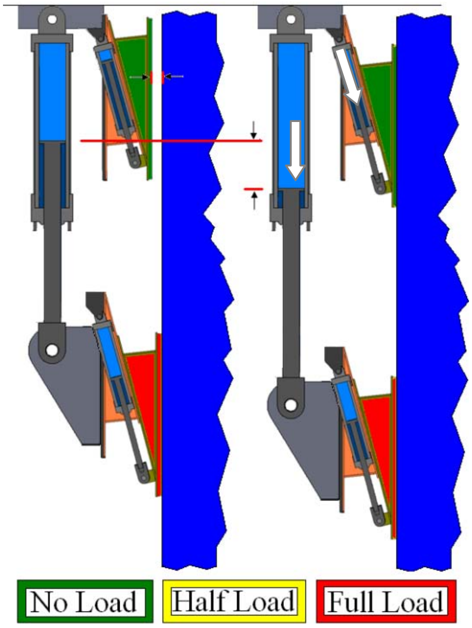

Figure 10: Step 6: Engaging Upper Wedges

Table 6: Step 6: Engaging Upper Wedges

Hydraulics:	**Upper Wedge**	**Lower Wedge**	**Lifting**
Initial Position	Minimum clearance	Engaged on pipe	#6- See Appendix B
Initial Pipe Load	None	Full	Full
Action	Extend	Locked	Lower
Controlled by	Synchronized Displacement	Displacement = constant	Average pressure
Feedback	Cylinder pressure, cylinder displacement, pad pressure	verify pressure shows engagement.	Displacement: keep average vertical displacement in line with UW.
Fixed Motion Ratio	1	---	0.97
Final Position	Engaged on pipe	Engaged on pipe	#7- See Appendix B
Final Pipe Load	None	Full	Full
Speed	Slow and smooth	0	Slow and smooth

Discussion: The Upper Wedge Cylinders extend while the Lifting Cylinders lower the pipe. There are 3 possible feedback modes for the Upper Wedges to indicate when the Engagement Pressure is being applied to the pipe: cylinder pressure, cylinder displacement, and pad pressure. The cylinder pressure may be the least accurate because the friction on the back of the wedge is unknown, and also the change in vertical pipe load will change the cylinder pressure. Cylinder displacement may work, however the displacement of the wedges at the Engagement Pressure may vary depending on the tilt of the pipe and other factors. Pad pressure will be the most accurate way of knowing the pressure on the pipe, but it may be difficult to use this signal as feedback for the cylinder movement in real-time.

7. Step 7: Loading Upper Pads

The pipe load has to be transferred to the Upper Wedges before the Lower Wedges can be retracted. The Lifting Cylinders lower the Lower Gripper until all the pipe load is carried by the Upper Wedges. See

Table 7 and Figure 11.

Table 7: Step 7: Loading Upper Pads

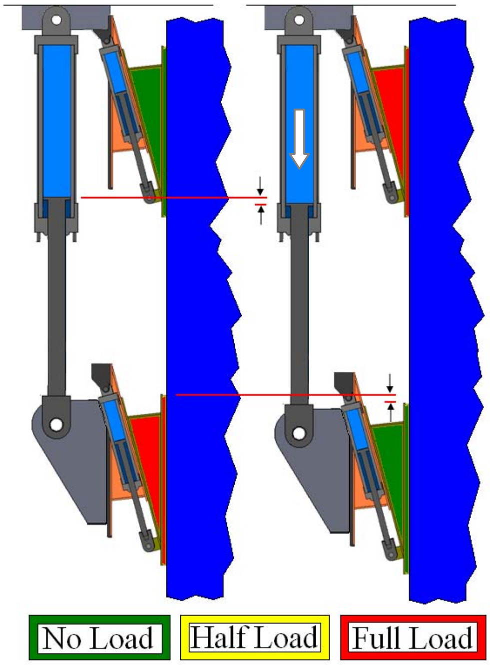

Figure 11: Step 7 Loading Upper Pads

Hydraulics:	Upper Wedge	Lower	
Initial Position	Engaged on pipe	Engaged on pipe	#7- See Appendix B
Initial Pipe Load	None	Full	Full
Action	Locked	Locked	Lower
Controlled by	Displacement = constant	Displacement = constant	Average pressure
Feedback	verify pressure shows engagement.	verify pressure shows engagement.	Av. pressure: Stop when LH carry only wt of lower gripper.
Fixed Motion Ratio	---	---	1
Final Position	Engaged on pipe	Engaged on pipe	#8- See Appendix B
Final Pipe Load	Full	None	None
Speed	0	0	Slow and smooth

Discussion: The Lifting Hydraulics will lower slightly more than is necessary to transfer all the weight from the Lower Wedges to the Upper Wedges. This lowering distance will be very small (on the order of 1 – 2 centimeters). The load seen by the Lifting Hydraulics will be the weight of the Lower Gripper (known) + the weight of the pipe (roughly known). The Upper Wedge Cylinder will see a decreased push force, due to the additional shear force applied to the Upper Wedges. Conversely the Lower Wedge Cylinder will see an increased push force in order to maintain Engagement Pressure, due to the decrease in shear force applied to the Lower Wedges. The wedges should stay stationary despite this change in force, due to having their cylinders hydraulically “locked”.

8. Step 8: Disengaging Lower Wedges
The Lower Wedges retract. The Lifting Cylinders lower the Lower Gripper while the Lower Wedges are retracting so that no relative motion occurs between the pad face and the pipe. The ratio of the displacement for Lifting Hydraulic to Lower Wedge Hydraulic is cos(14°):1. See

Figure 12: Step 8: Disengaging Lower Wedges

Table 8 and

Figure 12.

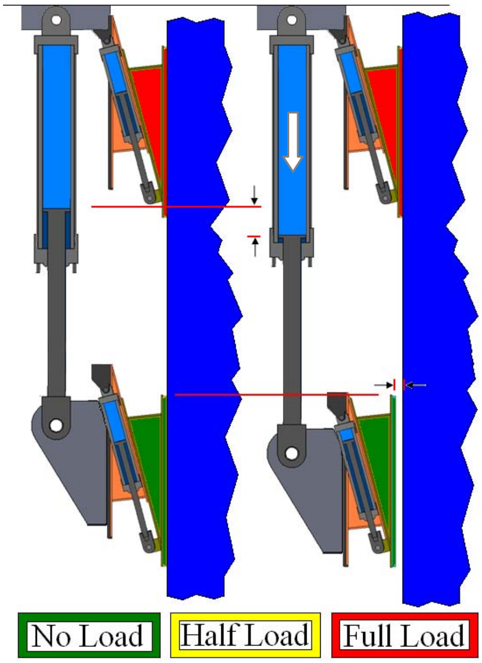

Figure 12: Step 8: Disengaging Lower Wedges

Table 8: Step 8: Disengaging Lower Wedges

Hydraulics:	**Upper Wedge**	**Lower Wedge**	**Lifting**
Initial Position	Engaged on pipe	Engaged on pipe	#8- See Appendix B
Initial Pipe Load	Full	None	None
Action	Locked	Retract	Lower
Controlled by	Displacement = constant	Synchronized Displacement	Average pressure
Feedback	verify pressure shows engagement	Displacement: Stop when LW reach min clearance	Displacement: keep average vertical displacement in line with LW.
Fixed Motion Ratio	---	-1	0.97
Final Position	Engaged on pipe	Minimum clearance	#9- See Appendix B
Final Pipe Load	Full	None	None

Speed	0	Slow and smooth	Slow and smooth

Discussion: It is necessary to move the Lower Wedges in unison with the Lifting Cylinders until it is certain that the Lower Wedges will not touch the pipe. In the next step the Lower Wedges can be retracted unilaterally, without the Lifting Cylinders.

9. Step 9: Retracting Lower Wedges

The Lower Wedges retract. There is now sufficient clearance between the Lower Wedges and the pipe to enable the wedges to retract without lifting the pipe. The Upper Wedges and Lifting Hydraulics remain locked during this step. See Table 9 and Figure 13.

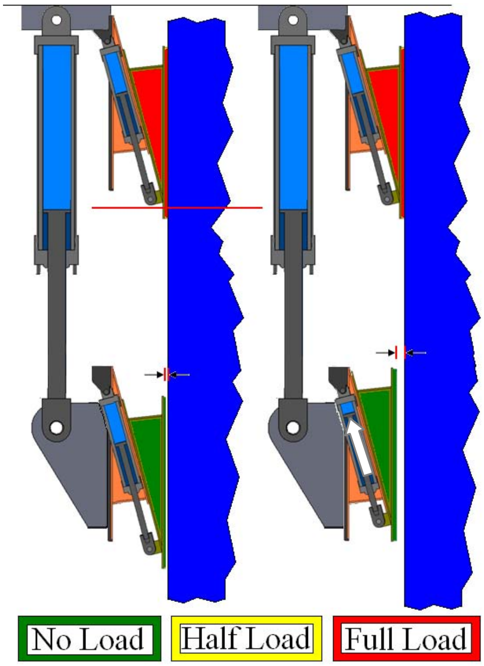

Figure 13: Step 9: Retracting Lower Wedges

Table 9: Step 9: Retracting Lower Wedge Normal Force

Hydraulics:	**Upper Wedge**	**Lower Wedge**	**Lifting**
Initial Position	Engaged on pipe	Minimum clearance	#9- See Appendix B
Initial Pipe Load	Full	None	Full
Action	Locked	Retract	Locked
Controlled by	Displacement = constant	Synchronized Displacement	Average pressure = constant
Feedback	verify pressure shows engagement	Displacement: Stop when LW are at max clearance	---
Fixed Motion Ratio	---	-1	---
Final Position	Engaged on pipe	Fully Retracted	#10- See Appendix B
Final Pipe Load	Full	None	Full
Speed	0	Slow and smooth	0

Discussion: Once the Upper Wedges have a minimum clearance, they will be retracted by themselves. This leaves a margin of safety in how much clearance they give the pipe when the Lower Gripper is raised(in the next step).

10. Step 10: Lifting Lower Gripper
The Lower Gripper must be lifted. The Upper Wedges remain engaged on the pipe and the Lifting Cylinders lift the Lower Gripper at a slow pace. See Table 10 and

Figure 14.

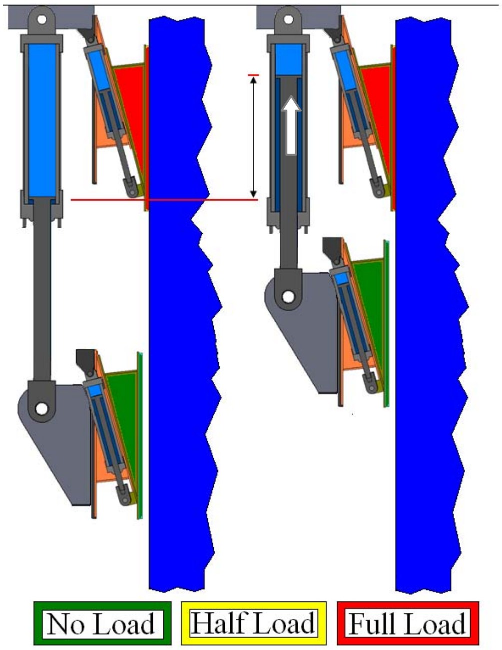

Figure 14: Step 10: Lifting Lower Gripper

Table 10: Step 10: Lifting Lower Gripper

Hydraulics:	**Upper Wedge**	**Lower Wedge**	**Lifting**
Initial Position	Engaged on pipe	Fully Retracted	#10- See Appendix B
Initial Pipe Load	Full	None	None
Action	Locked	Locked	Lift
Controlled by	Displacement = constant	Displacement = constant	Synchronized displacement
Feedback	verify pressure shows engagement	verify no pressure	Displacement: Stop when LG is at top position.
Fixed Motion Ratio	---	---	-1
Final Position	Engaged on pipe	Fully Retracted	#11- See Appendix B
Final Pipe Load	Full	None	None
Speed	---	---	Very slow and smooth

Discussion: The Lifting Cylinders move differently at the start of this step. Lifting the Lower Gripper is initially done with synchronized movement of all 6 cylinders and then a bottoming out of all cylinders at the upper end to align the lower gripper with the platform deck. This is called “rephrasing” of the cylinders.

11. Step 11: Extending Lower Wedges

The Upper Wedges extend from being fully retracted to the minimum clearance. The Lifting Cylinders and Lower Wedges remain locked in place. See Table 11 and Figure 15.

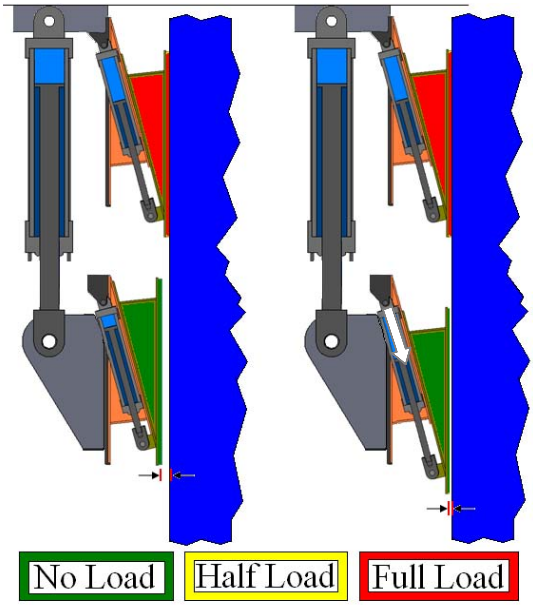

Figure 15: Step 11: Extending Lower Wedges

Table 11: Step 11: Extending Lower Wedges

Hydraulics:	Upper Wedge	Lower Wedge	Lifting
Initial Position	Engaged on pipe	Fully Retracted	#11- See Appendix B
Initial Pipe Load	Full	None	None
Action	Locked	Extend	Lift
Controlled by	Displacement = constant	Synchronized Displacement	Synchronized Displacement
Feedback	verify pressure shows engagement	Displacement: Stop when LW are at minimum clearance	---
Fixed Motion Ratio	---	---	1
Final Position	Engaged on pipe	Minimum clearance	#12- See Appendix B
Final Pipe Load	Full	None	None
Speed	0	Slow and smooth	0

Discussion: The Lower Wedges extend in unison to the defined minimum clearance.

12. Step 12: Engaging Lower Wedges

The Lower Wedges must extend to press on the pipe. The Lifting Cylinders lift the Lower Gripper while the Lower Wedges are extending so that no relative motion occurs between the pad face and the pipe. The ratio of the displacement for Lifting Hydraulic to Lower Wedge Hydraulic is cos(14°):1. See Table 12 and Figure 16.

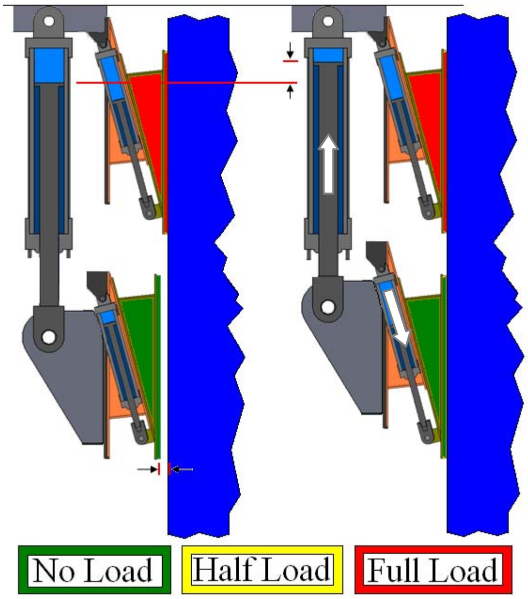

Figure 16: Step 12: Engaging Lower Wedges

Table 12: Step 12: Engaging Lower Wedges

Hydraulics:	**Upper Wedge**	**Lower Wedge**	**Lifting**
Initial Position	Engaged on pipe	Minimum clearance	#12- See Appendix B
Initial Pipe Load	Full	None	None
Action	Locked	Extend	Lift
Controlled by	Displacement = constant	Synchronized Displacement	Synchronized Displacement
Feedback	verify pressure shows engagement	Av. Pressure: Stop when Engagement Pressure reached	verify pressure shows no pipe load
Fixed Motion Ratio	---	1	-0.97
Final Position	Engaged on pipe	Engaged on pipe	#13- See Appendix B
Final Pipe Load	Full	None	None
Speed	0	Slow and smooth	Slow and smooth

Discussion: The Lower Wedge Cylinders extend while the Lifting Cylinders raise the Lower Gripper. There are 3 possible feedback modes for the Upper Wedges to indicate when the Engagement Pressure is being applied to the pipe: cylinder pressure, cylinder displacement, and pad pressure. The cylinder pressure may be the least accurate because the friction on the back of the wedge is unknown. Cylinder displacement may work, however the displacement of the wedges at the Engagement Pressure may vary depending on the tension in the pipe and whether there is a shear key being compressed. Pad pressure will be the most accurate way of knowing the pressure on the pipe, but it will be difficult to use this signal as feedback for the cylinder movement in real-time.

13. Step 13: Loading Lower Pads

Half of the pipe load has to be transferred to the Lower Pads in order to return to the Initial State. This is done by lifting the Lower Gripper with the Lifting Hydraulics until half the pipe load is carried by the Upper Wedge Pads and half by the Lower Wedge Pads. See Table 13 and Figure 17.

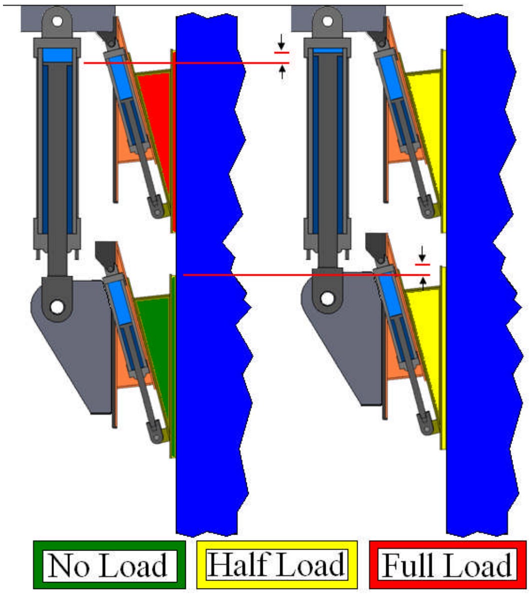

Figure 17: Step 13: Loading Lower Pads

Table 13: Step 13: Loading Upper Pads

Hydraulics:	**Upper Wedge**	**Lower Wedge**	**Lifting**
Initial Position	Engaged on pipe	Engaged on pipe	#9- See Appendix B
Initial Pipe Load	Full	None	None
Action	Locked	Locked	Lift
Controlled by	Displacement = constant	Displacement = constant	Average Pressure
Feedback	verify pressure shows engagement	verify pressure shows engagement	Average pressure: Stop when LH carry half wt of pipe + lower gripper.
Fixed Motion Ratio	---	---	-1
Final Position	Engaged on pipe	Engaged on pipe	#1- See Appendix B
Final Pipe Load	Half	Half	Half
Speed	0	0	Very slow and smooth

Discussion: The Lifting Hydraulics will rise to transfer half the weight from the Upper Wedges to the Lower Wedges. This lifting distance will be very small (on the order of 1 – 2 centimeters). The load seen by the Lifting Hydraulics will be the weight of the Lower Gripper (known) + half the weight of the pipe (roughly known). The Lower Wedge Cylinder will see a decreased push force, due to the additional shear force applied to the Lower Wedges. Conversely, the Upper Wedge Cylinder will see an increased push force in order to maintain Engagement Pressure, due to the decrease in shear force applied to the Upper Wedges. The wedges should stay stationary despite this change in force, due to having their cylinders hydraulically “locked”.

Appendix A: Terminology - Alphabetically

A. **Engaged on pipe**: The condition in which the Wedge Hydraulics provide the Engagement Pressure.
B. **Engagement Pressure**: the normal pressure exerted by the pads when engaged on the pipe. This pressure is required to provide a sufficient frictional force to prevent the pipe from slipping out of the pads. Currently our Engagement Pressure is 50 psi.
C. **Fixed Motion Ratio**: when two hydraulic subsystems are synchronized, the relative displacement is dictated by the fixed motion ratio. A negative sign indicates a retracting stroke, and a positive sign indicates an extending stroke.
D. **Lifting Cylinders:** Hydraulic cylinders attached between the Upper Gripper support structure and the Lower Gripper support structure. Responsible for raising and lowering the entire lower gripper as needed.
E. **Lower Gripper**: Refers to the entire gripper and support structure, including Lower Wedges, Lower Pads, and Lower Wedges.
F. **Lower Wedge Cylinders:** Hydraulic cylinders on the Lower Gripper responsible for pushing and pulling the steel wedges to engage and release the friction pad with the pipe.
G. **Minimum Clearance**: A designated radial clearance between the wedge face and the pipe. This is the distance necessary to ensure that the pipe does not touch the face of the pads.
H. **Normal Lowering Sequence**: describes the steps involved in the lowering of a typical pipe section.
I. **Pad Pressure**: the pressure detected in the fluid filled pad on the face of the wedge. This should be equal to the pressure on the pipe, but is different from the pressure seen in the wedge cylinders.
J. **Fully Retracted**: The position of the Wedge Cylinders when not applying pressure on the pipe.
K. **Upper Gripper**: Refers to the entire gripper and support structure, including Upper Wedges, Upper Pads, and Upper Wedges**.**
L. **Upper Wedge Cylinders**: Hydraulic cylinders on the Upper Gripper responsible for pushing and pulling the steel wedges to engage and release the friction pad with the pipe.

Appendix B: Lifting Cylinders Positions

The Lifting Cylinders have 4 functions:

1) To ensure that whenever a Wedge Hydraulic is extending or retracting, there is no relative vertical motion between the face of the pad and the pipe.
2) To cause the slight relative vertical motion between the pad surface and the pipe necessary for transferring the vertical lift load from one gripper to the other. (loading friction / tension layer).
3) To lower the pipe.
4) To raise the Lower Gripper.

In order to perform the above functions, the Lifting Cylinders are required to raise or lower the Lower Gripper during 9 out of 13 of the steps in the lowering process. A schematic of the positions and movements is given in Figure 18 below (schematic is not scaled). Notice that there are 9 distinct positions and movements for a typical lowering cycle (because 4 out of 13 steps do not require the Lifting Cylinders to move). The initial state is the same as described in the Normal Lowering Sequence above (both Upper and Lower Grippers are engaged and sharing load). UW = Upper Wedge, LW = Lower Wedge, LG = Lower Gripper.

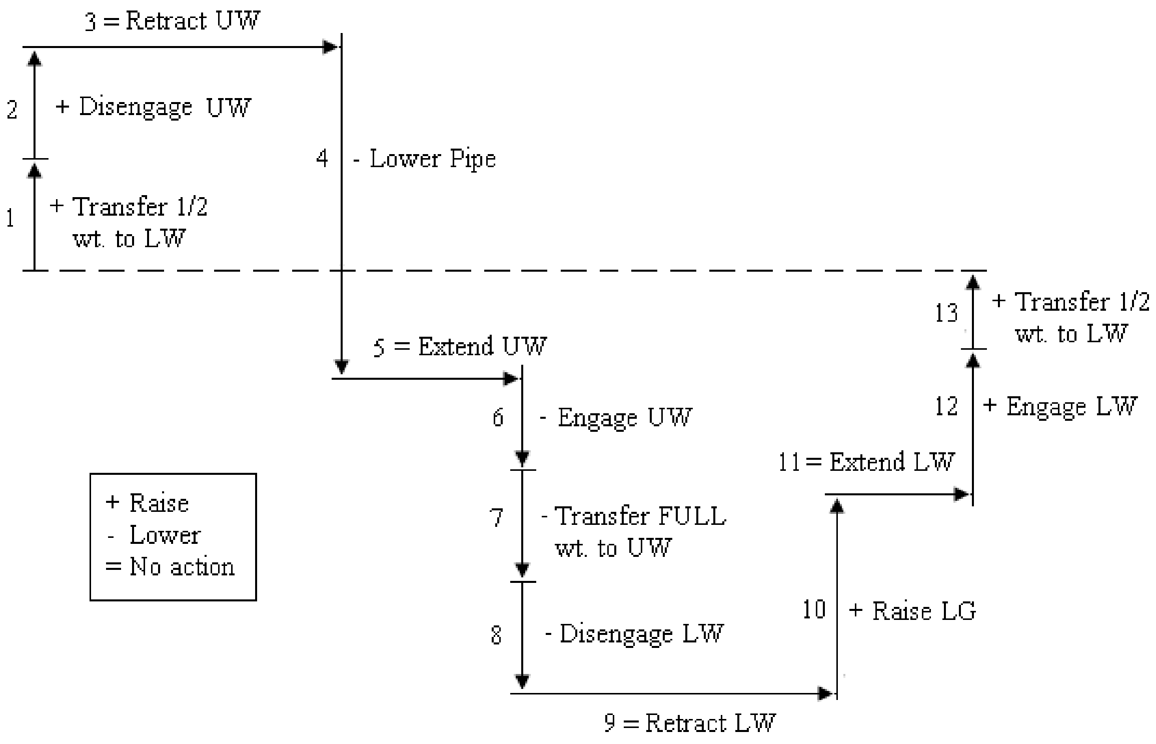

Figure 18: Lifting Cylinders position schematic

The following description contains specs from the 21 inch model. The following Figure 19 shows the movement of the Lower Gripper throughout a typical lowering sequence. Also included on this graph is the position of a marker on the pipe.

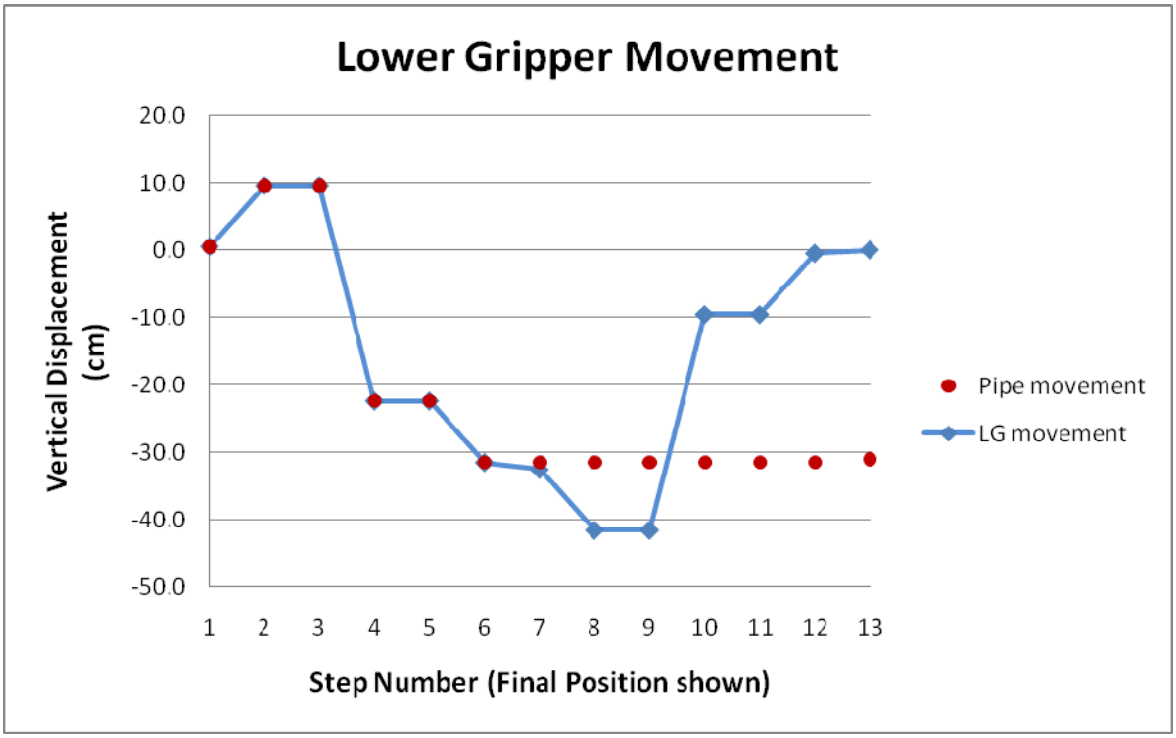

Figure 19: Lower Gripper Movement

Questions and Concerns

1) Sharing Vertical Load:

Two factors affect the lifting distance required to transfer load. Both of these factors increase as the pipe weight increases:

a. Deflection of the friction/tension layer
b. Axial deflection of the pipe under tension/compression

Sharing load might be difficult to achieve in practice. Calculations suggest that the distance required to transfer load should be very slight, due to the stiffness of the friction/tension layer, and the pipe.

2) Transferring Vertical Load:

Two possible control schemes for the Lifting Cylinders when transferring the load are: displacement control (based on Lifting Cylinder piston travel) or pressure control (based on load carried by Lifting Cylinder).

If displacement control is used, the increasing deflection in the friction/tension layer and in the pipe as the load increases will make it difficult to know exactly what distance is required to share the load.

If pressure control is used, the increasing load of the pipe will make it difficult to know exactly what pressure is required to share the load. This option may be the easier of the two, as we know roughly the weight of each new section of pipe, and can adjust the pressure required to share the load accordingly.

Another possibility is to never “share” load between the two grippers. When fabricating the pipe, the Upper Gripper will always carry the load of the pipe, and the Lower Gripper will merely remain engaged on the pipe as a backup.

3) Lifting Cylinders on a common manifold (gimbal ability):

The ability of the Lower Gripper to “tilt” with the pipe as it is lowered is desirable. The cylinders on all sides will share a common hydraulic manifold, and thus be maintained at the same pressure. This is necessary to ensure that the Lower Gripper cannot react to any moment exerted on it by the pipe.

All cylinders will see different displacements. See Figure 20.

Concerns:

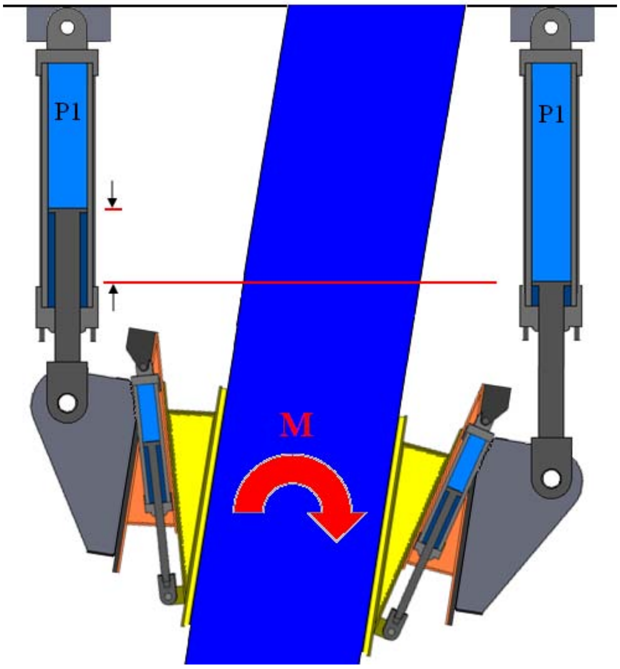

Figure 20: Lifting Cylinder Gimbal

- Maintaining equal pressure in all cylinders will depend on the ability of the hydraulic power source to respond quickly to pressure changes. Is this type of system possible?
- A universal joint will be required at both top and bottom joints of the Lifting Cylinders in order to accommodate rotation of the pipe about all lateral axes and to prevent binding of the clevis joints.

NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report

Appendix 6-5

Drawing Set Gripper and Guide

By

Makai Engineering

OTEC-2010-001

21 September 2010

Prepared for:

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Port Hueneme, CA 93043-4370
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Prepared by:

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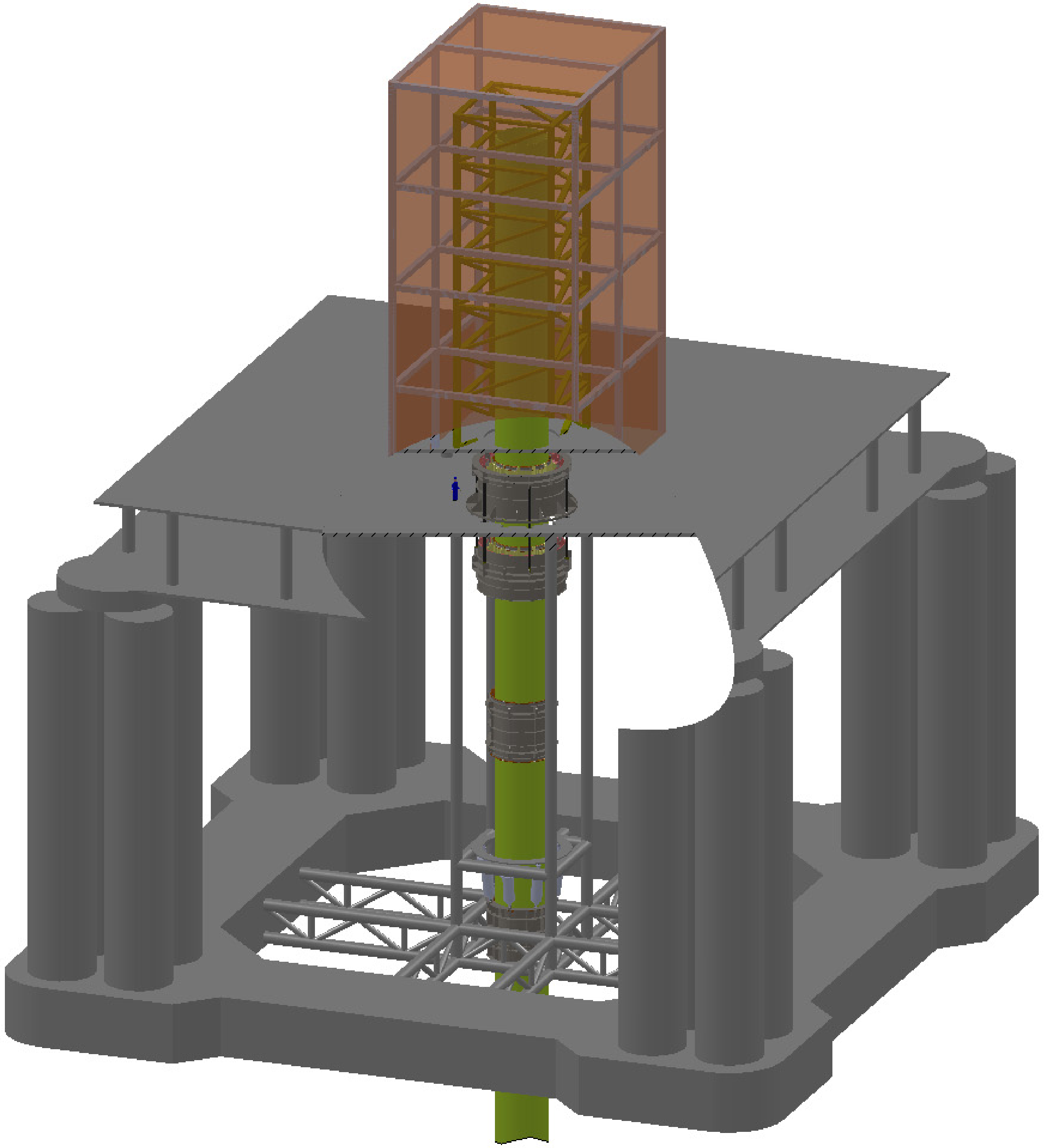
Distribution Statement A: Approved for public release; distribution is unlimited.

PROJECT:
10 MW OTEC PLANT:
COLD WATER PIPE LOWERING/HANDLING EQUIPMENT
GRIPPER AND GUIDE COMPONENTS

DESIGNED BY:
MAKAI OCEAN ENGINEERING, INC.



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S44	BOTTOM GUIDE ASSEMBLY
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M4	TOP GUIDE SLIDE LAYER
M5	BOTTOM GUIDE GEL BAG
M6	BOTTOM GUIDE WATER BAG
M7	BOTTOM GUIDE SLIDE LAYER

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TITLE SHEET

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DATE
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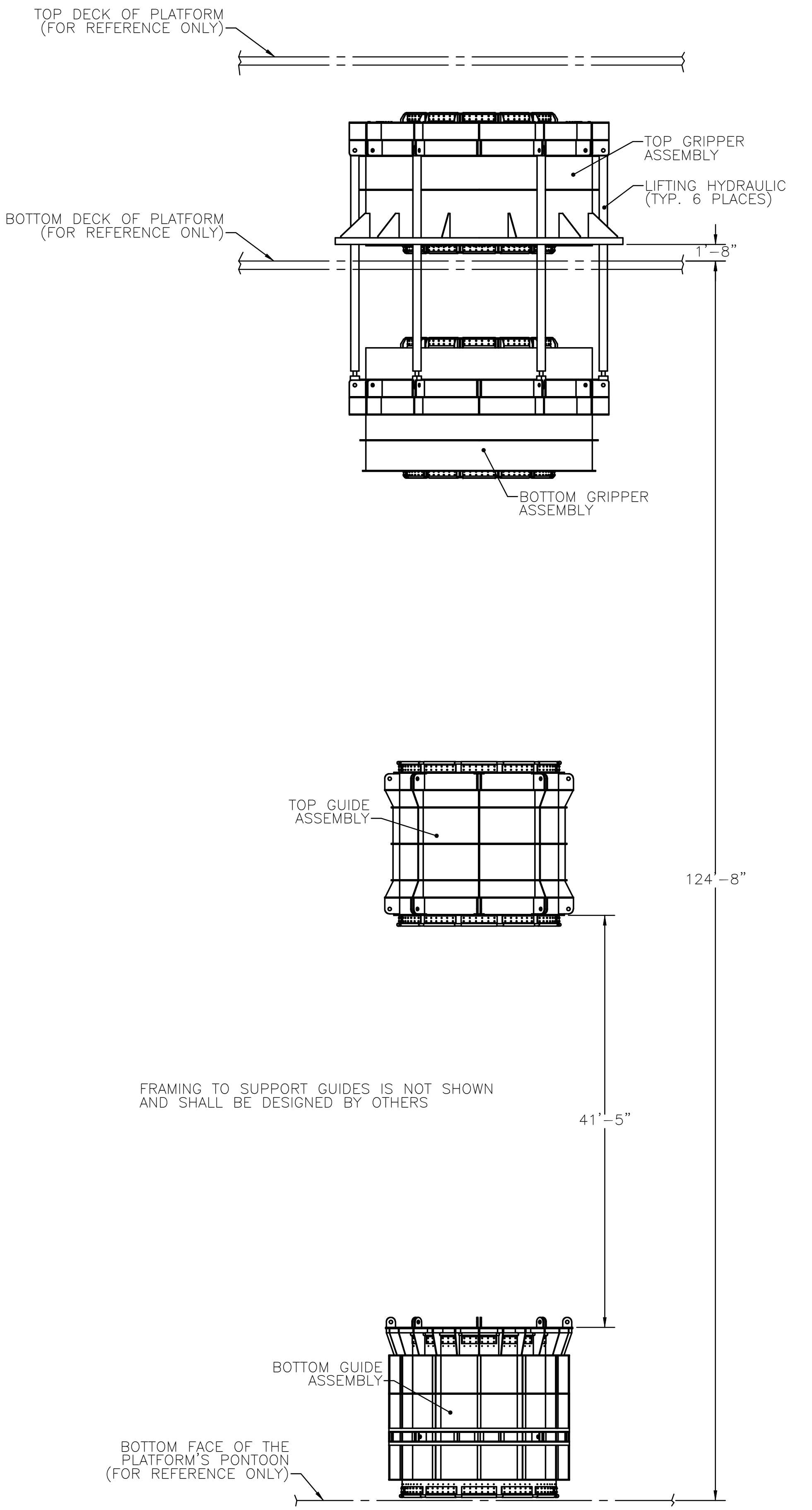
G1

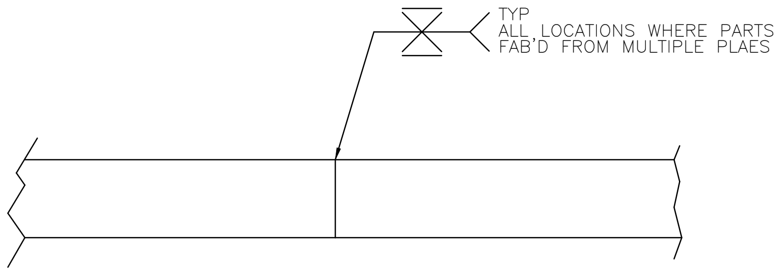
JOB NO. 15706
SHEET NO. 1 OF 61



1/G2 GENERAL COMPONENT ARRANGEMENT
SCALE 1 : 96

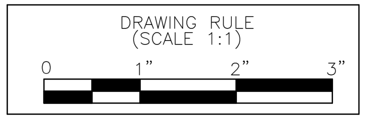
NOTES:

1. SEMI–SUBMERSIBLE PLATFORM DESIGN AND ATTACHMENTS BETWEEN PLATFORM AND THESE GRIPPER AND GUIDE COMPONENTS SHALL BE DESIGNED BY OTHERS.



ABBREVIATIONS

ABBREVIATION	MEANING
B.C.	BOLT CIRCLE
℄	CENTERLINE
CWP	COLD WATER PIPE
EQ.	EQUALLY
FAB'D	FABRICATED
FB	FLAT BAR
ISO	ISOMETRIC
L	LONG
M	METER
MW	MEGAWATT
REF	REFERENCE
REQ'D	REQUIRED
TBD	TO BE DETERMINED
THK	THICK
THRU	THROUGH
TYP	TYPICAL



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GENERAL COMPONENT ARRANGEMENT, ABBREVIATIONS, AND GENERAL NOTES

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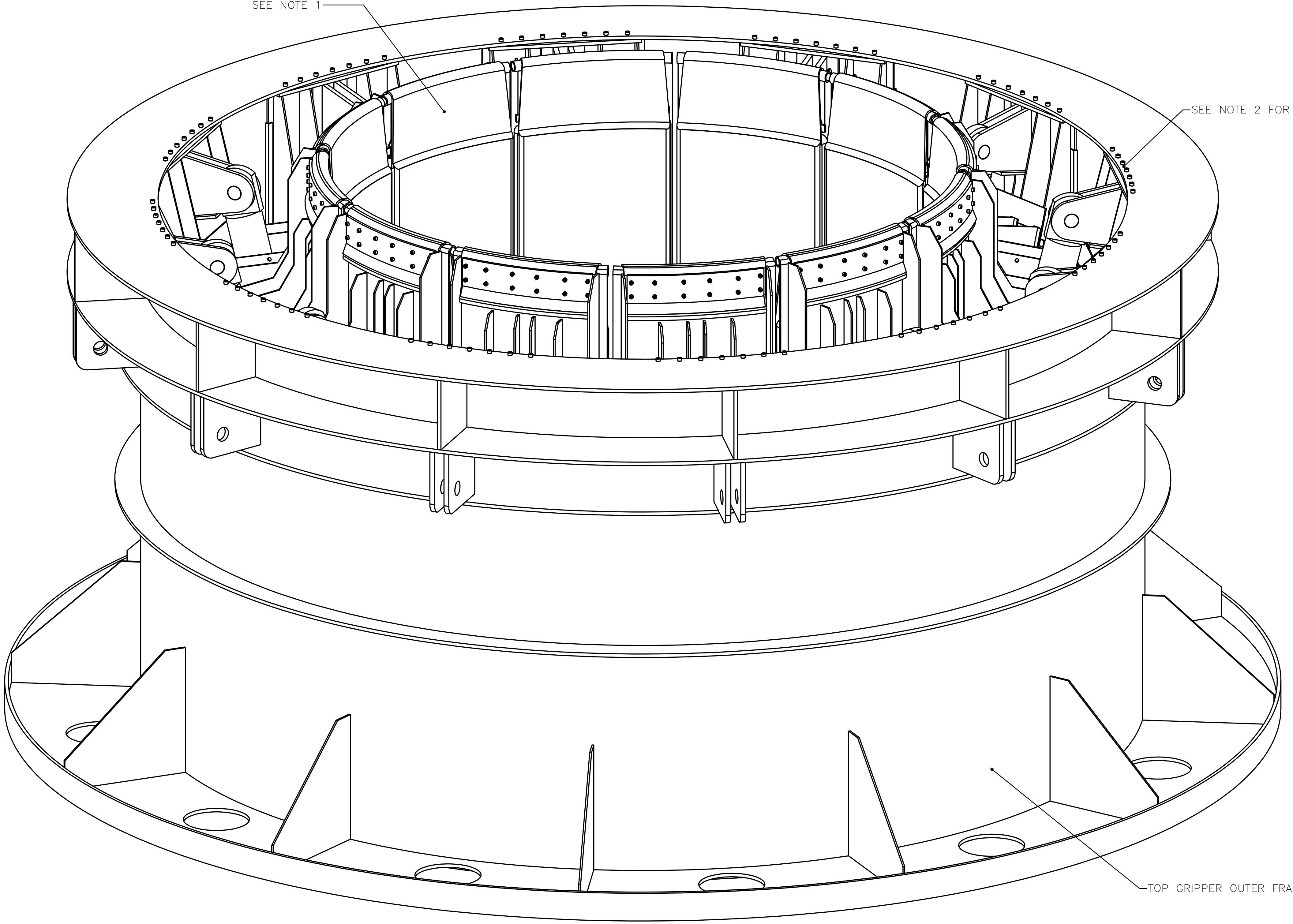
JOB NO. 15706
SHEET NO. 2 OF 61

NOTES:

1. THE TOP AND BOTTOM GRIPPER ASSEMBLIES ARE EXACTLY THE SAME WITH THE EXCEPTION OF THE OUTER FRAMES. EACH GRIPPER IS MADE UP OF 12 IDENTICAL WEDGE ASSEMBLIES SEE S3.
2. THE WEDGE ASSEMBLIES ARE ATTACHED TO THE OUTER FRAMES DIFFERENTLY FOR THE TOP AND BOTTOM GRIPPERS. TO ATTACH A WEDGE ASSEMBLY TO THE TOP GRIPPER OUTER FRAME:
   - A) SLIDE THE OUTER WEDGE (SEE S3) INTO THE GUIDES LOCATED ON THE FRAME (SEE S8). THE WEDGE ASSEMBLY SLIDES IN FROM THE BOTTOM OF THE FRAME.
   - B) AFTER THE TOP OF THE OUTER WEDGE HAS SEATED AGAINST THE TOP RING, BOLT IT INTO PLACE USING THE HOLES IN THE TOP RING.



THERE ARE 12 IDENTICAL WEDGE ASSEMBLIES INSIDE BOTH THE TOP AND BOTTOM GRIPPERS, SEE NOTE 1

SEE NOTE 2 FOR ATTACHMENT DETAILS

TOP GRIPPER OUTER FRAME, SEE 1/S6 (1 REQ'D)

ISO VIEW

1/S1 TOP GRIPPER ASSEMBLY
SCALE 1 : 16

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

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TOP GRIPPER ASSEMBLY

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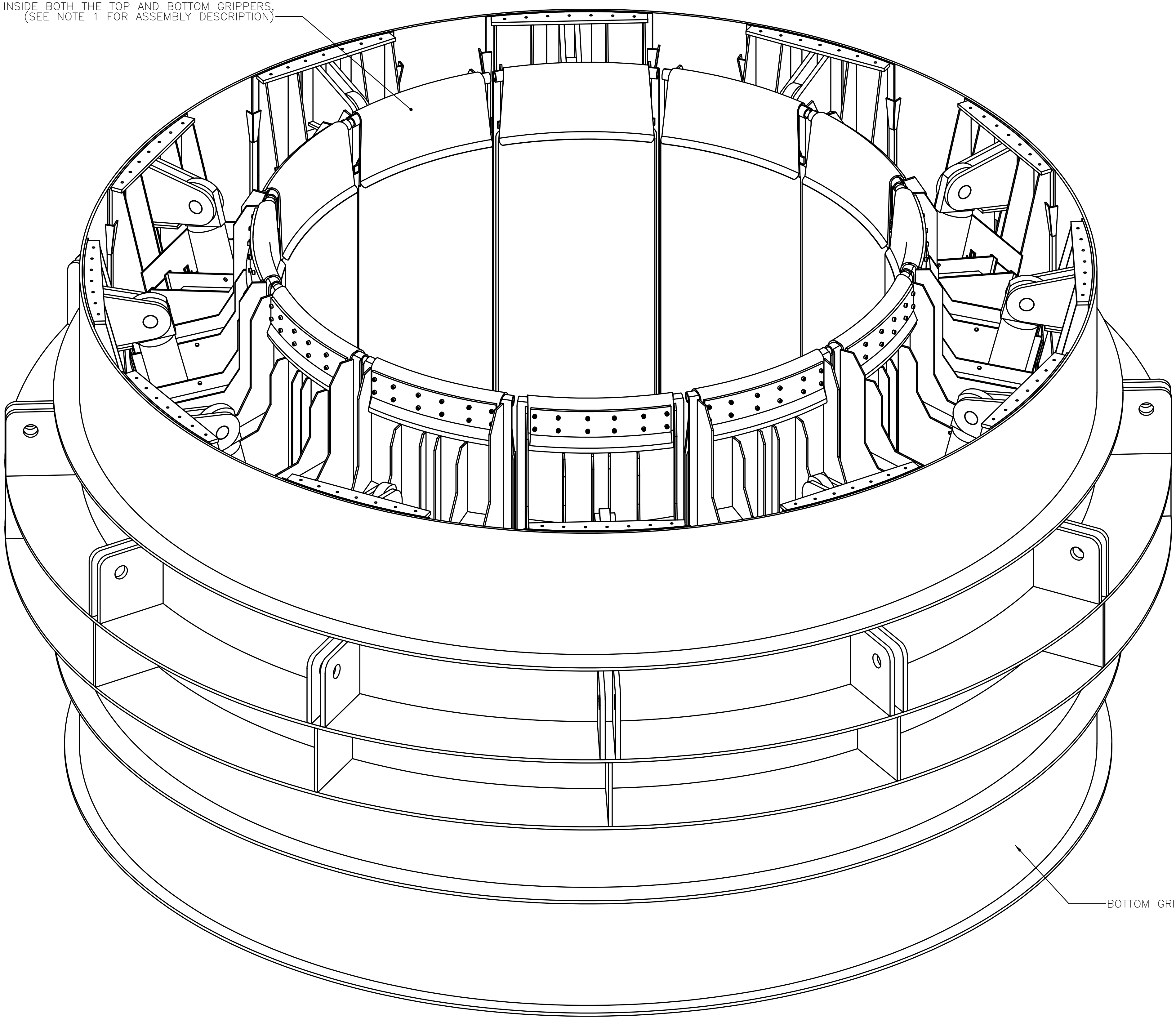
DRAWING NO. S1

JOB NO. 15706

SHEET NO. 3 OF 61

NOTES:

1. THE WEDGE ASSEMBLIES ARE ATTACHED TO THE OUTER FRAMES DIFFERENTLY FOR THE TOP AND BOTTOM GRIPPERS. TO ATTACH A WEDGE ASSEMBLY TO THE BOTTOM GRIPPER OUTER FRAME:
    - A) SLIDE THE OUTER WEDGE (SEE S3) INTO THE GUIDES LOCATED ON THE FRAME (SEE S14). THE OUTER WEDGES SLIDE IN FROM THE TOP OF THE OUTER FRAME.
    - B) CONTINUE TO SLIDE THE OUTER WEDGE DOWN UNTIL ITS BOTTOM SEATS AGAINST THE BOTTOM RING, BOLT IT INTO PLACE USING THE HOLES IN THE BOTTOM RING.



THERE ARE 12 IDENTICAL WEDGE ASSEMBLIES INSIDE BOTH THE TOP AND BOTTOM GRIPPERS. (SEE NOTE 1 FOR ASSEMBLY DESCRIPTION)

BOTTOM GRIPPER OUTER FRAME, SEE 1/S9 (1 REQ'D)

ISO VIEW

1/S2 BOTTOM GRIPPER ASSEMBLY
SCALE 1 : 16

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

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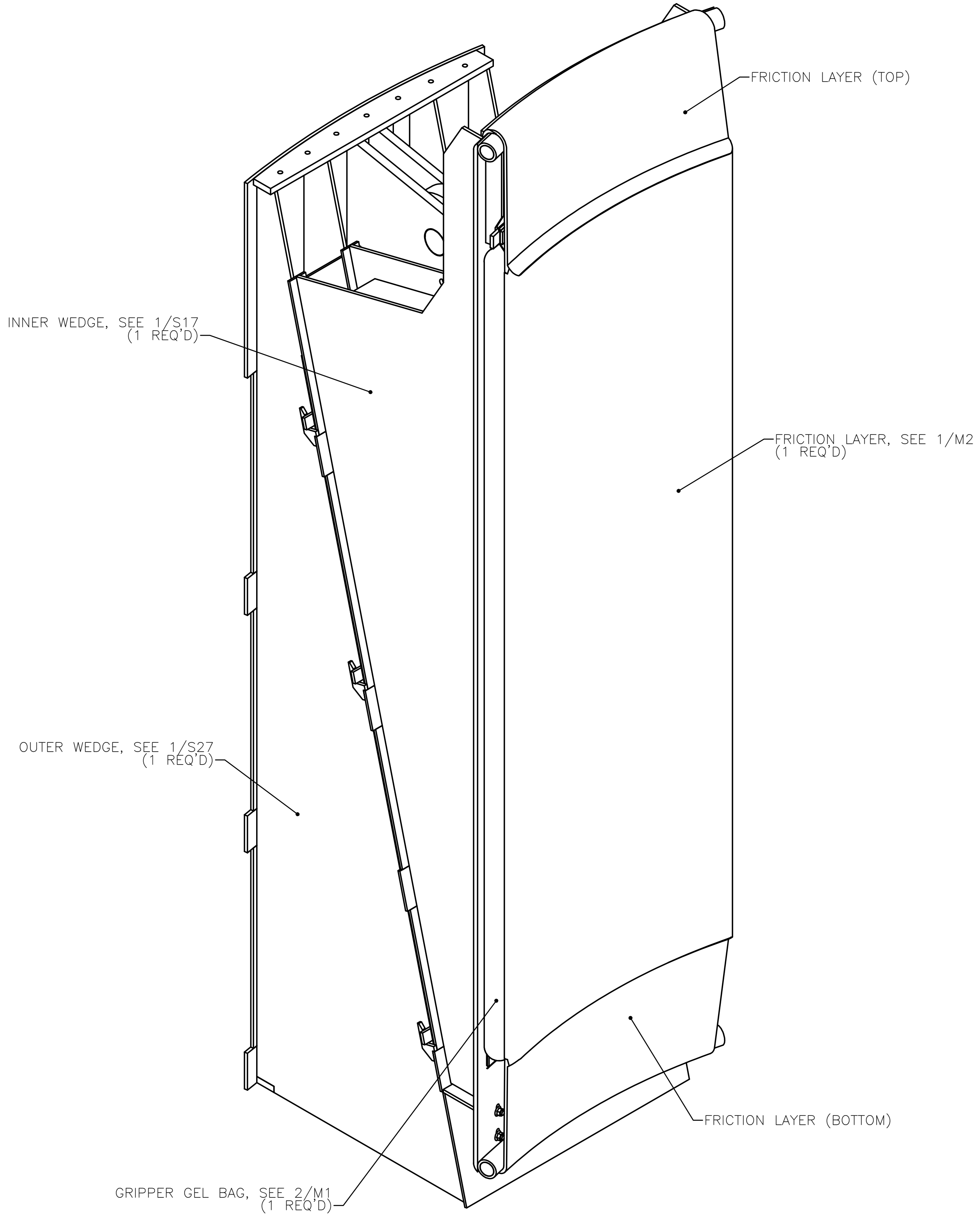
JOB NO. 15706

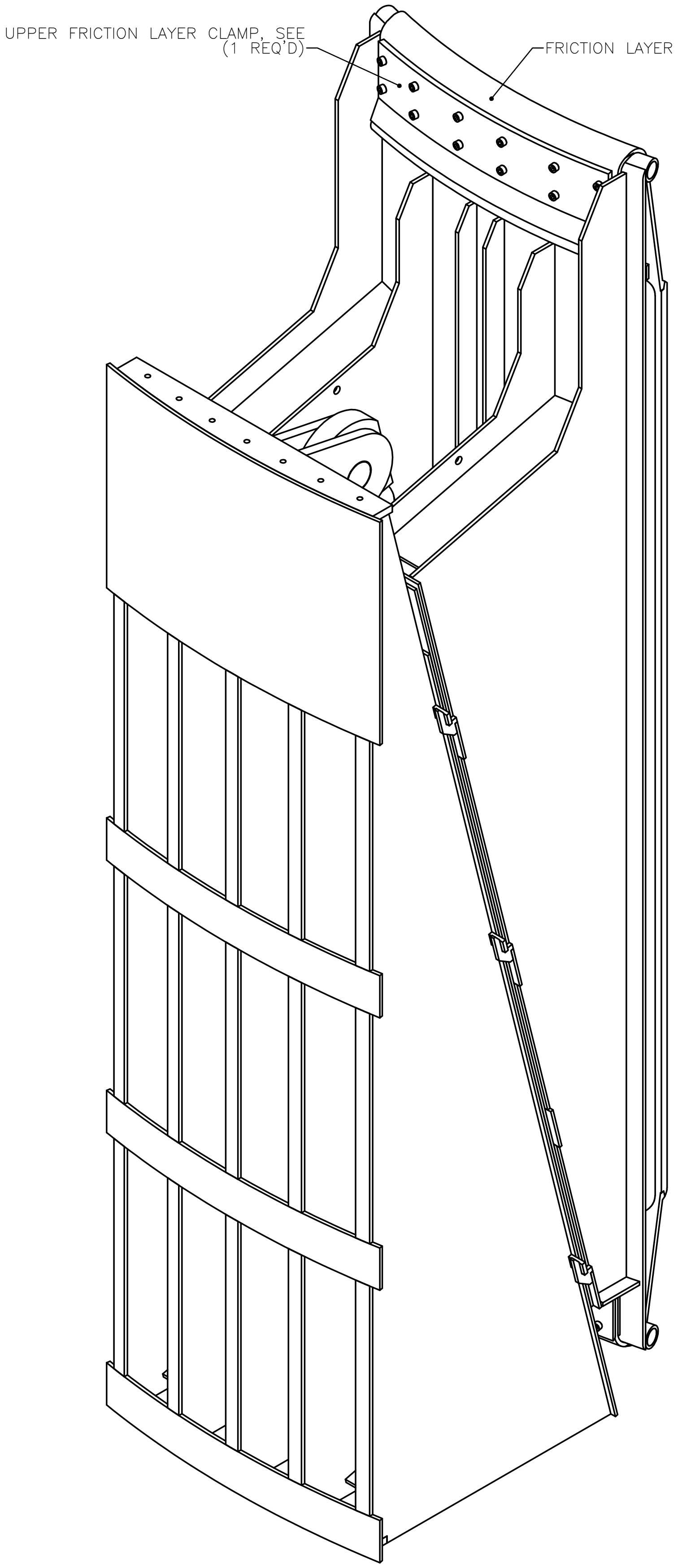
SHEET NO. 4 OF 61

NOTES:

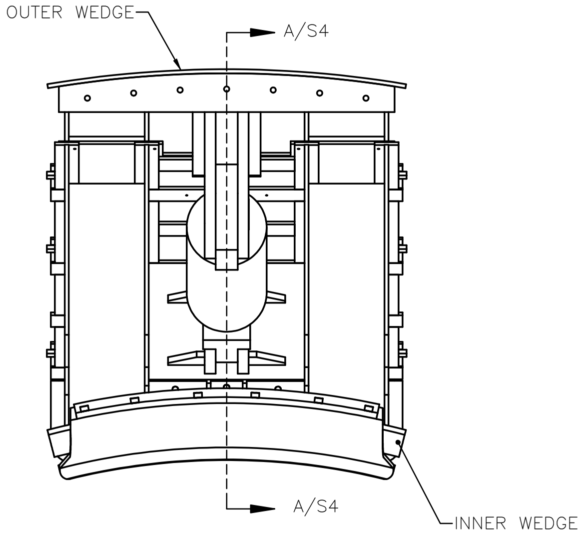
1. THE REQ'D QUANTITY OF EACH COMPONENT PART CALLED OUT HERE, IS THE NUMBER REQ'D PER WEDGE ASSEMBLY.



ISO VIEW (LOOKING FROM THE FRONT)



ISO VIEW (LOOKING FROM THE BACK)



TOP VIEW
SCALE 1 : 12

1/S3 WEDGE ASSEMBLY
SCALE 1 : 10

DRAWING RULE
(SCALE 1:1)

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WEDGE ASSEMBLY

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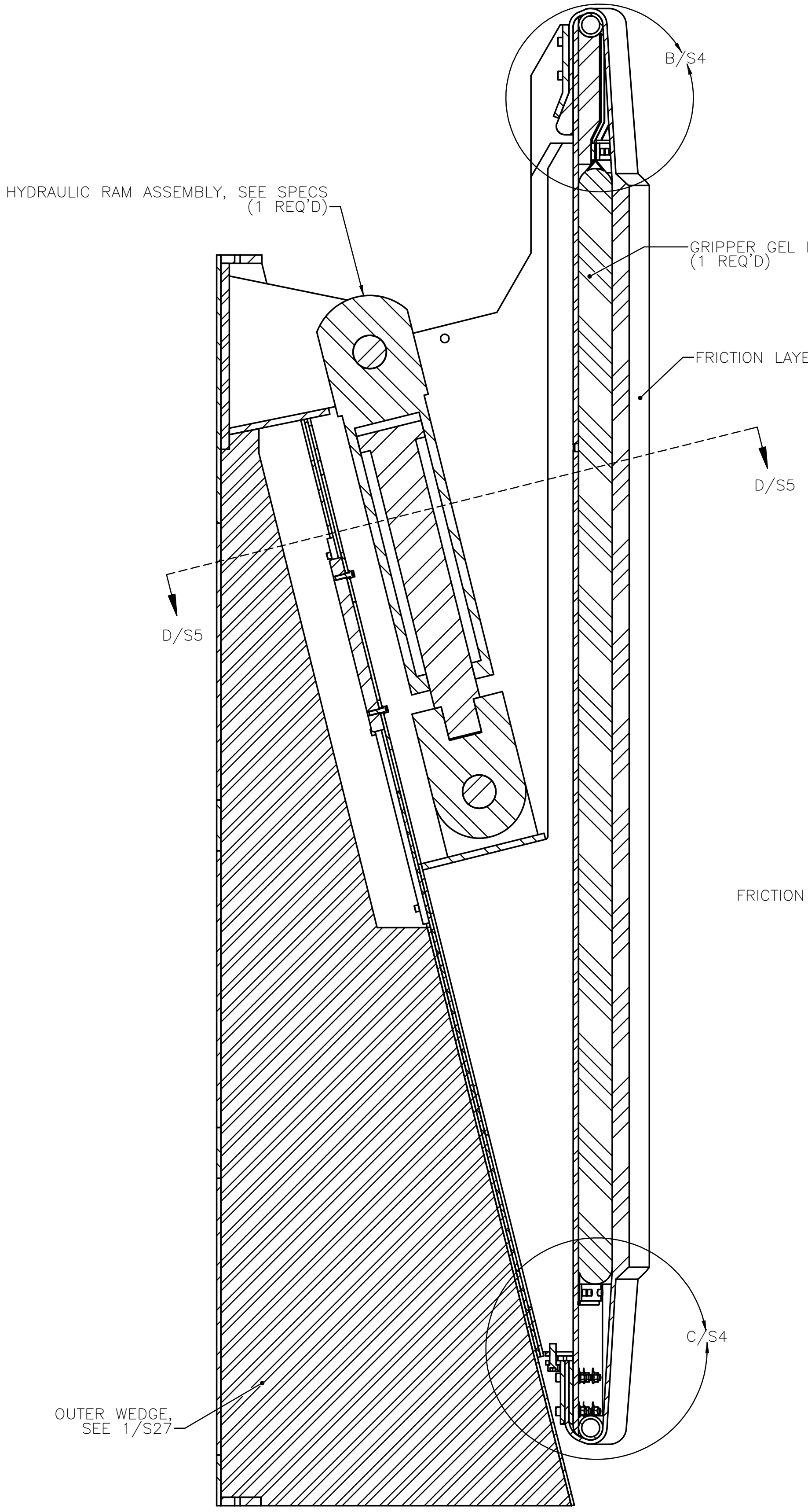
DATE
DRAWING NO. S3

JOB NO. 15706

SHEET NO. 5 OF 61

NOTES:

1. THE WEDGE ASSEMBLY CONSISTS OF THE INNER AND OUTER WEDGE. THE INNER WEDGE SLIDES RELATIVE TO THE OUTER WEDGE WHEN ACTED UPON BY A HYDRAULIC RAM. THERE IS A LINEAR GUIDE SYSTEM BETWEEN THE INNER AND OUTER WEDGE, WHICH CONSISTS OF TRACK (CONNECTED TO THE OUTER WEDGE) AND A SLIDER (CONNECTED TO THE INNER WEDGE). THIS SYSTEM IS SHOWN IN DETAIL E/S5. A SHEET OF HDPE IS ATTACHED TO THE ANGLED FACE OF THE INNER WEDGE AND ACTS AS A BUSHING BETWEEN THE TWO WEDGES. THIS SHEET IS CALLED THE "SLIDE SHEET". ATTACHED TO THE CURVED FACE OF THE INNER WEDGE WITH A SERIES OF CLAMPING PLATES IS A GEL BAG AND A SHEET OF RUBBER CALLED THE "FRICTION LAYER." ONE OF THE BOTTOM CLAMPING PLATES OF THE FRICTION LAYER IS CALLED THE TENSIONING PLATE AS IT HAS THE ABILITY TO TENSION THE FRICTION LAYER AFTER IT IS CLAMPED TO IT.
2. THE FRICTION LAYER SHALL FIRST BE CLAMPED INTO THE UPPER FRICTION LAYER CLAMP. THEN THE TENSIONING PLATE AND LOWER FRICTION LAYER CLAMP SHALL BE CLAMPED TO THE FRICTION LAYER SUCH THAT THE END OF THE FRICTION LAYER IS FLUSH WITH THE FLANGE ON THE TENSIONING CLAMP (SEE DETAIL C/S4). ONCE THE CLAMP IS AFFIXED TO THE FRICTION LAYER, THE PLATES SHALL BE PULLED SUCH THAT THE FRICTION LAYER WRAPS AROUND THE LOWER PIPE AND THE TENSIONING BOLTS CAN BE THREADED INTO PLACE. THESE BOLTS SHALL THEN BE TIGHTENED TO A TORQUE TBD. AFTER THE TENSIONING BOLTS ARE PROPERLY TORQUED, THE CLAMPING BOLTS PASSING THROUGH THE SLOTTED HOLES SHALL BE NUTTED AND TIGHTENED. DETAIL C/S4 DISPLAYS THE FINAL ASSEMBLY.
3. THE REQ'D QUANTITY OF EACH COMPONENT PART CALLED OUT HERE, IS THE NUMBER REQ'D PER WEDGE ASSEMBLY.



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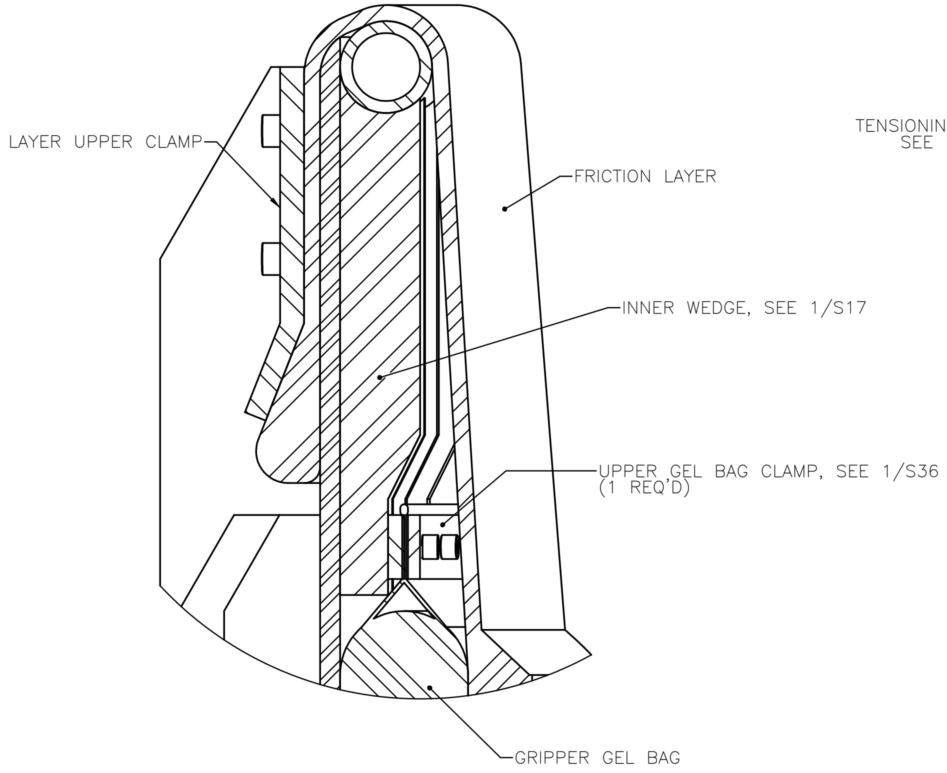
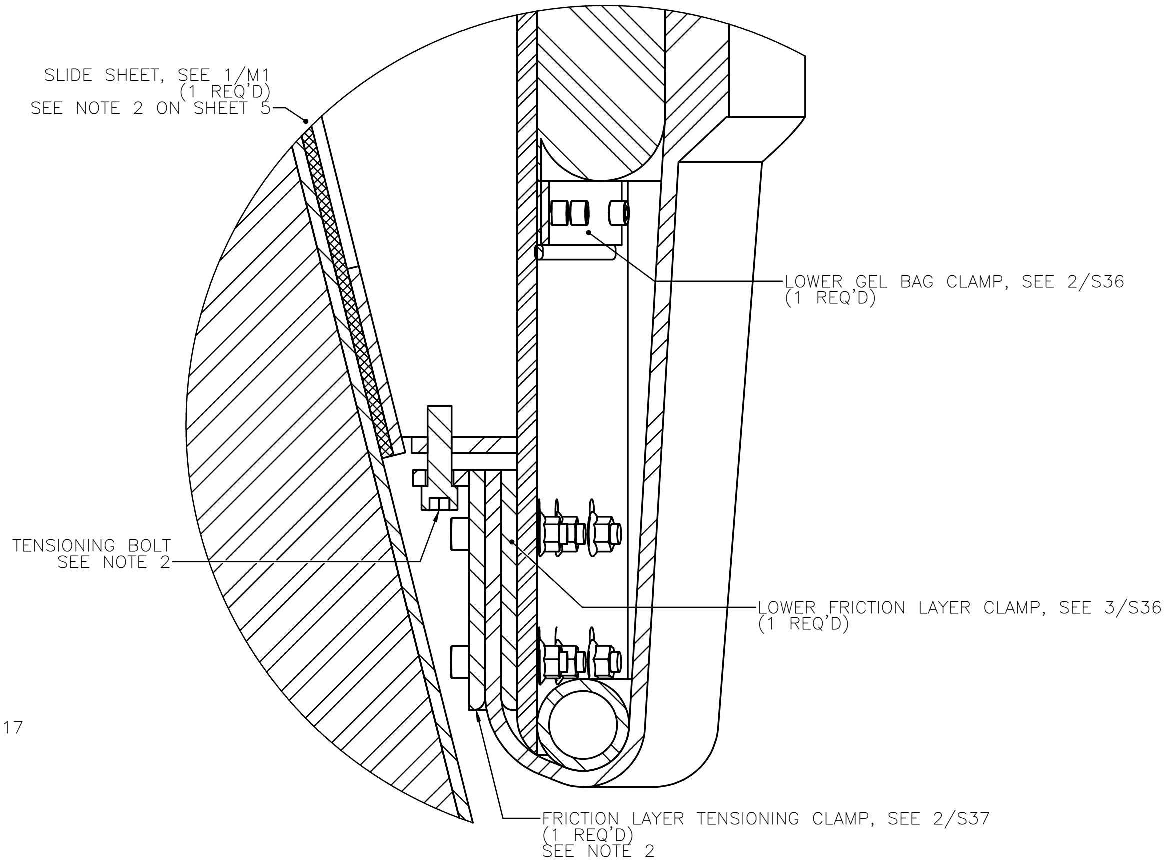


DETAIL B/S4
SCALE 1 : 3



DETAIL C/S4
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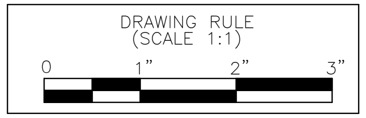

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WEDGE ASSEMBLY (CONT.)

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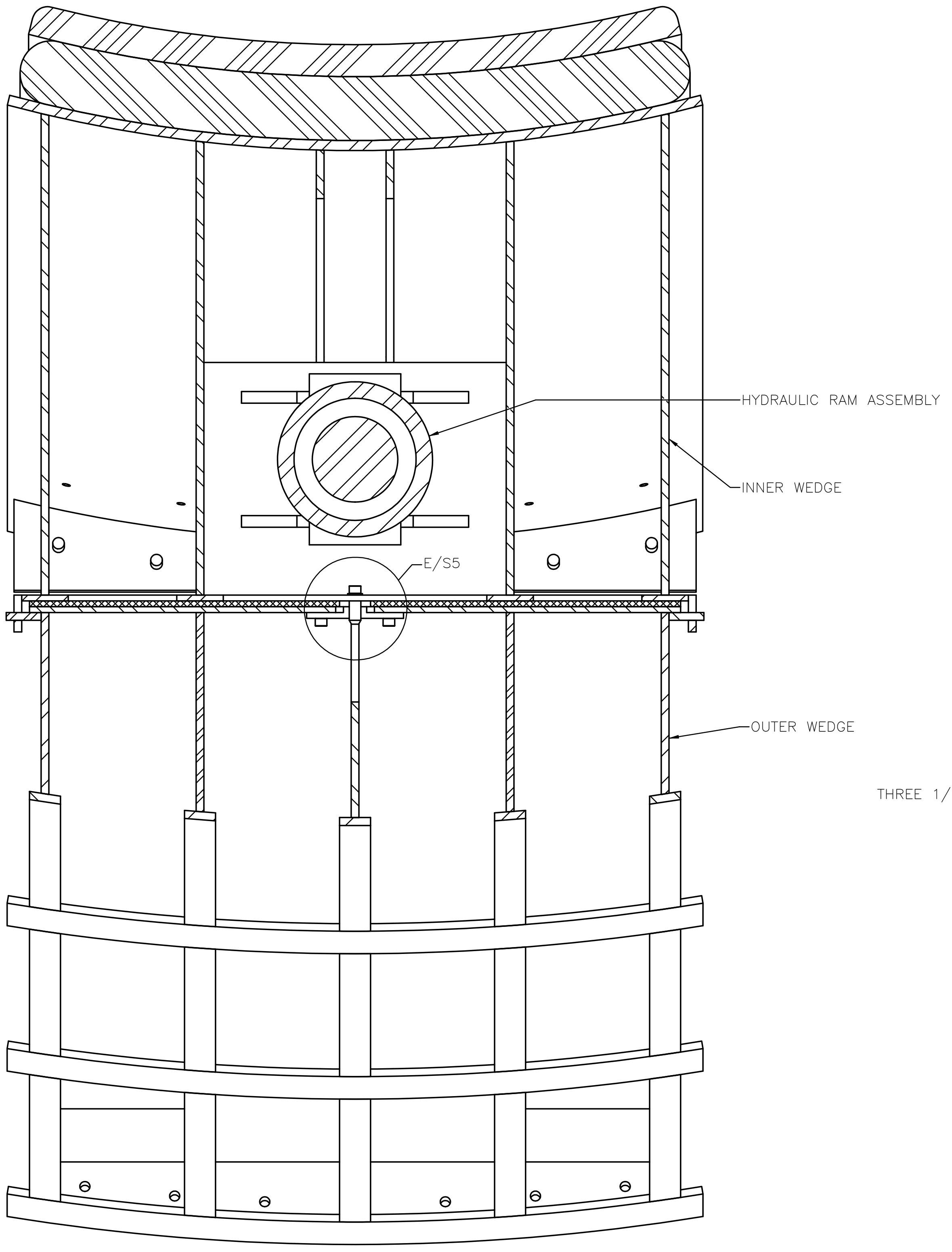
DATE
DRAWING NO. S4

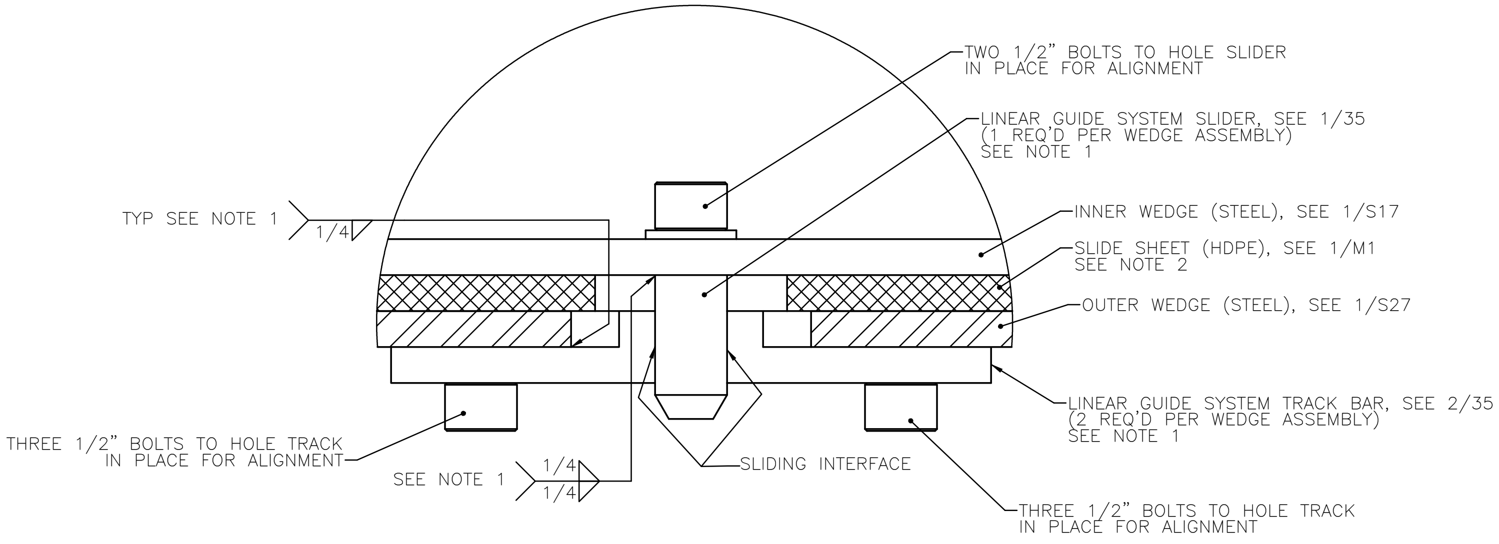
JOB NO. 15706
SHEET NO. 6 OF 61

NOTES:

1. THE LINEAR GUIDE SYSTEM SHALL BE INITIALLY BOLTED IN PLACE AND THE WEDGES SHOP ASSEMBLED TO ENSURE PROPER ALIGNMENT. ONCE THE GUIDE SYSTEM IS ADJUSTED SO THE WEDGES ARE ALIGNED, THE COMPONENTS SHOULD BE DISASSEMBLED AND THE TRACKS AND SLIDER SHALL BE WELDED IN PLACE AS SPECIFIED BY DETAIL E/S5.
2. THE SLIDE SHEET SHALL ALSO BE TEMPORARILY BOLTED IN PLACE DURING THE SHOP ASSEMBLE ALIGNMENT TEST. ONCE THE COMPONENTS ARE CORRECTLY ALIGNED, THE SLIDE SHEET SHALL BE REMOVED AND A FINAL ASSEMBLY PERFORMED. FINAL ASSEMBLY SHALL CONSIST OF ROUGHENING THE HDPE SHEET ON THE INNER WEDGE SIDE WITH A COURSE GRIT SAND PAPER AND APPLYING AN APPROVED CONSTRUCTION ADHESIVE BETWEEN THE SHEET AND METAL SURFACE. THIS SHALL BE IMMEDIATELY FOLLOWED BY TIGHTENING THE METAL FASTENERS IN PLACE. <u>DO NOT ROUGHEN THE UN-ADHERED SIDE OF THE HDPE.</u> THIS FINAL ASSEMBLY STEP SHOULD BE DONE <u>AFTER</u> THE LINEAR GUIDE SLIDER HAS BEEN WELDED INTO PLACE TO ENSURE THE HDPE IS NOT MELTED.



SECTION D/S5-D/S5
SCALE 1 : 5



DETAIL E/S5
SCALE 1 : 1

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

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PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

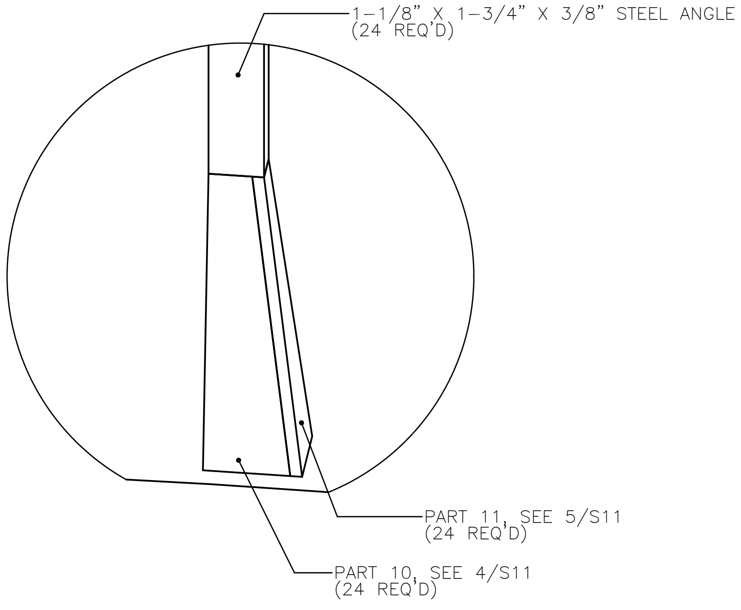
WEDGE ASSEMBLY (CONT.)

MAKAI
OCEAN ENGINEERING, INC.

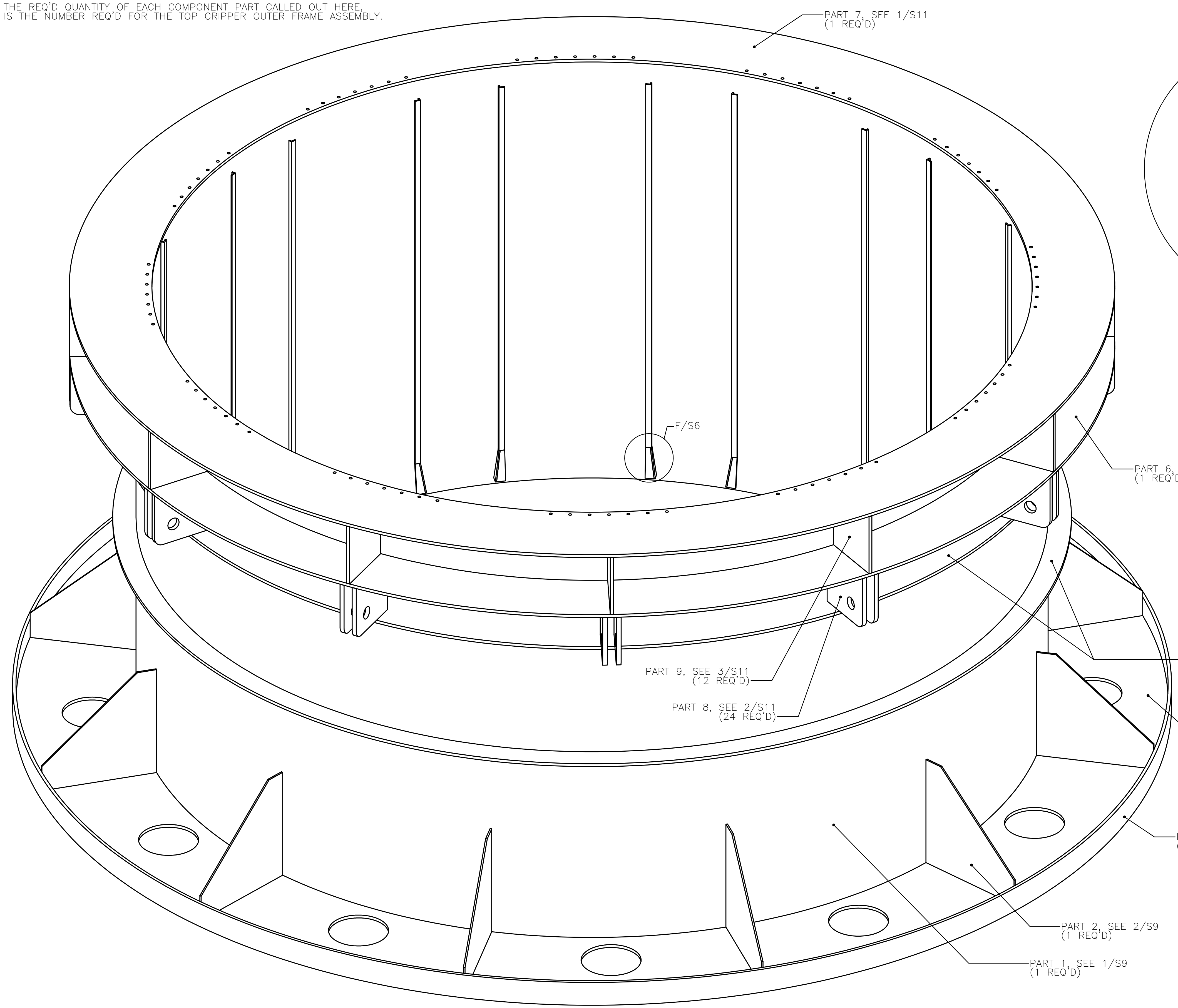
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S5
JOB NO. 15706
SHEET NO. 7 OF 61

NOTES:

1. THE REQ'D QUANTITY OF EACH COMPONENT PART CALLED OUT HERE, IS THE NUMBER REQ'D FOR THE TOP GRIPPER OUTER FRAME ASSEMBLY.



DETAIL F/S6
SCALE 1 : 3



ISO VIEW

1/S6 TOP GRIPPER OUTER FRAME ASSEMBLY: PART CALLOUTS
SCALE 1 : 16

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

TOP GRIPPER OUTER
FRAME ASSEMBLY

MAKAI
OCEAN ENGINEERING, INC.

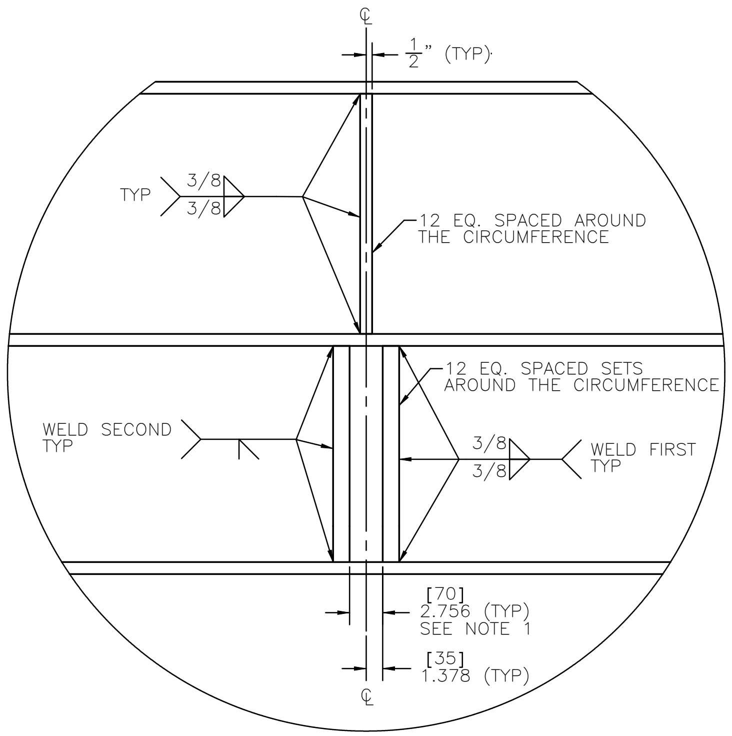
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S6

JOB NO. 15706

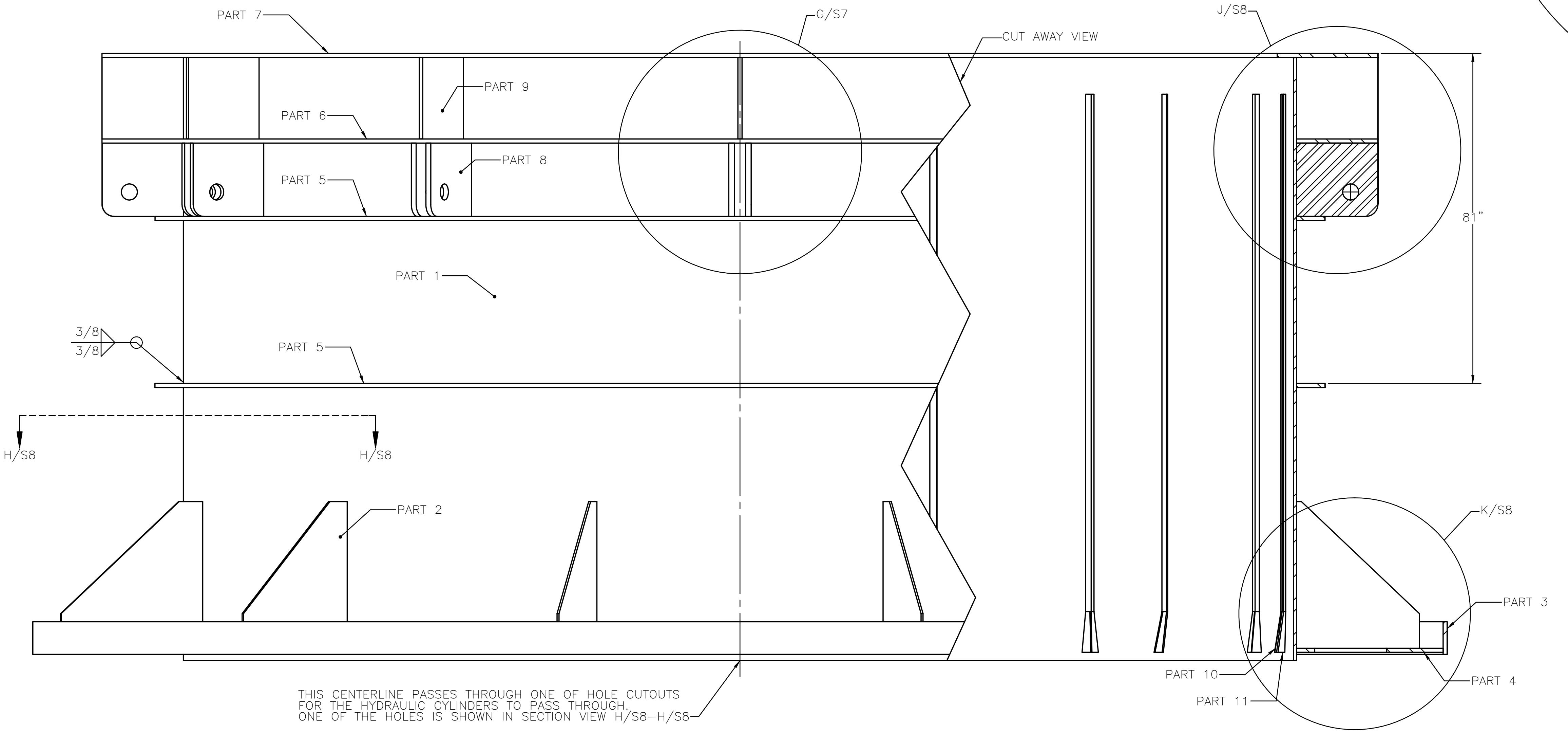
SHEET NO. 8 OF 61

NOTES:

1. THE BRACKETED DIMENSIONS ARE IN MILLIMETERS.



DETAIL G/S7
SCALE 1 : 8



SIDE VIEW

1/S7 TOP GRIPPER OUTER FRAME ASSEMBLY
SCALE 1 : 16

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD MANASSAS, VA 20110-4121

TOP GRIPPER OUTER
FRAME ASSEMBLY (CONT.)

MAKAI
OCEAN ENGINEERING, INC.

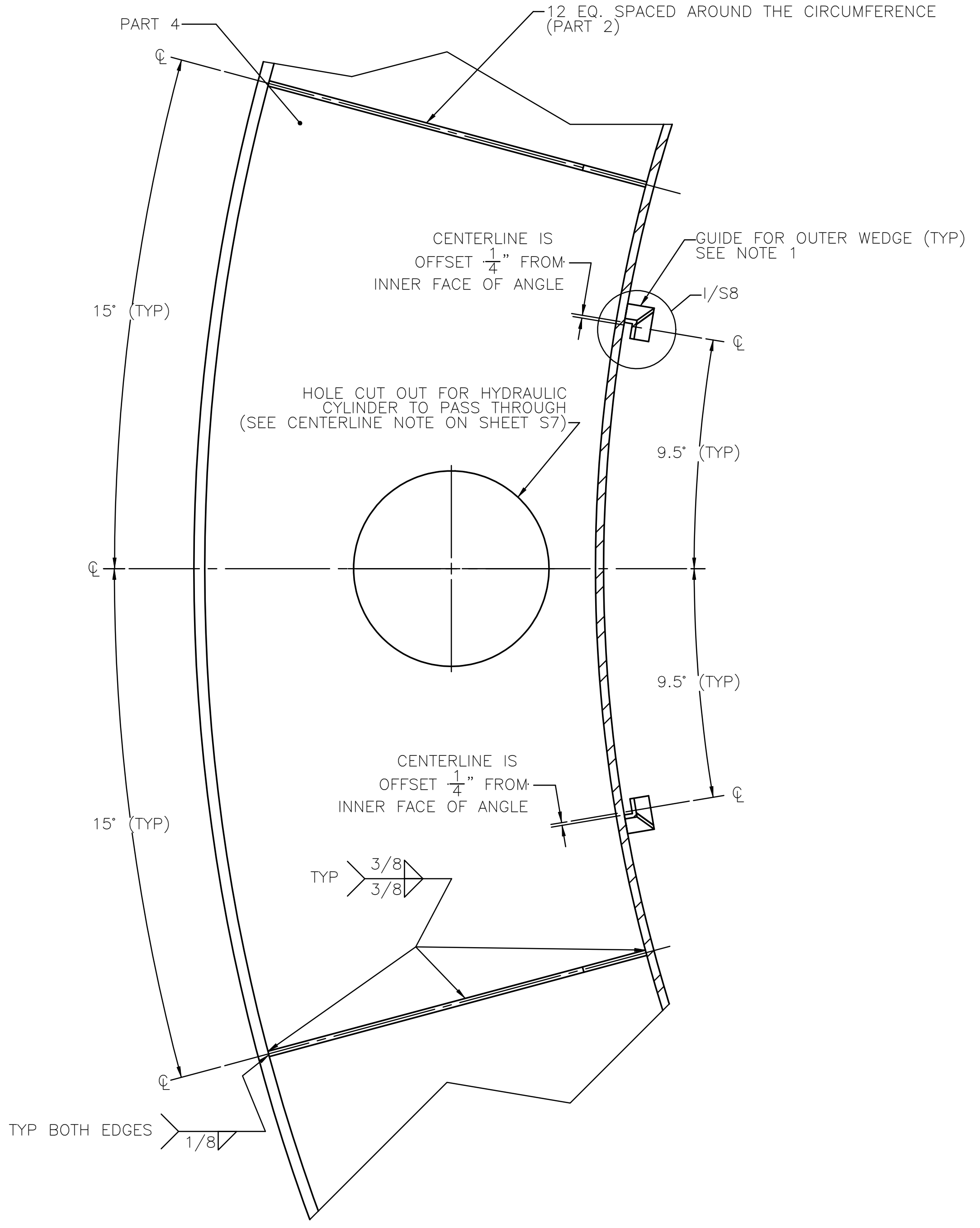
DESIGNED: A. LANDHERR SUBMITTED:
DRAWN: A. LANDHERR DATE: 9/18/2010
CHECKED: D. JENSEN SCALE: SHOWN
APPROVED: DRAWING NO. S7
MANAGER-CHIEF ENGINEER DATE

JOB NO. 15706

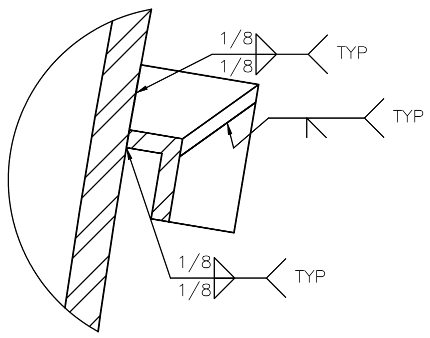
SHEET NO. 9 OF 61

NOTES:

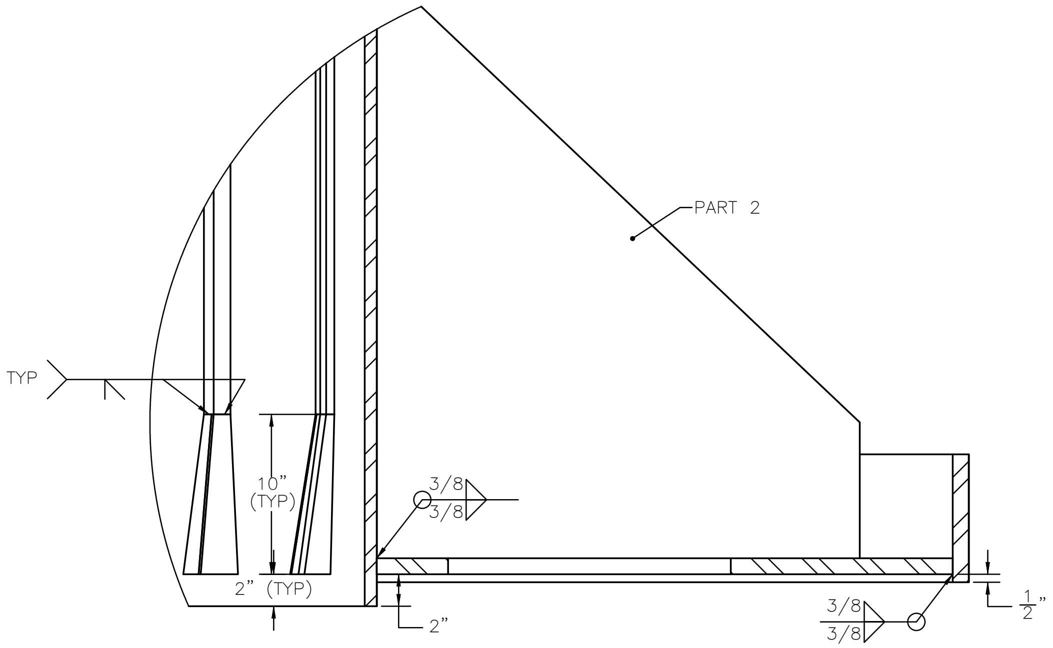
1. THERE ARE 12 SETS OF OUTER WEDGE GUIDES EQUALLY SPACED AROUND THE CIRCUMFERENCE. THE GUIDE TRACKS ARE STEEL ANGLE WITH TWO PLATES WELDED AT ONE END TO MAKE A FLARE TO EASE ASSEMBLY.



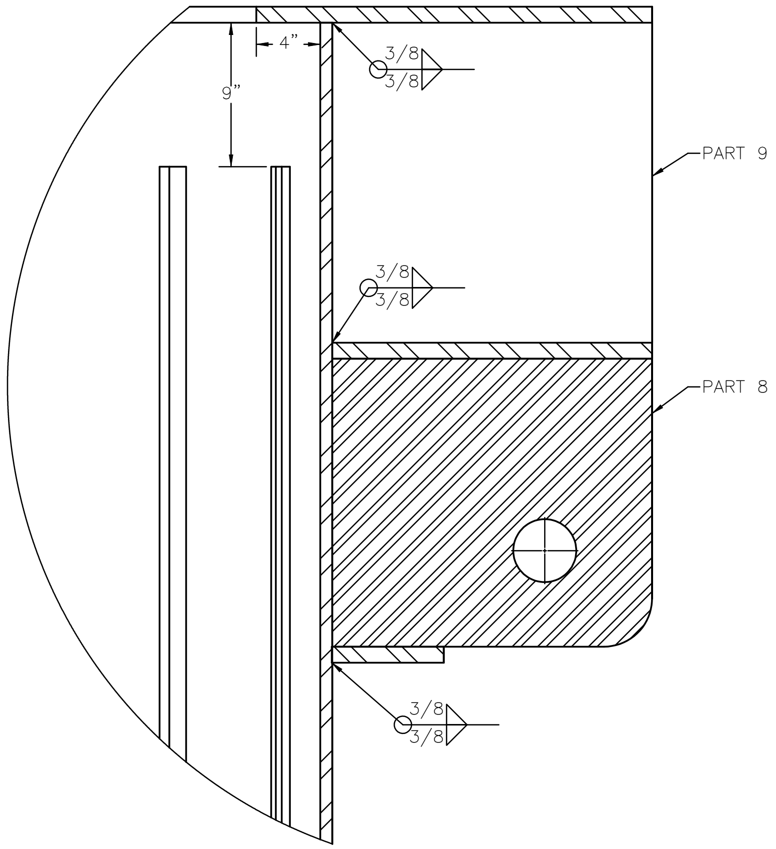
SECTION H/S8-H/S8
SCALE 1 : 8



DETAIL I/S8
SCALE 1 : 2



DETAIL K/S8
SCALE 1 : 6



DETAIL J/S8
SCALE 1 : 6

DRAWING RULE
(SCALE 1:1)

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

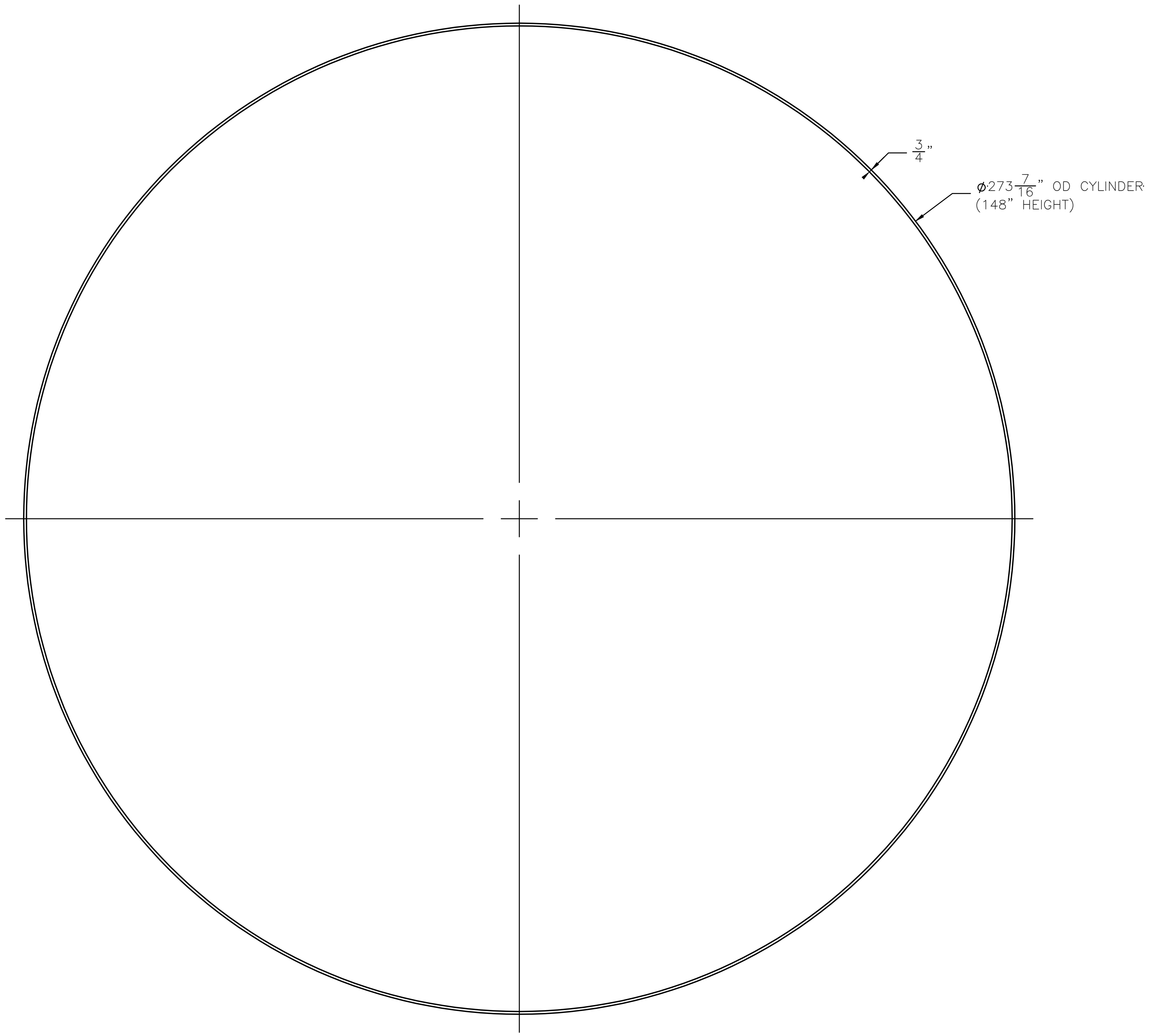
LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

TOP GRIPPER OUTER
FRAME ASSEMBLY (CONT.)

MAKAI
OCEAN ENGINEERING, INC.

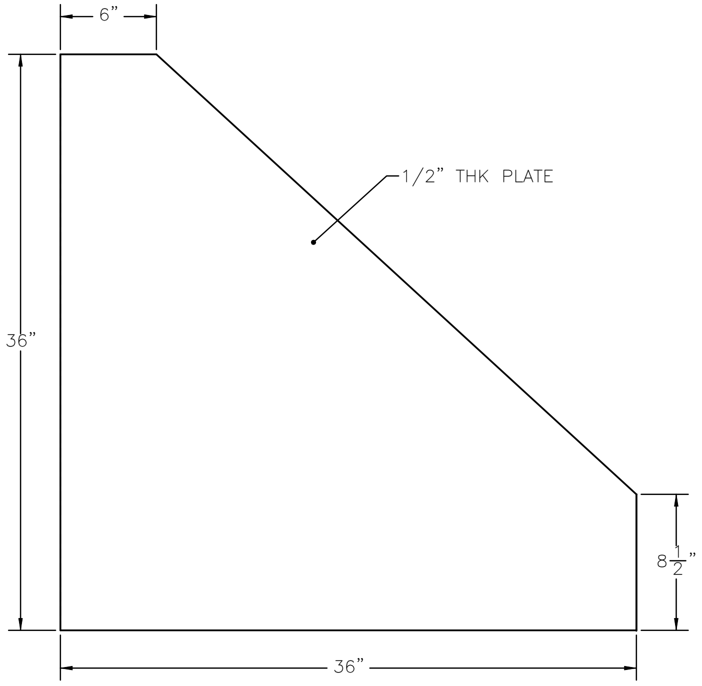
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S8

JOB NO. 15706



TOP VIEW

1/S9 PART 1
SCALE 1 : 20



SIDE VIEW

2/S9 PART 2
SCALE 1 : 6

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

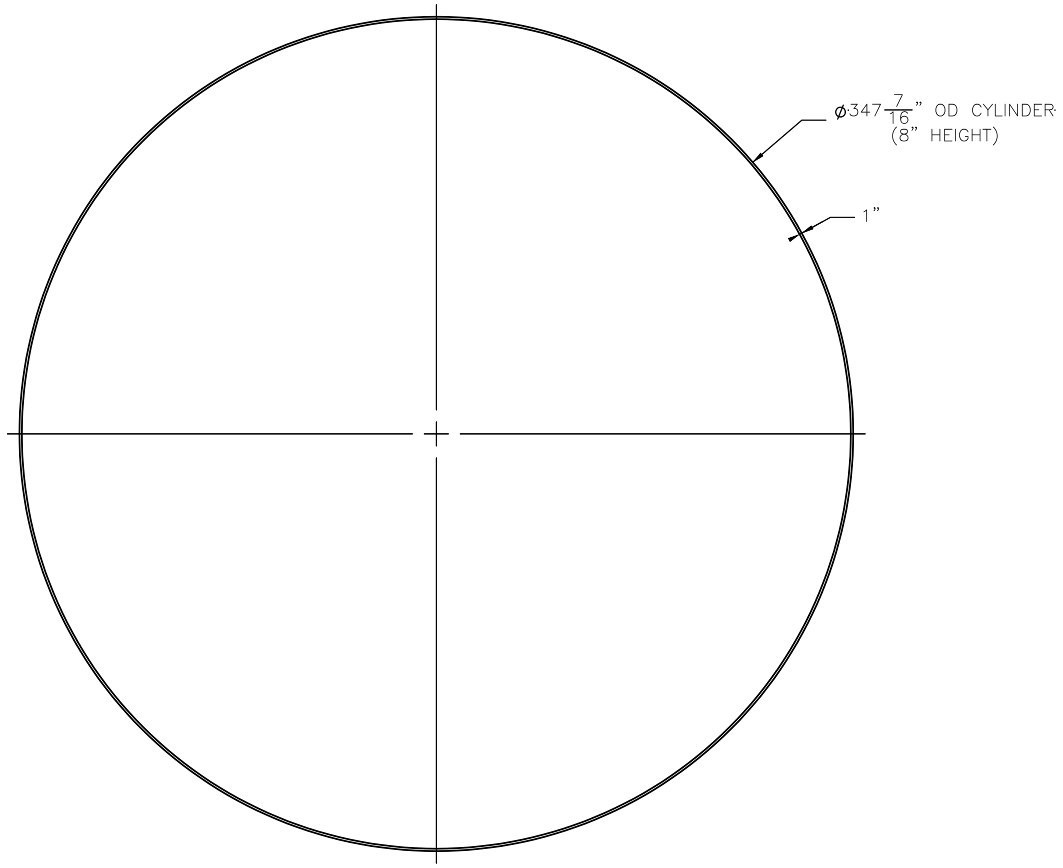
TOP GRIPPER OUTER FRAME
ASSEMBLY PARTS I

MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR	SUBMITTED:
DRAWN: A. LANDHERR	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED:	DRAWING NO. S9
MANAGER-CHIEF ENGINEER DATE	

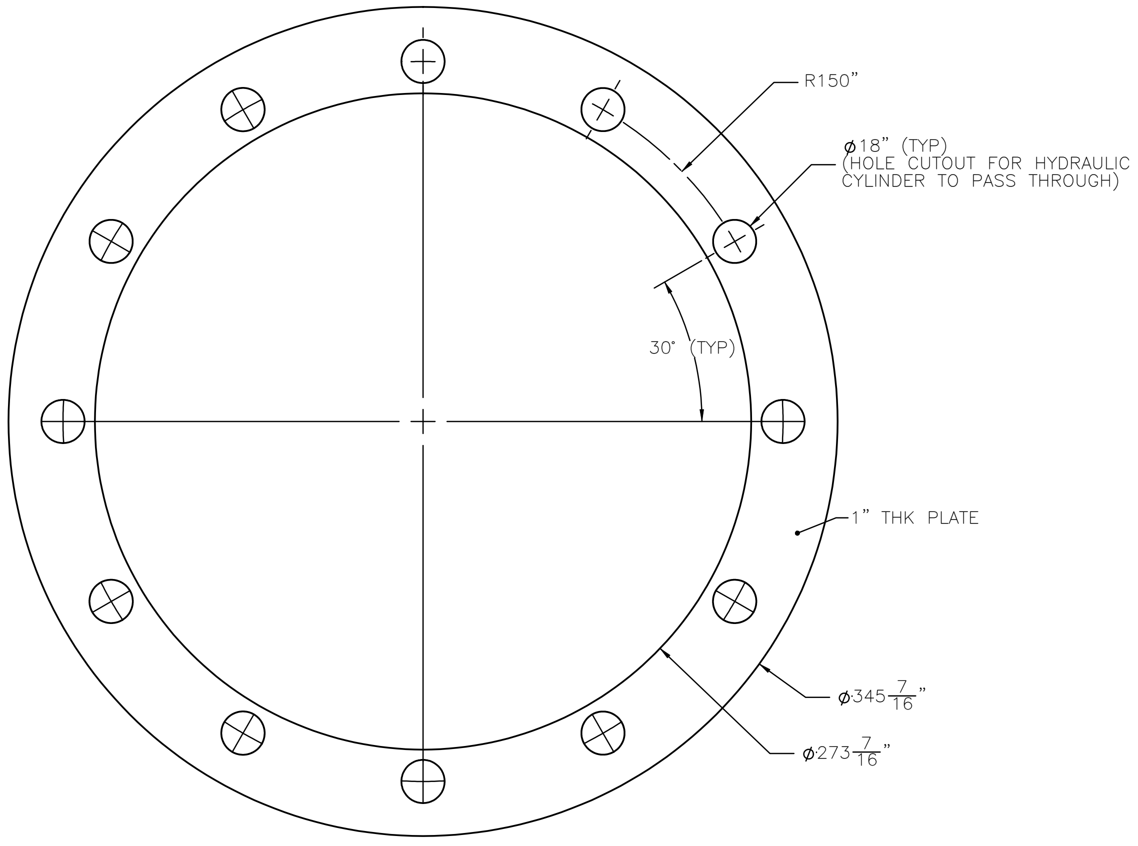
JOB NO. 15706

SHEET NO. 11 OF 61



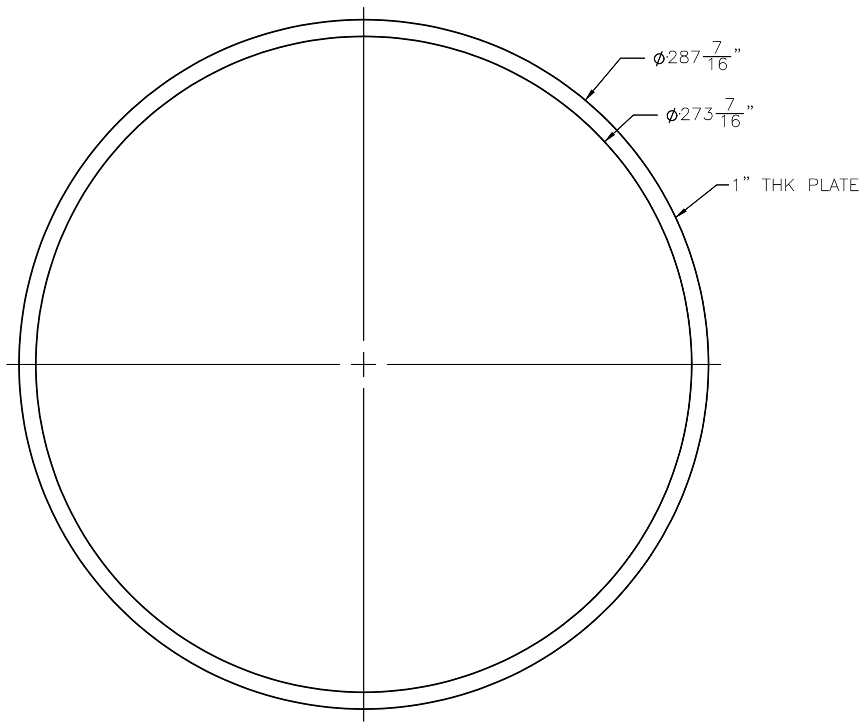
TOP VIEW

1/S10 PART 3
SCALE 1 : 40



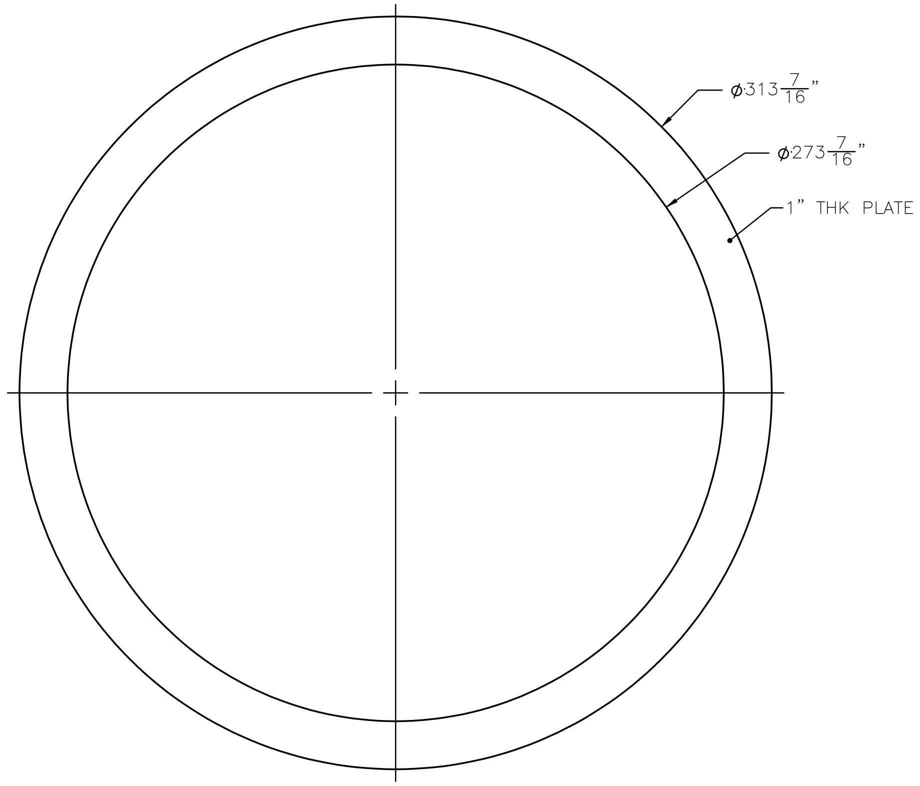
TOP VIEW

2/S10 PART 4
SCALE 1 : 40



TOP VIEW

3/S10 PART 5
SCALE 1 : 40



TOP VIEW

4/S10 PART 6
SCALE 1 : 40

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

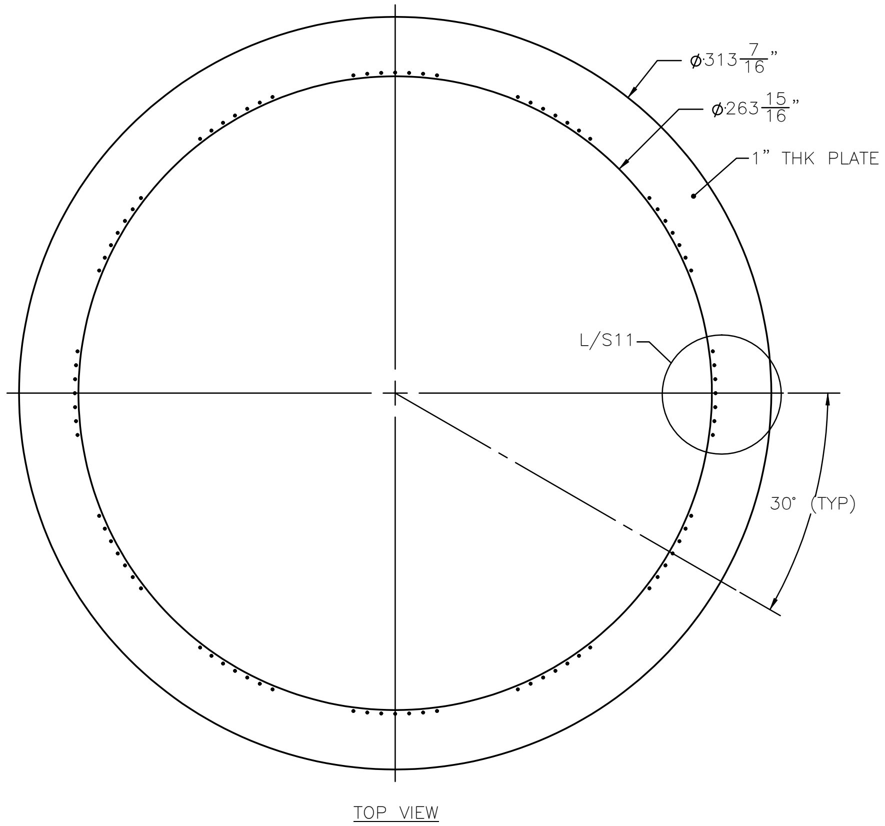
TOP GRIPPER OUTER FRAME
ASSEMBLY PARTS II

MAKAI
OCEAN ENGINEERING, INC.

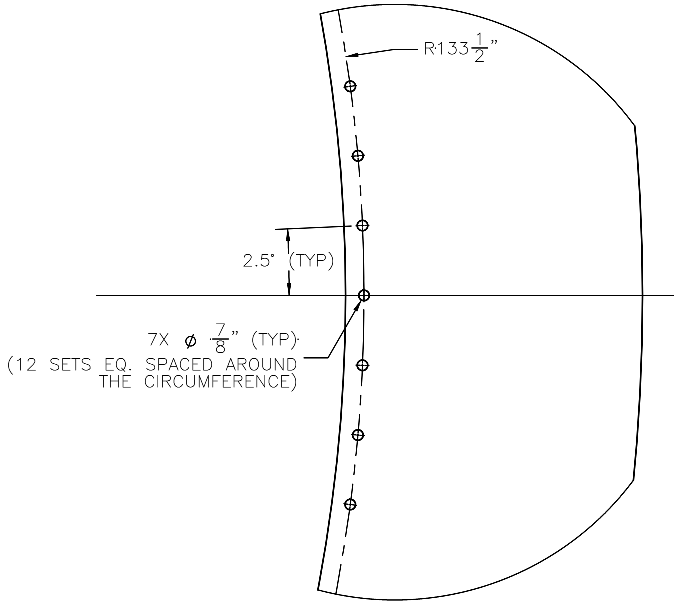
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER DATE
DRAWING NO. S10

JOB NO. 15706

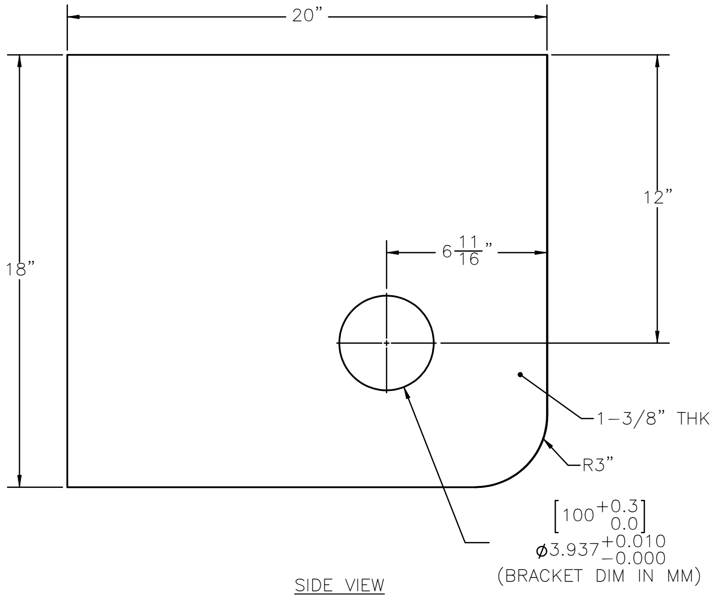
SHEET NO. 12 OF 61



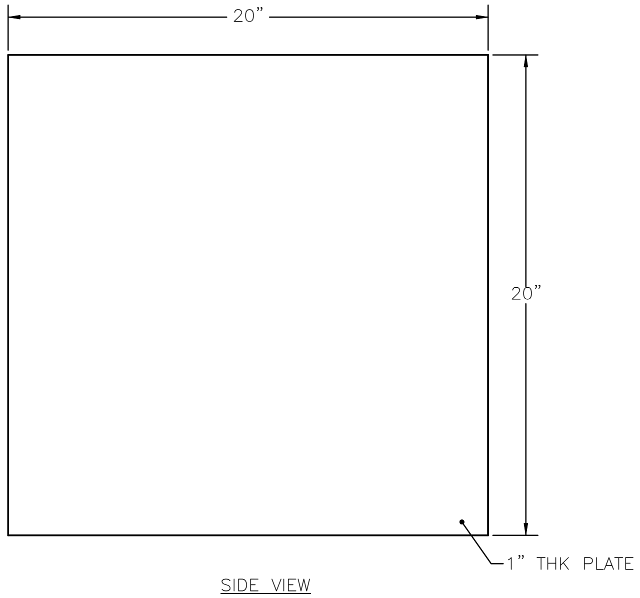
1/S11 PART 7
SCALE 1 : 40



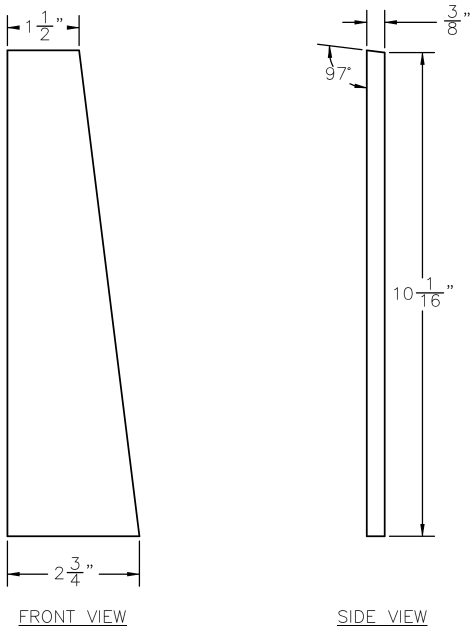
DETAIL L/S11
SCALE 1 : 8



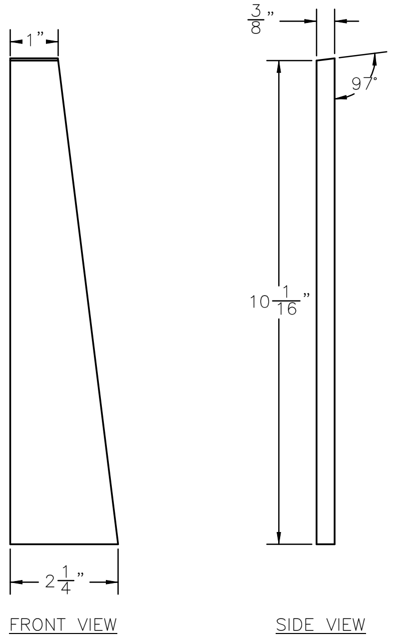
2/S11 PART 8
SCALE 1 : 4



3/S11 PART 9
SCALE 1 : 4



4/S11 PART 10
SCALE 1 : 2



5/S11 PART 11
SCALE 1 : 2

DRAWING RULE
(SCALE 1:1)

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

TOP GRIPPER OUTER FRAME
ASSEMBLY PARTS III

MAKAI
OCEAN ENGINEERING, INC.

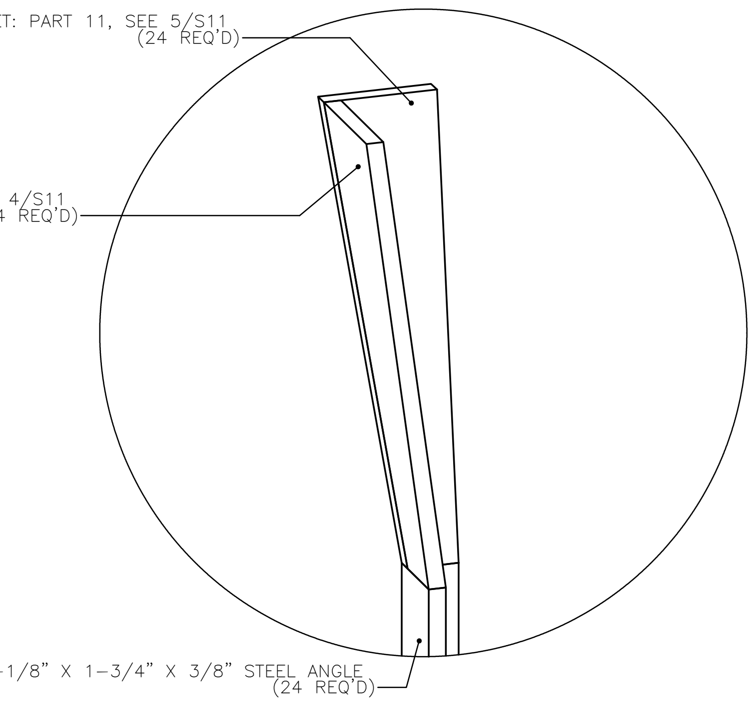
DESIGNED: A. LANDHERR SUBMITTED:
DRAWN: A. LANDHERR DATE: 9/18/2010
CHECKED: D. JENSEN SCALE: SHOWN
APPROVED: DRAWING NO. S11
MANAGER-CHIEF ENGINEER DATE

JOB NO. 15706

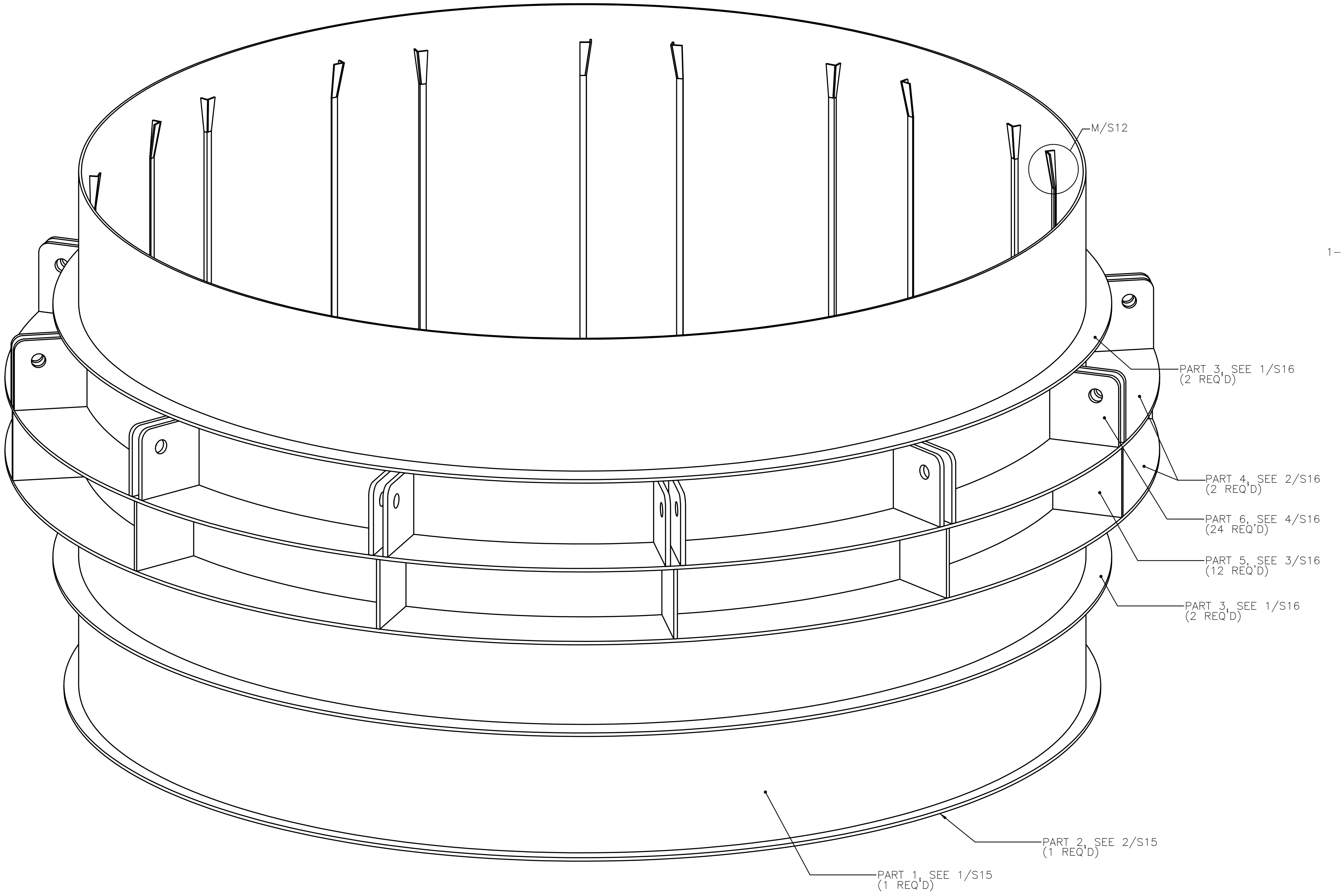
SHEET NO. 13 OF 61

NOTES:

1. THE REQ'D QUANTITY OF EACH COMPONENT PART CALLED OUT HERE, IS THE NUMBER REQ'D FOR THE BOTTOM GRIPPER OUTER FRAME ASSEMBLY.



DETAIL M/S12
SCALE 1 : 2



ISO VIEW

1/S12 BOTTOM GRIPPER OUTER FRAME ASSEMBLY: PART CALLOUTS
SCALE 1 : 16

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

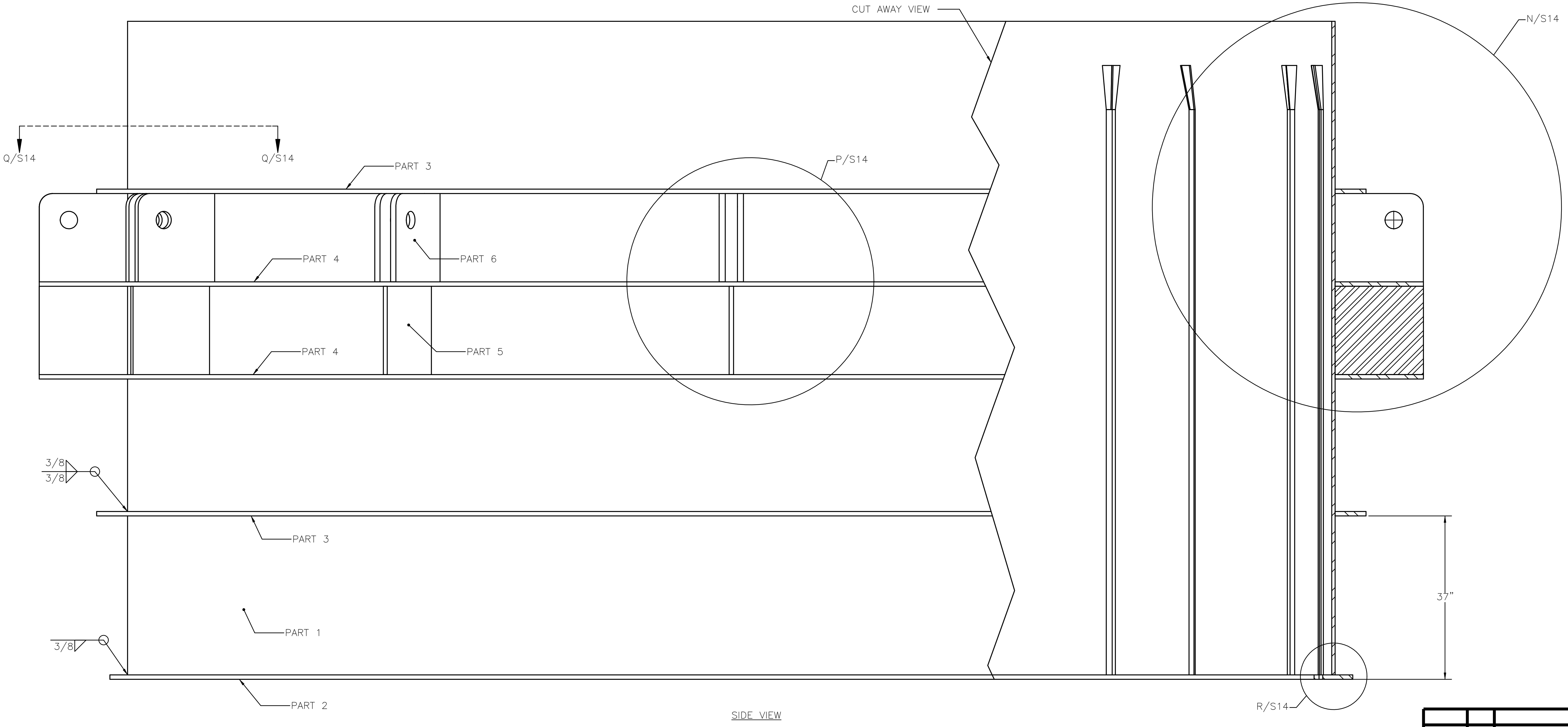
BOTTOM GRIPPER OUTER FRAME ASSEMBLY

MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S12

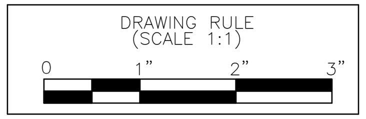
JOB NO. 15706

SHEET NO. 14 OF 61



SIDE VIEW

1/S13 BOTTOM GRIPPER OUTER FRAME ASSEMBLY
SCALE 1 : 16



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

BOTTOM GRIPPER OUTER FRAME
ASSEMBLY (CONT.)

MAKAI
OCEAN ENGINEERING, INC.

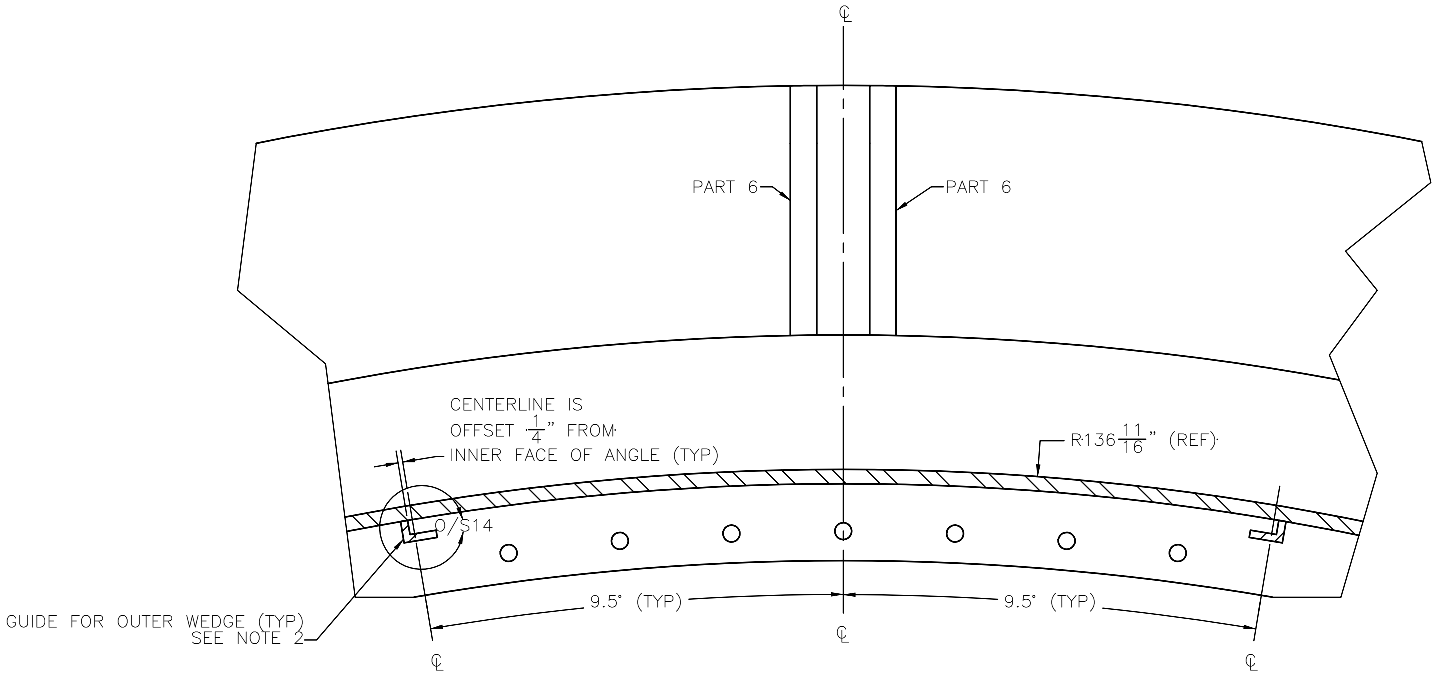
DESIGNED: A. LANDHERR SUBMITTED:
DRAWN: A. LANDHERR DATE: 9/18/2010
CHECKED: D. JENSEN SCALE: SHOWN
APPROVED:
DRAWING NO. S13
MANAGER–CHIEF ENGINEER DATE

JOB NO. 15706

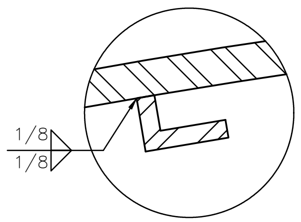
SHEET NO. 15 OF 61

NOTES:

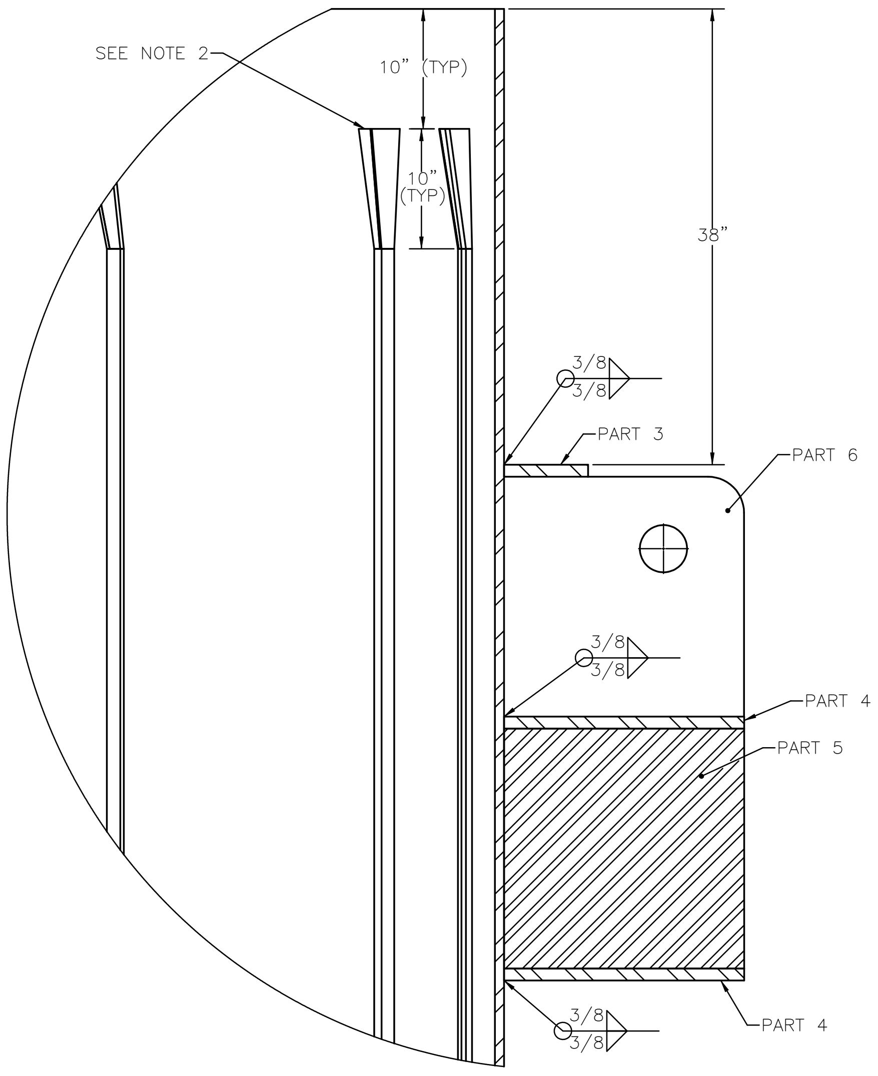
1. THE BRACKETED DIMENSIONS ARE IN MILLIMETERS.
2. THE OUTER WEDGE GUIDES ARE THE SAME FOR THE TOP AND BOTTOM GRIPPERS, WITH THE EXCEPTION THAT THE FLARE POINTS UP FOR THE BOTTOM GRIPPER. REFER TO SHEET S8 FOR WELD DETAILS. SIMILAR TO THE TOP GRIPPER OUTER FRAME, THERE ARE 12 SETS OF GUIDES EQUALLY SPACED AROUND THE CIRCUMFERENCE.



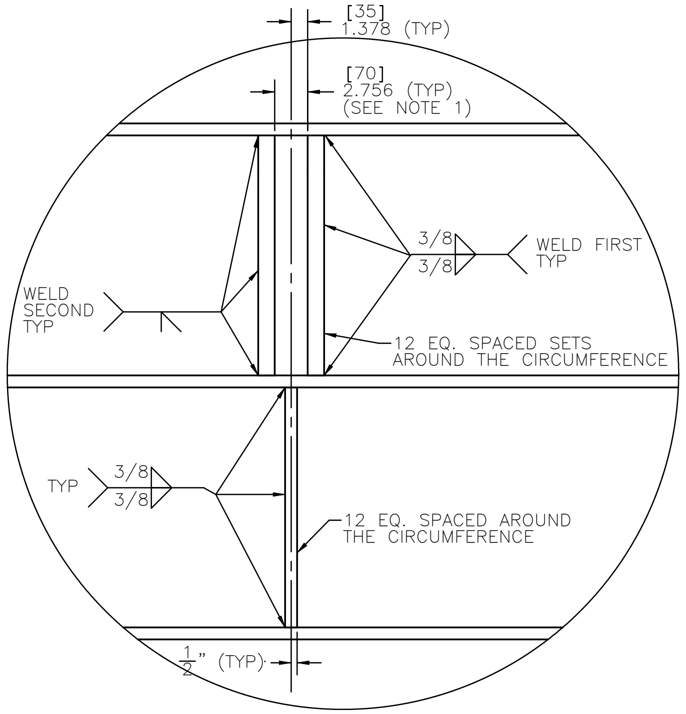
SECTION Q/S14–Q/S14
SCALE 1 : 5



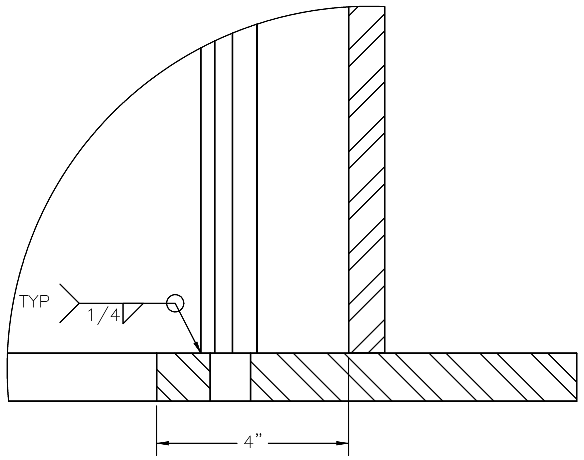
DETAIL O/S14
SCALE 1 : 2



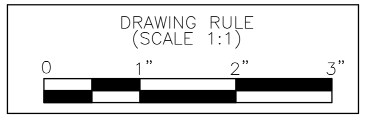
DETAIL N/S14
SCALE 1 : 8



DETAIL P/S14
SCALE 1 : 8



DETAIL R/S14
SCALE 1 : 2



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

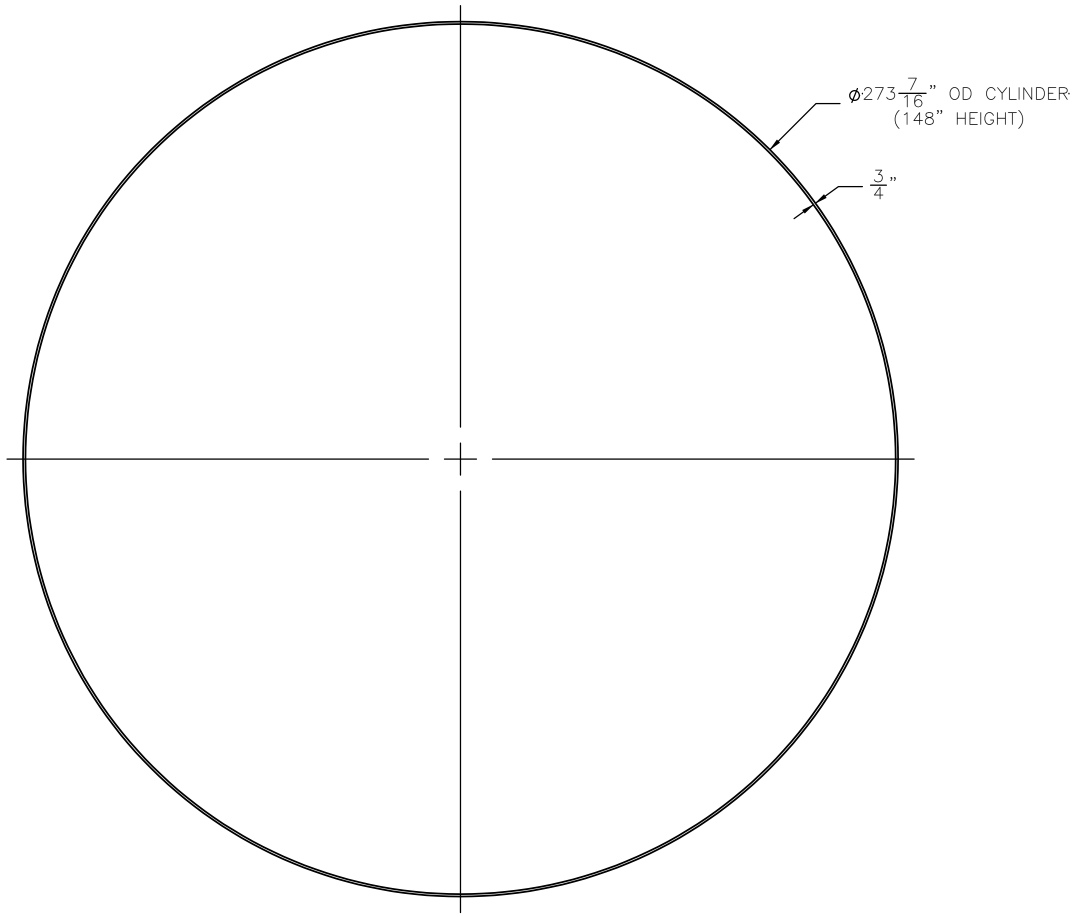
LOCKHEED MARTIN 9255 WELLINGTON ROAD MANASSAS, VA 20110–4121

BOTTOM GRIPPER OUTER FRAME ASSEMBLY (CONT.)

MAKAI
OCEAN ENGINEERING, INC.

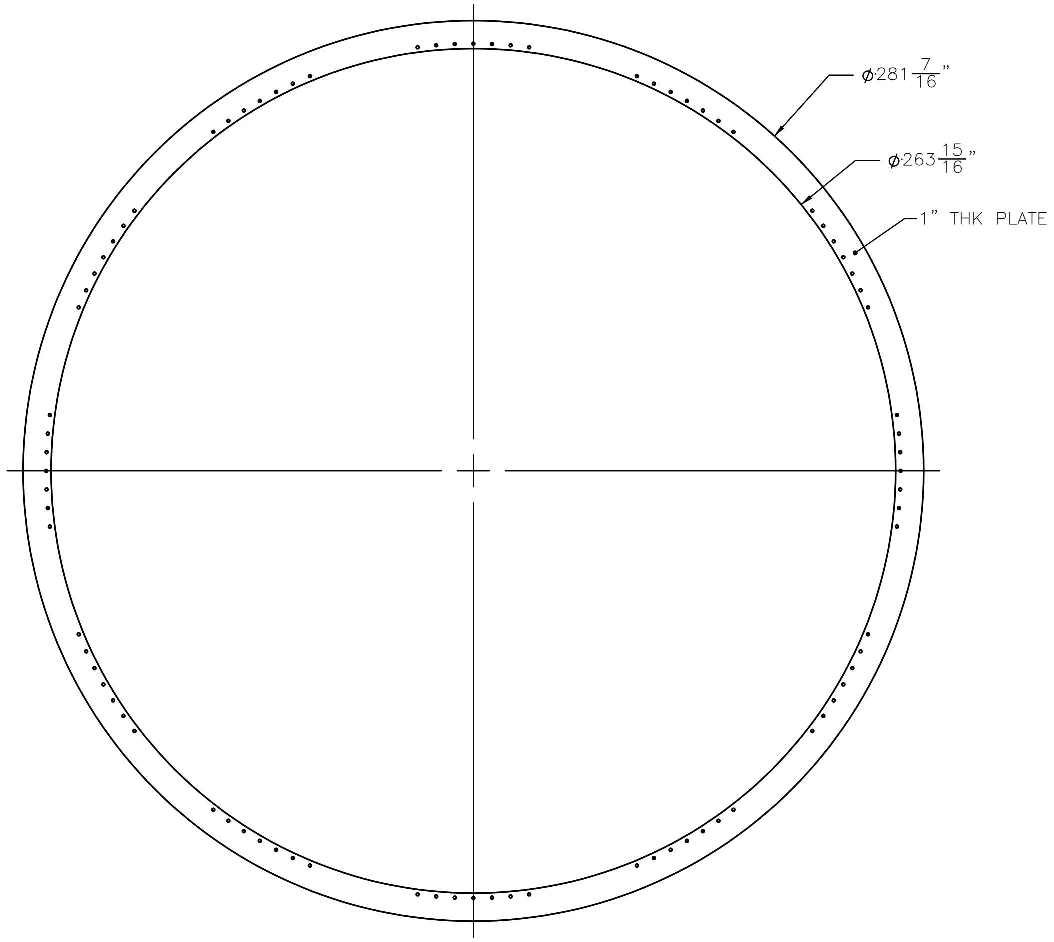
DESIGNED: A. LANDHERR SUBMITTED:
DRAWN: A. LANDHERR DATE: 9/18/2010
CHECKED: D. JENSEN SCALE: SHOWN
APPROVED:
DRAWING NO. S14
MANAGER–CHIEF ENGINEER DATE

JOB NO. 15706
SHEET NO. 16 OF 61



TOP VIEW

1/S15 PART 1
SCALE 1 : 30



TOP VIEW

2/S15 PART 2
SCALE 1 : 30

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

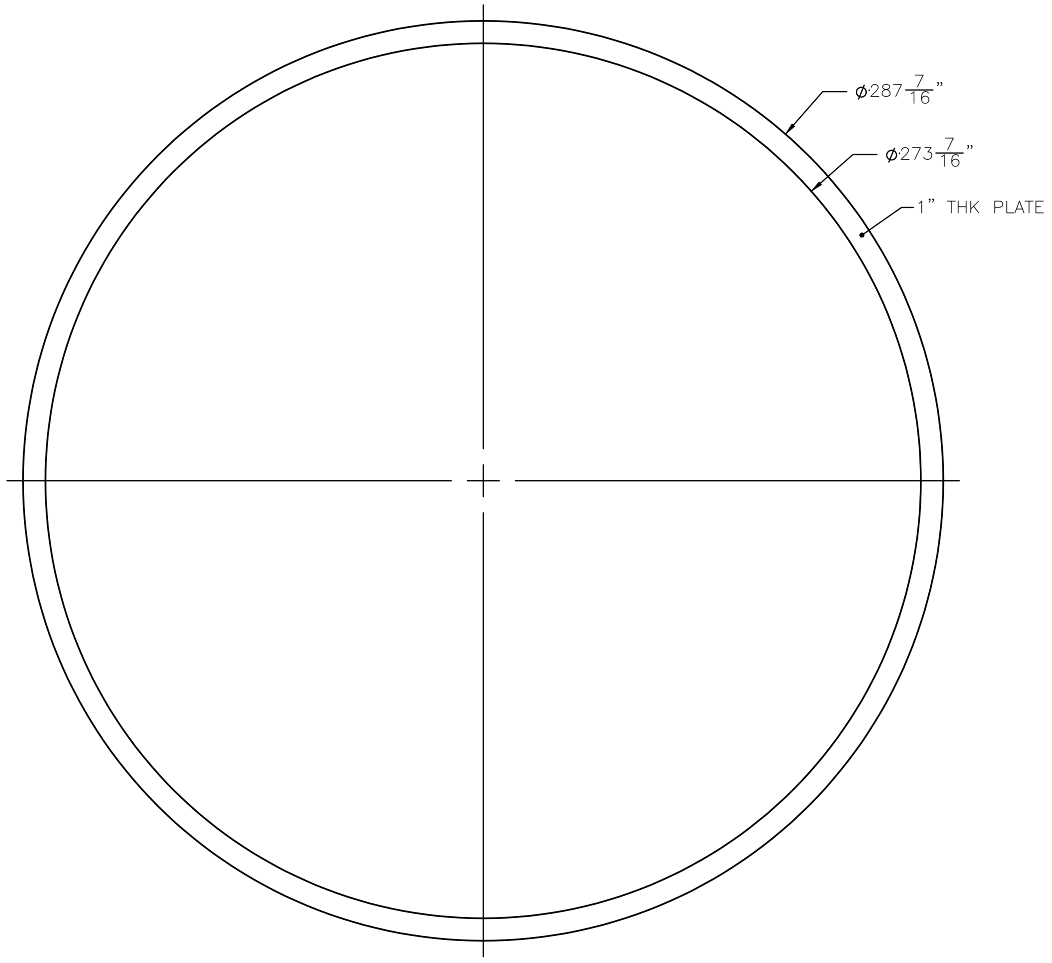
BOTTOM GRIPPER OUTER FRAME
ASSEMBLY PARTS I

MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S15

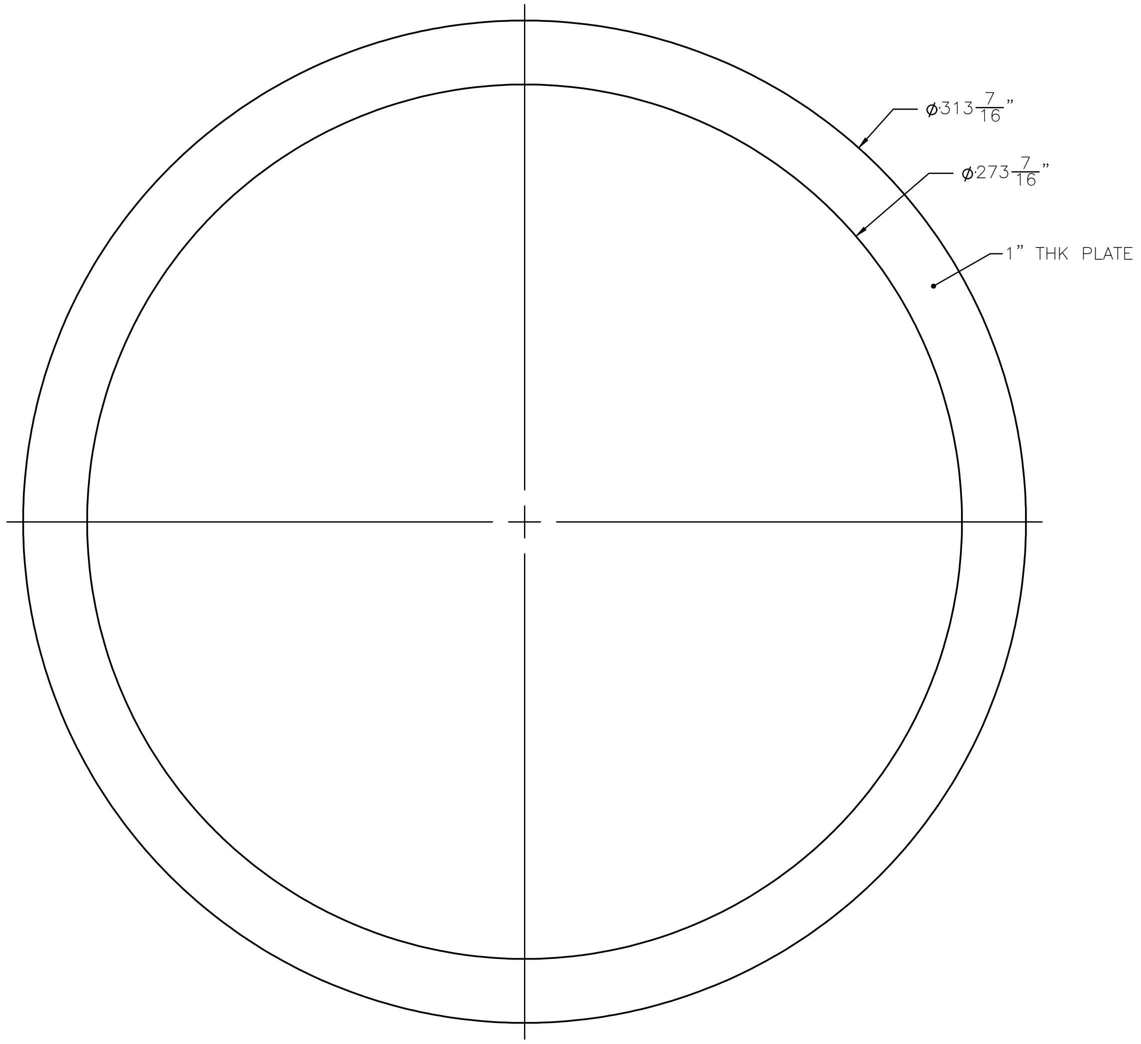
JOB NO. 15706

SHEET NO. 17 OF 61



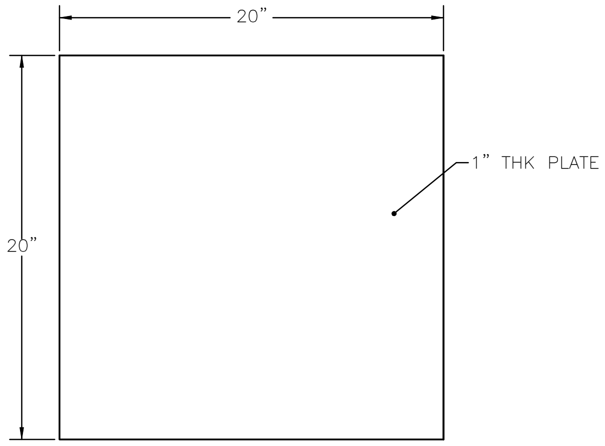
TOP VIEW

1/S16 PART 3
SCALE 1 : 30



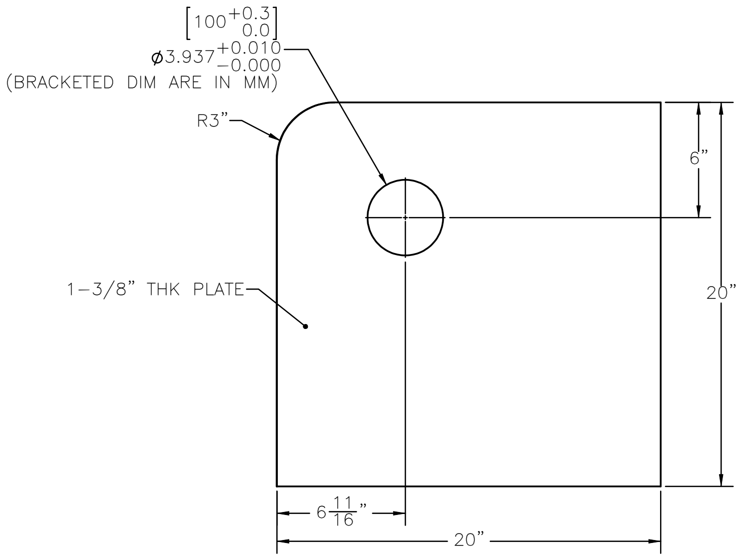
TOP VIEW

2/S16 PART 4
SCALE 1 : 30



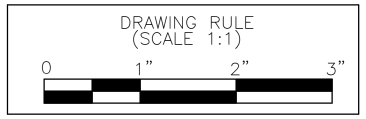
SIDE VIEW

3/S16 PART 5
SCALE 1 : 5



SIDE VIEW

4/S16 PART 6
SCALE 1 : 5



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

BOTTOM GRIPPER OUTER FRAME
ASSEMBLY PARTS II

MAKAI
OCEAN ENGINEERING, INC.

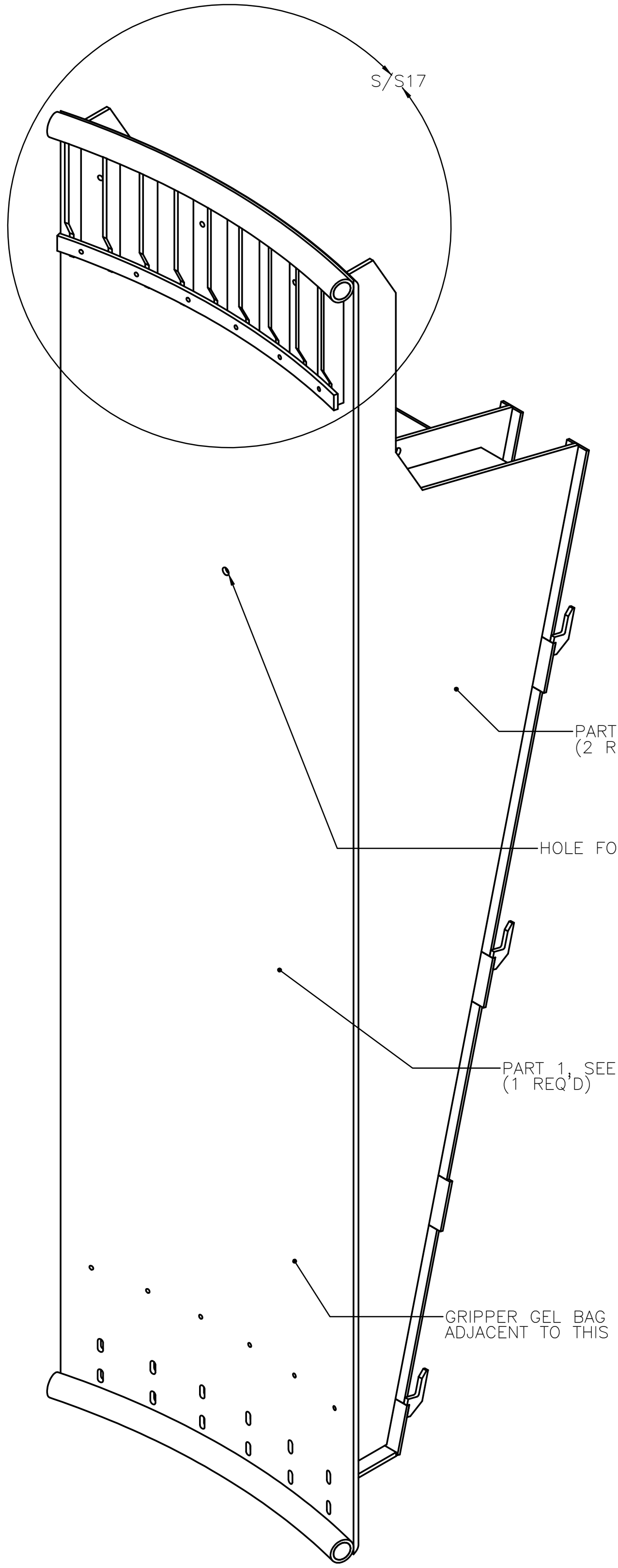
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S16

JOB NO. 15706

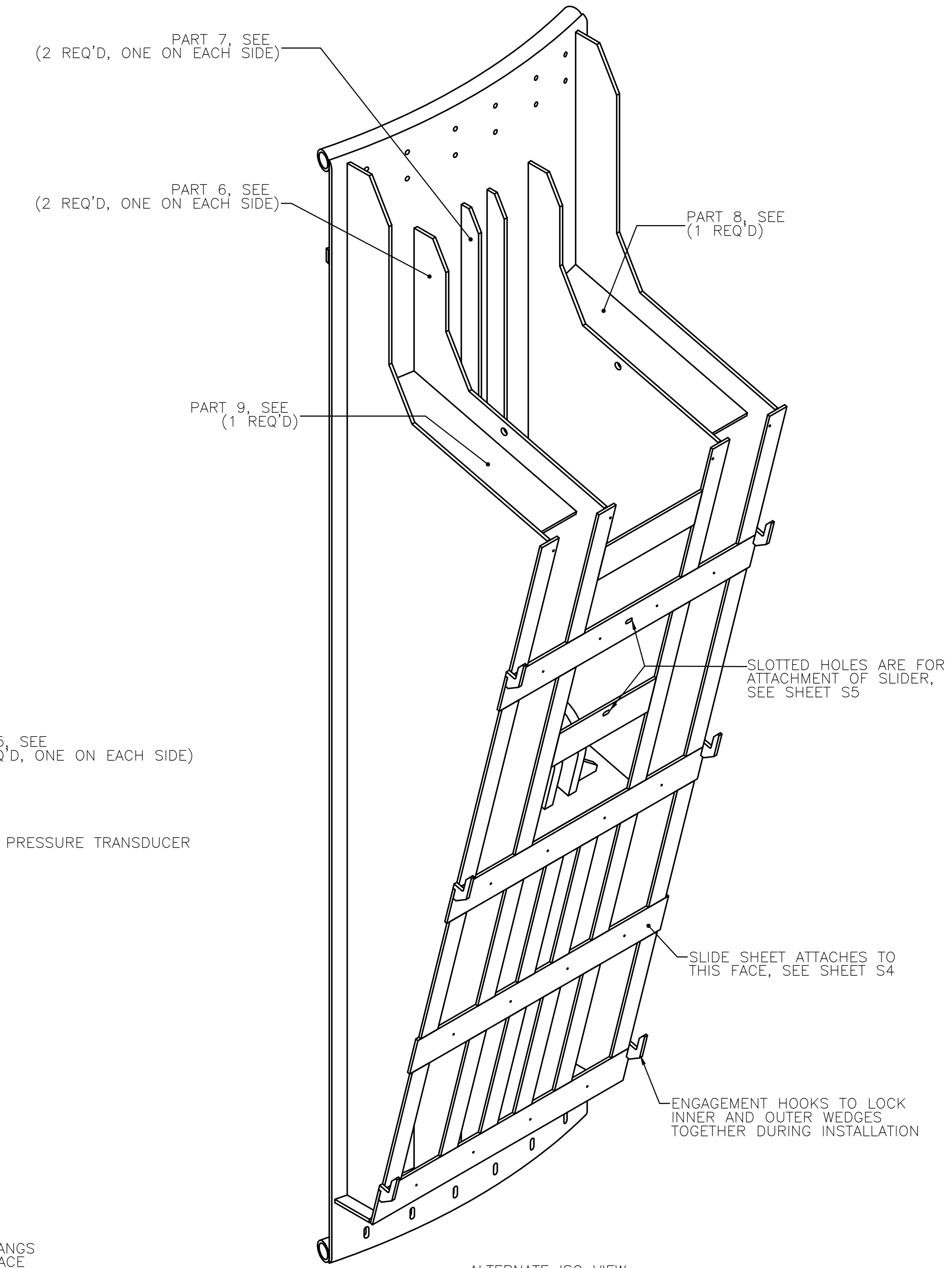
SHEET NO. 18 OF 61

NOTES:

1. THE REQ'D QUANTITY OF EACH COMPONENT PART CALLED OUT HERE, IS THE NUMBER REQ'D PER INNER WEDGE ASSEMBLY. THERE ARE 12 INNER WEDGE ASSEMBLIES IN THE TOP GRIPPER AND 12 INNER WEDGE ASSEMBLIES IN THE BOTTOM GRIPPER.

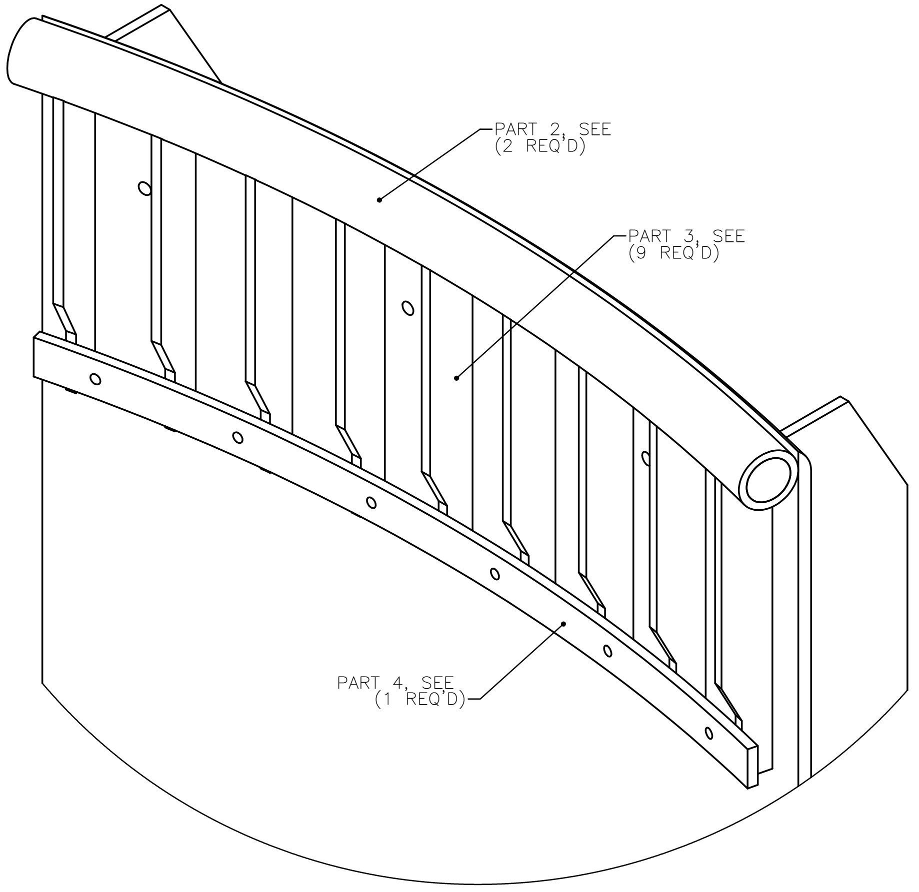


ISO VIEW



ALTERNATE ISO VIEW

1/S17 INNER WEDGE ASSEMBLY: PART CALLOUTS
SCALE 1 : 10



DETAIL S/S17
SCALE 1 : 4

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

INNER WEDGE ASSEMBLY

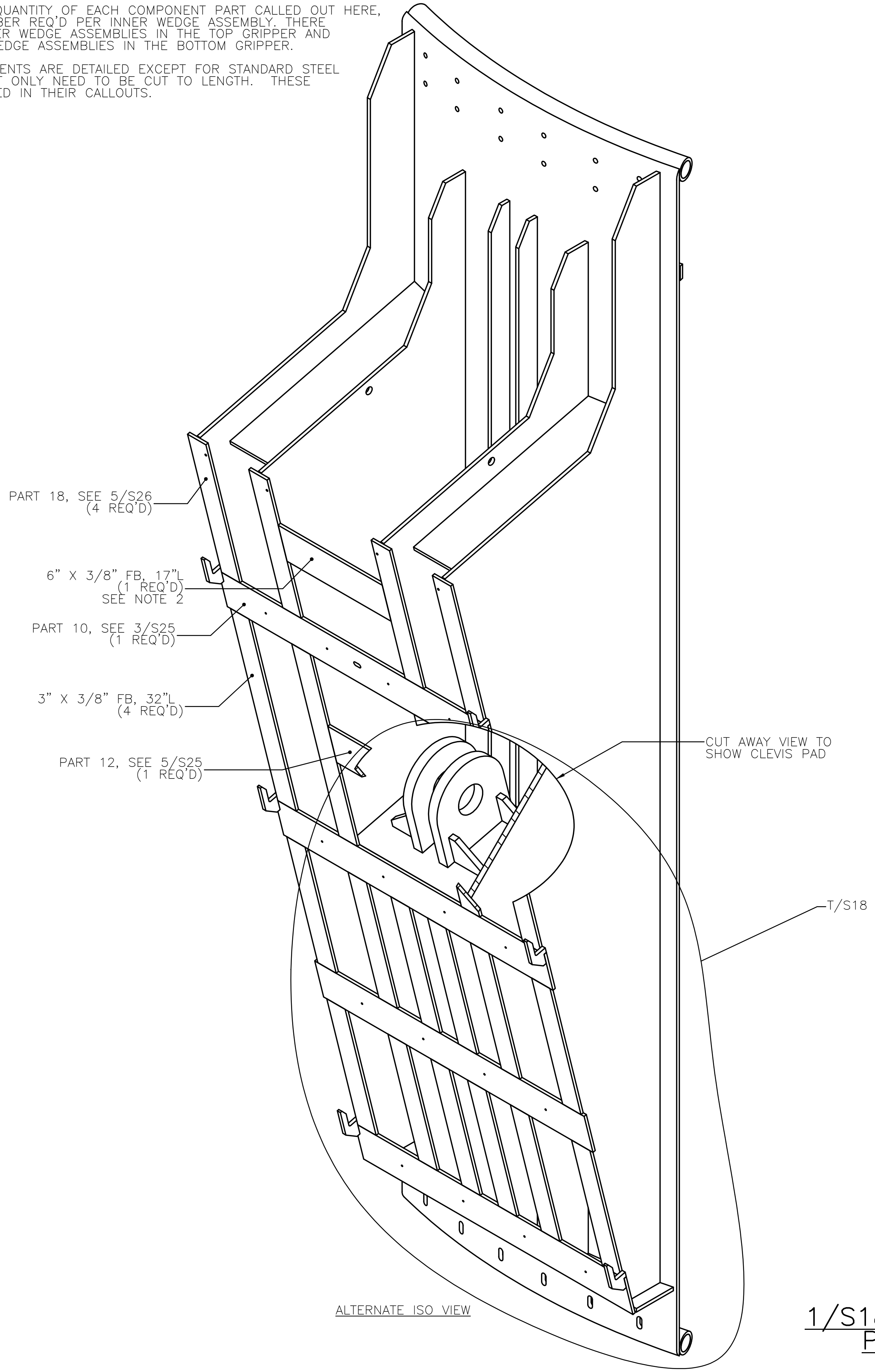
MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S17

JOB NO. 15706

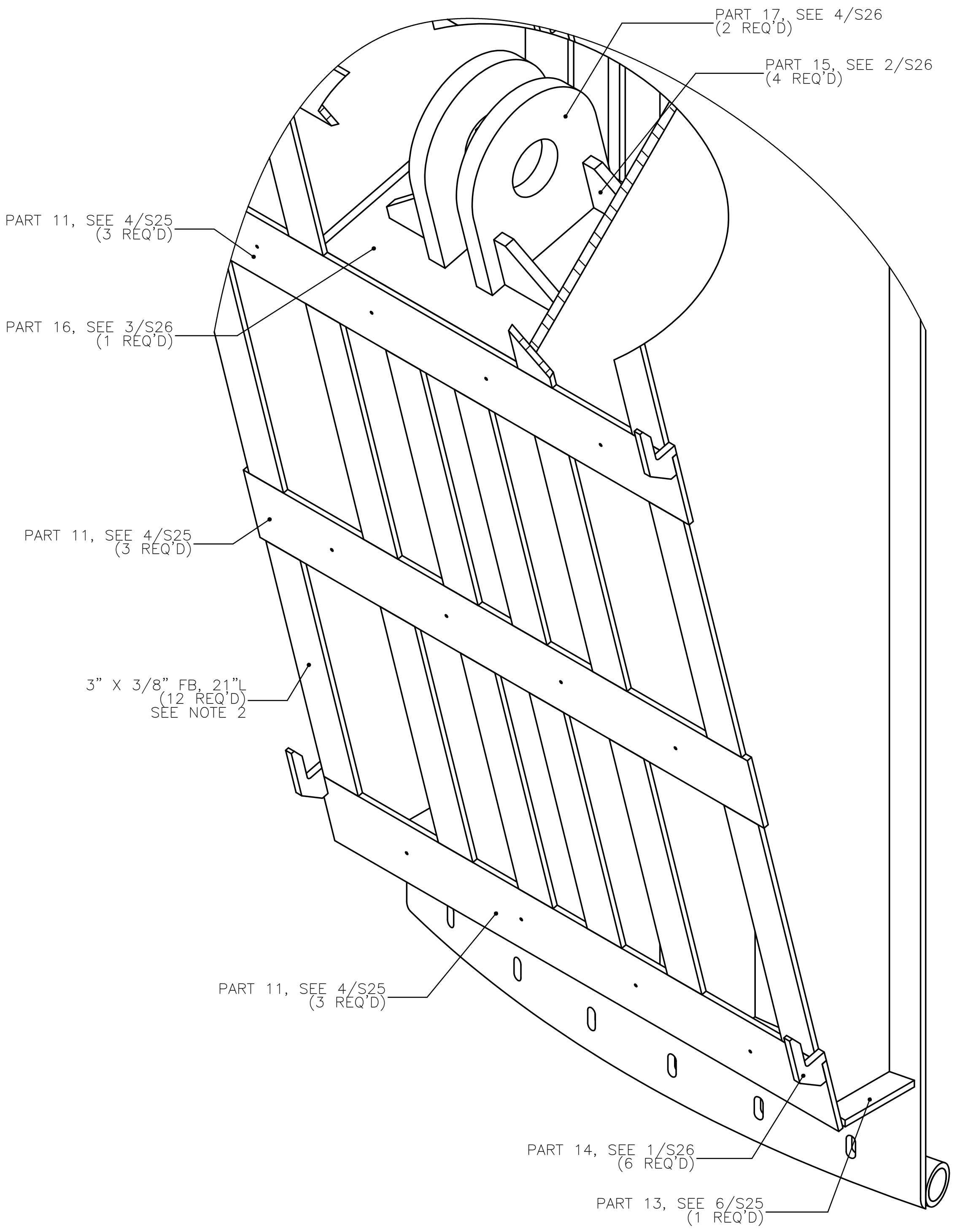
NOTES:

1. THE REQ'D QUANTITY OF EACH COMPONENT PART CALLED OUT HERE, IS THE NUMBER REQ'D PER INNER WEDGE ASSEMBLY. THERE ARE 12 INNER WEDGE ASSEMBLIES IN THE TOP GRIPPER AND 12 INNER WEDGE ASSEMBLIES IN THE BOTTOM GRIPPER.
2. ALL COMPONENTS ARE DETAILED EXCEPT FOR STANDARD STEEL SHAPES THAT ONLY NEED TO BE CUT TO LENGTH. THESE ARE SPECIFIED IN THEIR CALLOUTS.



ALTERNATE ISO VIEW

1/S18 INNER WEDGE ASSEMBLY: PART CALLOUTS (CONT.)
SCALE 1 : 10



DETAIL T/S18
SCALE 1 : 5

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

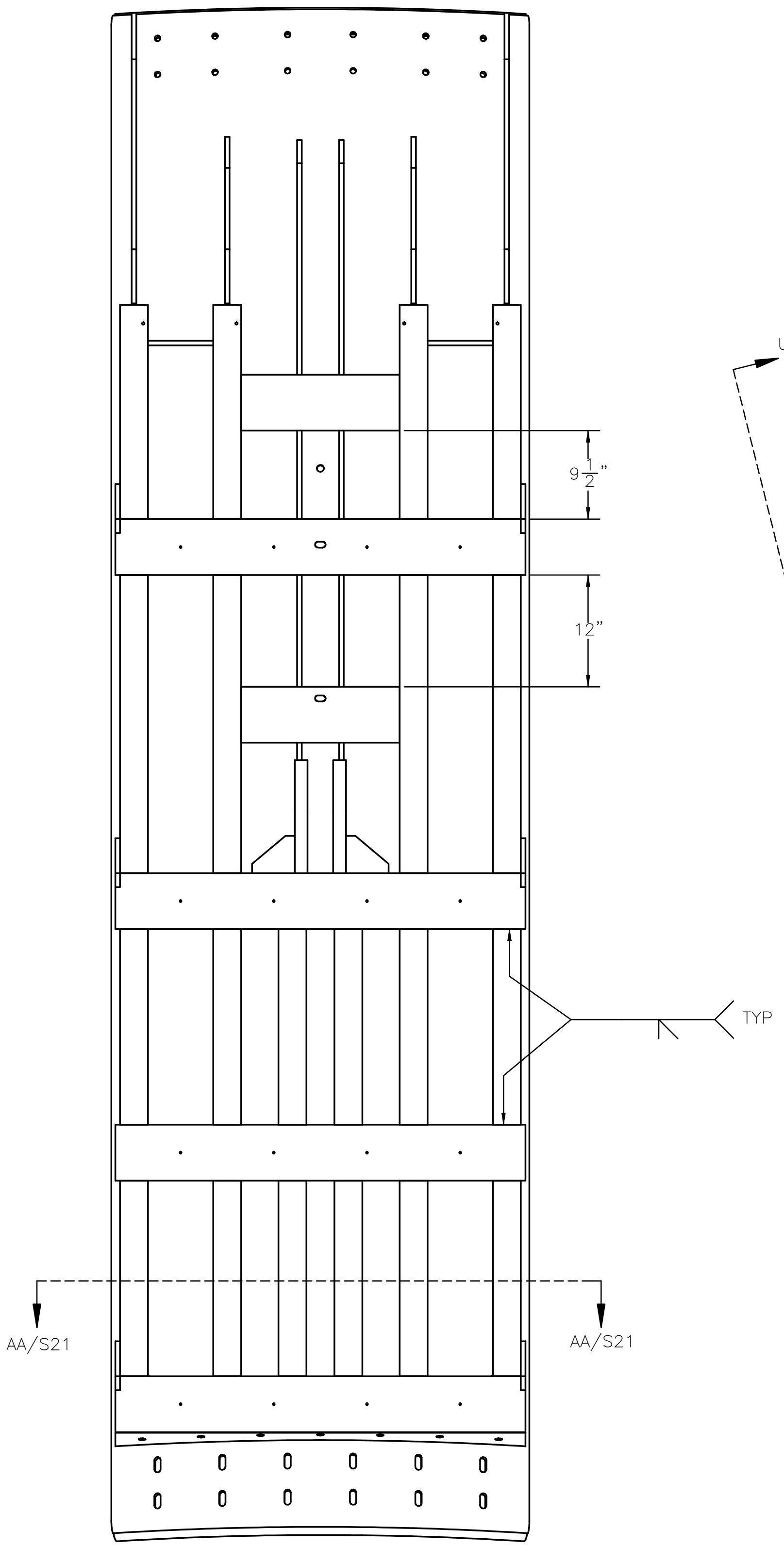
INNER WEDGE ASSEMBLY (CONT.)

MAKAI
OCEAN ENGINEERING, INC.

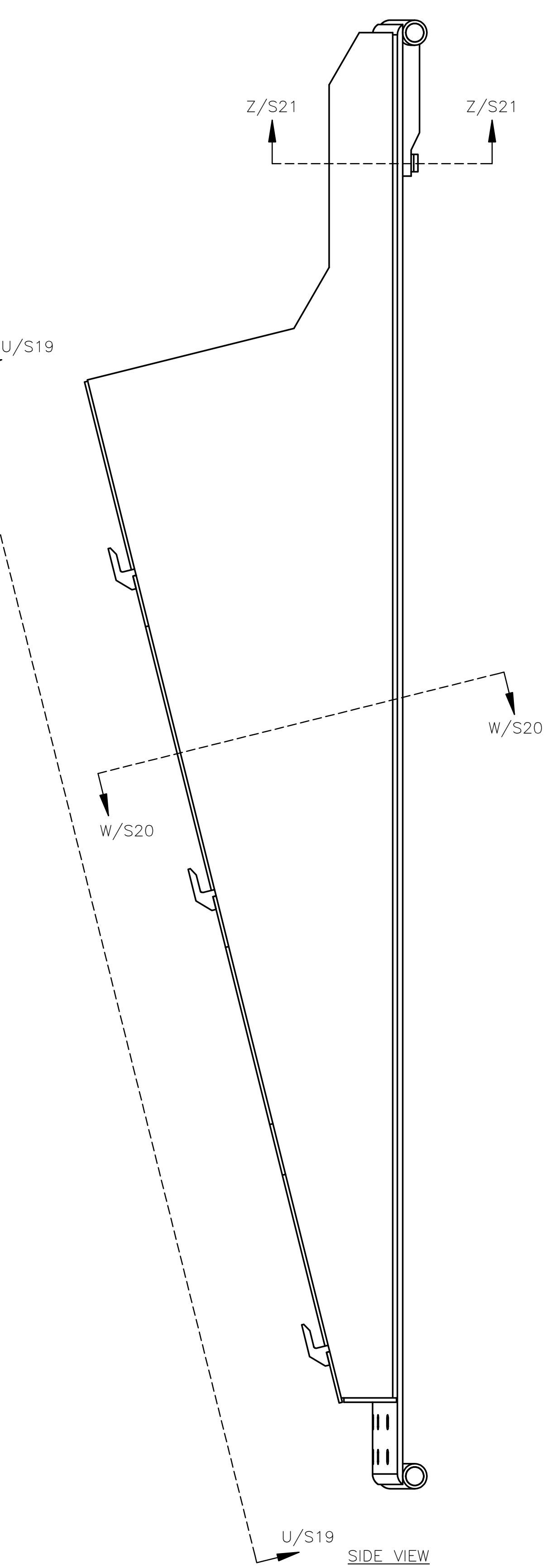
DESIGNED: A. LANDHERR	SUBMITTED:
DRAWN: A. LANDHERR	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED: MANAGER-CHIEF ENGINEER DATE	DRAWING NO. S18

JOB NO. 15706

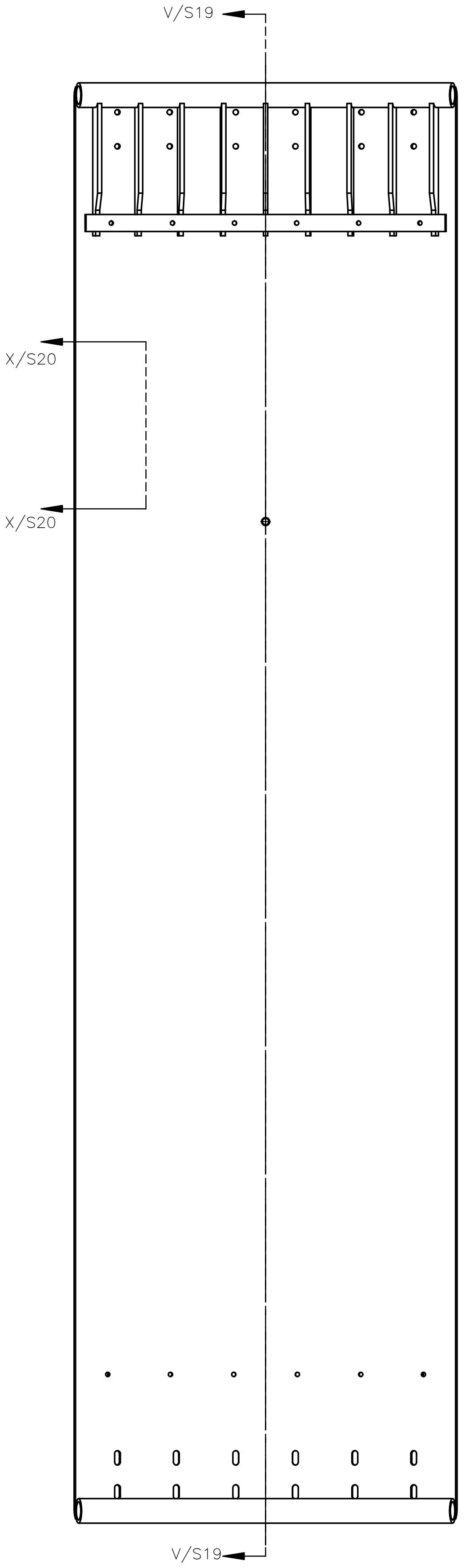
SHEET NO. 20 OF 61



SECTION U/S19–U/S19
SCALE 1 : 10

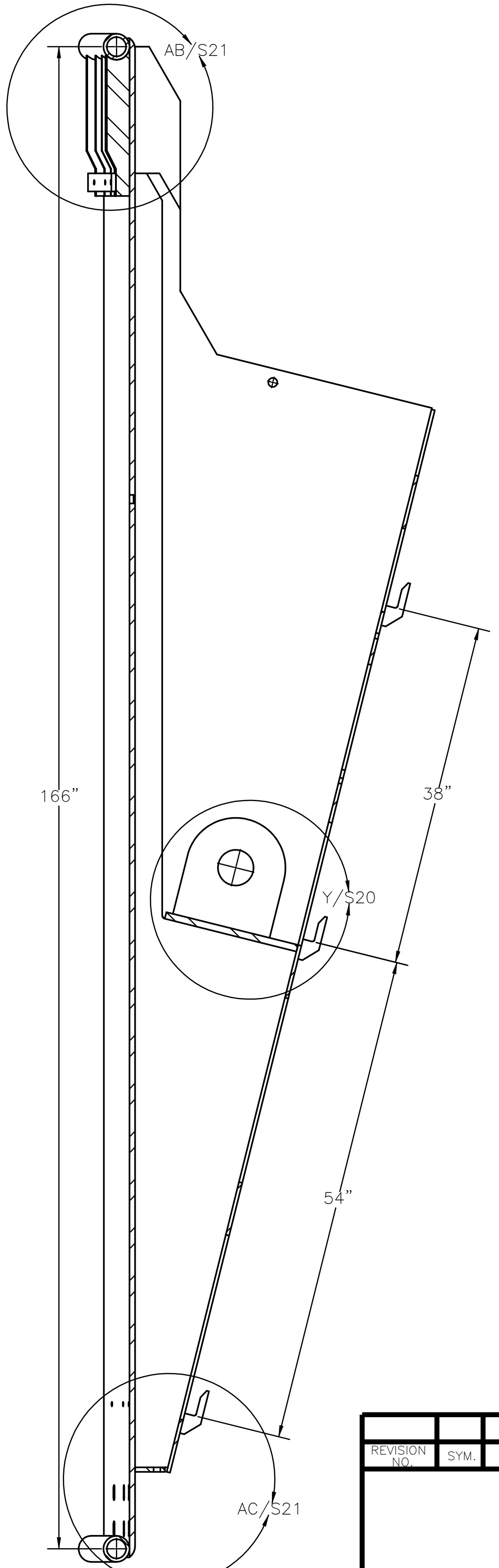


SIDE VIEW

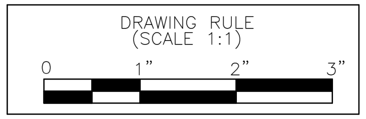


FRONT VIEW

1/S19 INNER WEDGE ASSEMBLY
SCALE 1 : 10



SECTION V/S19–V/S19
SCALE 1 : 10



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

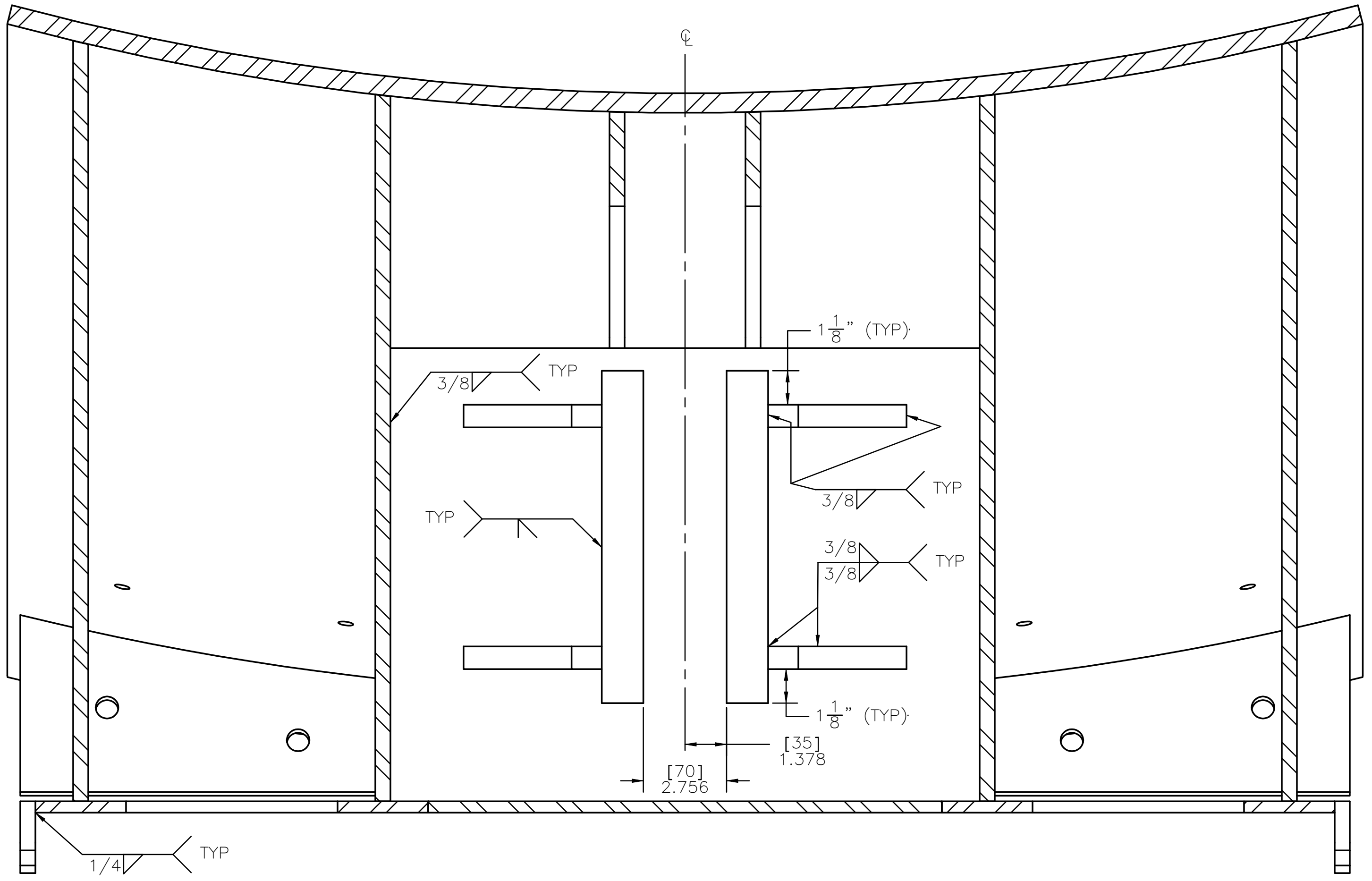
INNER WEDGE ASSEMBLY (CONT.)

MAKAI
OCEAN ENGINEERING, INC.

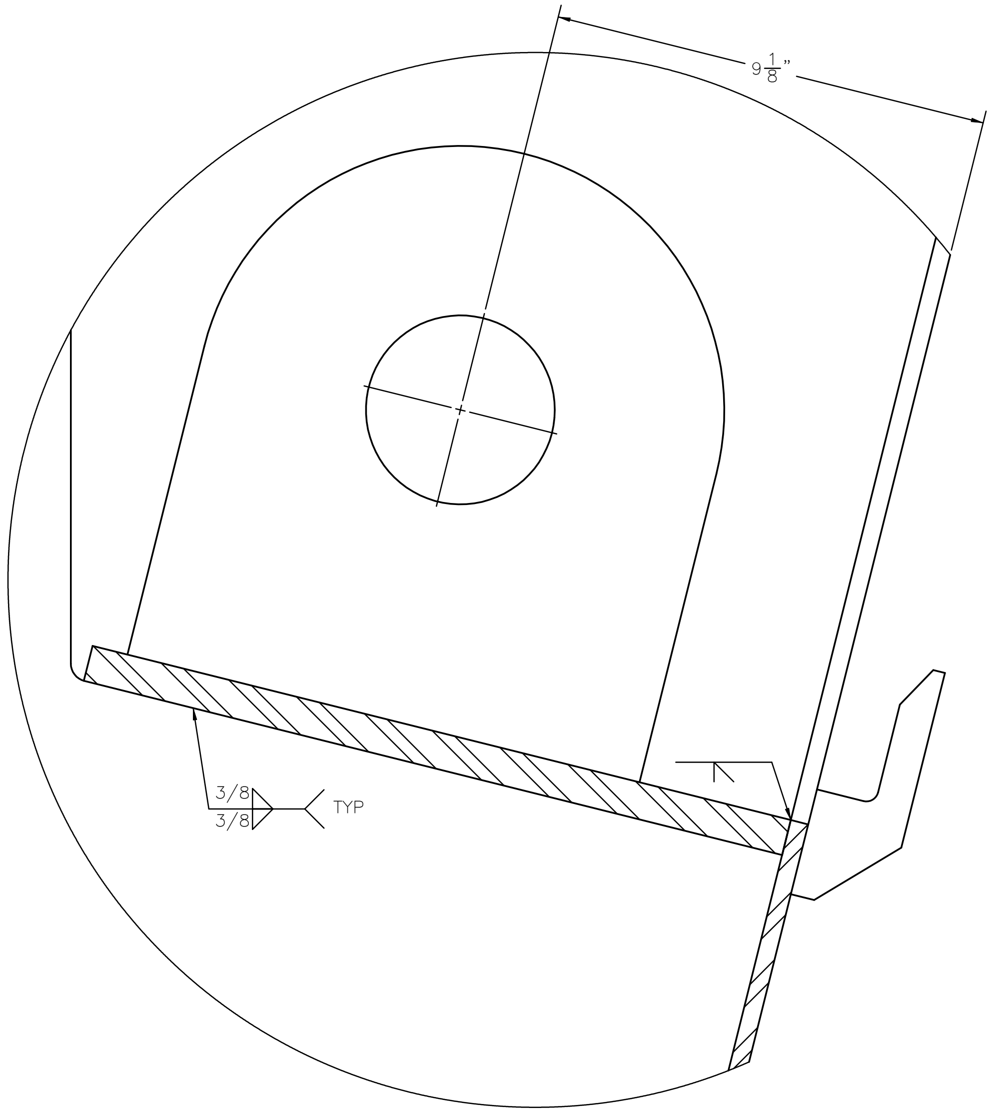
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER–CHIEF ENGINEER
DATE
DRAWING NO. S19

JOB NO. 15706

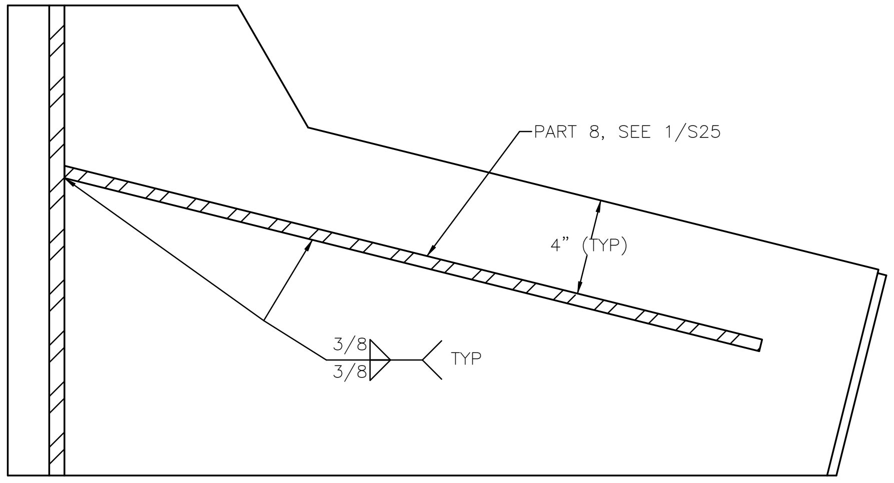
SHEET NO. 21 OF 61



SECTION W/S20–W/S20
SCALE 1 : 3



DETAIL Y/S20
SCALE 1 : 2



SECTION X/S20–X/S20
SCALE 1 : 4

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

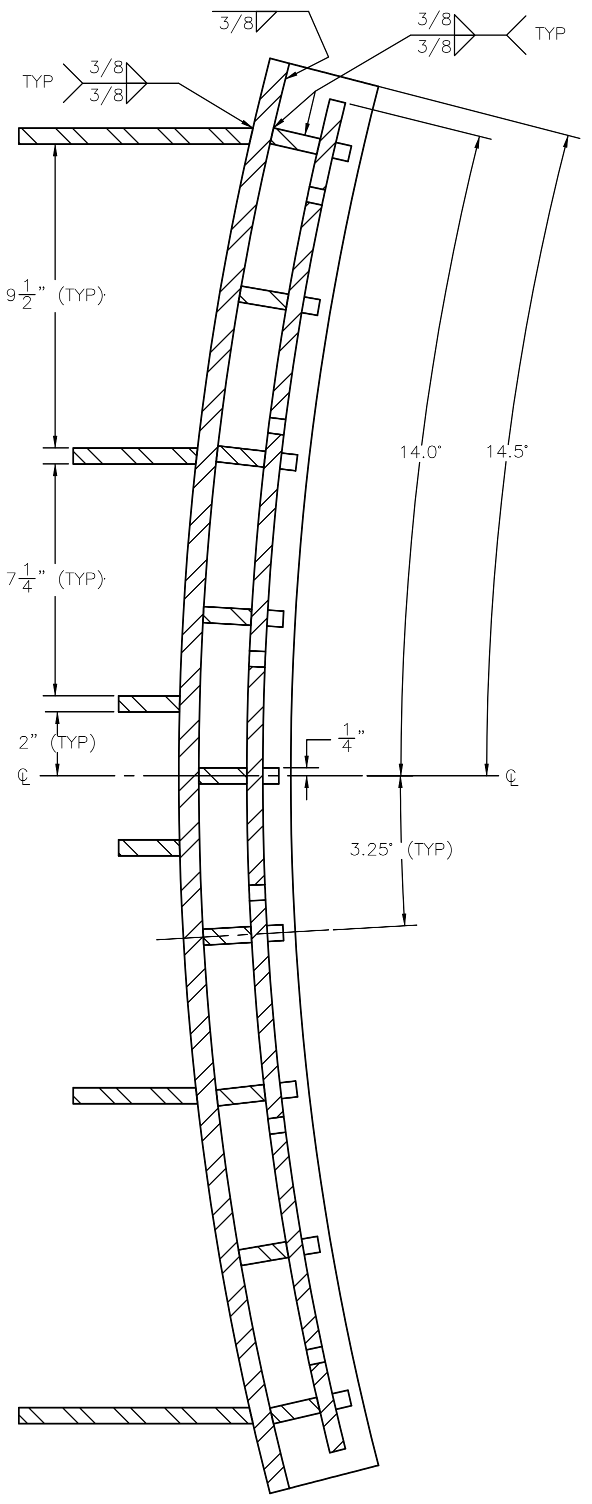
INNER WEDGE ASSEMBLY (CONT.)

MAKAI
OCEAN ENGINEERING, INC.

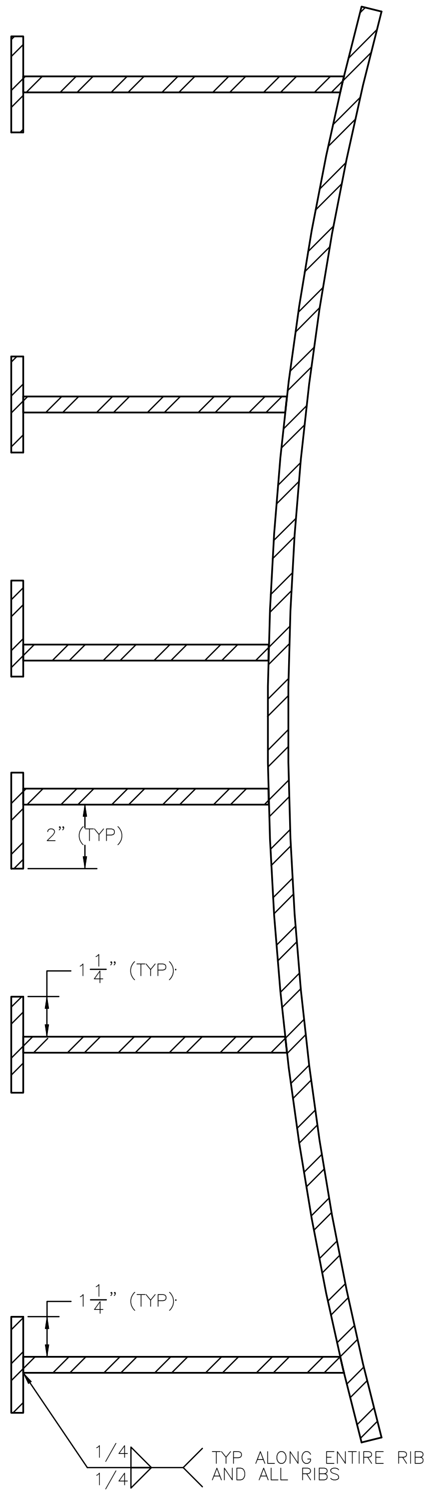
DESIGNED: A. LANDHERR	SUBMITTED:
DRAWN: A. LANDHERR	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED:	DRAWING NO. S20
MANAGER-CHIEF ENGINEER DATE	

JOB NO. 15706

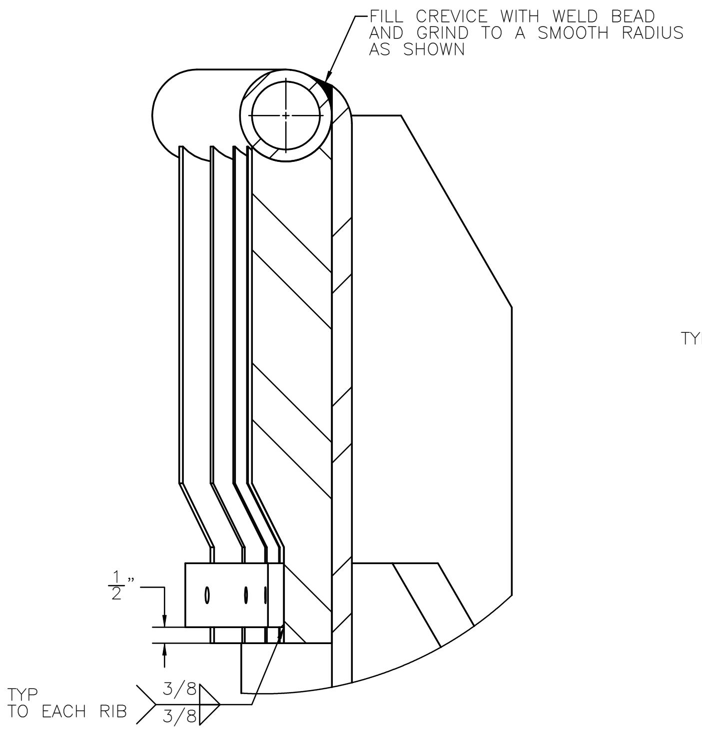
SHEET NO. 22 OF 61



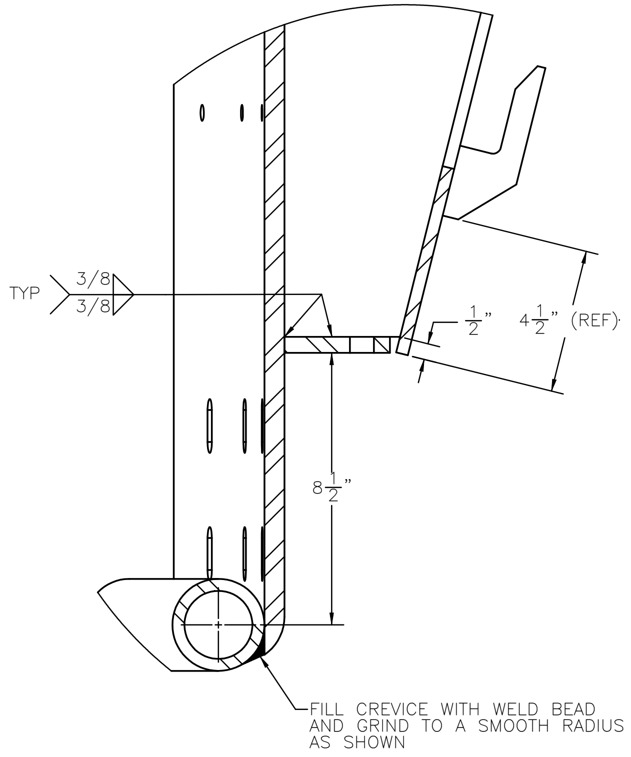
SECTION Z/S21–Z/S21
SCALE 1 : 3



SECTION AA/S21–AA/S21
SCALE 1 : 3



DETAIL AB/S21
SCALE 1 : 3



DETAIL AC/S21
SCALE 1 : 3

DRAWING RULE
(SCALE 1:1)

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

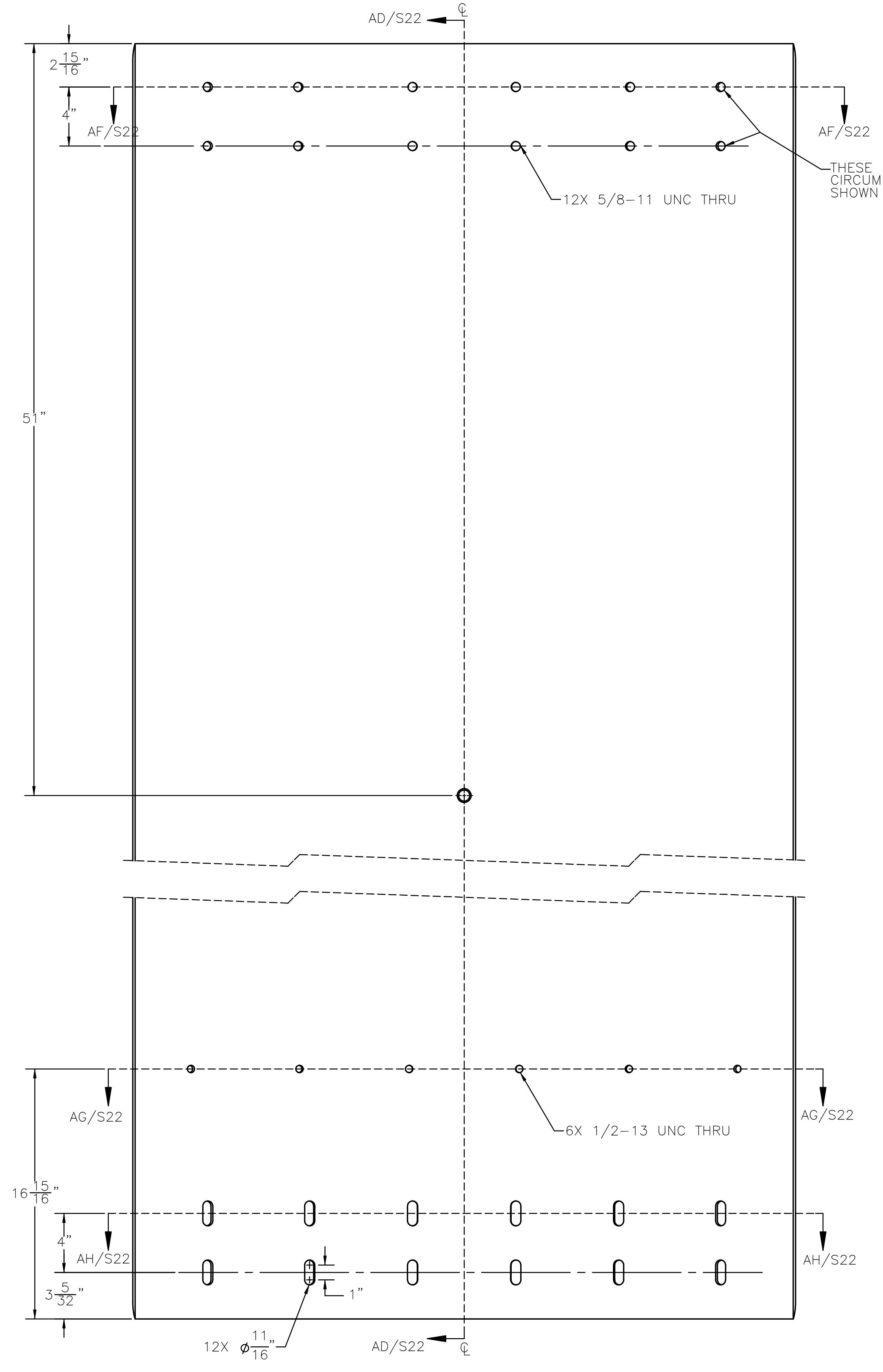
INNER WEDGE ASSEMBLY (CONT.)

MAKAI
OCEAN ENGINEERING, INC.

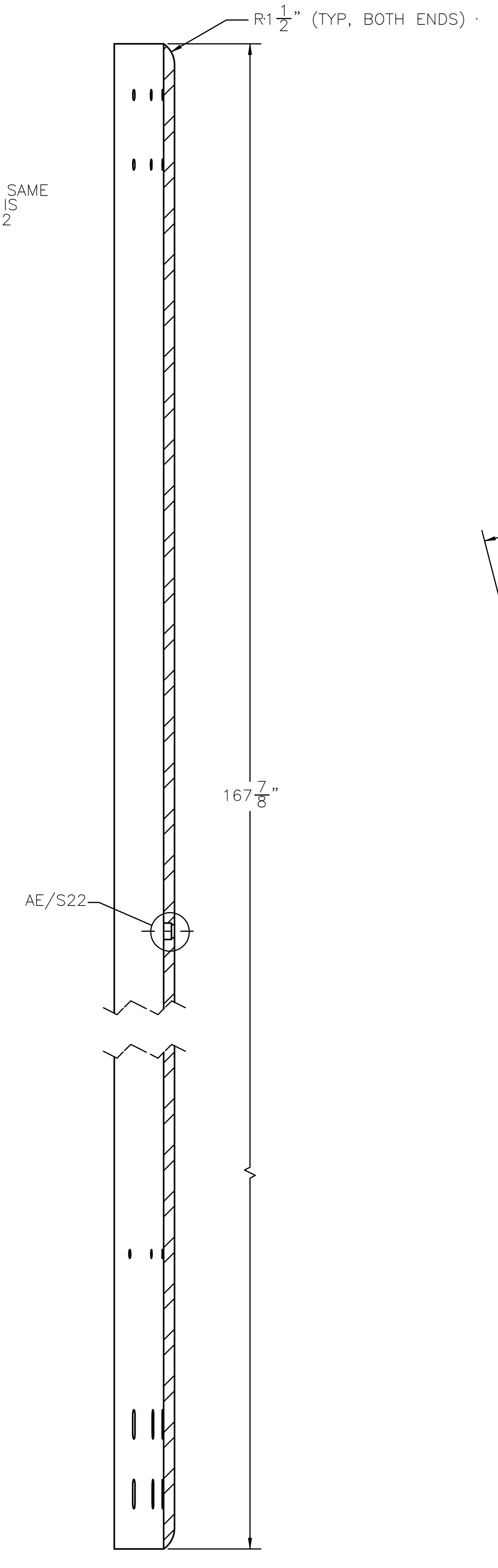
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER–CHIEF ENGINEER
DATE
DRAWING NO. S21

JOB NO. 15706

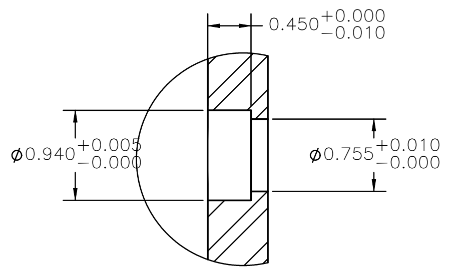
SHEET NO. 23 OF 61



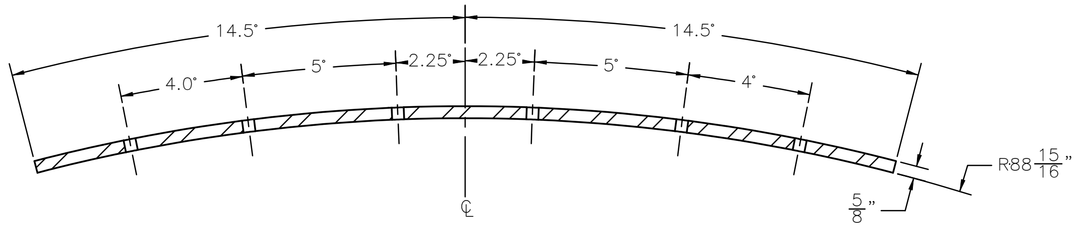
1/S22 PART 1
SCALE 1 : 5



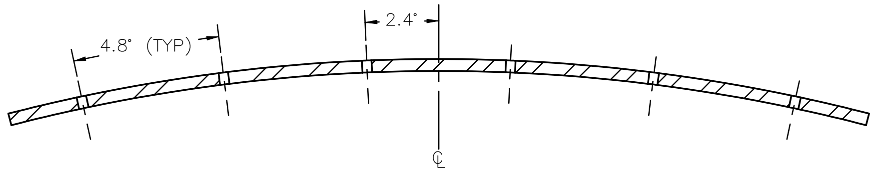
SECTION AD/S22-AD/S22
SCALE 1 : 5



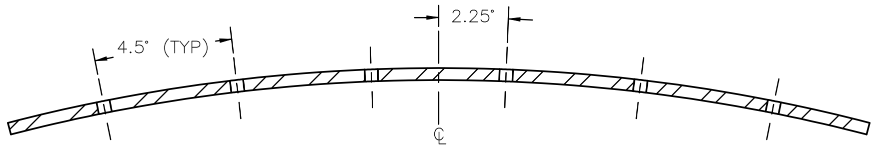
DETAIL AE/S22
SCALE 1 : 1



SECTION AF/S22-AF/S22
SCALE 1 : 5

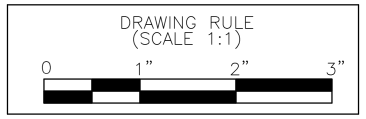


SECTION AG/S22-AG/S22
SCALE 1 : 5



SECTION AH/S22-AH/S22
SCALE 1 : 5

DRAWING RULE
(SCALE 1:1)



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

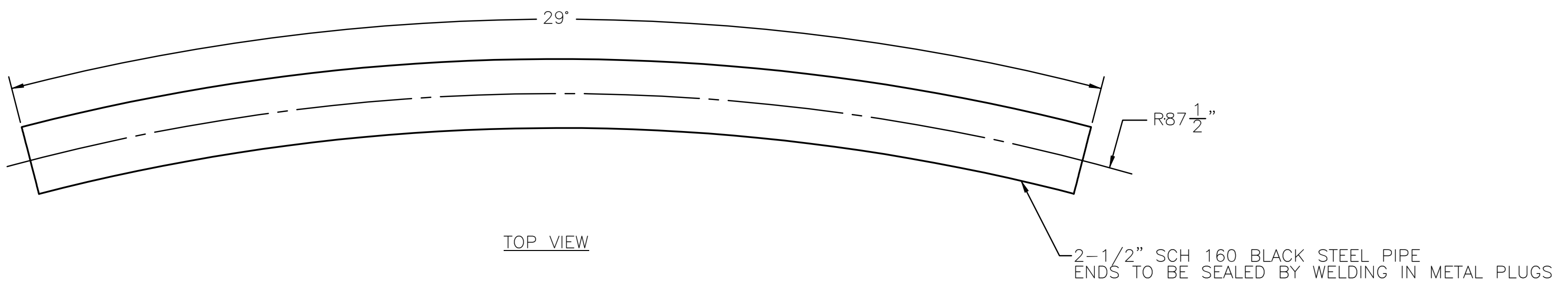
INNER WEDGE
ASSEMBLY PARTS I

MAKAI
OCEAN ENGINEERING, INC.

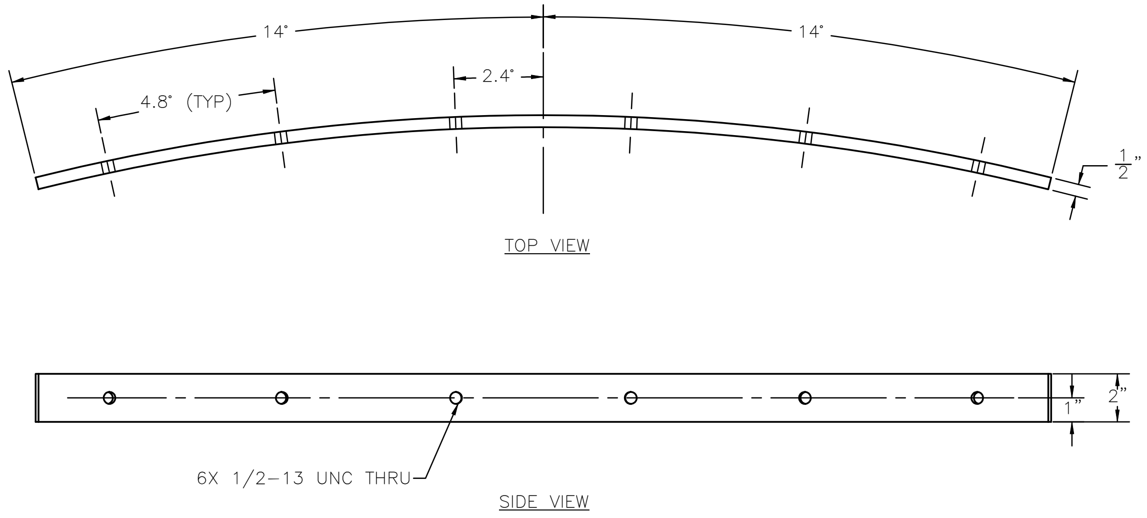
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S22

JOB NO. 15706

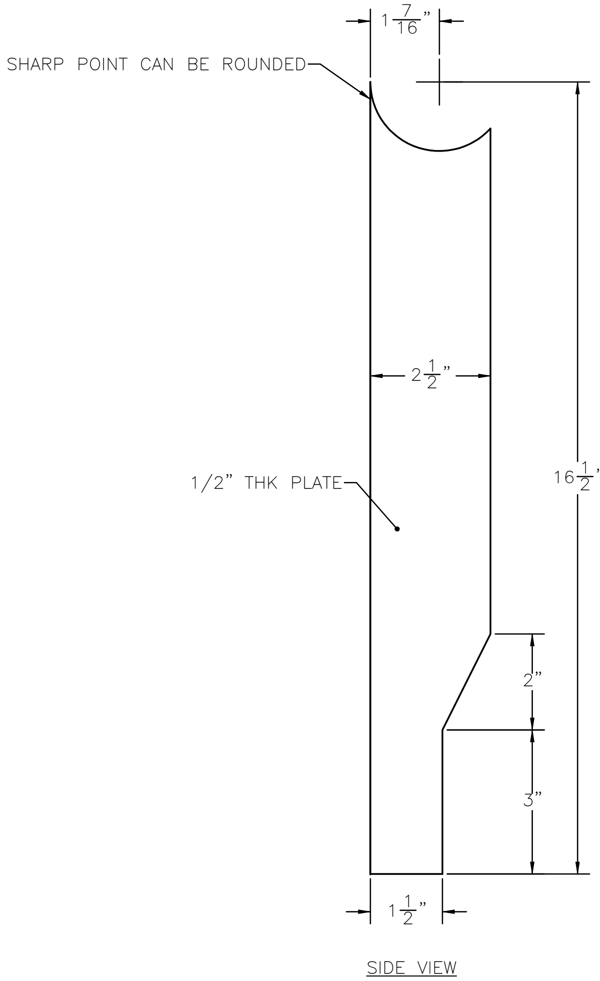
SHEET NO. 24 OF 61



1/S23 PART 2
SCALE 1 : 4



3/S23 PART 4
SCALE 1 : 4



2/S23 PART 3
SCALE 1 : 2

DRAWING RULE
(SCALE 1:1)

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

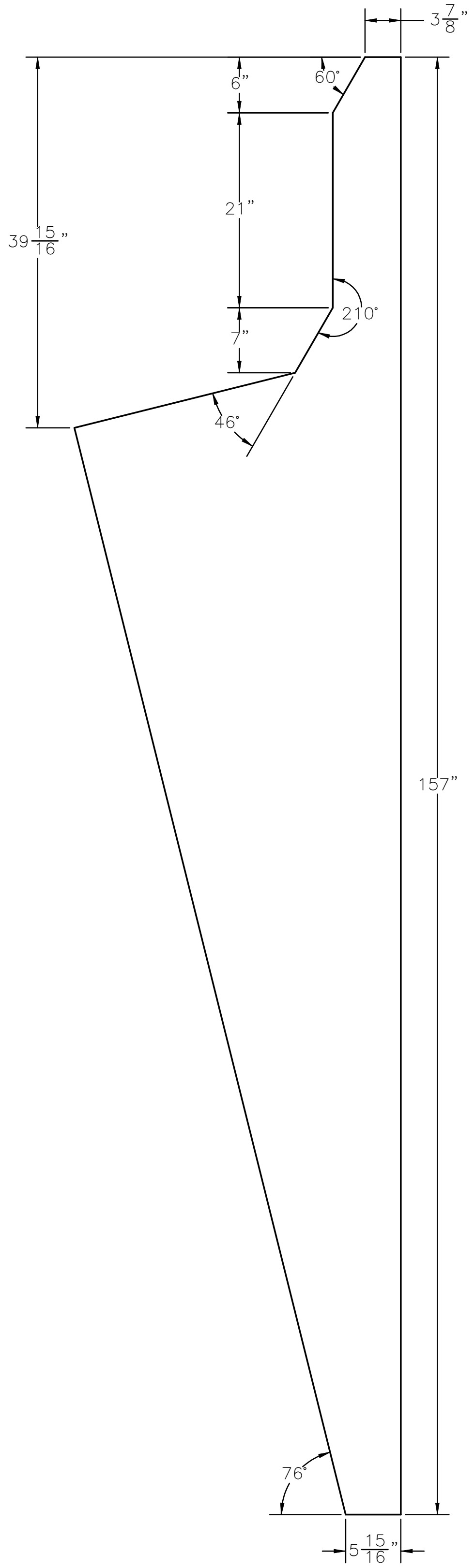
LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

INNER WEDGE
ASSEMBLY PARTS II

MAKAI
OCEAN ENGINEERING, INC.

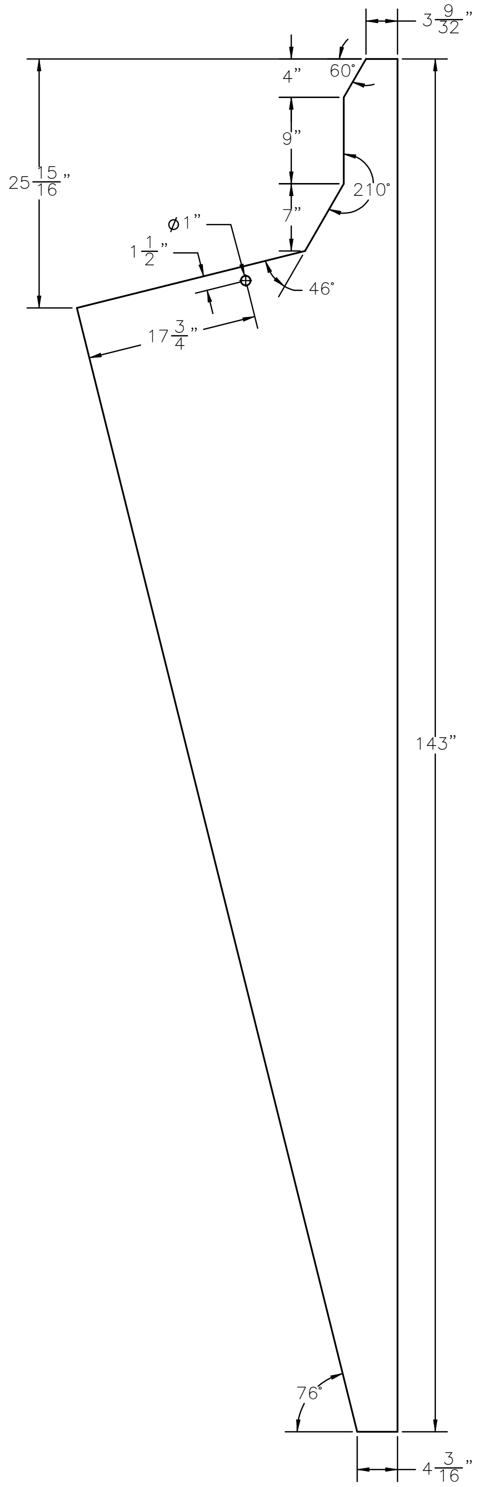
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S23

JOB NO. 15706
SHEET NO. 25 OF 61



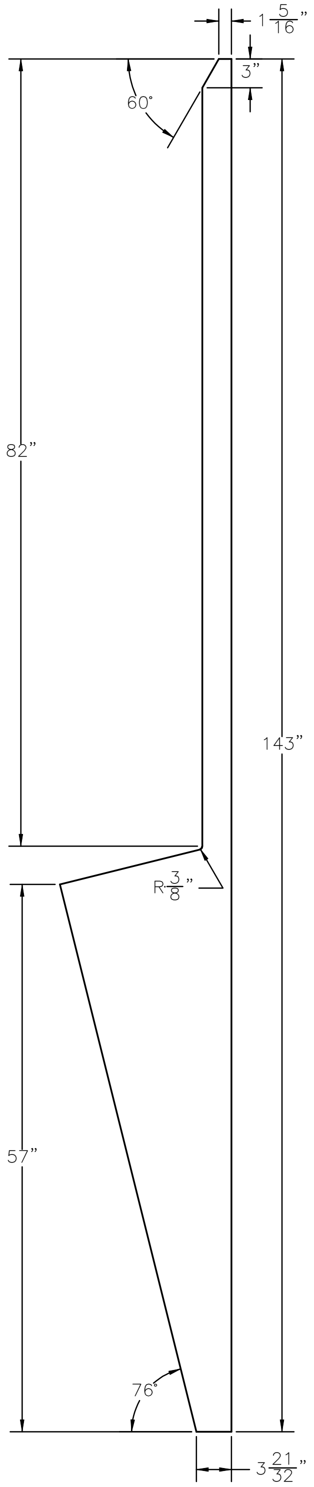
SIDE VIEW

1/S24 PART 5
SCALE 1 : 10



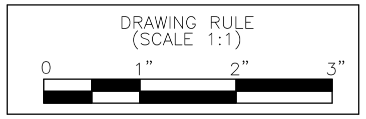
SIDE VIEW

2/S24 PART 6
SCALE 1 : 10



SIDE VIEW

3/S24 PART 7
SCALE 1 : 10



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

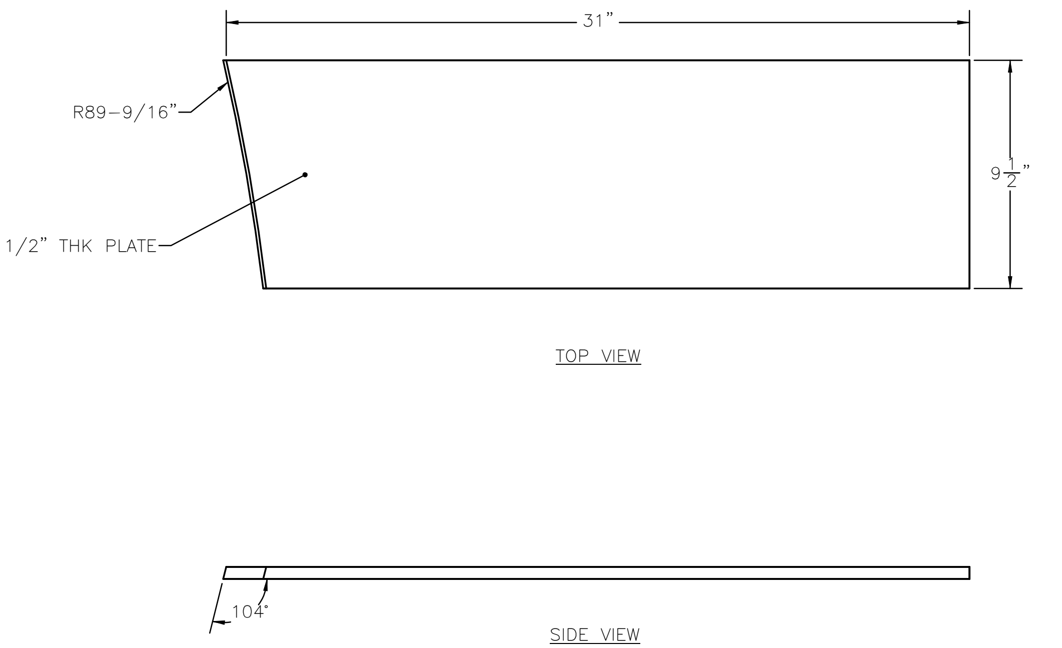
LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

INNER WEDGE
ASSEMBLY PARTS III

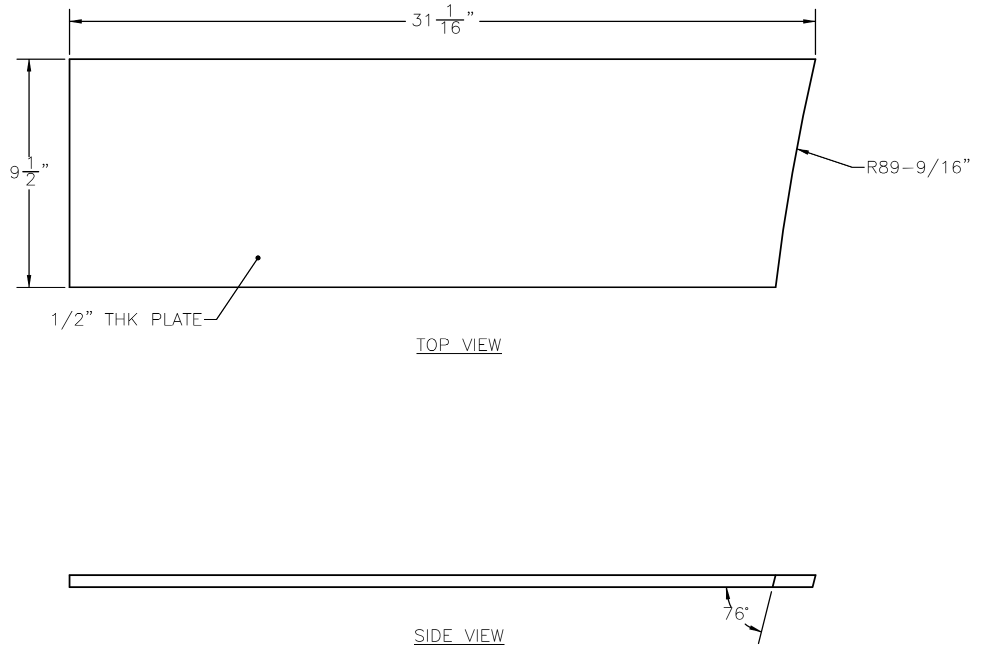
MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR SUBMITTED:
DRAWN: A. LANDHERR DATE: 9/18/2010
CHECKED: D. JENSEN SCALE: SHOWN
APPROVED:
DRAWING NO. S24
MANAGER-CHIEF ENGINEER DATE

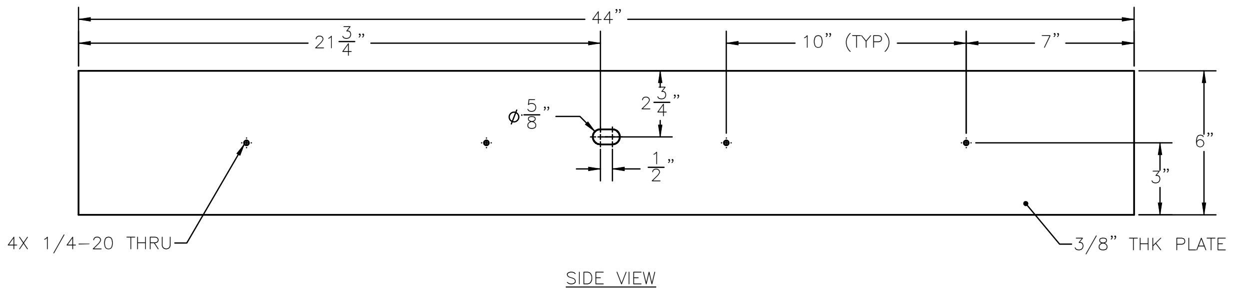
JOB NO. 15706
SHEET NO. 26 OF 61



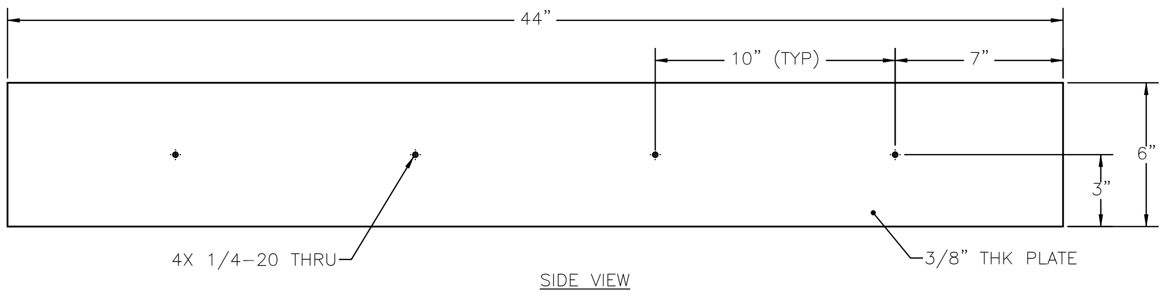
1/S25 PART 8
SCALE 1 : 4



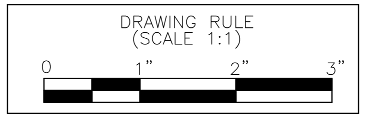
2/S25 PART 9
SCALE 1 : 4

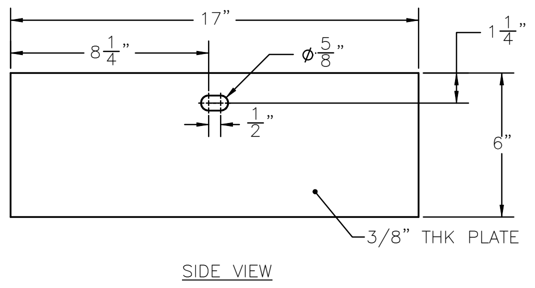


3/S25 PART 10
SCALE 1 : 4

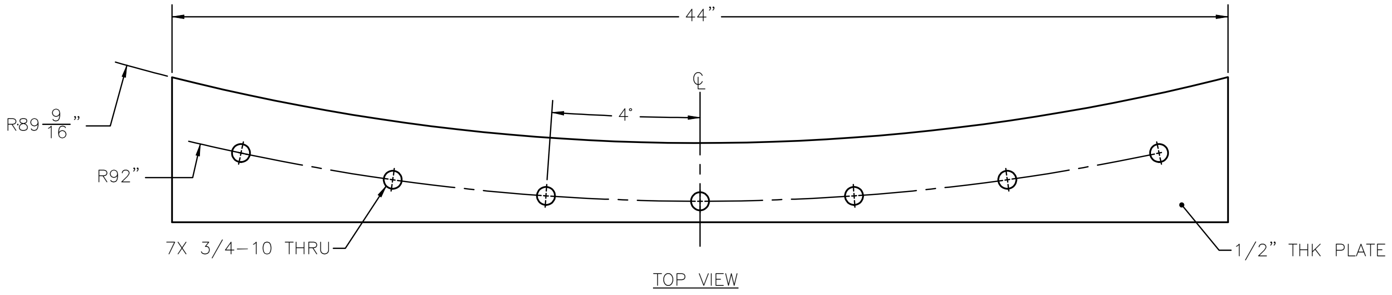


4/S25 PART 11
SCALE 1 : 4





5/S25 PART 12
SCALE 1 : 4



6/S25 PART 13
SCALE 1 : 4

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

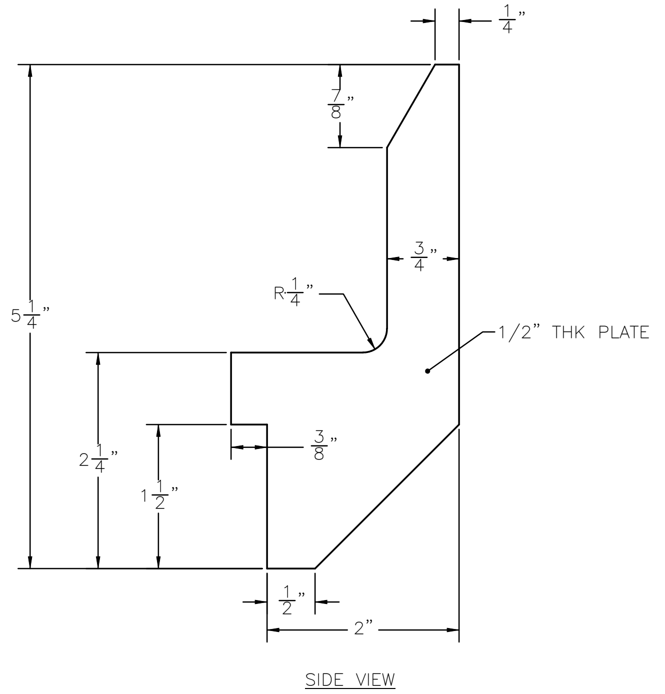
INNER WEDGE ASSEMBLY PARTS IV

MAKAI
OCEAN ENGINEERING, INC.

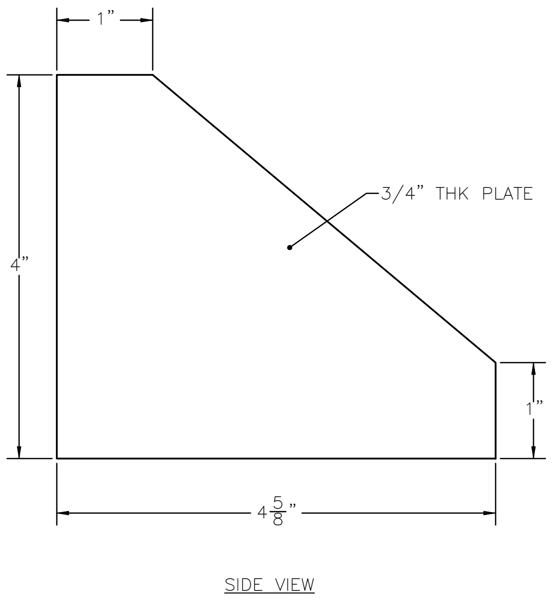
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S25

JOB NO. 15706

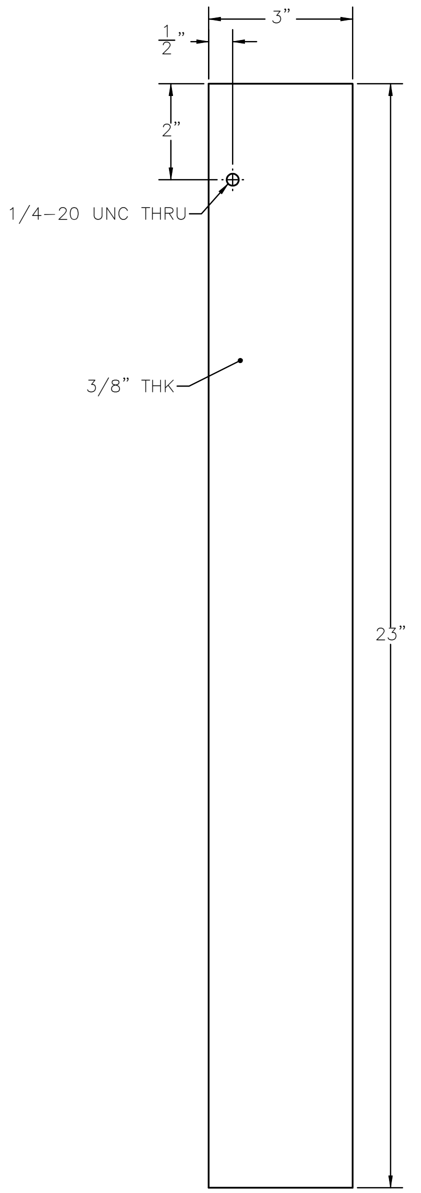
SHEET NO. 27 OF 61



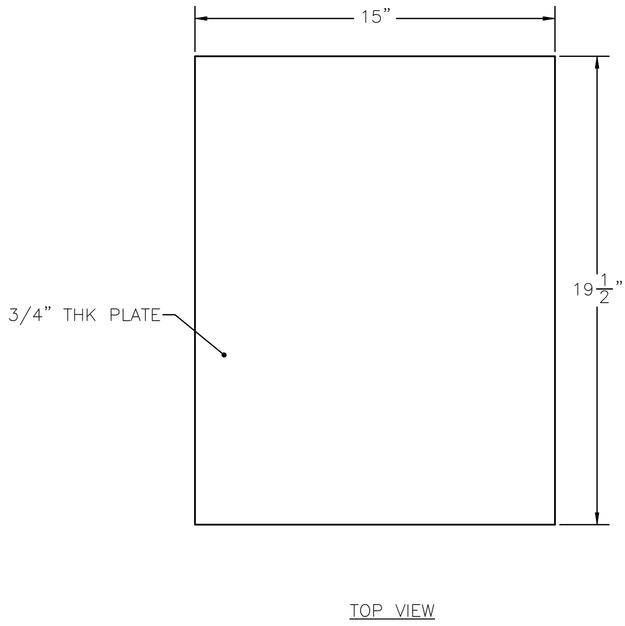
1/S26 PART 14
SCALE 1 : 1



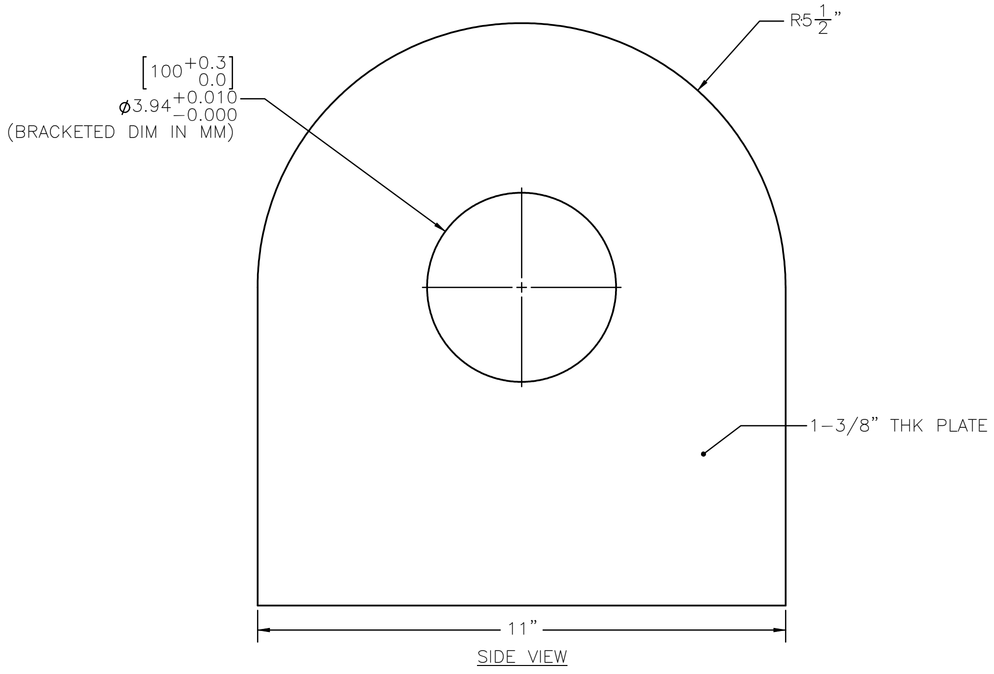
2/S26 PART 15
SCALE 1 : 1



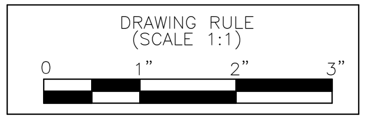
5/S26 PART 18
SCALE 1 : 2



3/S26 PART 16
SCALE 1 : 4



4/S26 PART 17
SCALE 1 : 2



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

INNER WEDGE ASSEMBLY PARTS V

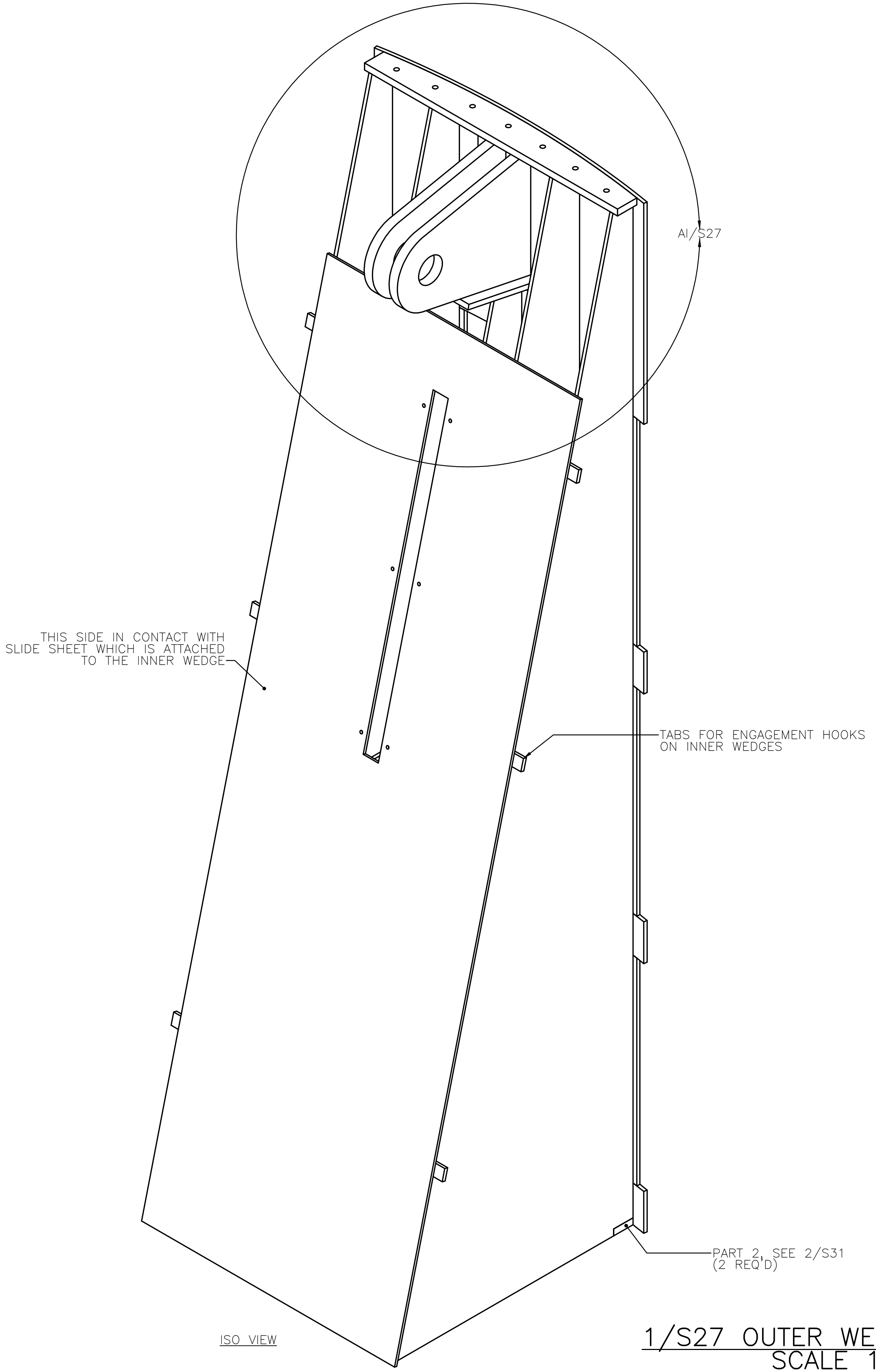
MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR SUBMITTED:
DRAWN: A. LANDHERR DATE: 9/18/2010
CHECKED: D. JENSEN SCALE: SHOWN
APPROVED: DRAWING NO. S26
MANAGER-CHIEF ENGINEER DATE

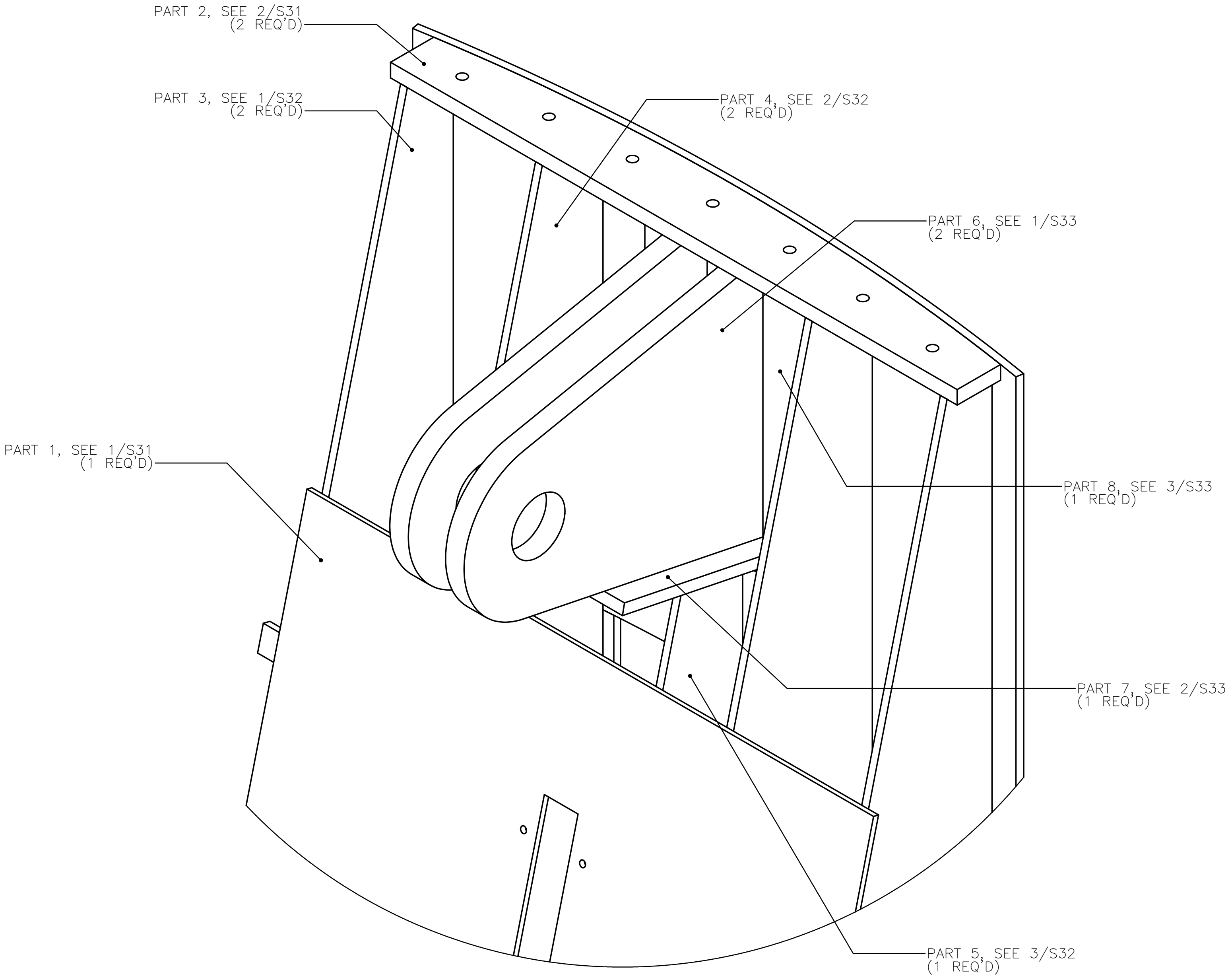
JOB NO. 15706 SHEET NO. 28 OF 61

NOTES:

1. THE REQ'D QUANTITY OF EACH COMPONENT PART CALLED OUT HERE, IS THE NUMBER REQ'D PER OUTER WEDGE ASSEMBLY. THERE ARE 12 OUTER WEDGE ASSEMBLIES IN THE TOP GRIPPER AND 12 OUTER WEDGE ASSEMBLIES IN THE BOTTOM GRIPPER.



1/S27 OUTER WEDGE ASSEMBLY
SCALE 1 : 8



DETAIL AI/S27
SCALE 1 : 4

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

OUTER WEDGE ASSEMBLY

MAKAI
OCEAN ENGINEERING, INC.

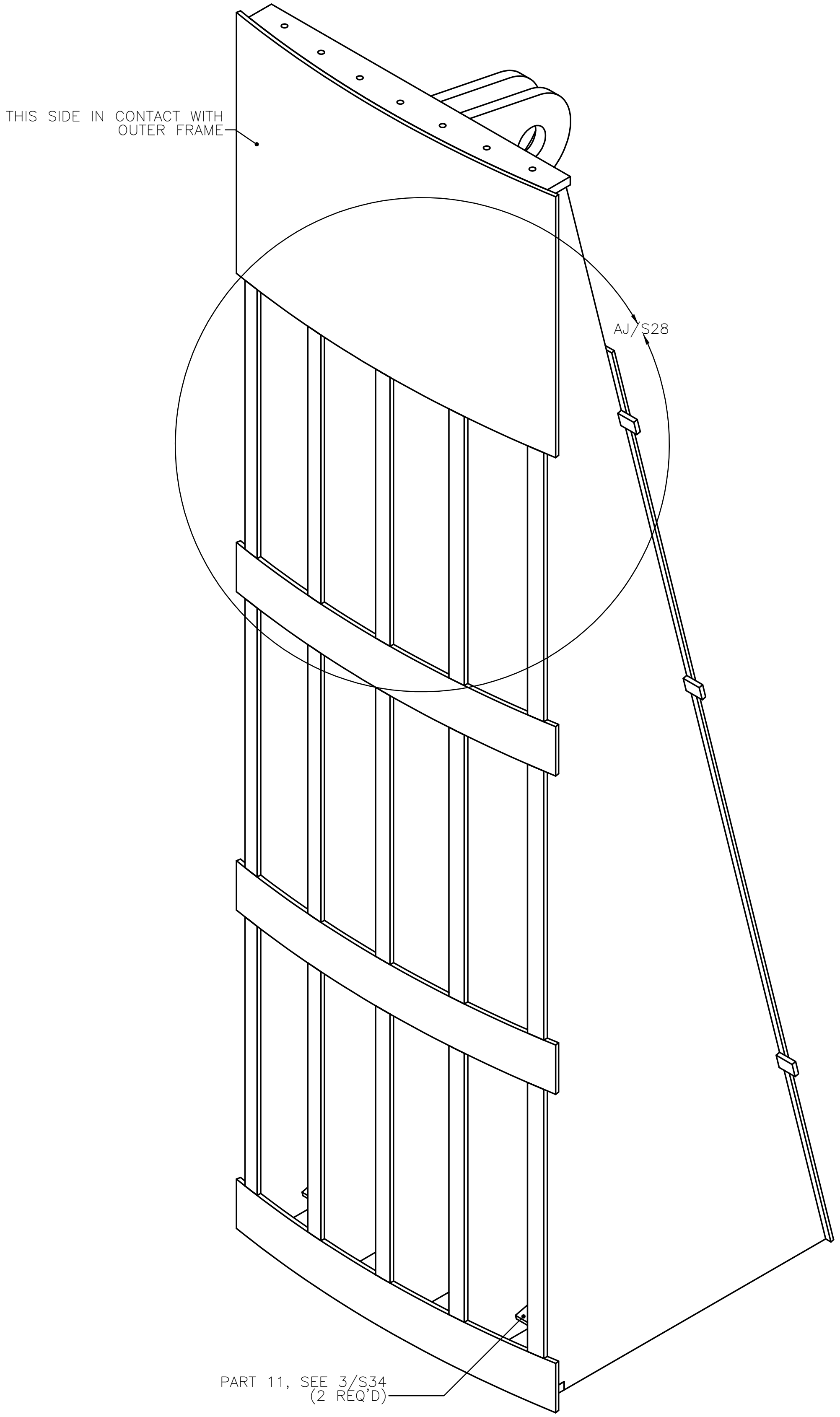
DESIGNED: A. LANDHERR	SUBMITTED:
DRAWN: A. LANDHERR	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED:	DRAWING NO. S27
MANAGER-CHIEF ENGINEER	DATE

JOB NO. 15706

SHEET NO. 29 OF 61

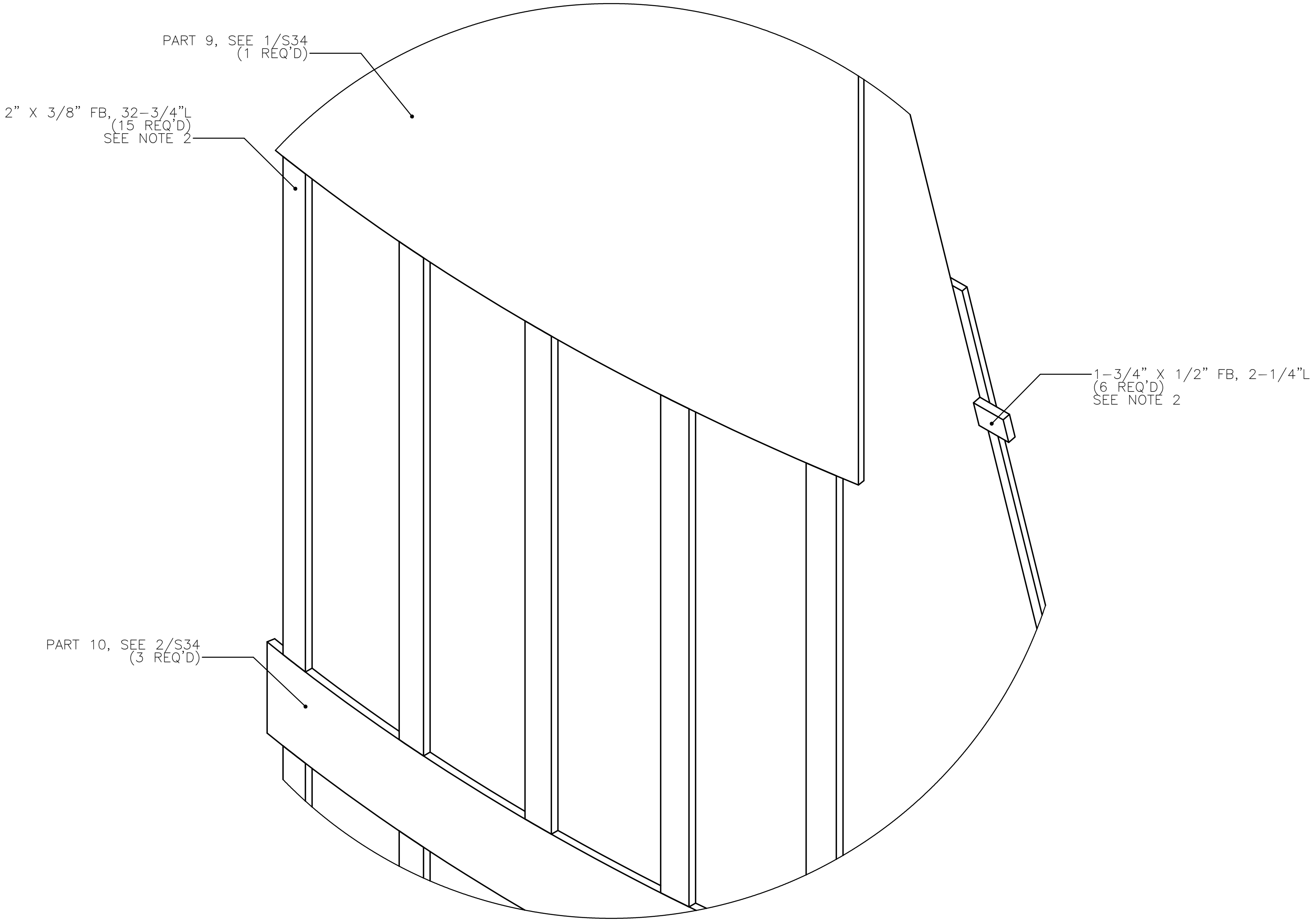
NOTES:

1. THE REQ'D QUANTITY OF EACH COMPONENT PART CALLED OUT HERE, IS THE NUMBER REQ'D PER OUTER WEDGE ASSEMBLY. THERE ARE 12 OUTER WEDGE ASSEMBLIES IN THE TOP GRIPPER AND 12 OUTER WEDGE ASSEMBLIES IN THE BOTTOM GRIPPER.
2. ALL COMPONENTS ARE DETAILED EXCEPT FOR STANDARD STEEL SHAPES THAT ONLY NEED TO BE CUT TO LENGTH. THESE ARE SPECIFIED IN THEIR CALLOUTS.



ALTERNATE ISO VIEW

1/S28 OUTER WEDGE ASSEMBLY
SCALE 1 : 8



DETAIL AJ/S28
SCALE 1 : 4

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

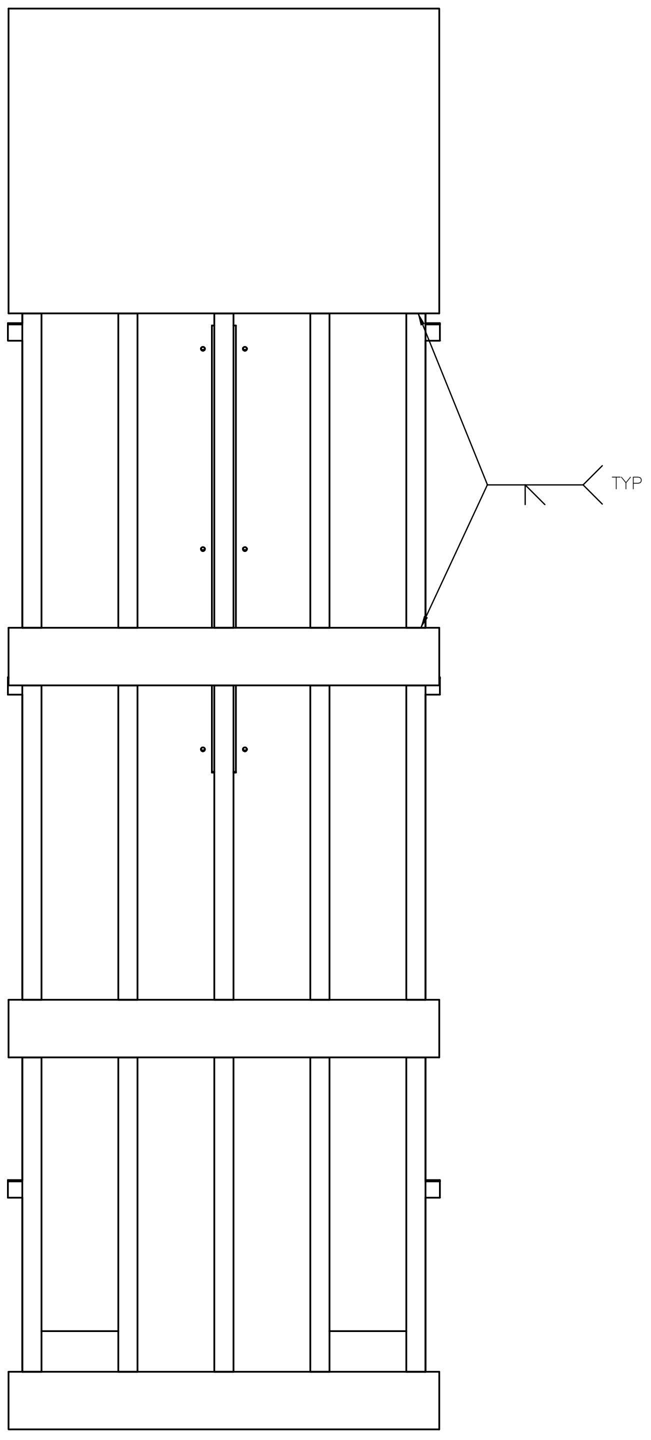
OUTER WEDGE ASSEMBLY (CONT.)

MAKAI
OCEAN ENGINEERING, INC.

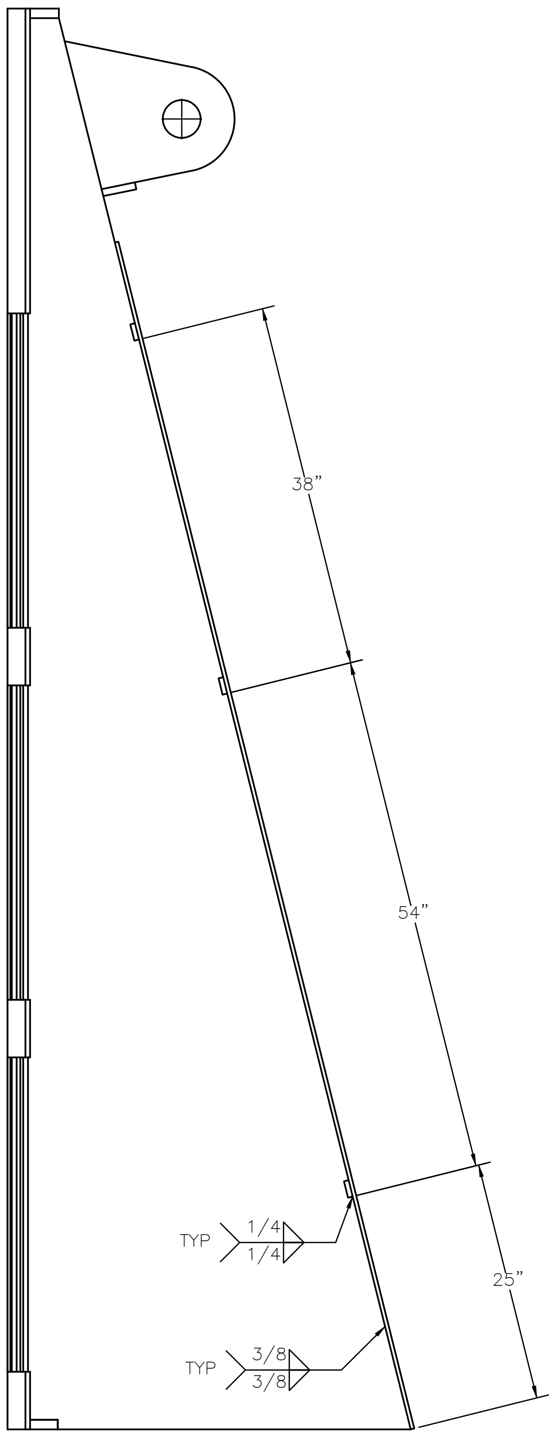
DESIGNED: A. LANDHERR	SUBMITTED:
DRAWN: A. LANDHERR	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED:	DRAWING NO. S28
MANAGER-CHIEF ENGINEER	DATE

JOB NO. 15706

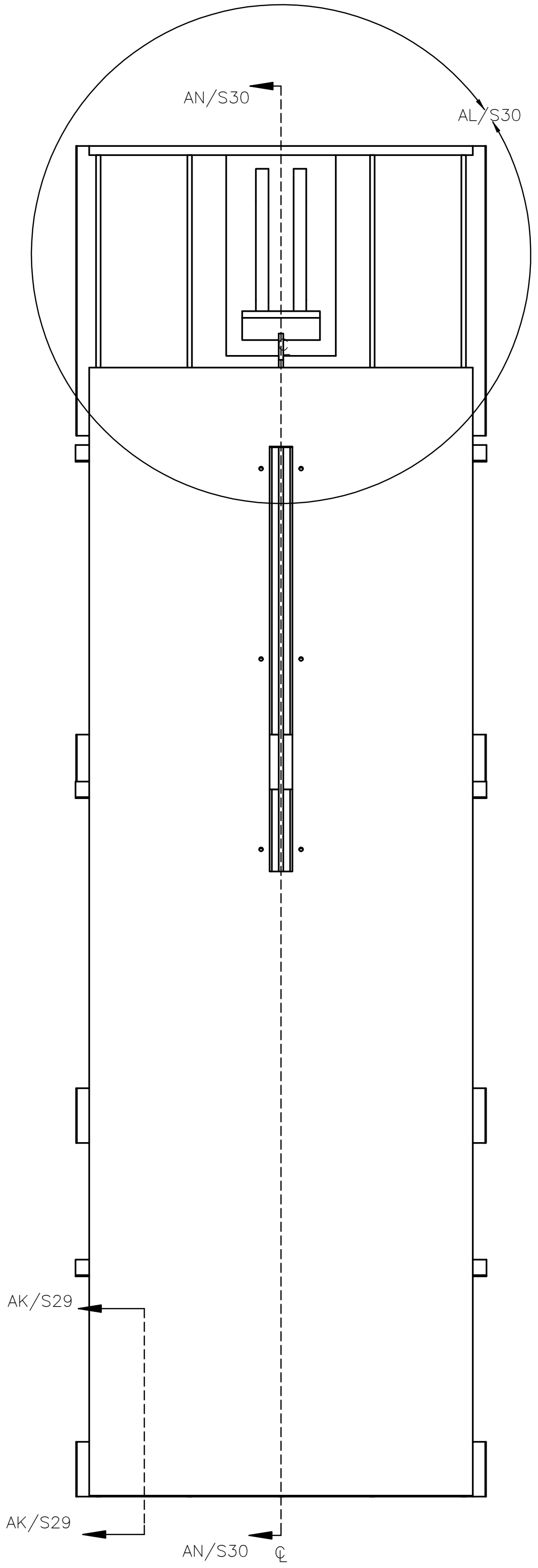
SHEET NO. 30 OF 61



BACK VIEW

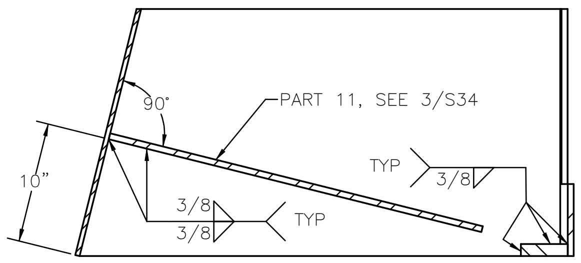


LEFT SIDE VIEW



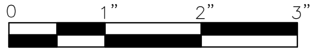
FRONT VIEW

1/S29 OUTER WEDGE ASSEMBLY
SCALE 1 : 10



SECTION AK/S29–AK/S29
SCALE 1 : 8

DRAWING RULE
(SCALE 1:1)



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

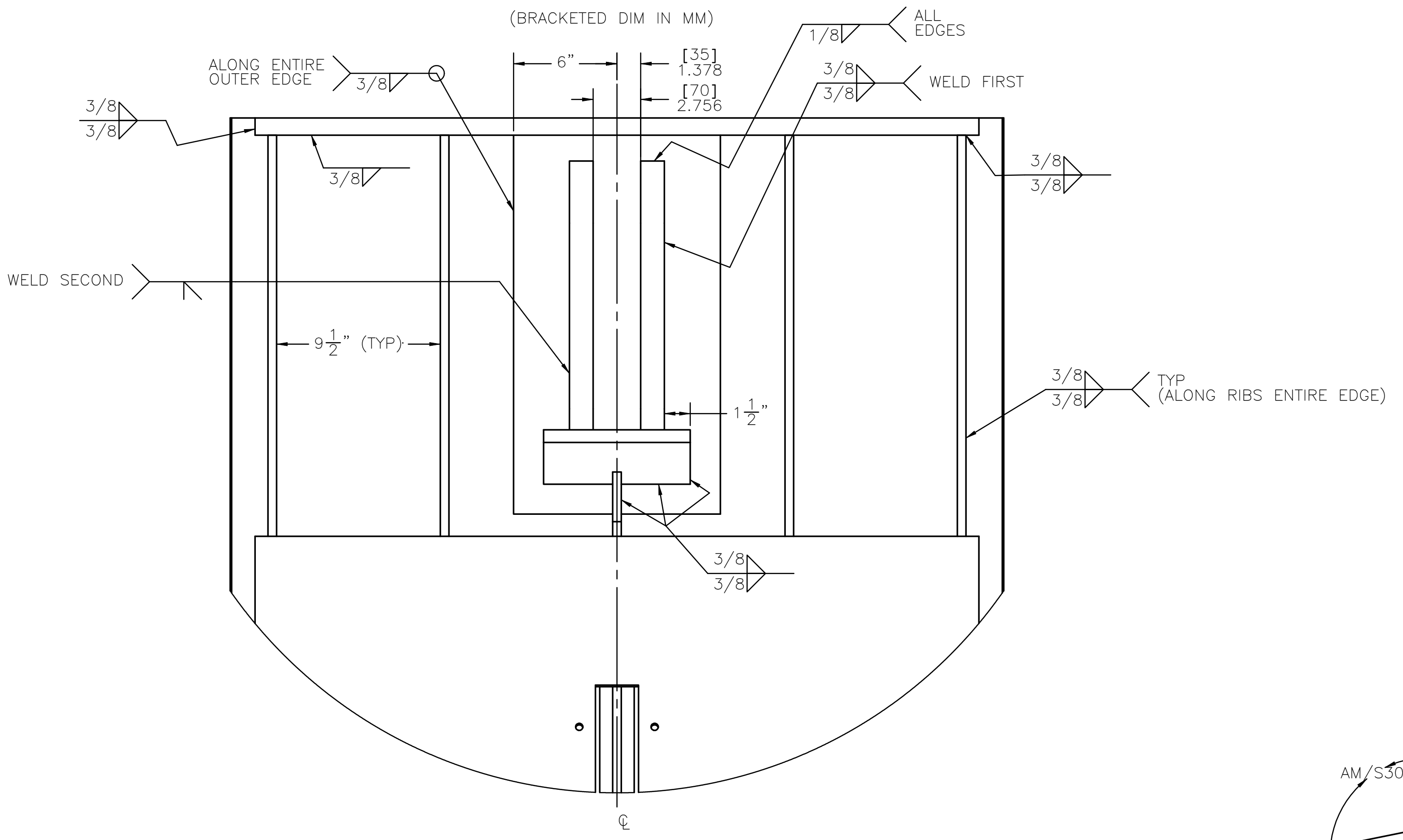
OUTER WEDGE ASSEMBLY (CONT.)

MAKAI
OCEAN ENGINEERING, INC.

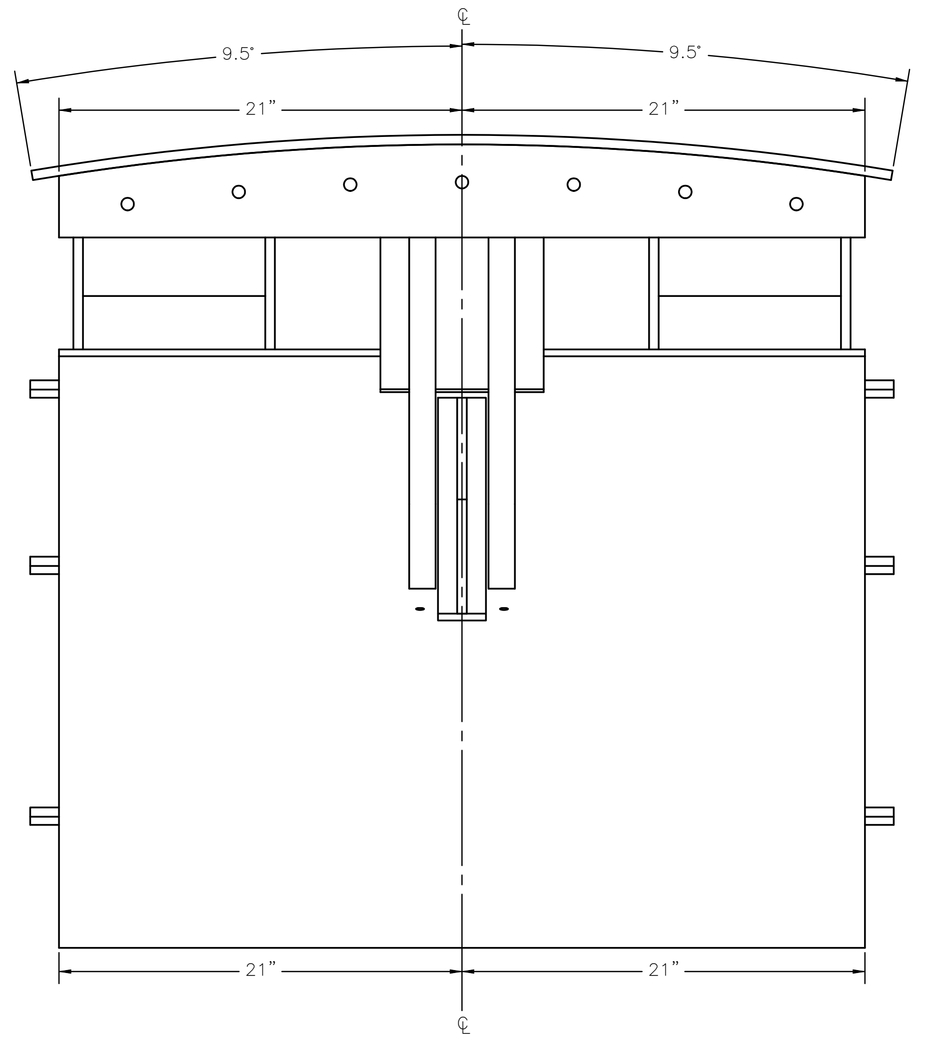
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER–CHIEF ENGINEER
DATE
DRAWING NO. S29

JOB NO. 15706

SHEET NO. 31 OF 61

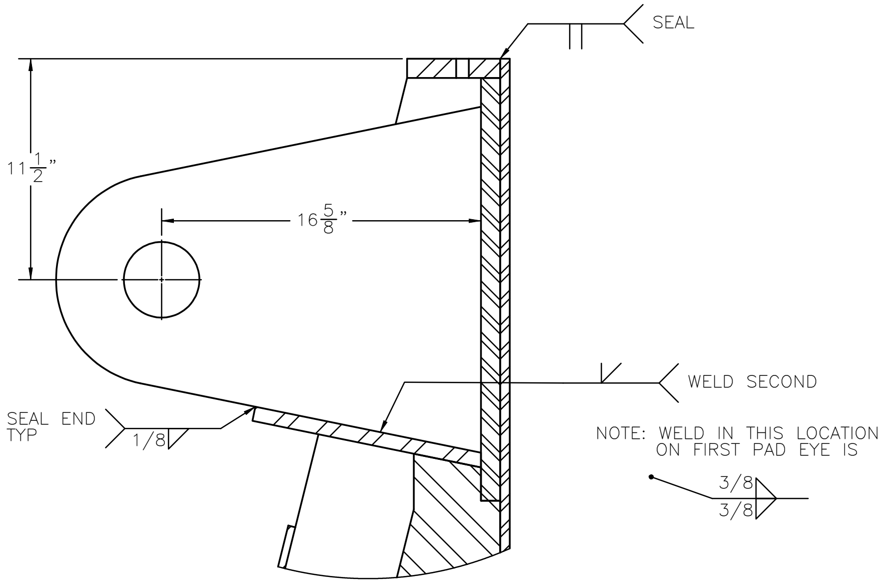


DETAIL AL/S30
SCALE 1 : 5



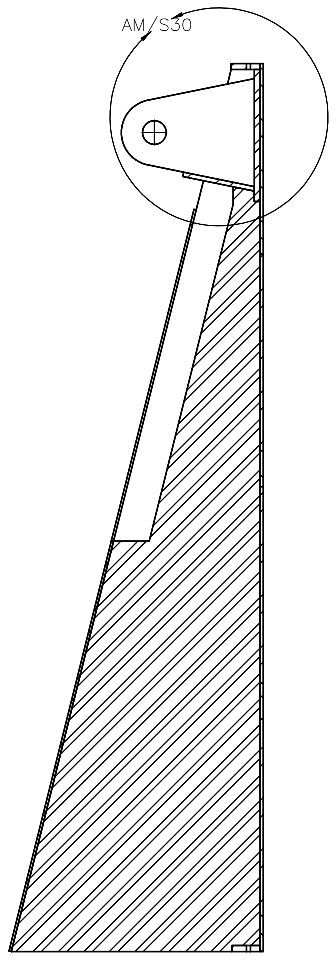
TOP VIEW

1/S30 OUTER WEDGE ASSEMBLY
SCALE 1 : 5



NOTE: WELD IN THIS LOCATION ON FIRST PAD EYE IS

DETAIL AM/S30
SCALE 1 : 5



SECTION AN/S30–AN/S30
SCALE 1 : 16

DRAWING RULE
(SCALE 1:1)

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

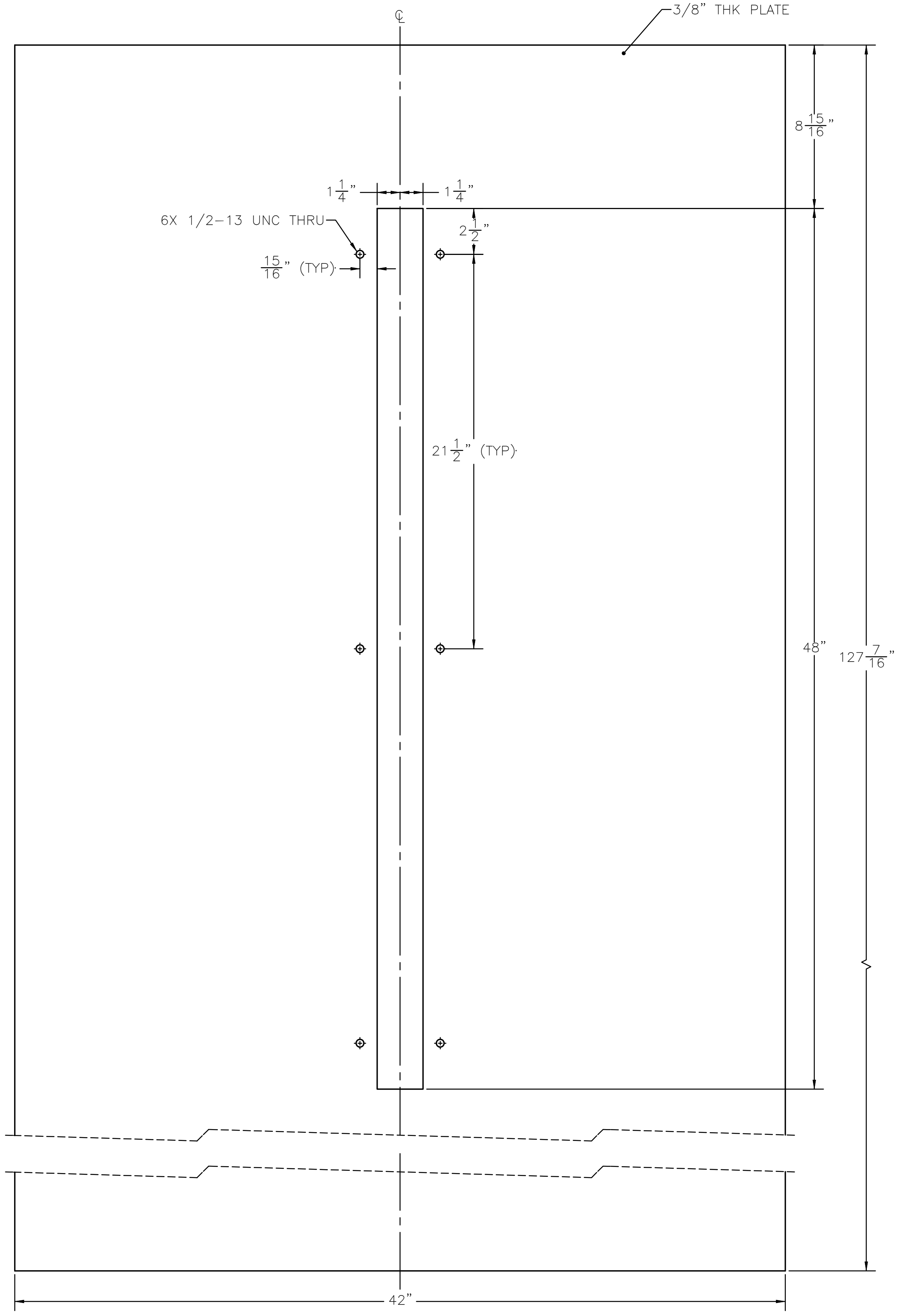
OUTER WEDGE ASSEMBLY (CONT.)

MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER–CHIEF ENGINEER
DATE
DRAWING NO. S30

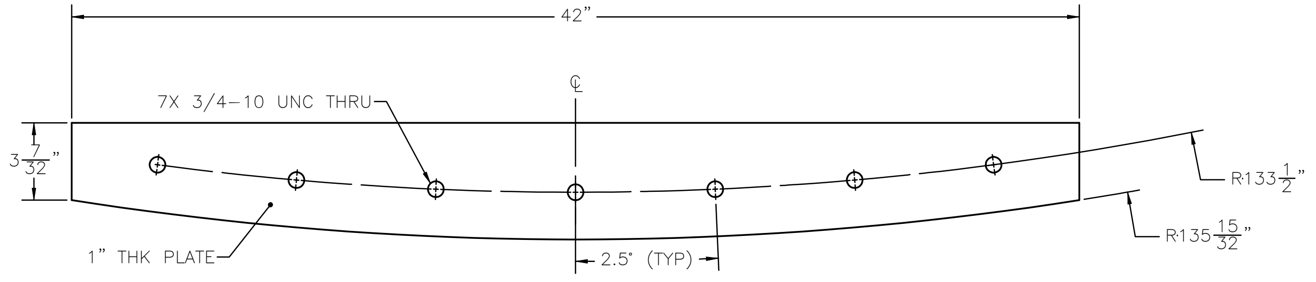
JOB NO. 15706

SHEET NO. 32 OF 61



FRONT VIEW

1/S31 PART 1
SCALE 1 : 4



TOP VIEW

2/S31 PART 2
SCALE 1 : 4

DRAWING RULE
(SCALE 1:1)

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

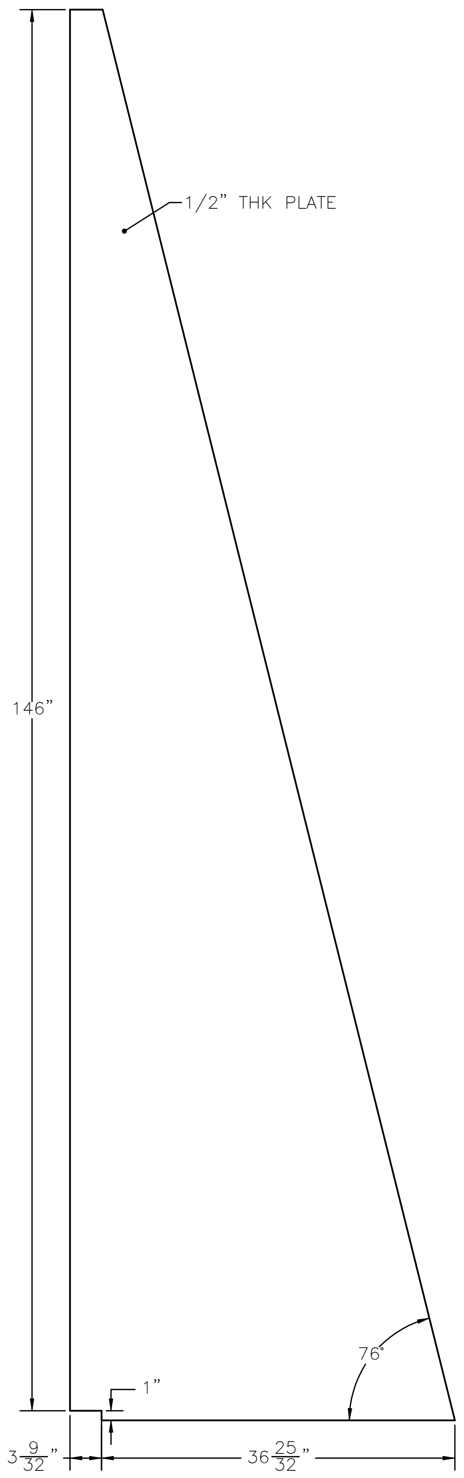
OUTER WEDGE ASSEMBLY PARTS I

MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S31

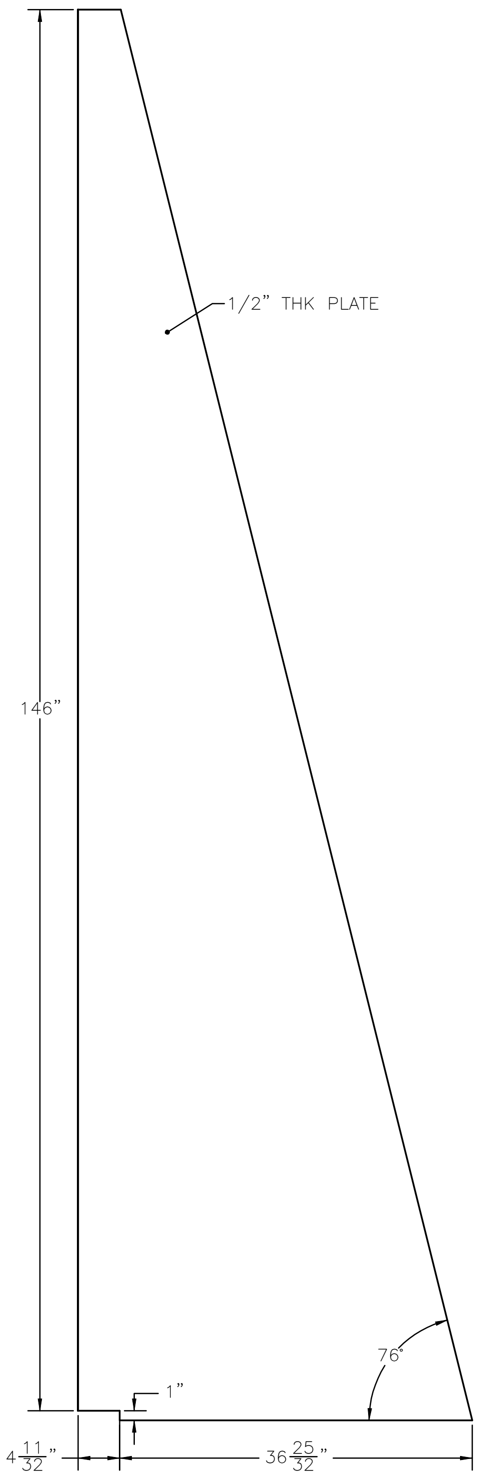
JOB NO. 15706

SHEET NO. 33 OF 61



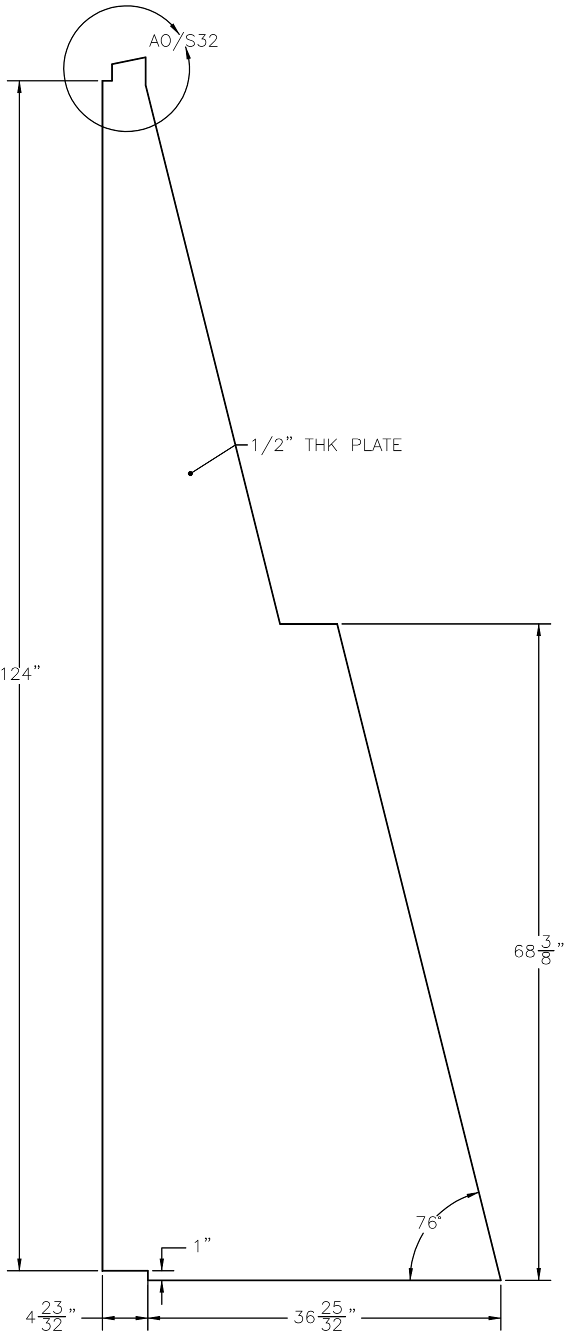
SIDE VIEW

1/S32 PART 3
SCALE 1 : 10



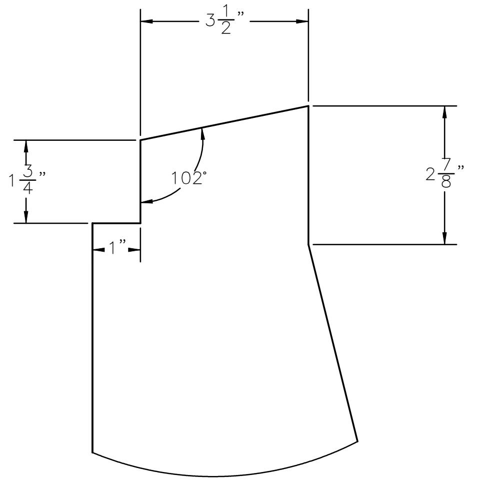
SIDE VIEW

2/S32 PART 4
SCALE 1 : 10

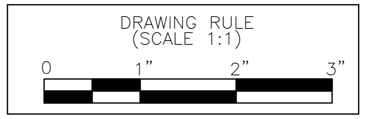


SIDE VIEW

3/S32 PART 5
SCALE 1 : 10



DETAIL A0/S32
SCALE 1 : 2



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

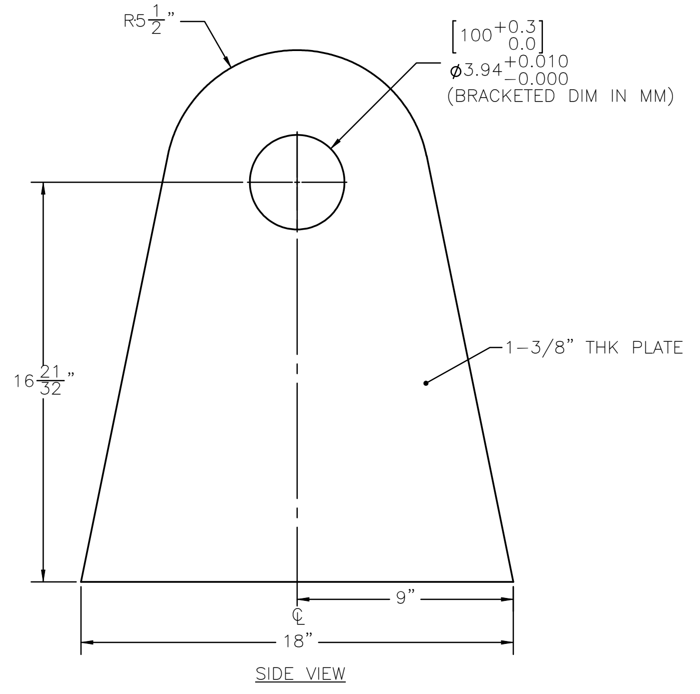
OUTER WEDGE ASSEMBLY PARTS II

MAKAI
OCEAN ENGINEERING, INC.

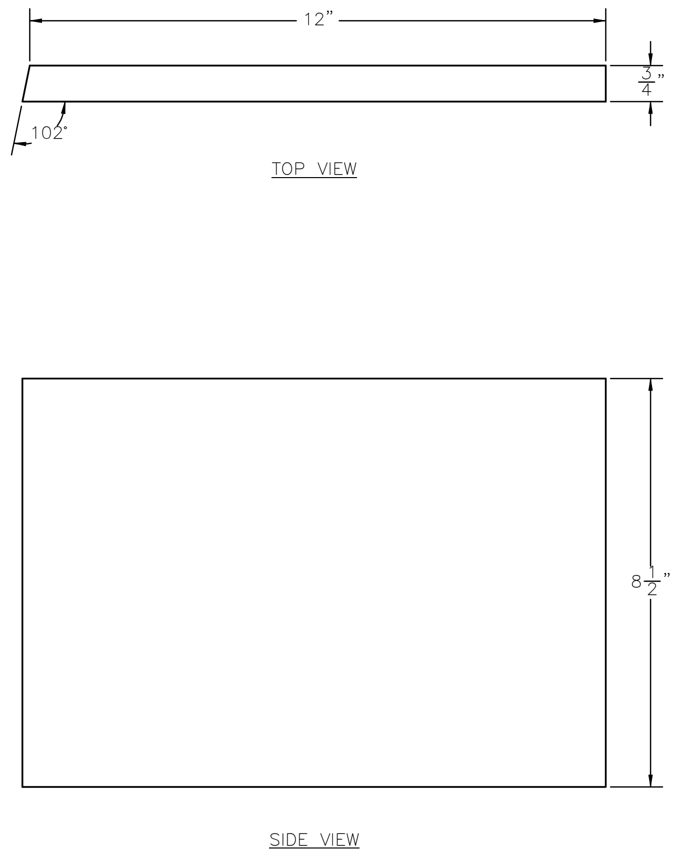
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S32

JOB NO. 15706

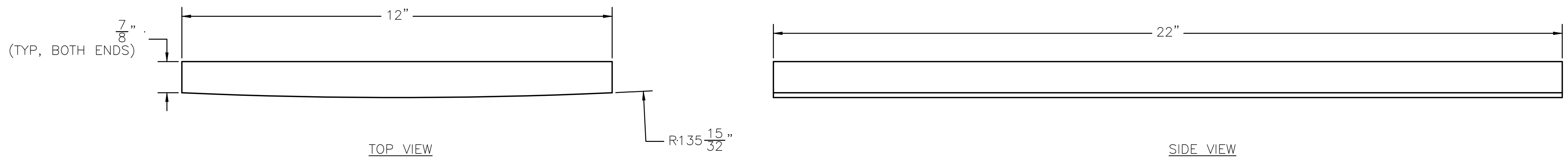
SHEET NO. 34 OF 61



1/S33 PART 6
SCALE 1 : 4



2/S33 PART 7
SCALE 1 : 2



3/S33 PART 8
SCALE 1 : 2

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

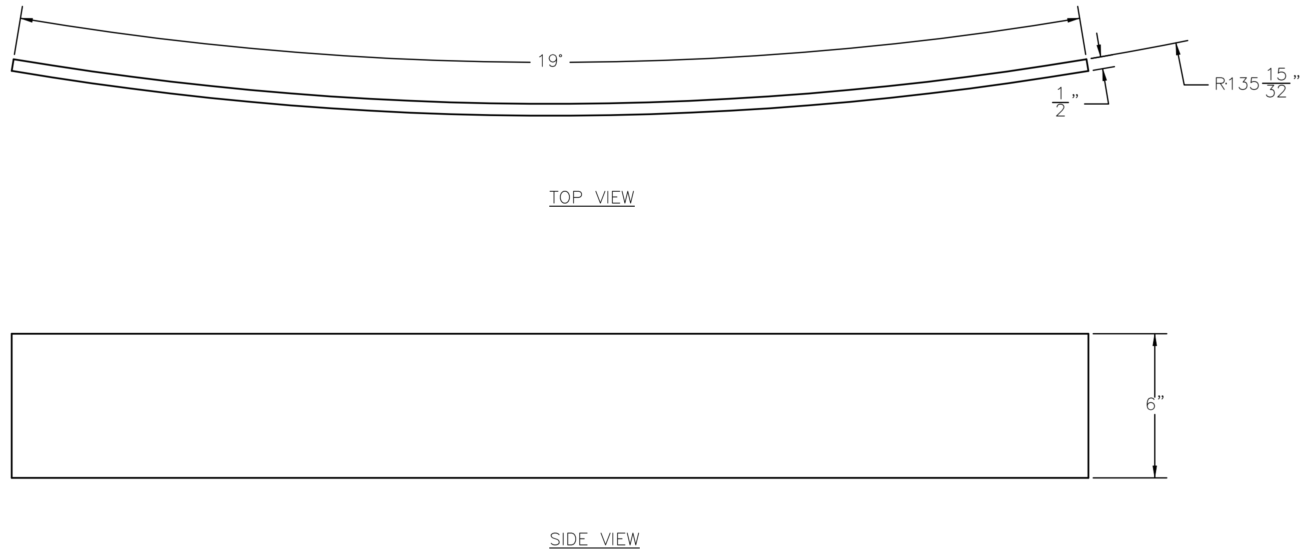
LOCKHEED MARTIN 9255 WELLINGTON ROAD MANASSAS, VA 20110−4121

OUTER WEDGE ASSEMBLY PARTS III

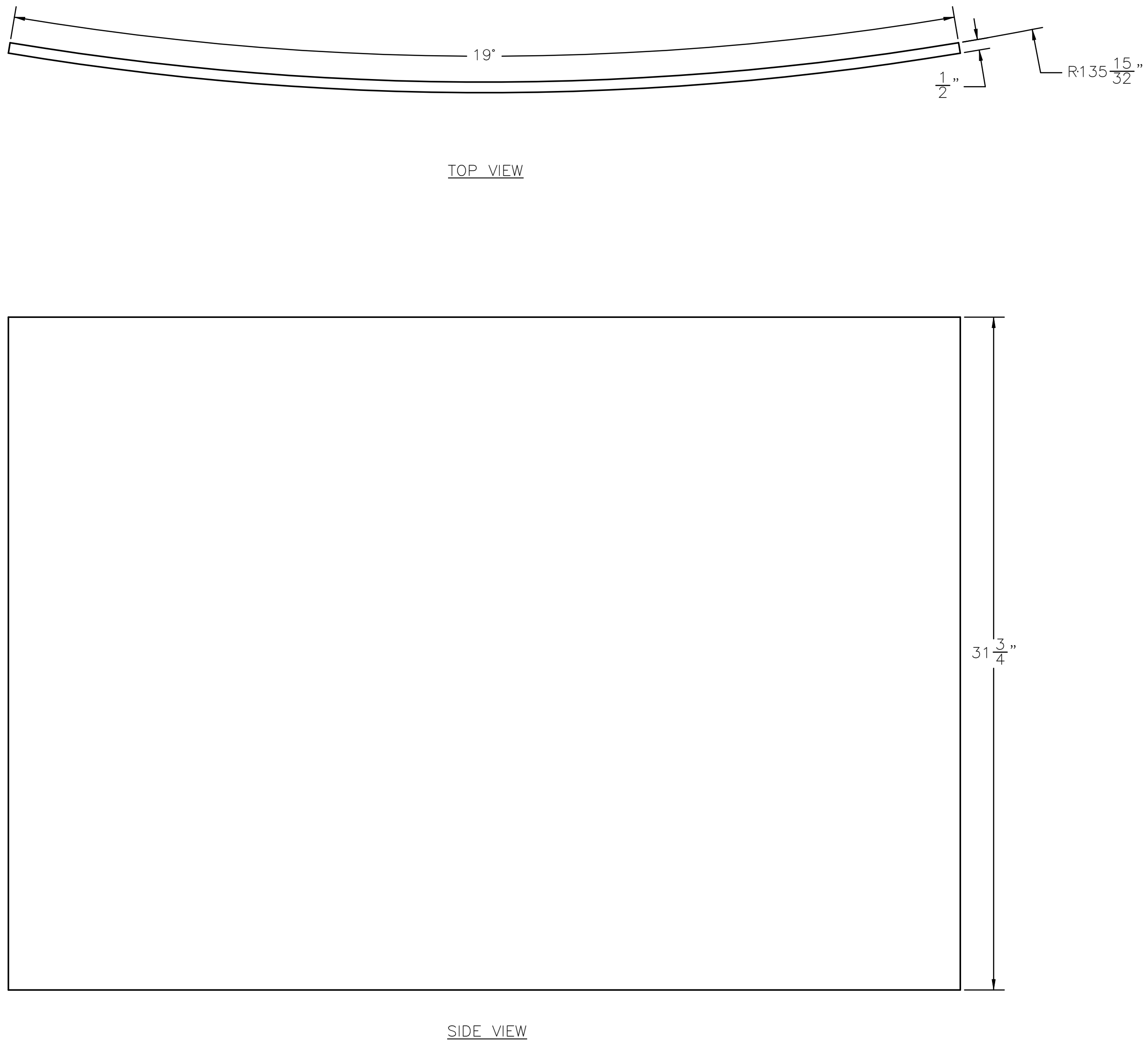
MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER−CHIEF ENGINEER
DATE
DRAWING NO. S33

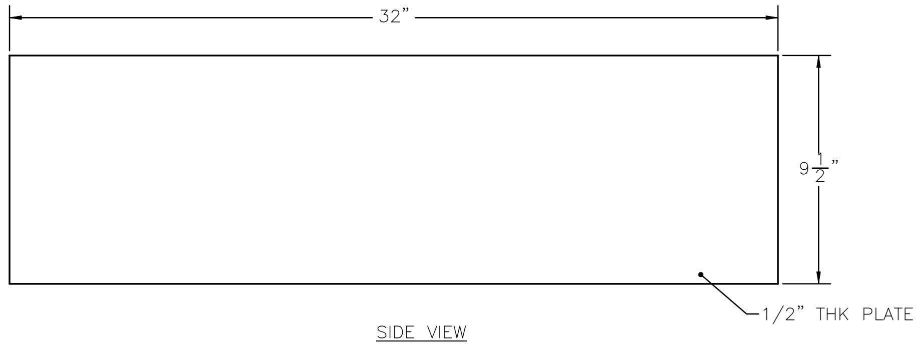
JOB NO. 15706
SHEET NO. 35 OF 61



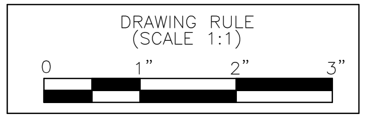
2/S34 PART 10
SCALE 1 : 4



1/S34 PART 9
SCALE 1 : 4



3/S34 PART 11
SCALE 1 : 4



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

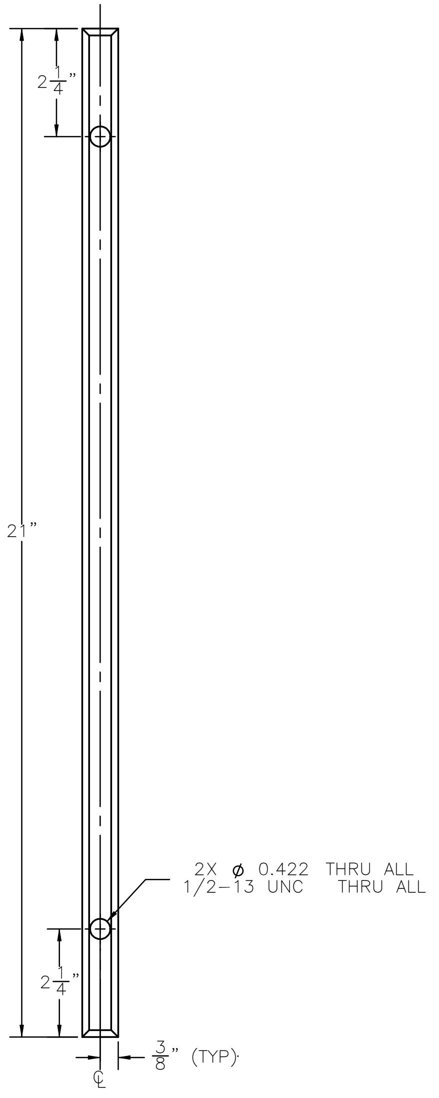
LOCKHEED MARTIN 9255 WELLINGTON ROAD MANASSAS, VA 20110-4121

OUTER WEDGE ASSEMBLY PARTS IV

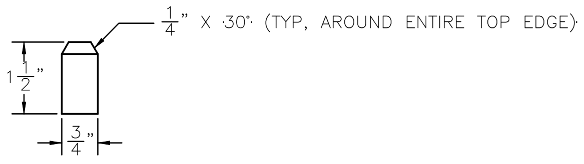
MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S34

JOB NO. 15706
SHEET NO. 36 OF 61

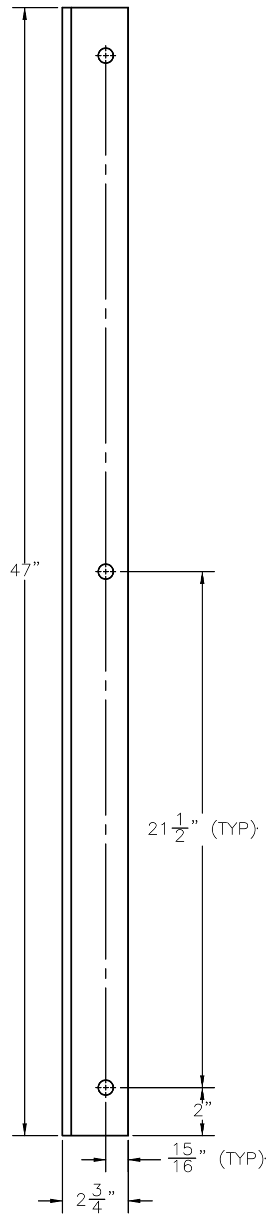


TOP VIEW

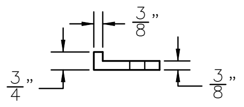


FRONT VIEW

1/S35 LINEAR GUIDE SYSTEM SLIDER
SCALE 1 : 2



TOP VIEW



FRONT VIEW

2/S35 LINEAR GUIDE SYSTEM TRACK
SCALE 1 : 4

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

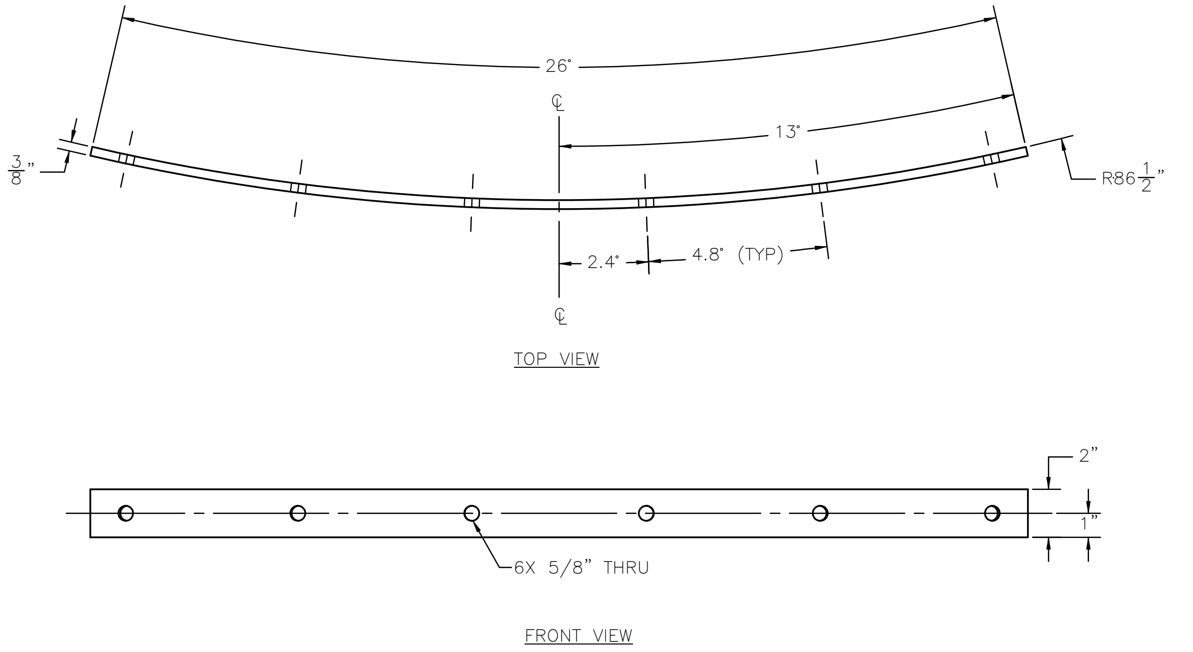
LINEAR GUIDE SYSTEM
SLIDER AND TRACK

MAKAI
OCEAN ENGINEERING, INC.

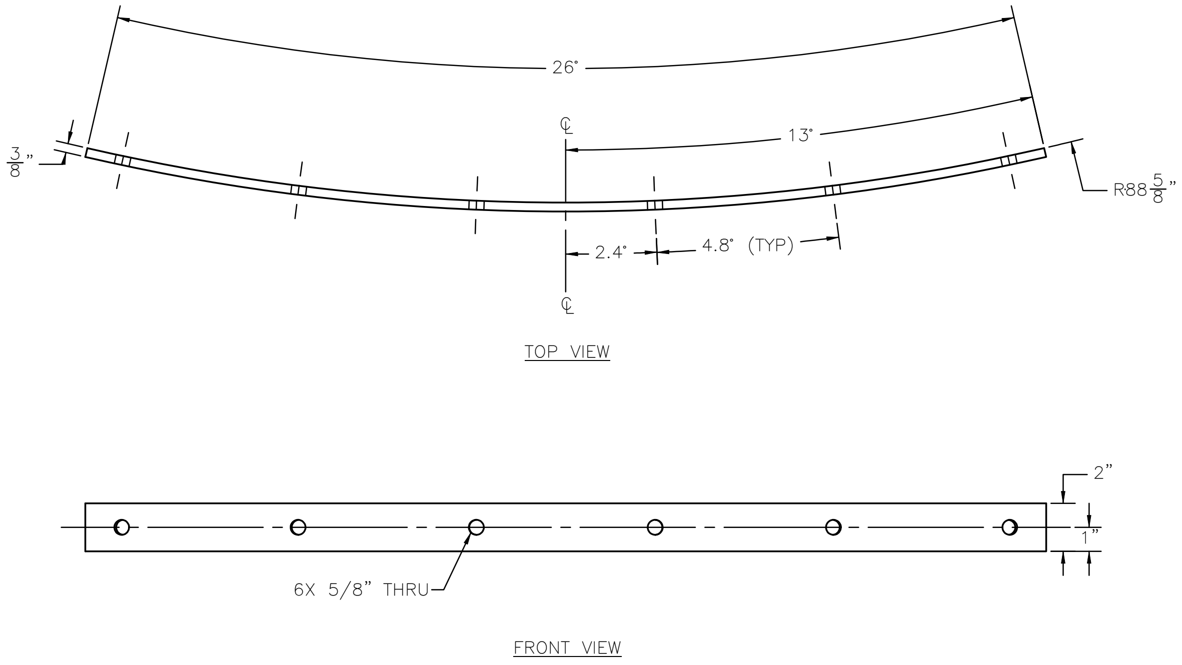
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S35

JOB NO. 15706

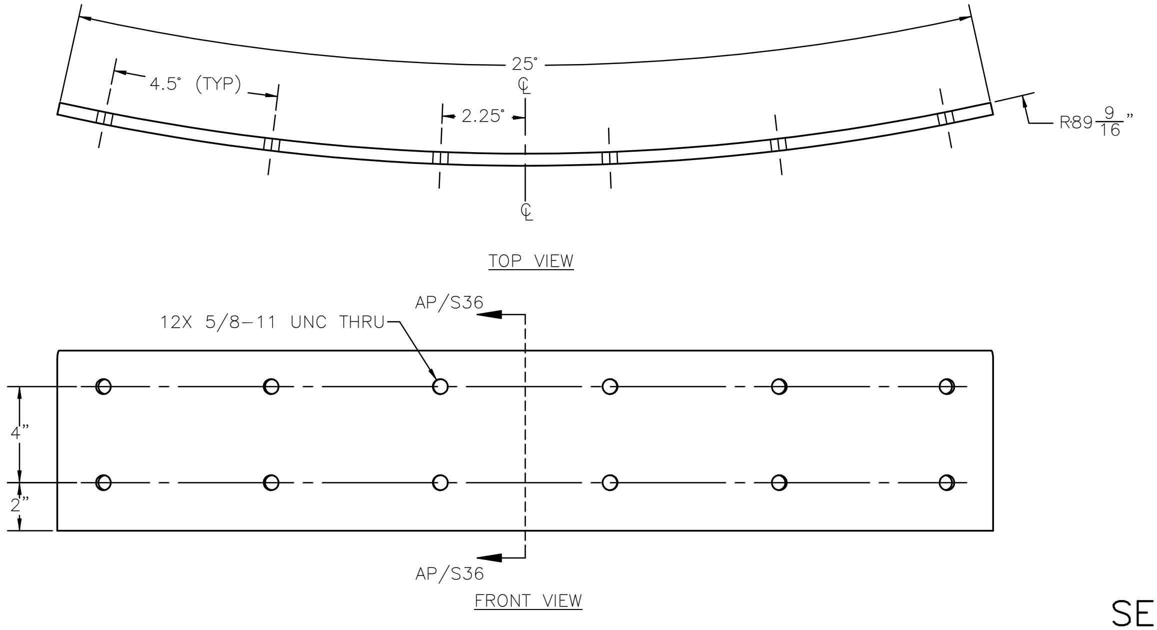
SHEET NO. 37 OF 61



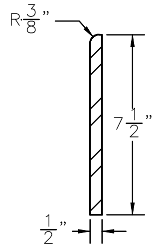
1/S36 UPPER GEL BAG CLAMP
SCALE 1 : 4



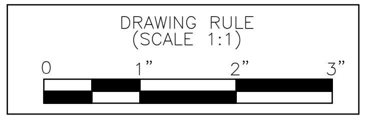
2/S36 LOWER GEL BAG CLAMP
SCALE 1 : 4



3/S36 LOWER FRICTION LAYER CLAMP
SCALE 1 : 4



SECTION AP/S36-AP/S36



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD MANASSAS, VA 20110-4121

GRIPPER GEL BAG CLAMPS AND LOWER FRICTION LAYER CLAMP

MAKAI OCEAN ENGINEERING, INC.

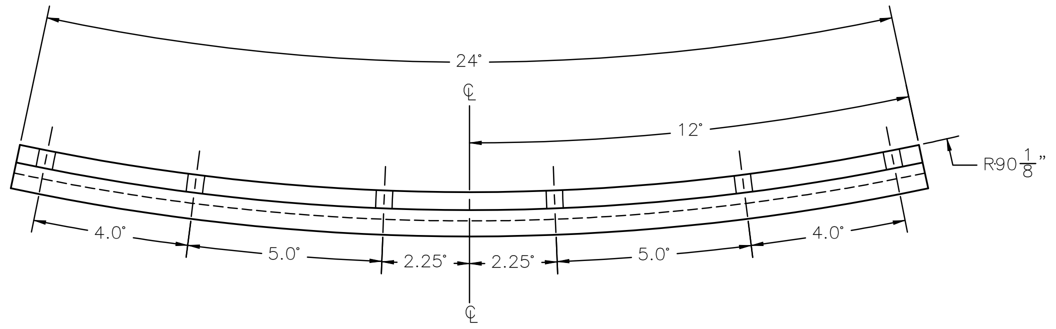
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S36

JOB NO. 15706

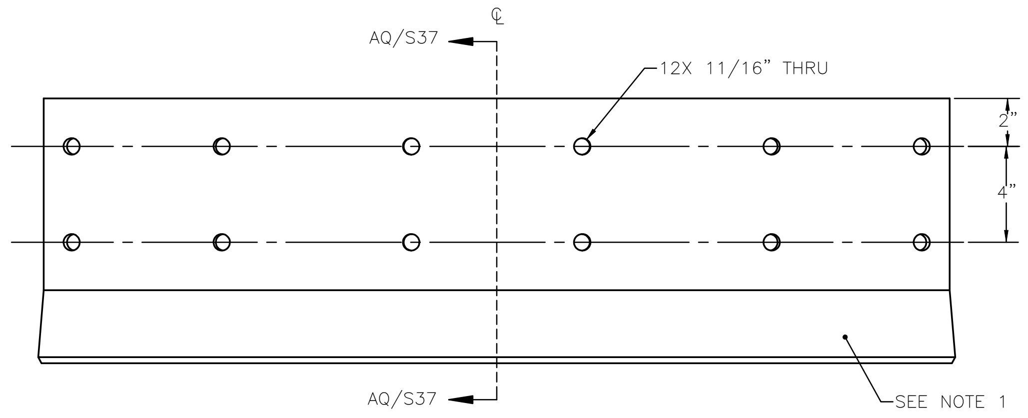
SHEET NO. 38 OF 61

NOTES:

1. THIS PLATE CAN BE FABRICATED FROM BENDING A SINGLE PLATE OR WELDING TWO PLATES TOGETHER, FABRICATOR TO USE DISCRETION. IF WELD OPTION IS CHOSEN, THE INSIDE FACE OF THE PLATE MUST BE SMOOTH AND FREE FROM WELD SLAG.

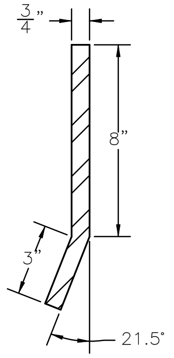


TOP VIEW

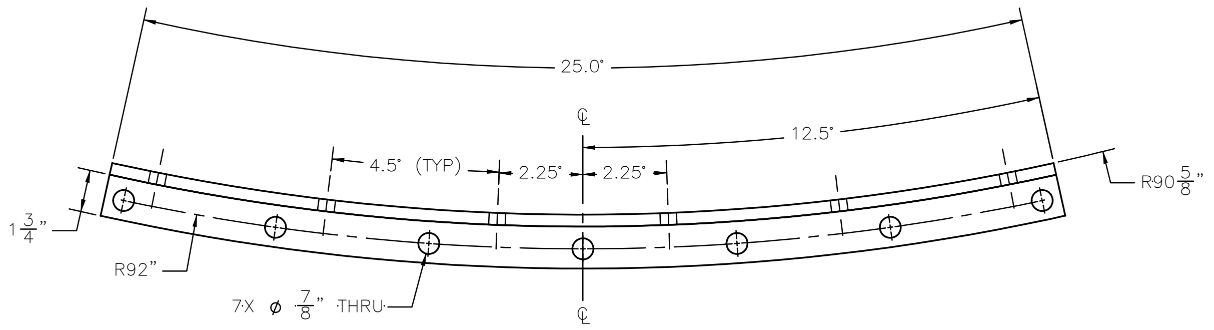


FRONT VIEW

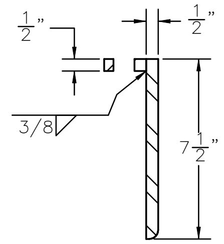
1/S37 UPPER FRICTION LAYER CLAMP
SCALE 1 : 4



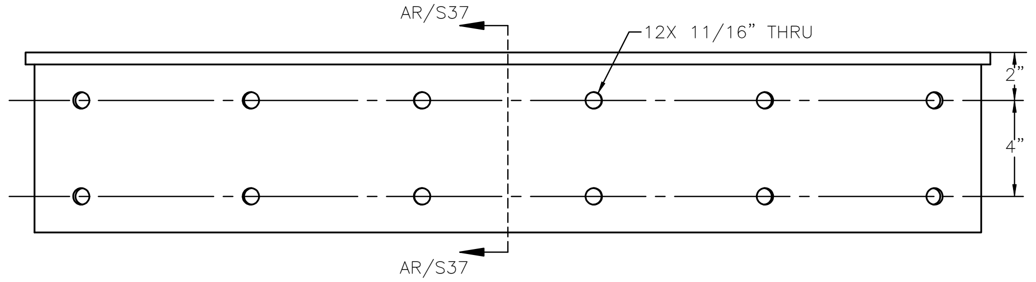
SECTION AQ/S37–AQ/S37
SCALE 1 : 4



TOP VIEW

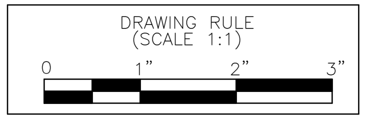


SECTION AR/S37–AR/S37
SCALE 1 : 4



FRONT VIEW

2/S37 FRICTION LAYER TENSIONING CLAMP
SCALE 1 : 4



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD MANASSAS, VA 20110-4121

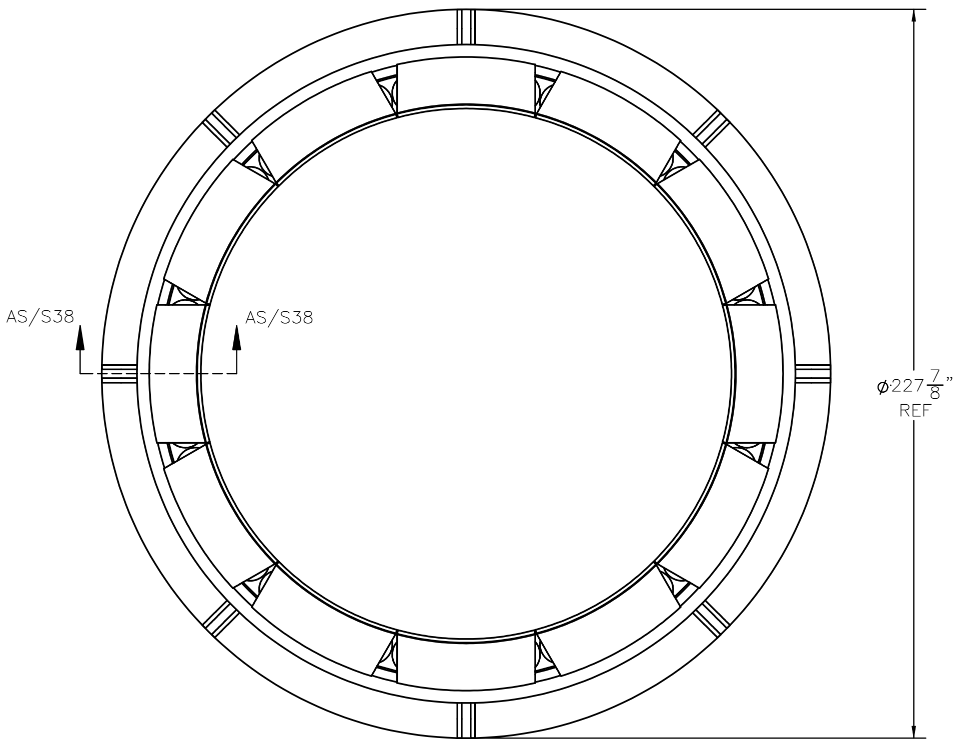
UPPER FRICTION LAYER AND
FRICTION LAYER TENSIONING CLAMP

MAKAI
OCEAN ENGINEERING, INC.

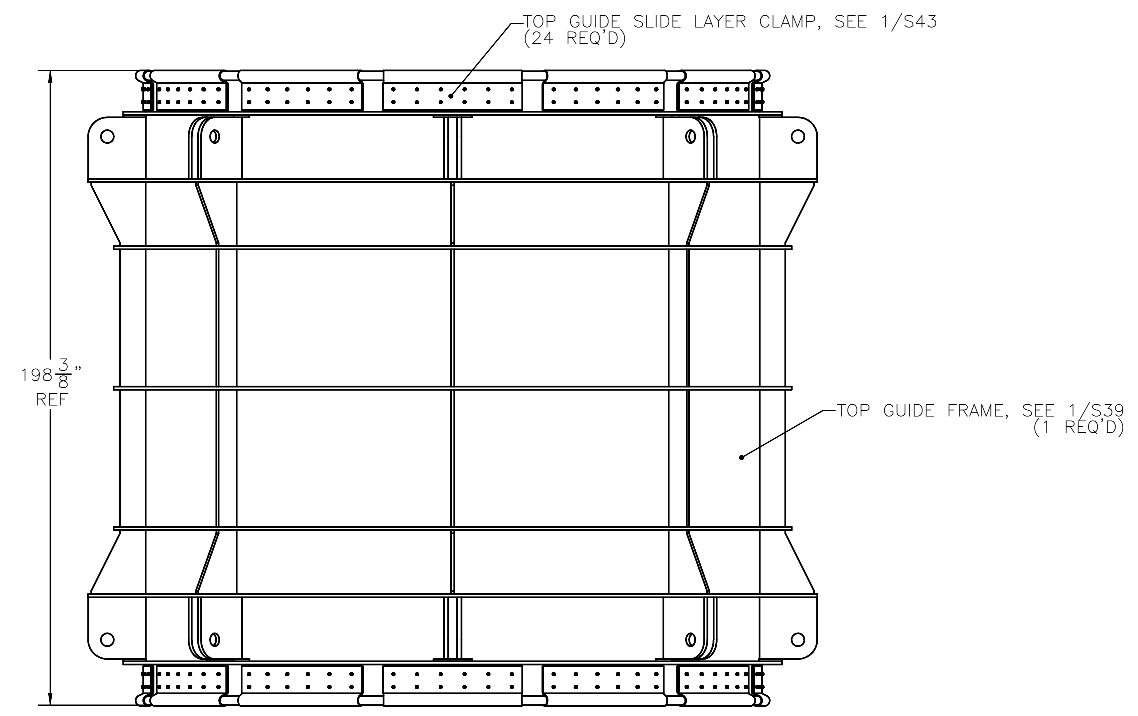
DESIGNED: A. LANDHERR	SUBMITTED:
DRAWN: A. LANDHERR	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED:	DRAWING NO. S37
MANAGER–CHIEF ENGINEER DATE	

JOB NO. 15706

SHEET NO. 39 OF 61

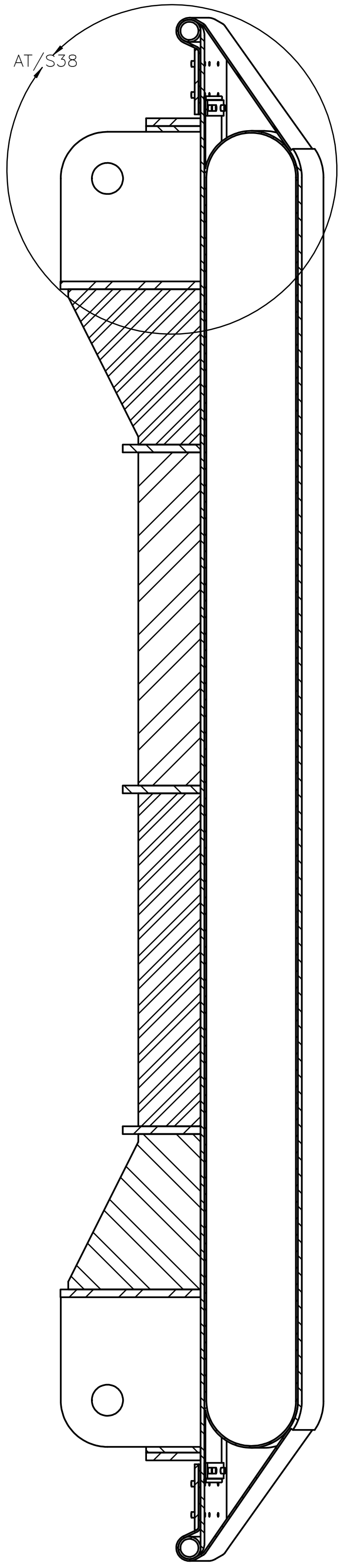


TOP VIEW

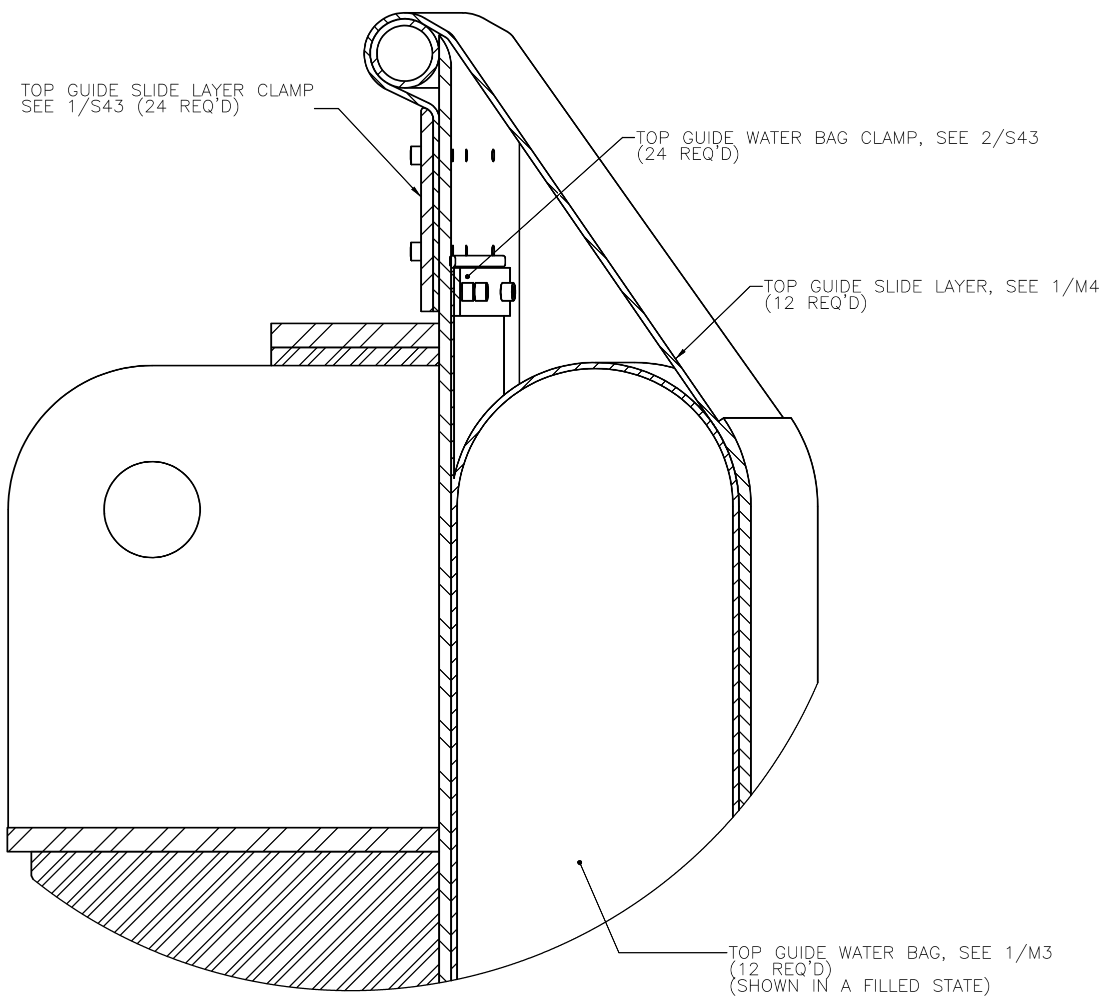


SIDE VIEW

1/S38 TOP GUIDE ASSEMBLY
SCALE 1 : 30



SECTION AS/S38–AS/S38
SCALE 1 : 12



DETAIL AT/S38
SCALE 1 : 4

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

TOP GUIDE ASSEMBLY

MAKAI
OCEAN ENGINEERING, INC.

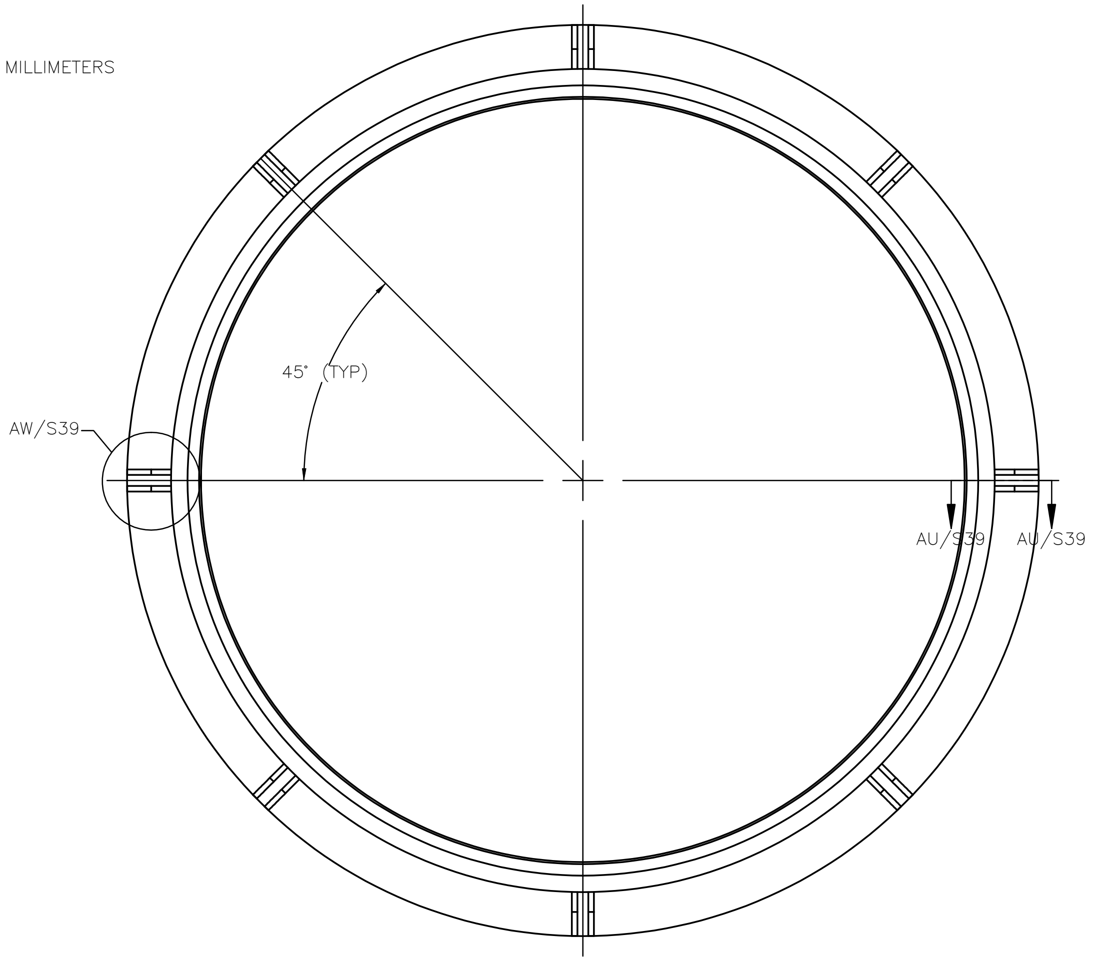
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER–CHIEF ENGINEER
DATE
DRAWING NO. S38

JOB NO. 15706

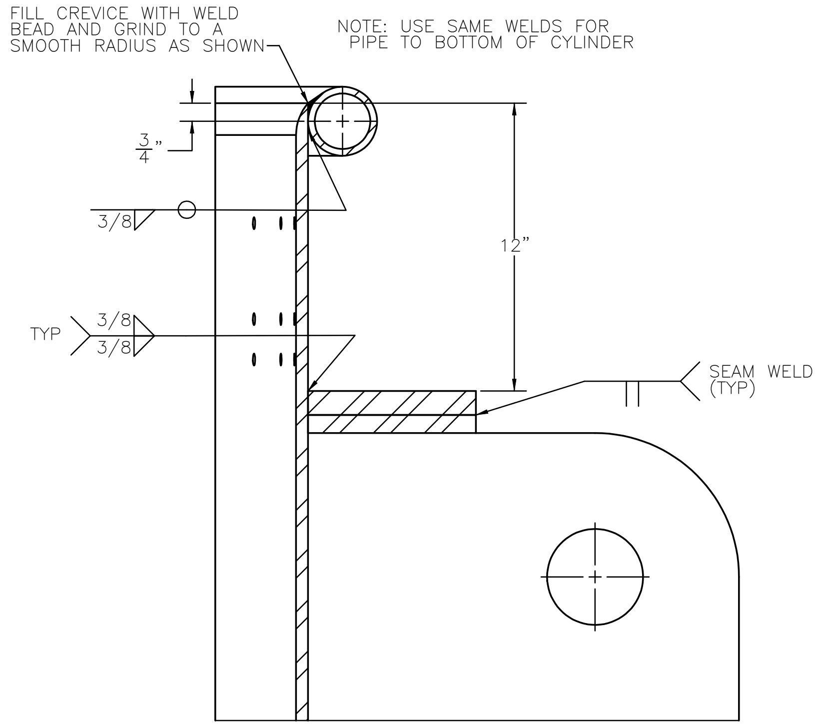
SHEET NO. 40 OF 61

NOTES

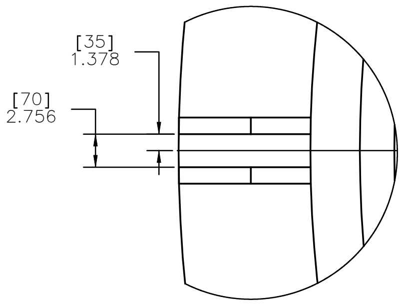
1. DIMENSIONS IN [] ARE MILLIMETERS



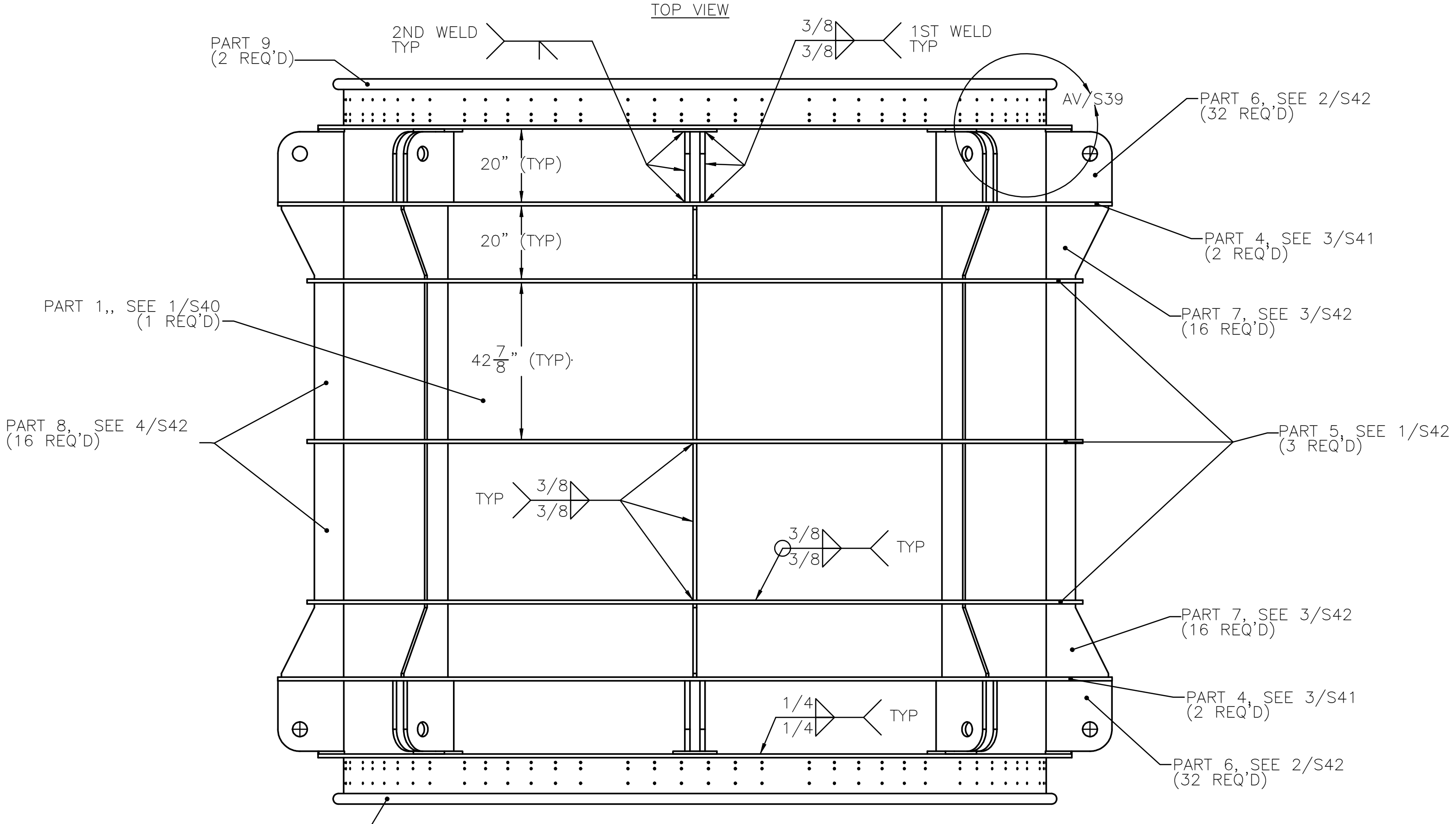
TOP VIEW



SECTION AU/S39–AU/S39
SCALE 1 : 4



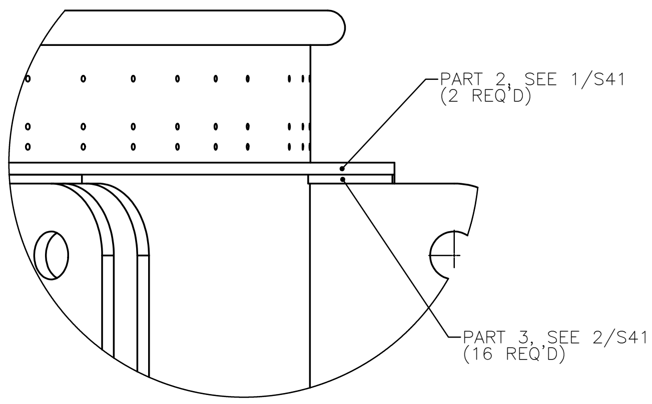
DETAIL AW/S39
SCALE 1 : 8



SIDE VIEW

1/S39 TOP GUIDE FRAME ASSEMBLY
SCALE 1 : 24

NOTE
TYP ON ABOVE DIM'S ASSUMES THERE IS SYMMETRY W.R.T. THE HORIZ CENTERLINE OF GUIDE ASSY.



DETAIL AV/S39
SCALE 1 : 8

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

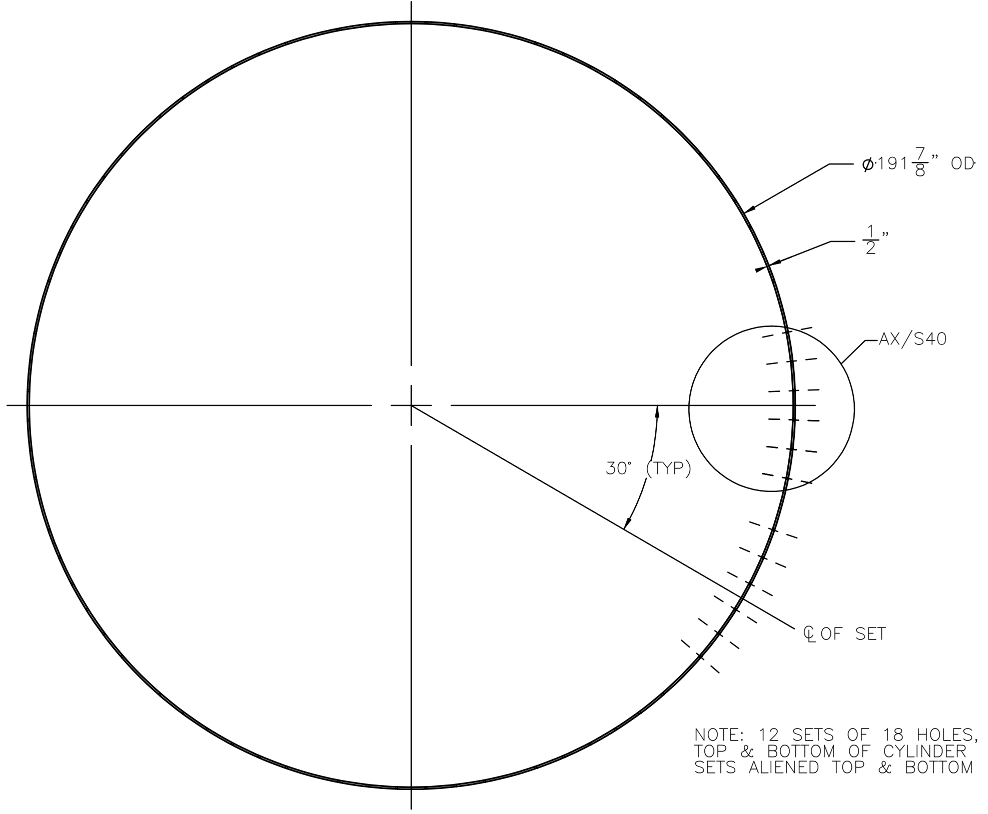
TOP GUIDE FRAME ASSEMBLY

MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: N. REESE
SUBMITTED:
DRAWN: N. REESE
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER–CHIEF ENGINEER
DATE
DRAWING NO. S39

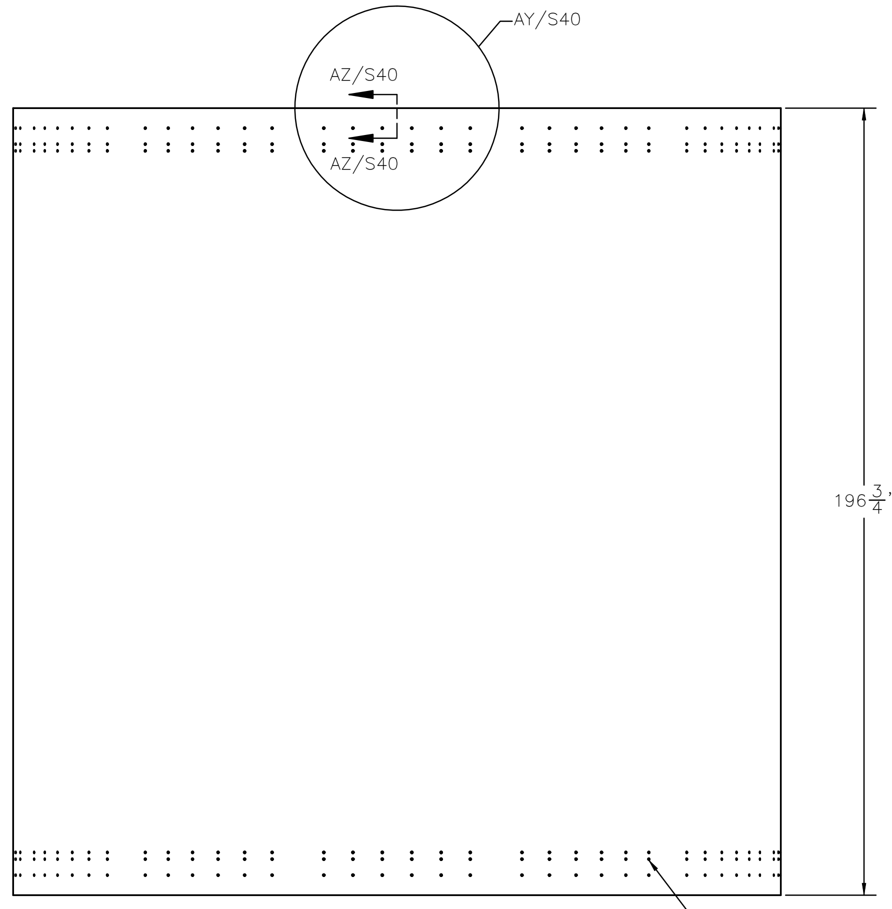
JOB NO.

SHEET NO. 41 OF 61



NOTE: 12 SETS OF 18 HOLES,
TOP & BOTTOM OF CYLINDER
SETS ALIENED TOP & BOTTOM

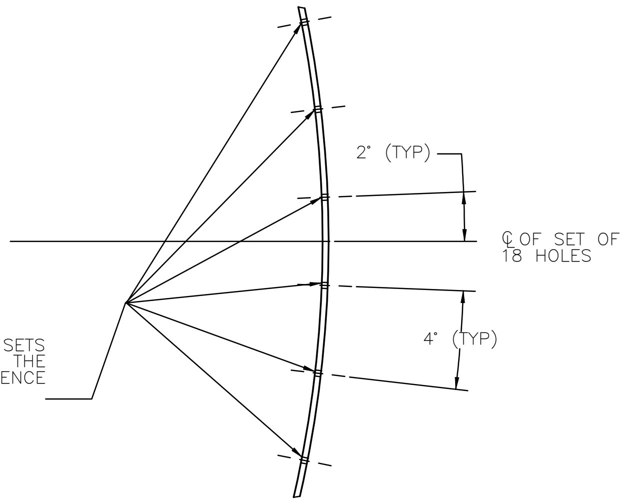
TOP VIEW



FOR HOLE VERTICAL LOCATIONS MIRROR IMAGE OF DETAIL AY/S40

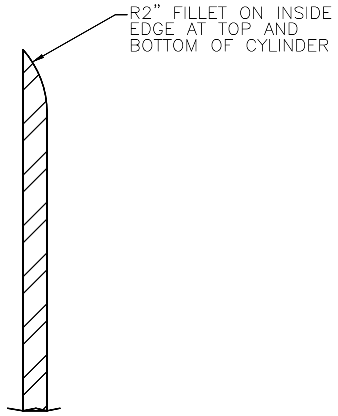
SIDE VIEW

1/S40 TOP GUIDE ASSEMBLY: PART 1
SCALE 1 : 30

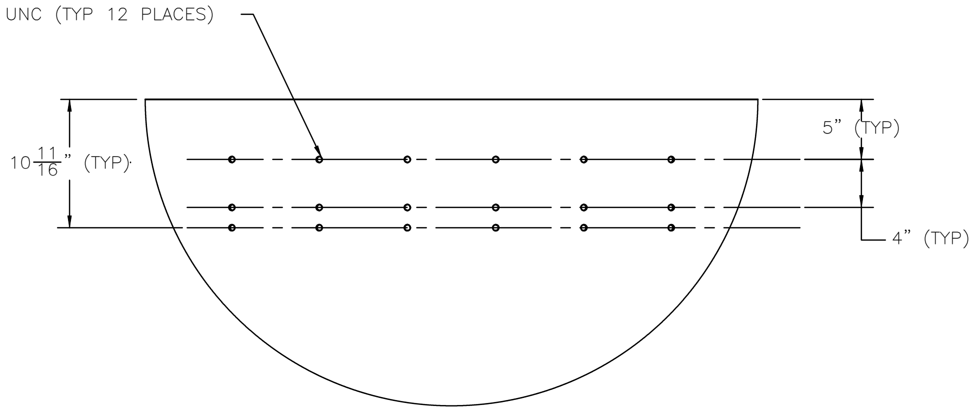


THERE ARE 12 EQ. SPACED SETS
OF THESE HOLES AROUND THE
CIRCUMFERENCE

DETAIL AX/S40
SCALE 1 : 8



SECTION AZ/S40–AZ/S40
SCALE 1 : 2



DETAIL AY/S40
SCALE 1 : 8

DRAWING RULE
(SCALE 1:1)

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

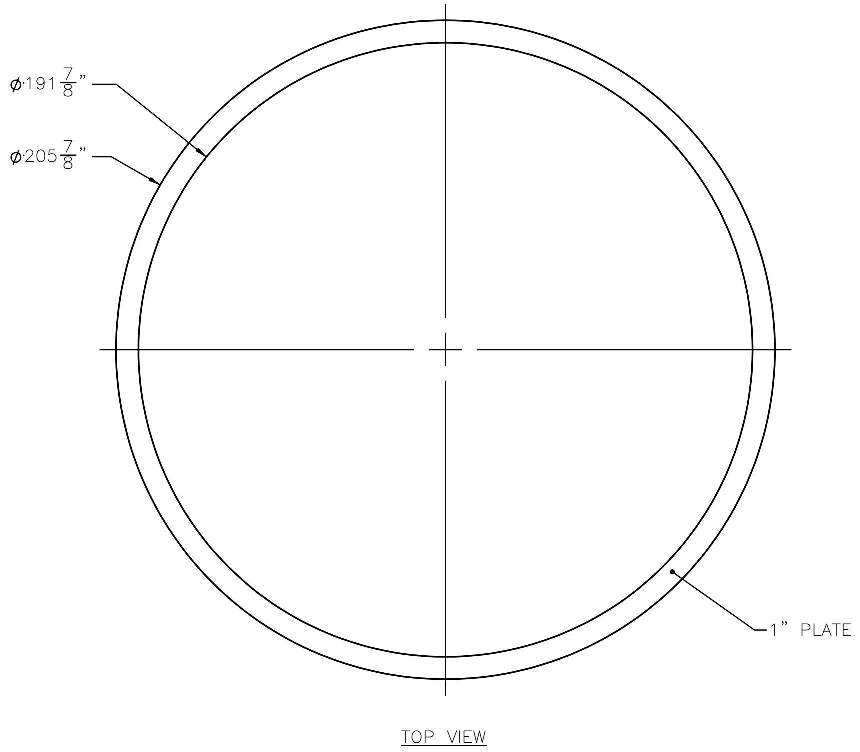
TOP GUIDE FRAME
ASSEMBLY PARTS I

MAKAI
OCEAN ENGINEERING, INC.

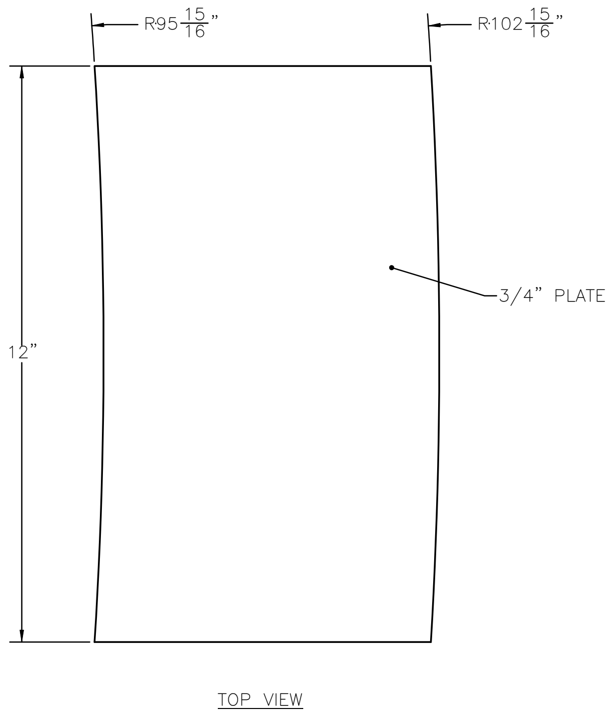
DESIGNED: N. REESE	SUBMITTED:
DRAWN: N. REESE	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED:	DRAWING NO. S40
MANAGER–CHIEF ENGINEER DATE	

JOB NO. 15706

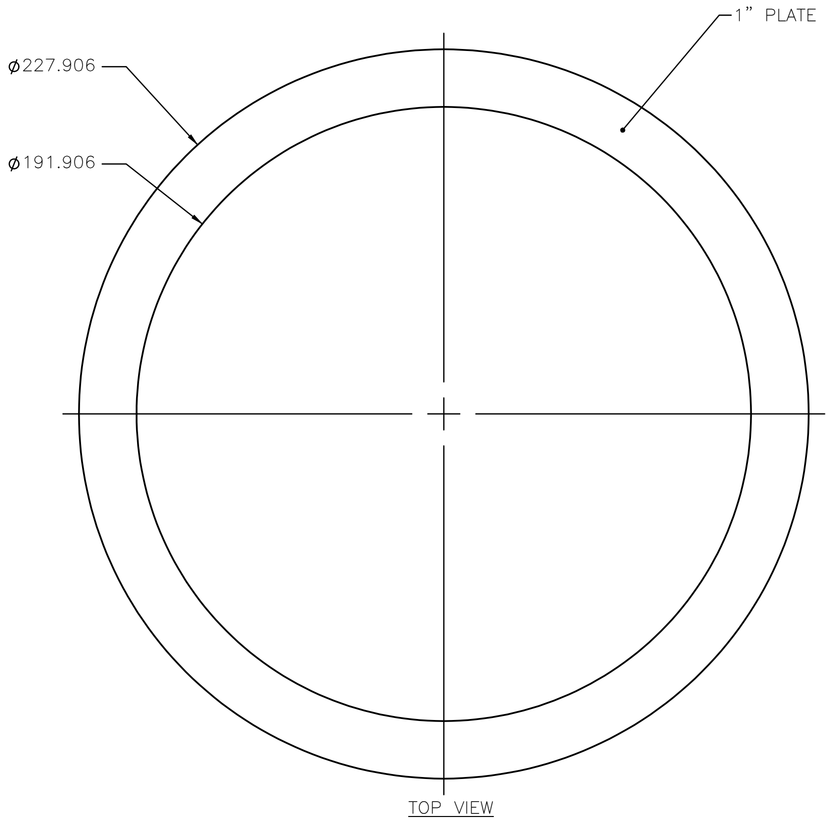
SHEET NO. 42 OF 61



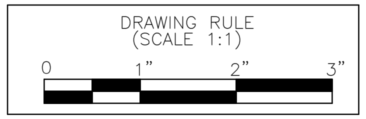
1/S41 TOP GUIDE ASSEMBLY: PART 2
SCALE 1 : 30



2/S41 TOP GUIDE ASSEMBLY: PART 3
SCALE 1 : 2



3/S41 TOP GUIDE ASSEMBLY: PART 4
SCALE 1 : 30



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

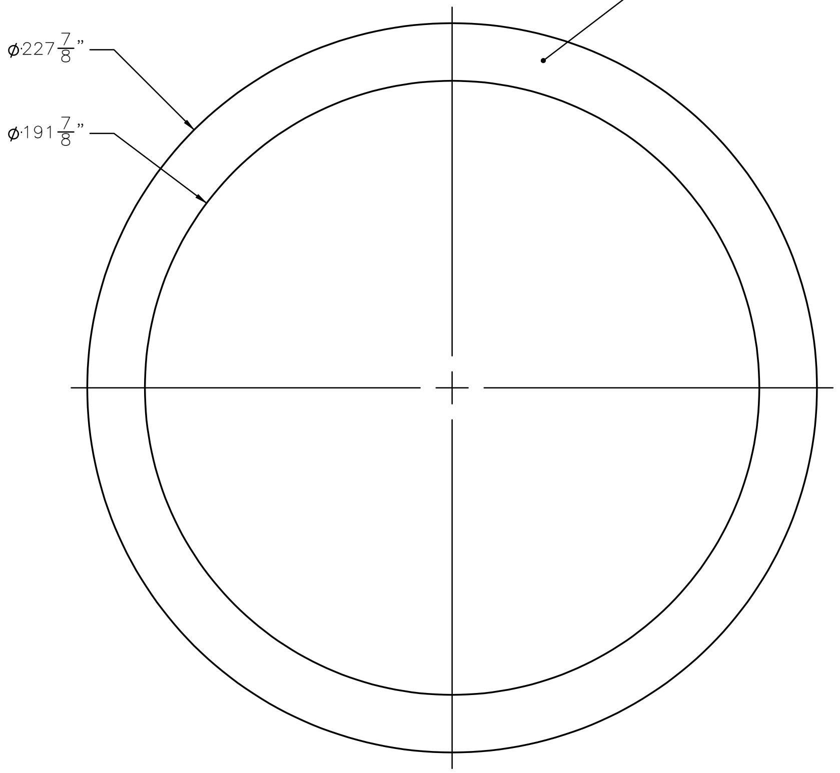
TOP GUIDE FRAME
ASSEMBLY PARTS II

MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: N. REESE
SUBMITTED:
DRAWN: N. REESE
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER–CHIEF ENGINEER
DATE
DRAWING NO. S41

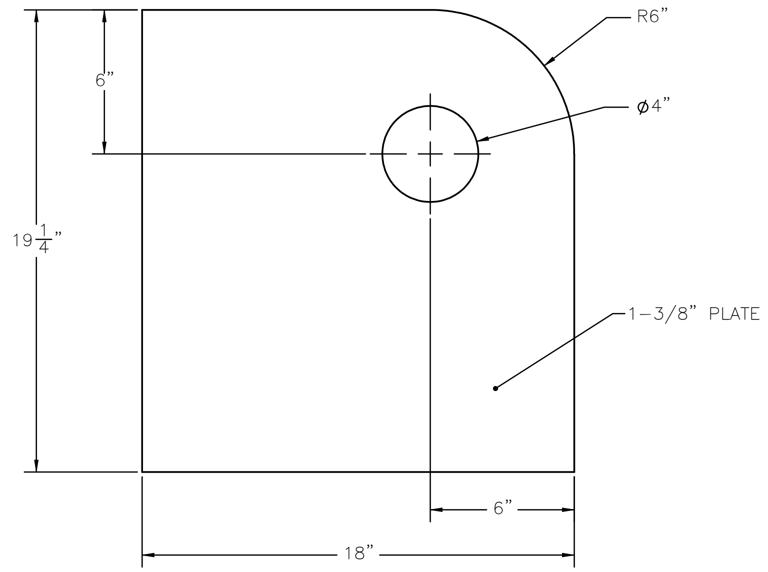
JOB NO. 15706

SHEET NO. 43 OF 61



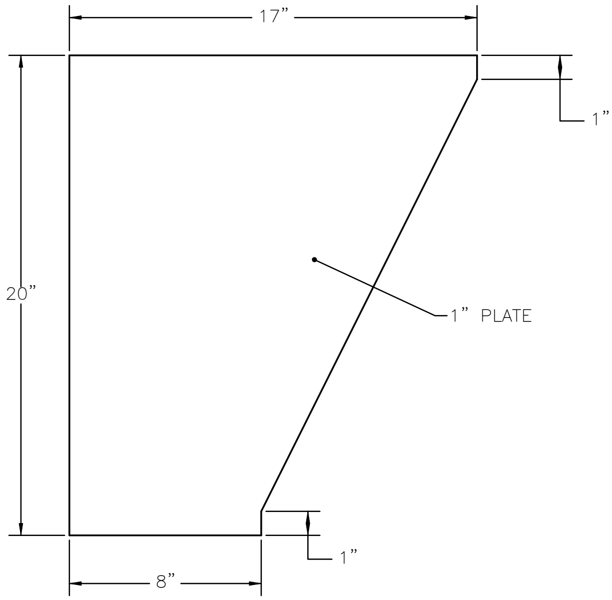
TOP VIEW

1/S42 TOP GUIDE ASSEMBLY: PART 5
SCALE 1 : 30



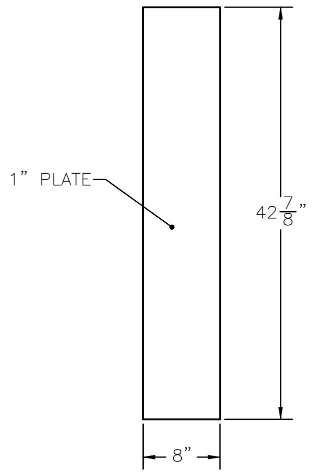
SIDE VIEW

2/S42 TOP GUIDE ASSEMBLY: PART 6
SCALE 1 : 4



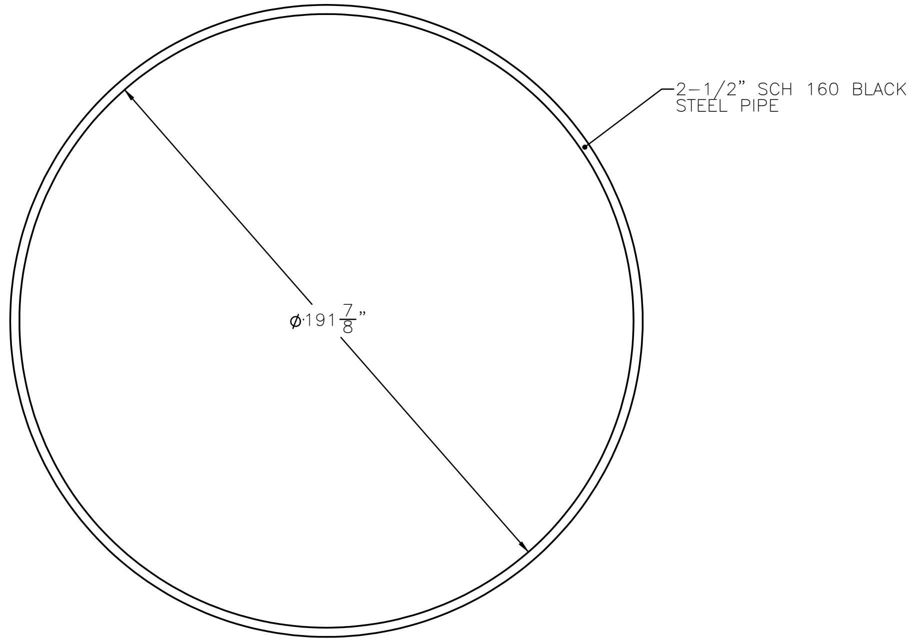
SIDE VIEW

3/S42 TOP GUIDE ASSEMBLY: PART 7
SCALE 1 : 4



SIDE VIEW

4/S42 TOP GUIDE ASSEMBLY: PART 8
SCALE 1 : 10



TOP VIEW

5/S42 TOP GUIDE ASSEMBLY: PART 9
SCALE 1 : 30

DRAWING RULE
(SCALE 1:1)

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

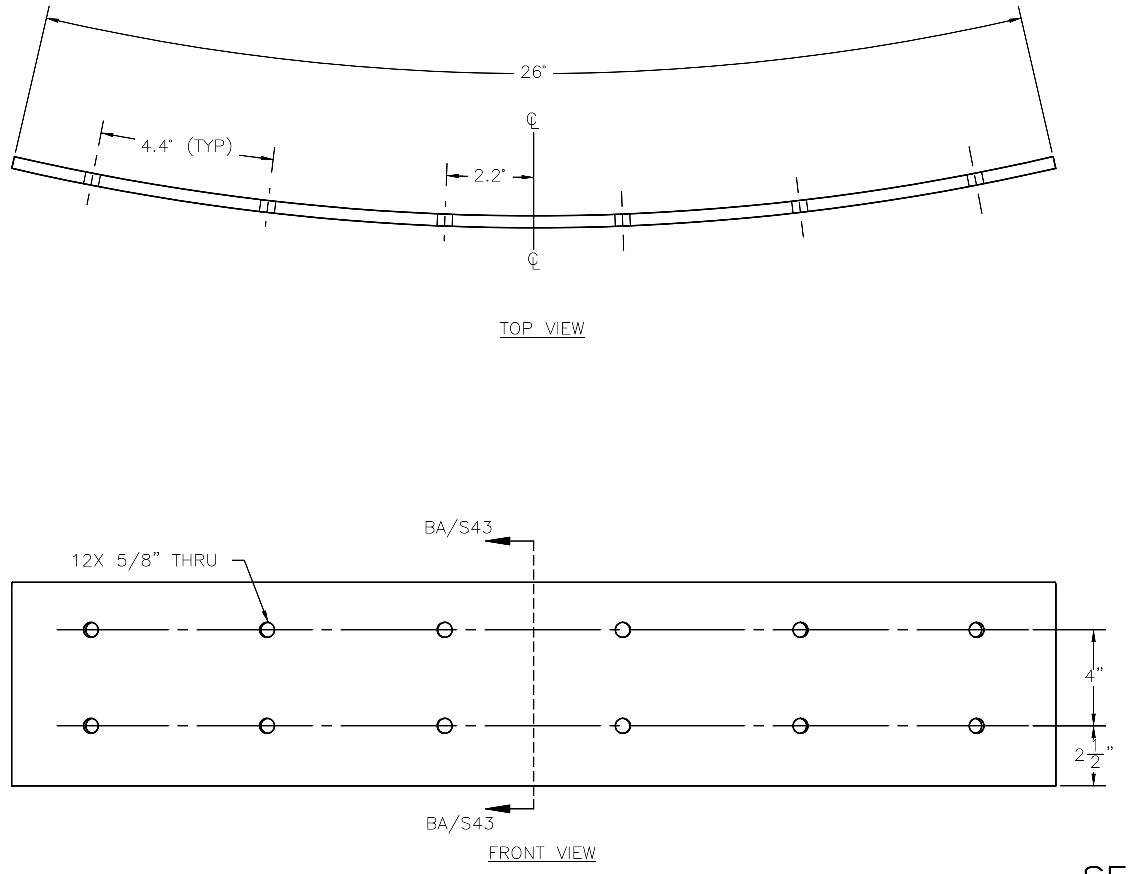
LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

TOP GUIDE FRAME
ASSEMBLY PARTS III

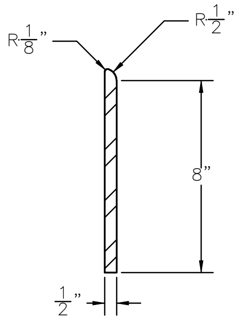
MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: N. REESE
SUBMITTED:
DRAWN: N. REESE
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S42

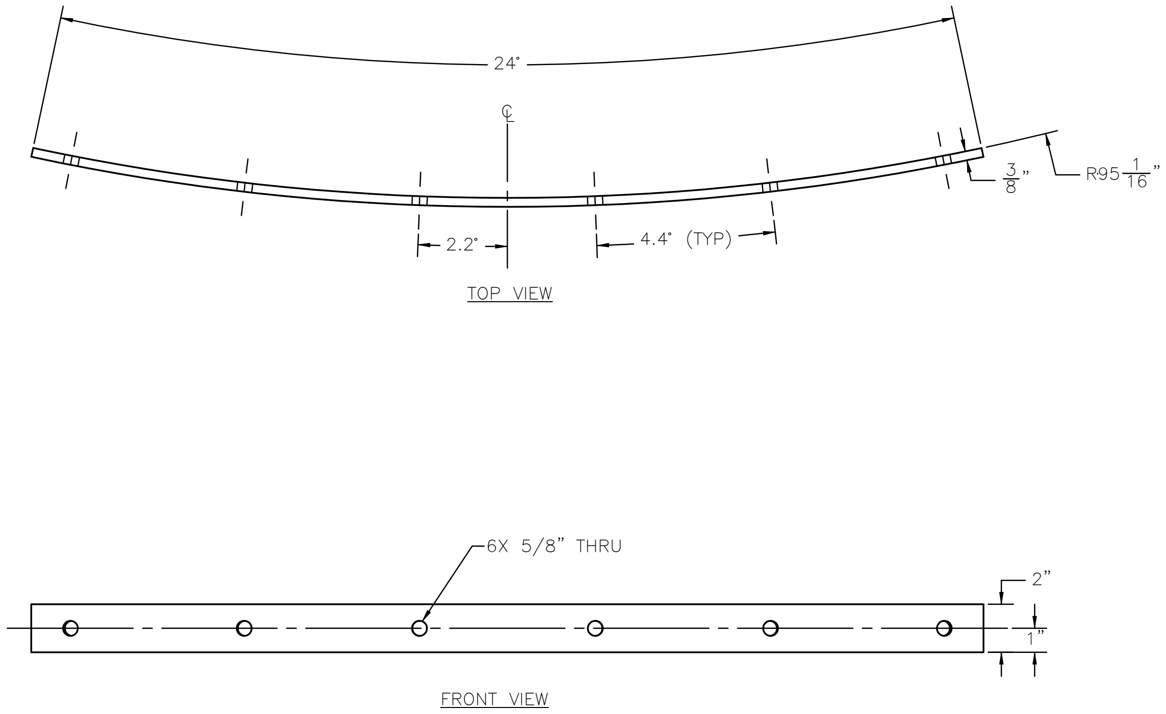
JOB NO. 15706
SHEET NO. 44 OF 61



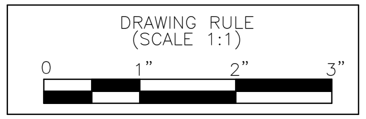
1/S43 TOP GUIDE SLIDE LAYER CLAMP
SCALE 1 : 4



SECTION BA/S43–BA/S43
SCALE 1 : 4



2/S43 TOP GUIDE WATER BAG CLAMP
SCALE 1 : 4



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

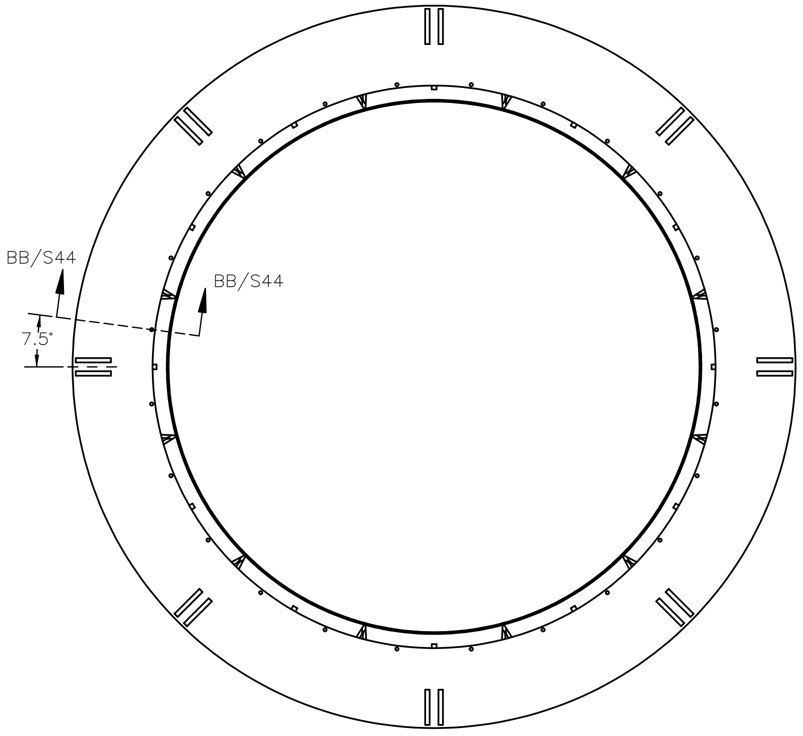
TOP GUIDE SLIDE LAYER
AND WATER BAG CLAMPS

MAKAI
OCEAN ENGINEERING, INC.

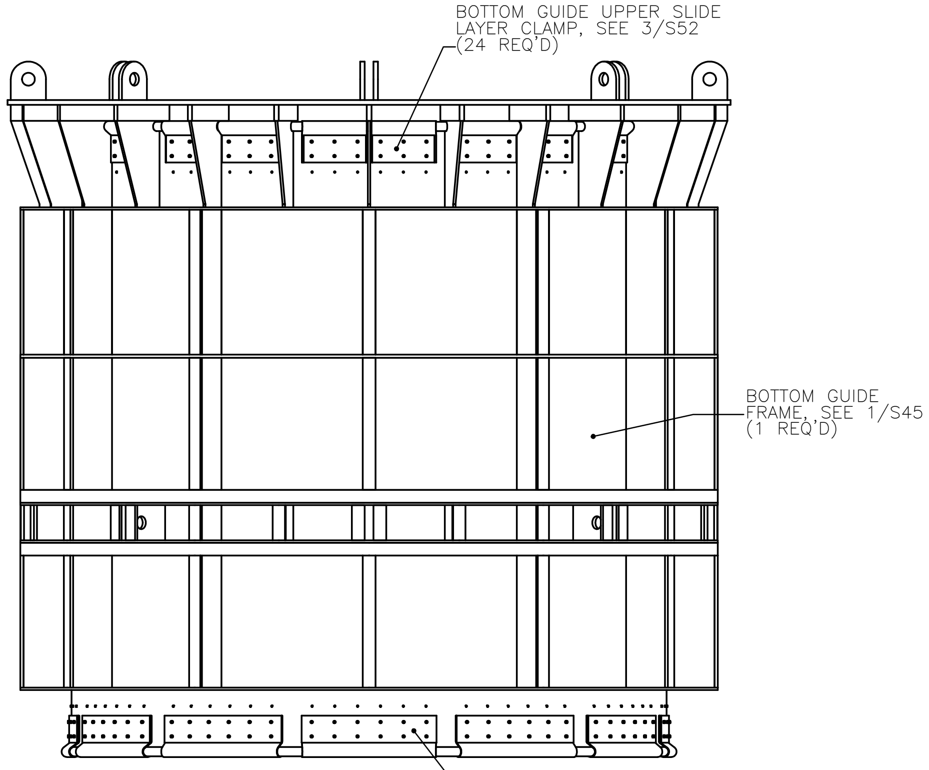
DESIGNED: A. LANDHERR	SUBMITTED:
DRAWN: A. LANDHERR	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED:	DRAWING NO. S43
MANAGER–CHIEF ENGINEER DATE	

JOB NO. 15706

SHEET NO. 45 OF 61

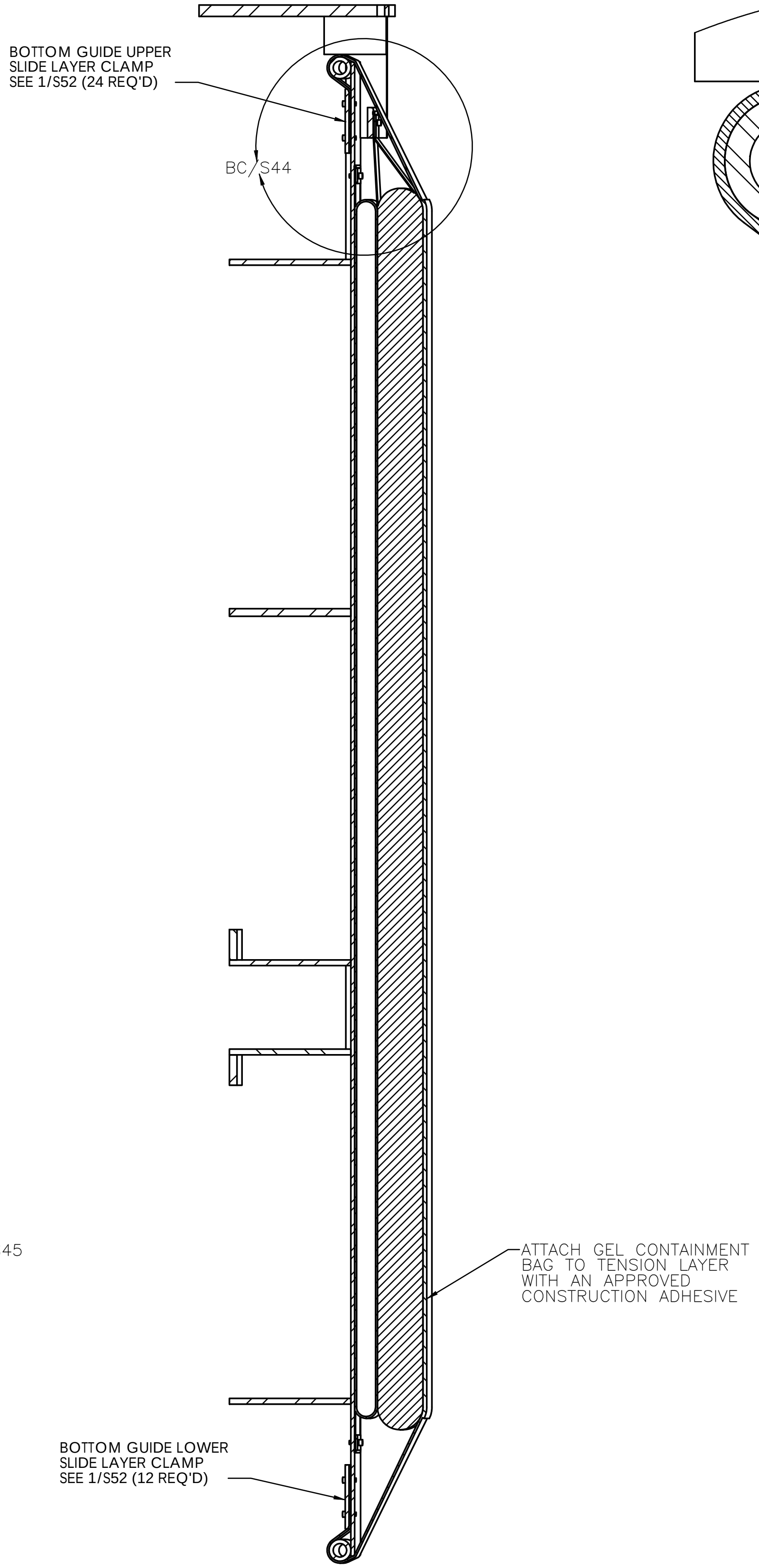


TOP VIEW

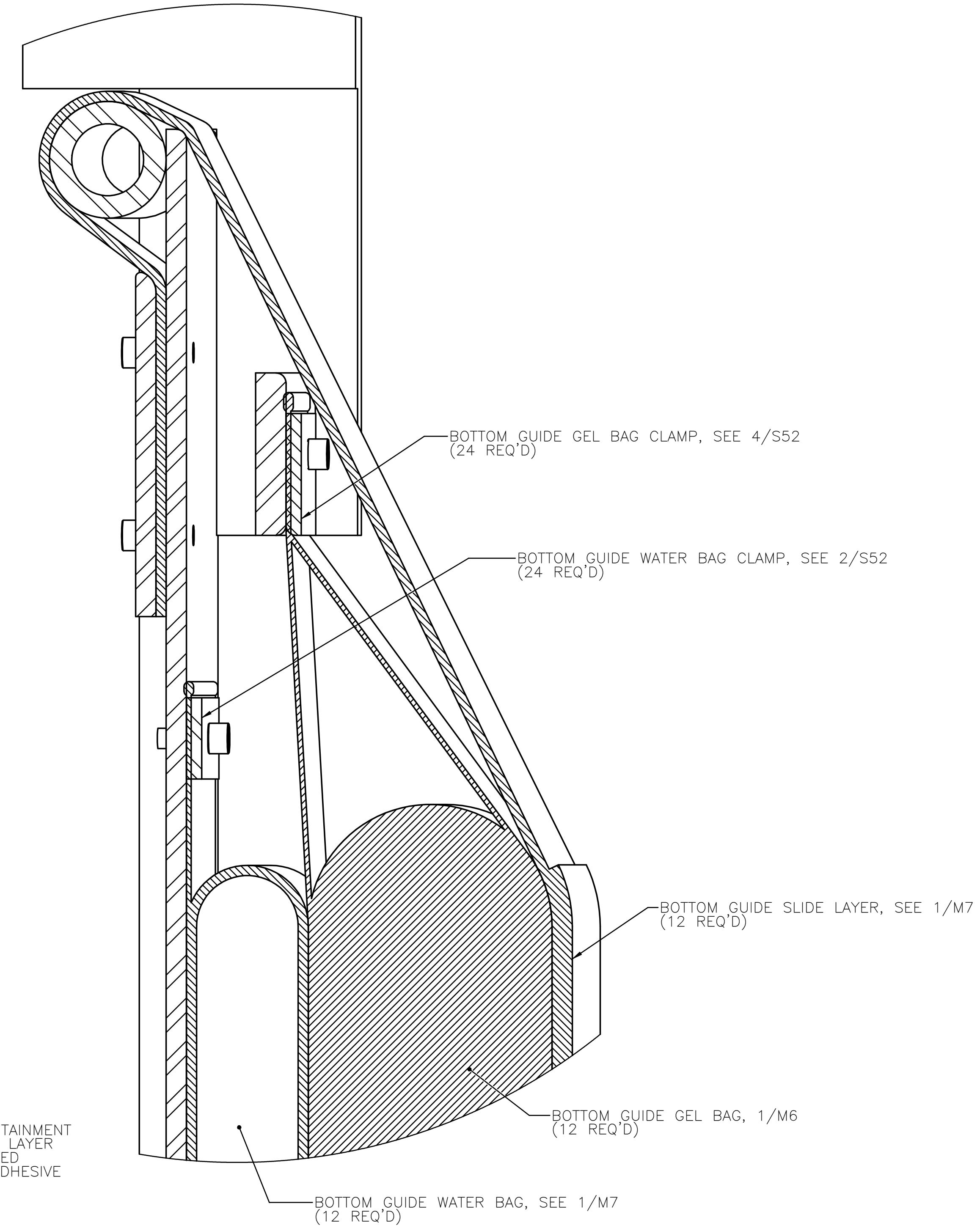


SIDE VIEW

1/S44 BOTTOM GUIDE ASSEMBLY
SCALE 1 : 30



SECTION BB/S44–BB/S44
SCALE 1 : 12



DETAIL BC/S44
SCALE 1 : 2

DRAWING RULE
(SCALE 1:1)

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

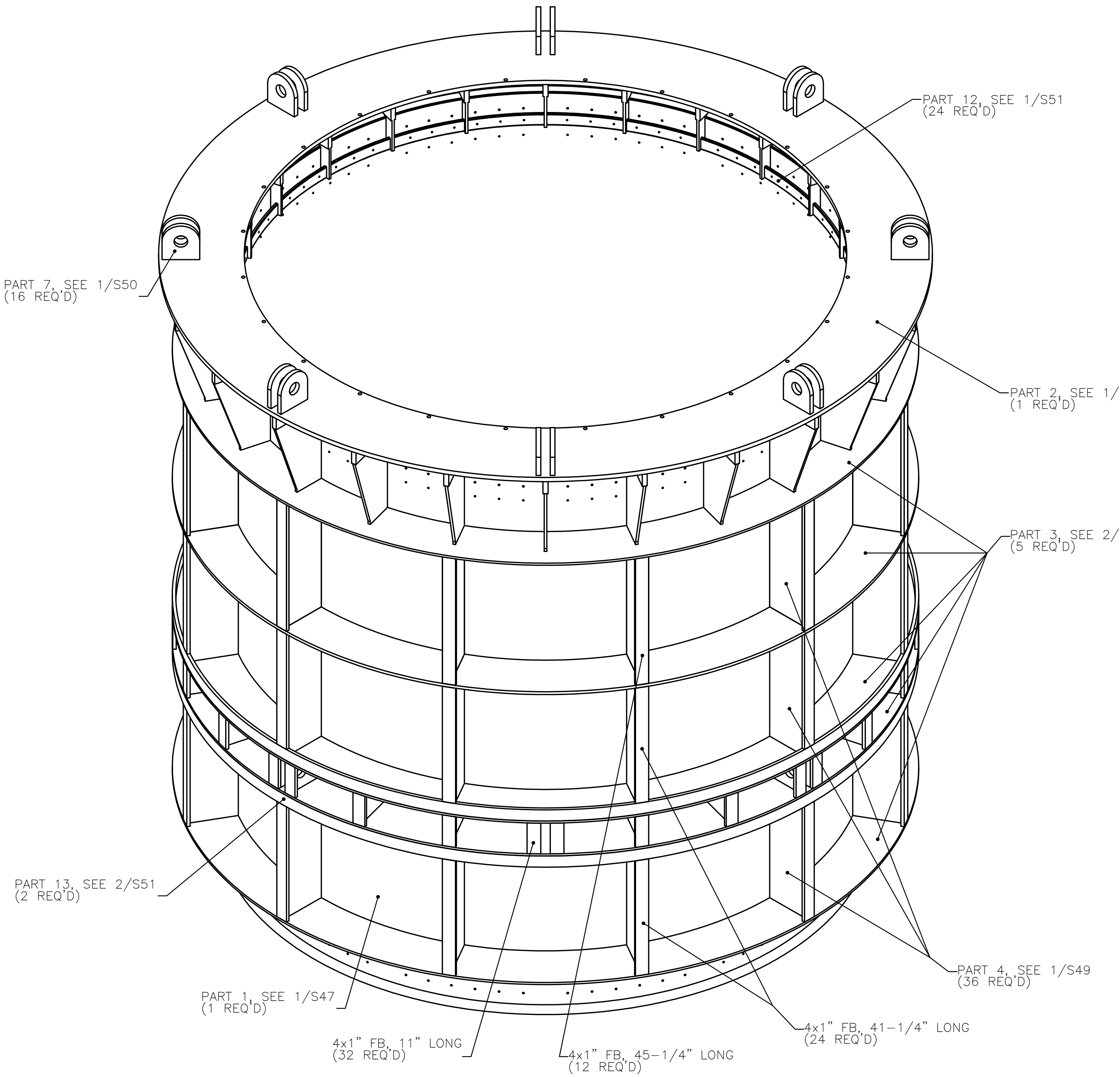
BOTTOM GUIDE ASSEMBLY

MAKAI
OCEAN ENGINEERING, INC.

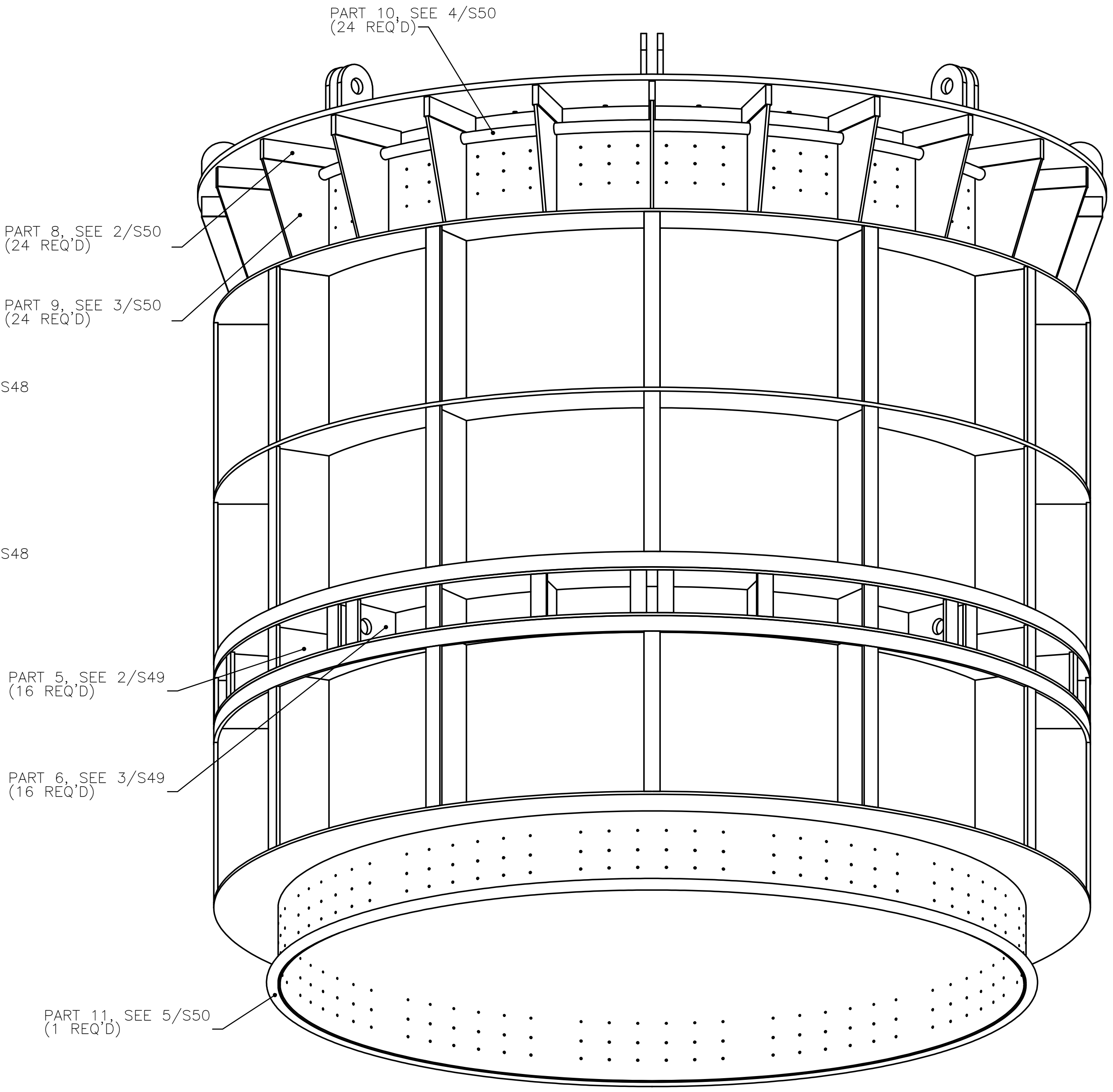
DESIGNED: A. LANDHERR	SUBMITTED:
DRAWN: A. LANDHERR	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED: MANAGER–CHIEF ENGINEER DATE	DRAWING NO. S44

JOB NO. 15706

SHEET NO. 46 OF 61



ISOMETRIC VIEW



ISOMETRIC VIEW

1/S45 BOTTOM GUIDE ASSEMBLY
SCALE 1 : 20

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

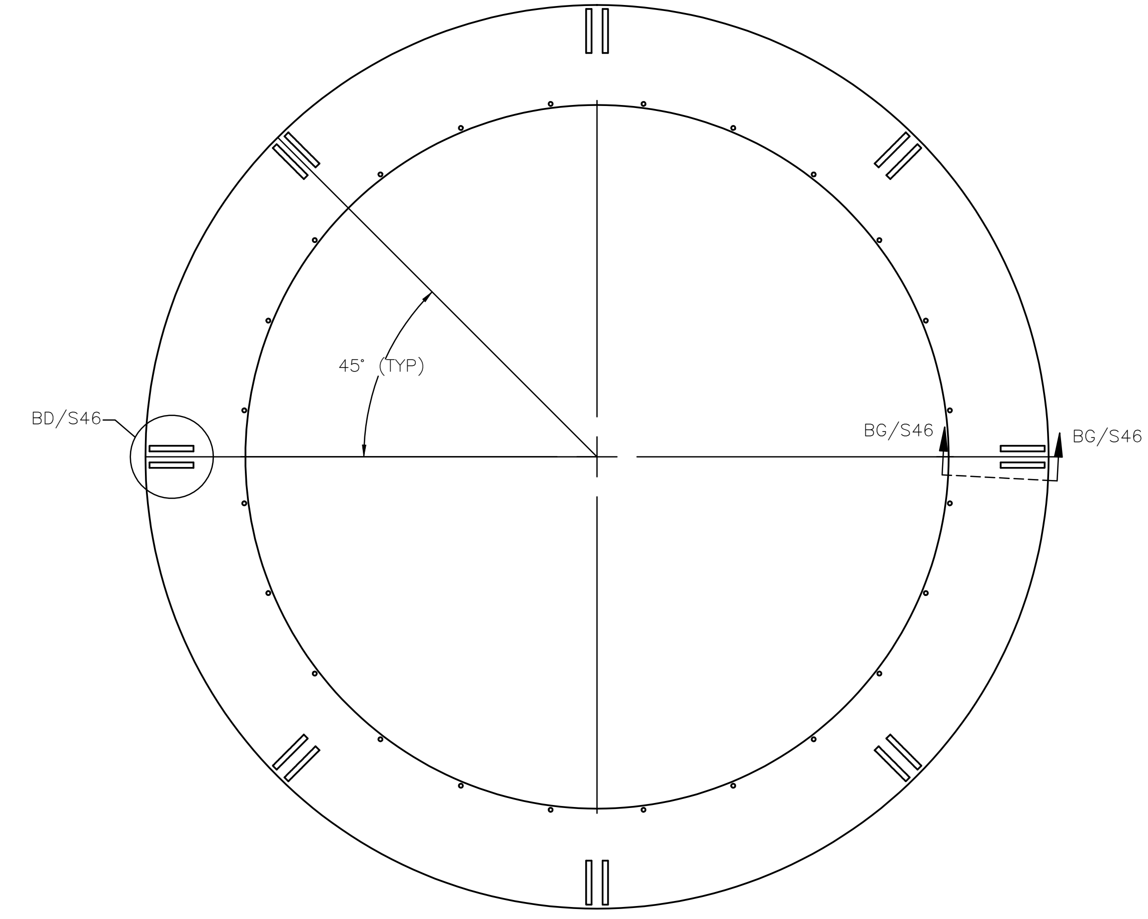
BOTTOM GUIDE FRAME ASSEMBLY

MAKAI
OCEAN ENGINEERING, INC.

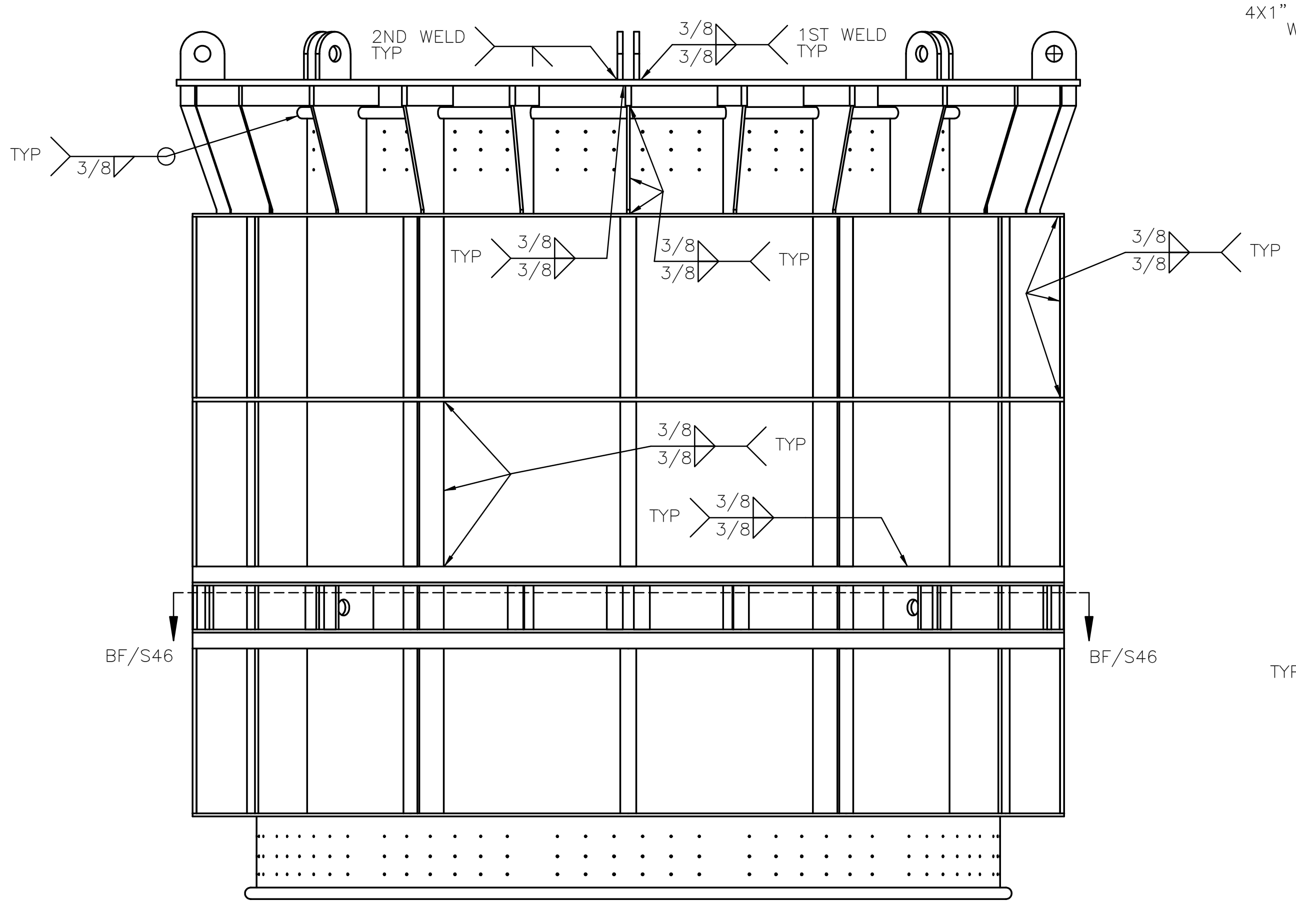
DESIGNED: N. REESE
SUBMITTED:
DRAWN: N. REESE
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
DRAWING NO. S45
MANAGER-CHIEF ENGINEER
DATE

JOB NO. 15706

SHEET NO. 47 OF 61



TOP VIEW

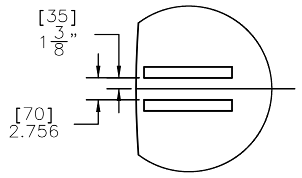


SIDE VIEW

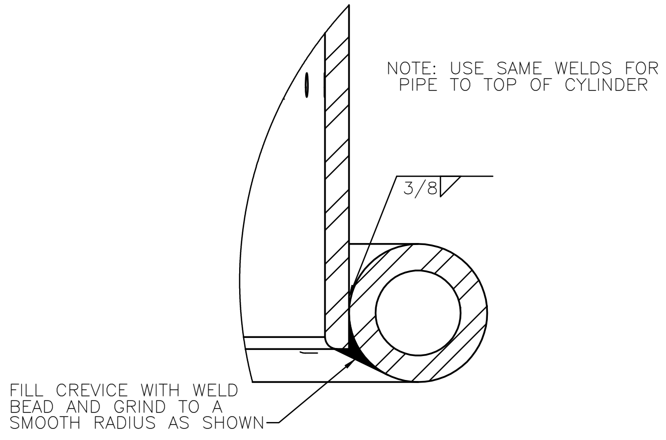
1/S46 BOTTOM GUIDE ASSEMBLY
SCALE 1 : 24

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

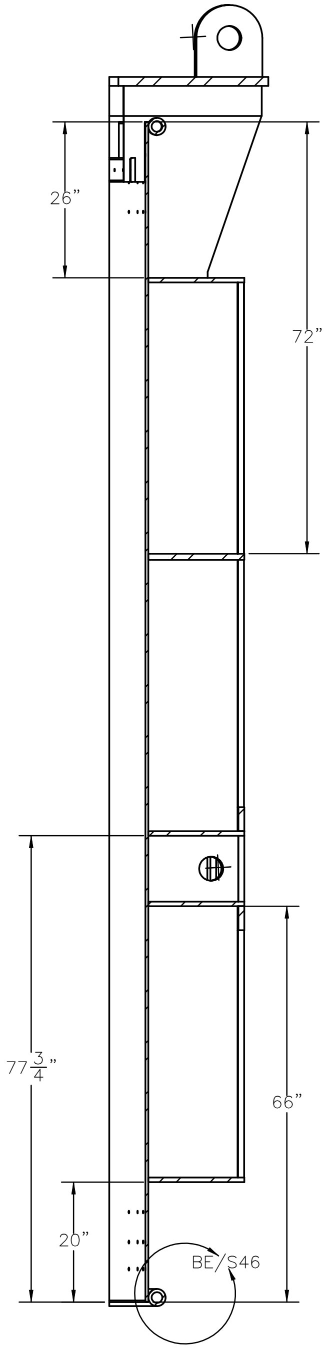
BRACKETED DIMENSIONS IN MM



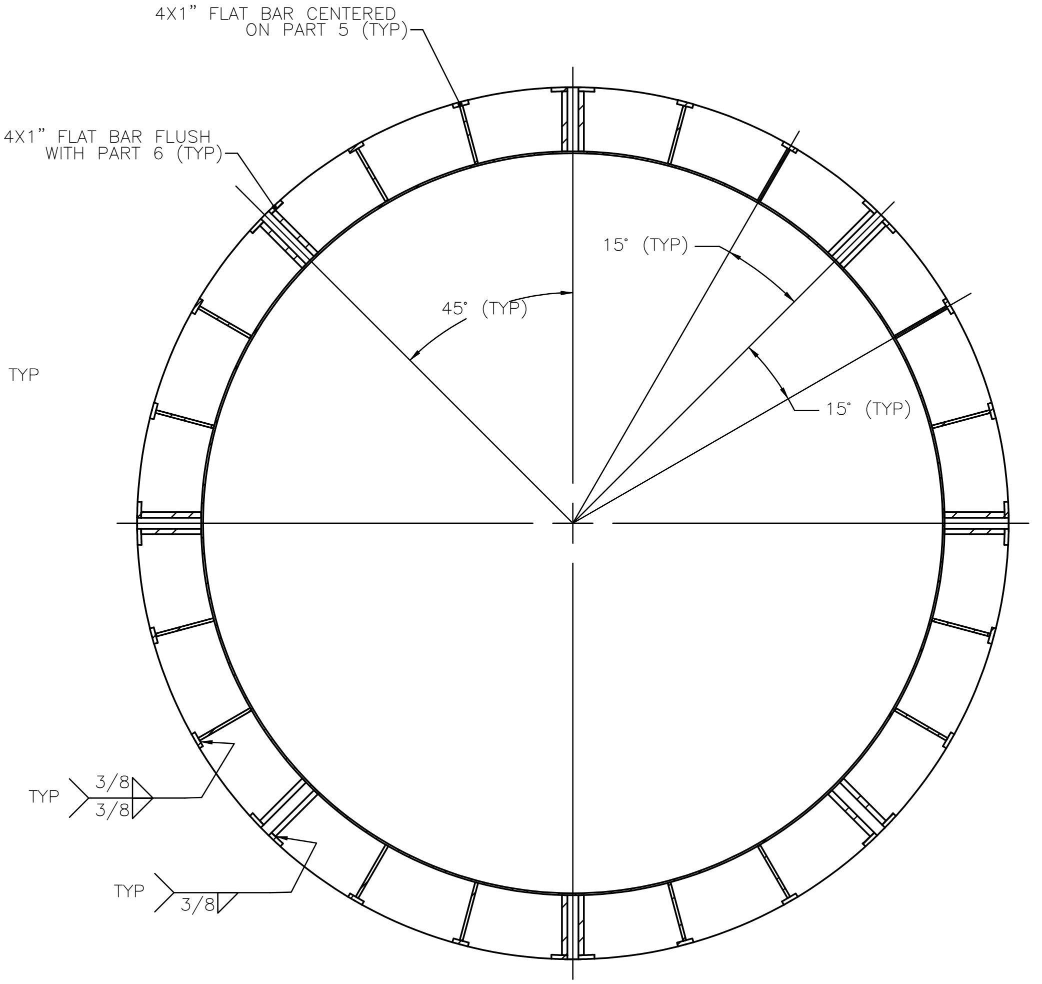
DETAIL BD/S46
SCALE 1 : 12



DETAIL BE/S46
SCALE 1 : 2



SECTION BG/S46–BG/S46
SCALE 1 : 16



SECTION BF/S46–BF/S46
SCALE 1 : 24

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

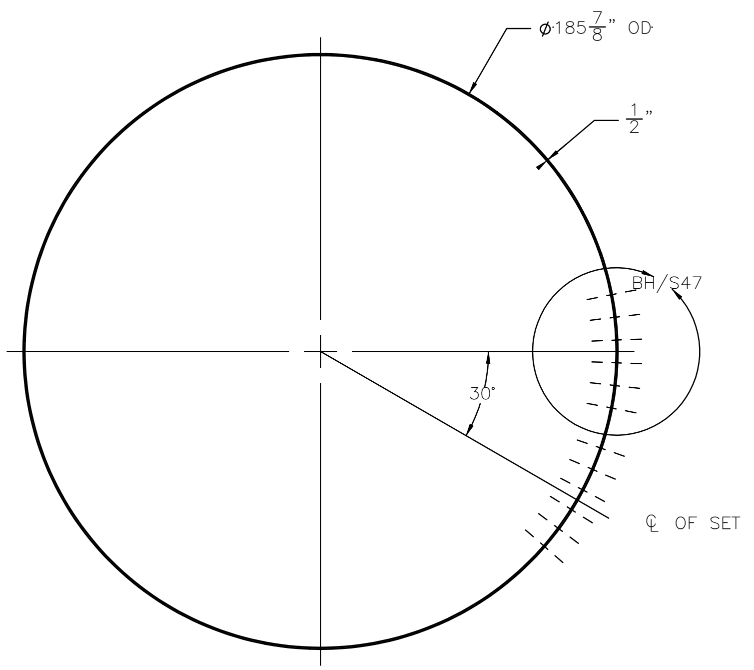
BOTTOM GUIDE FRAME
ASSEMBLY (CONT.)

MAKAI
OCEAN ENGINEERING, INC.

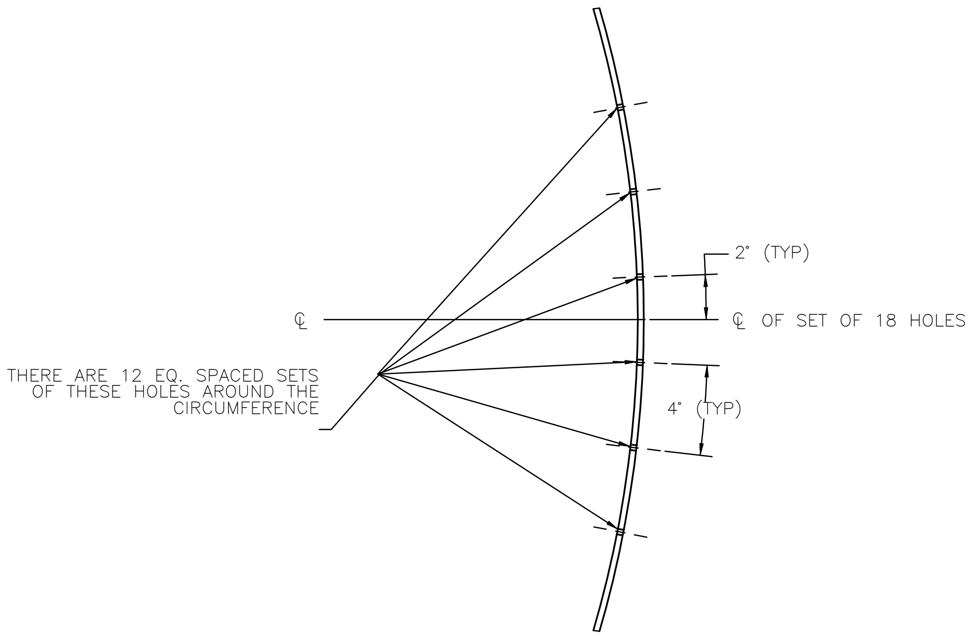
DESIGNED: N. REESE	SUBMITTED:
DRAWN: N. REESE	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED: MANAGER–CHIEF ENGINEER DATE	DRAWING NO. S46

JOB NO. 15706

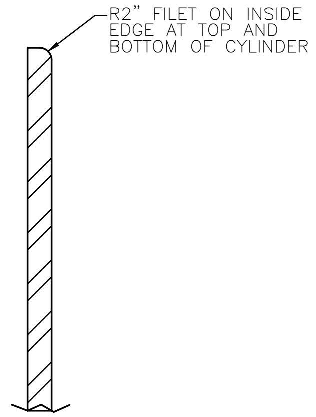
SHEET NO. 48 OF 61



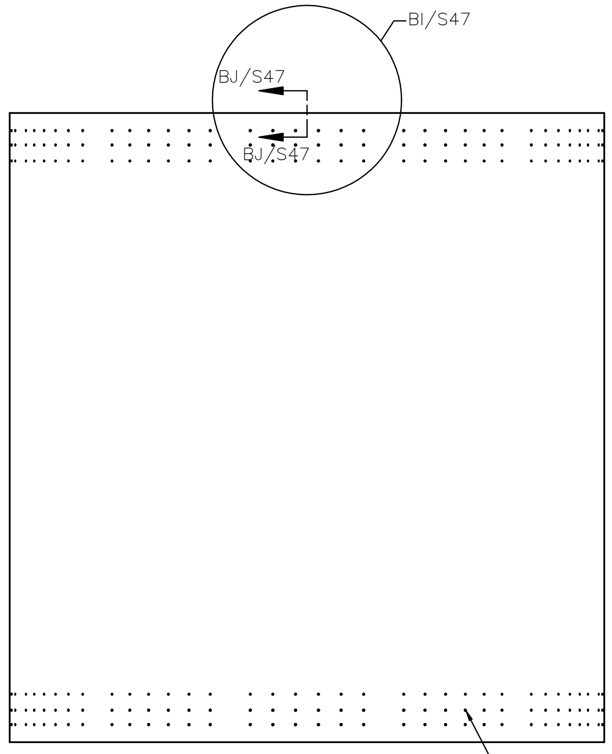
TOP VIEW



DETAIL BH/S47
SCALE 1 : 8



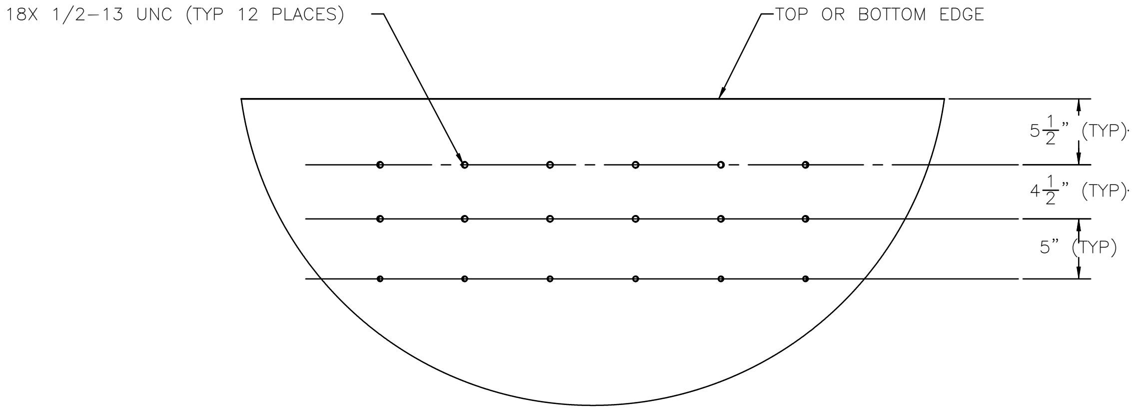
SECTION BJ/S47–BJ/S47
SCALE 1 : 2



SIDE VIEW

FOR HOLE VERTICAL LOCATIONS MIRROR IMAGE OF DETAIL EP

1/S47 BOTTOM GUIDE ASSEMBLY: PART 1
SCALE 1 : 30



DETAIL BI/S47
SCALE 1 : 8

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

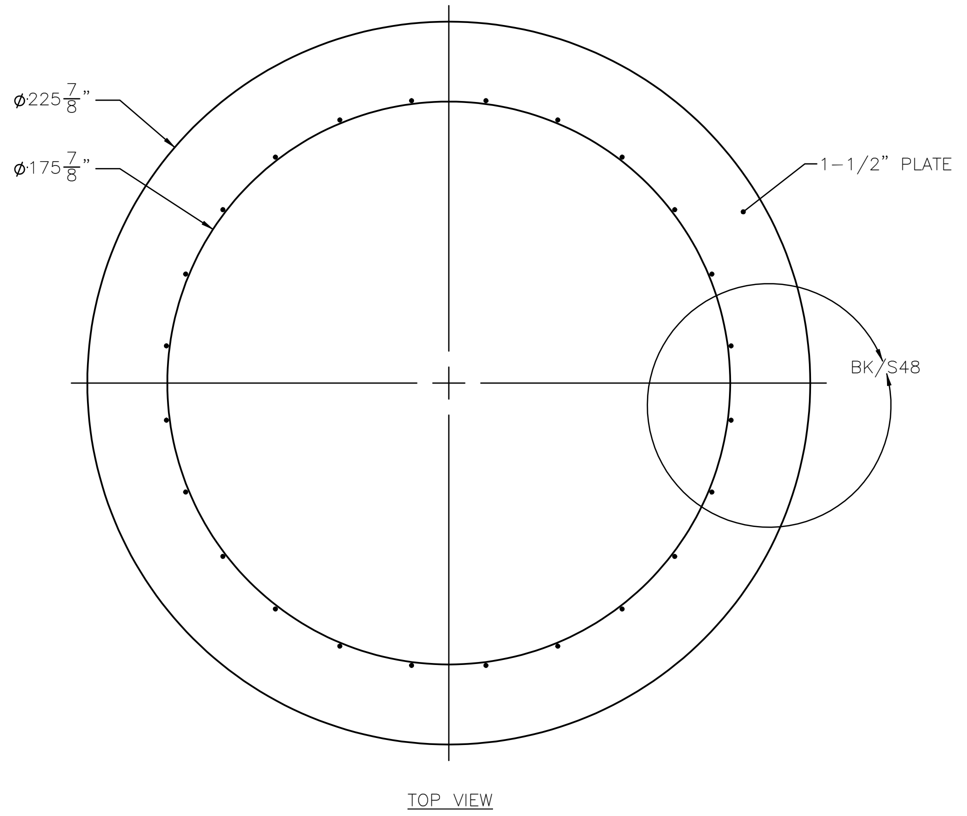
BOTTOM GUIDE FRAME
ASSEMBLY PARTS I

MAKAI
OCEAN ENGINEERING, INC.

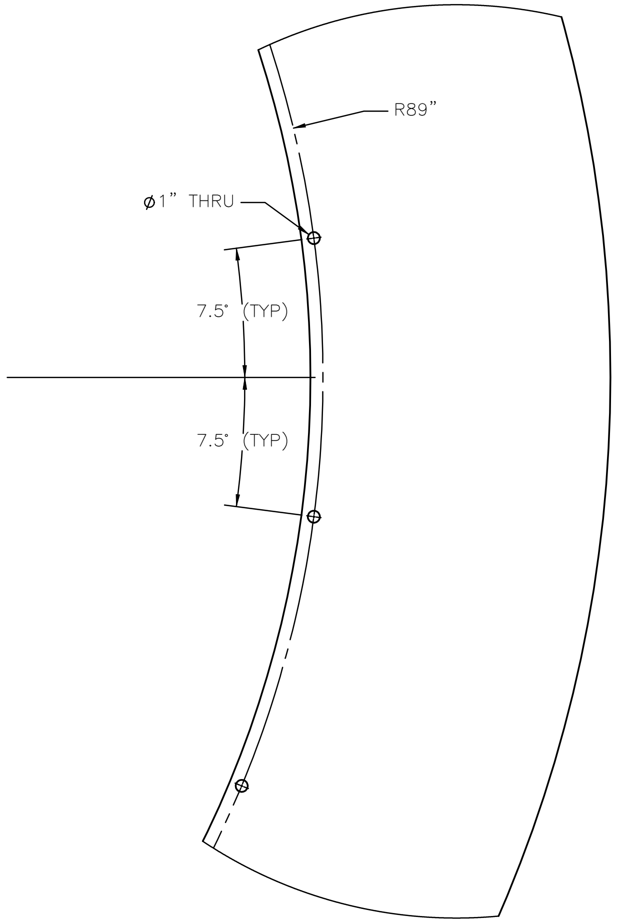
DESIGNED: N. REESE
SUBMITTED:
DRAWN: N. REESE
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
DRAWING NO. S47
MANAGER–CHIEF ENGINEER
DATE

JOB NO. 15706

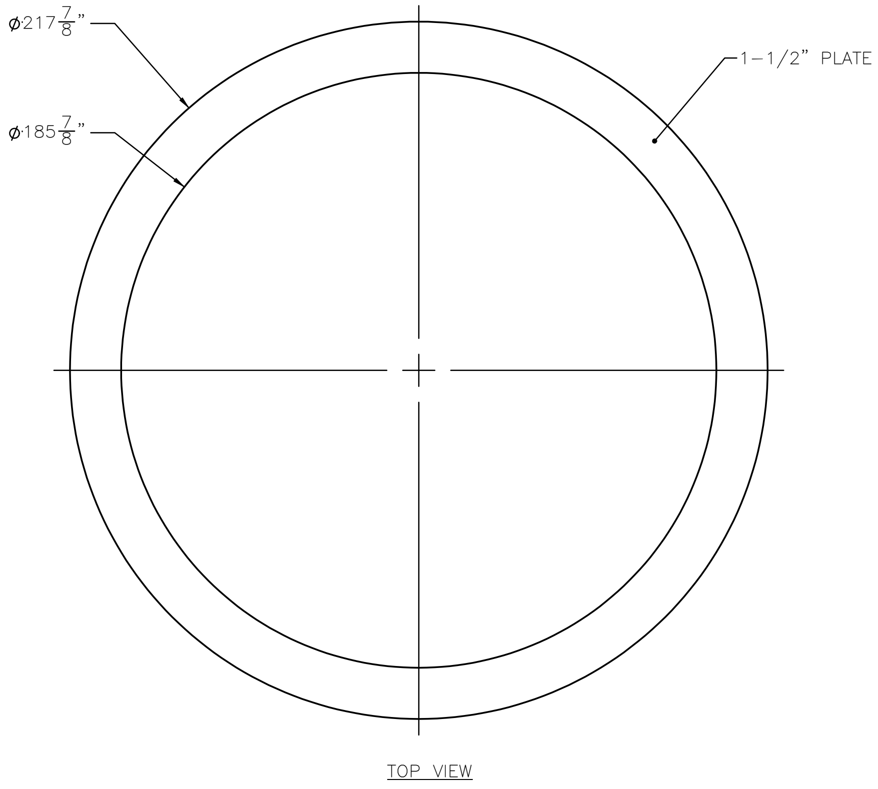
SHEET NO. 49 OF 61



1/S48 BOTTOM GUIDE ASSEMBLY: PART 2
SCALE 1 : 30



DETAIL BK/S48
SCALE 1 : 8



2/S48 BOTTOM GUIDE ASSEMBLY: PART 3
SCALE 1 : 30

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

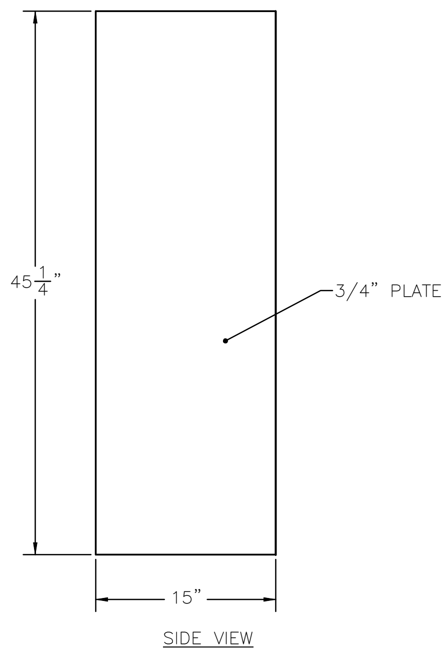
NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

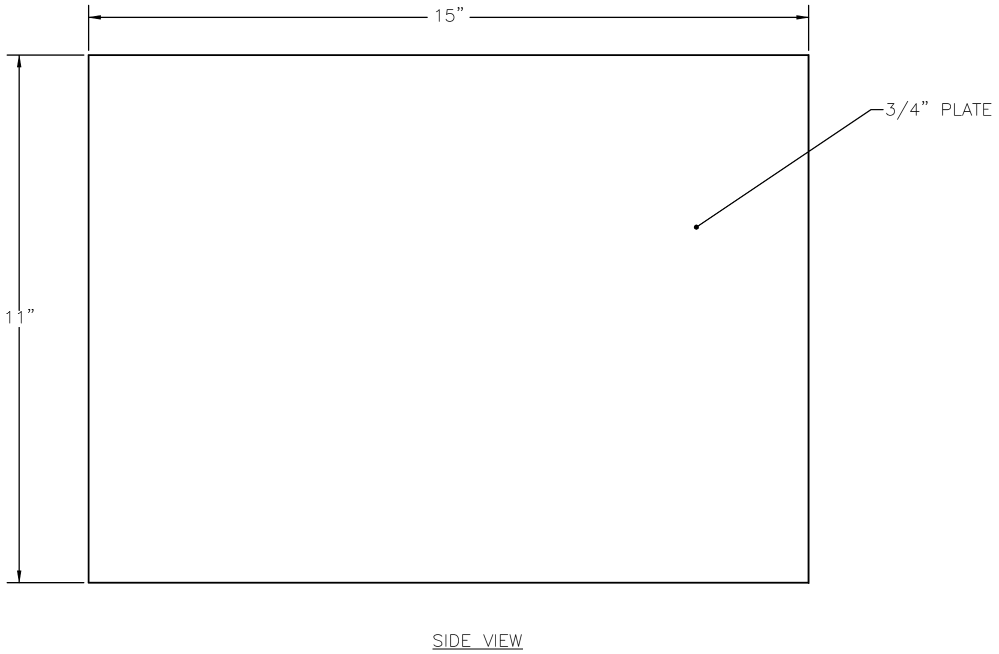
BOTTOM GUIDE FRAME
ASSEMBLY PARTS II

MAKAI
OCEAN ENGINEERING, INC.

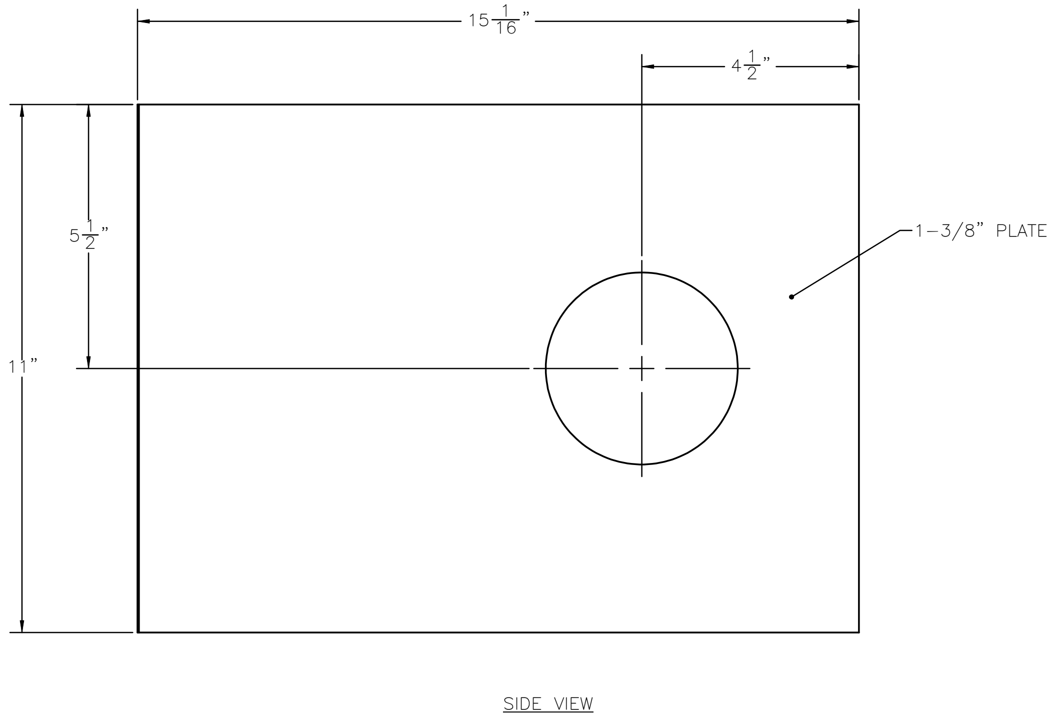
DESIGNED: N. REESE
SUBMITTED:
DRAWN: N. REESE
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S48
JOB NO. 15706
SHEET NO. 50 OF 61



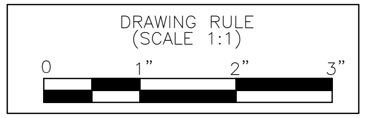
1/S49 BOTTOM GUIDE ASSEMBLY: PART 4
SCALE 1 : 8



2/S49 BOTTOM GUIDE ASSEMBLY: PART 5
SCALE 1 : 2



3/S49 BOTTOM GUIDE ASSEMBLY: PART 6
SCALE 1 : 2



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

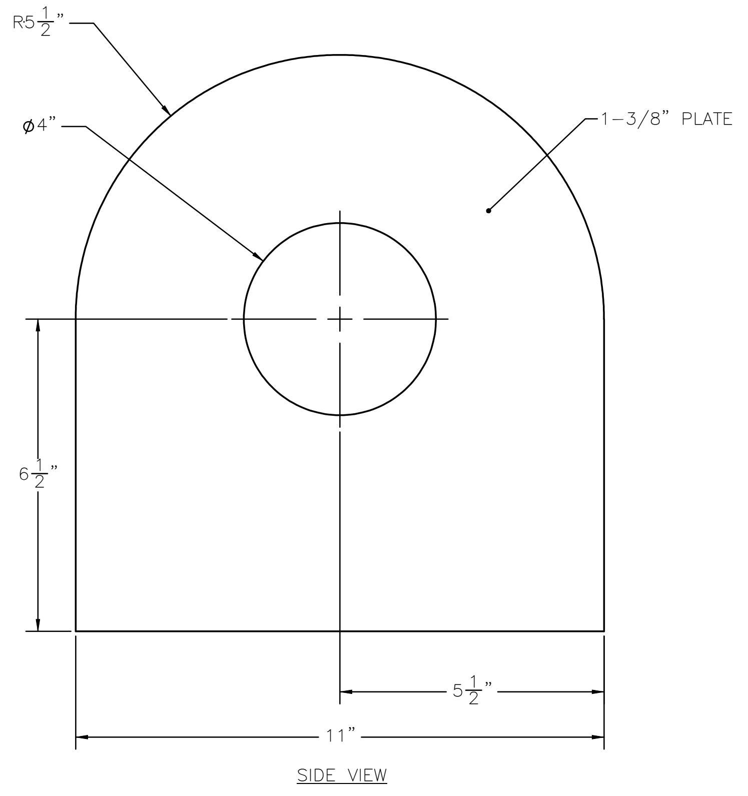
LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

BOTTOM GUIDE FRAME
ASSEMBLY PARTS III

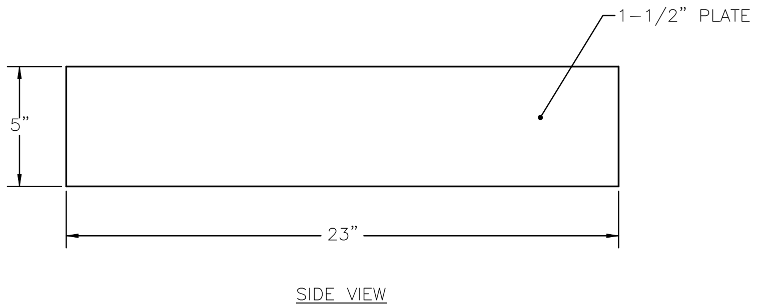
MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: N. REESE
SUBMITTED:
DRAWN: N. REESE
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
DRAWING NO. S49
MANAGER-CHIEF ENGINEER
DATE

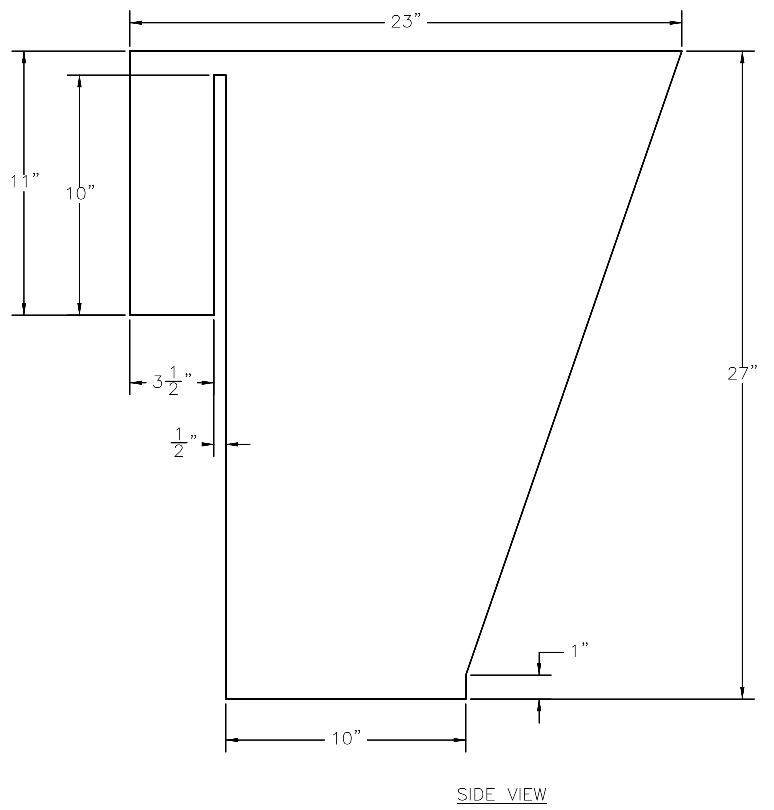
JOB NO. 15706
SHEET NO. 51 OF 61



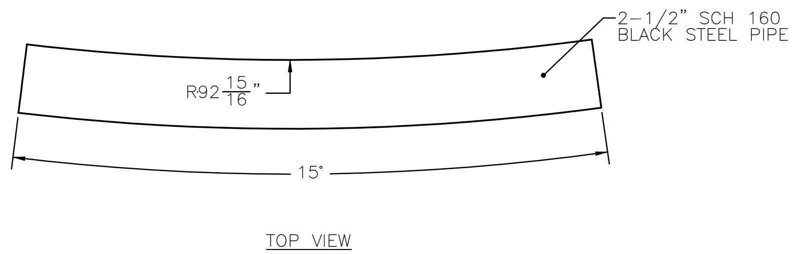
1/S50 BOTTOM GUIDE ASSEMBLY: PART 7
SCALE 1 : 2



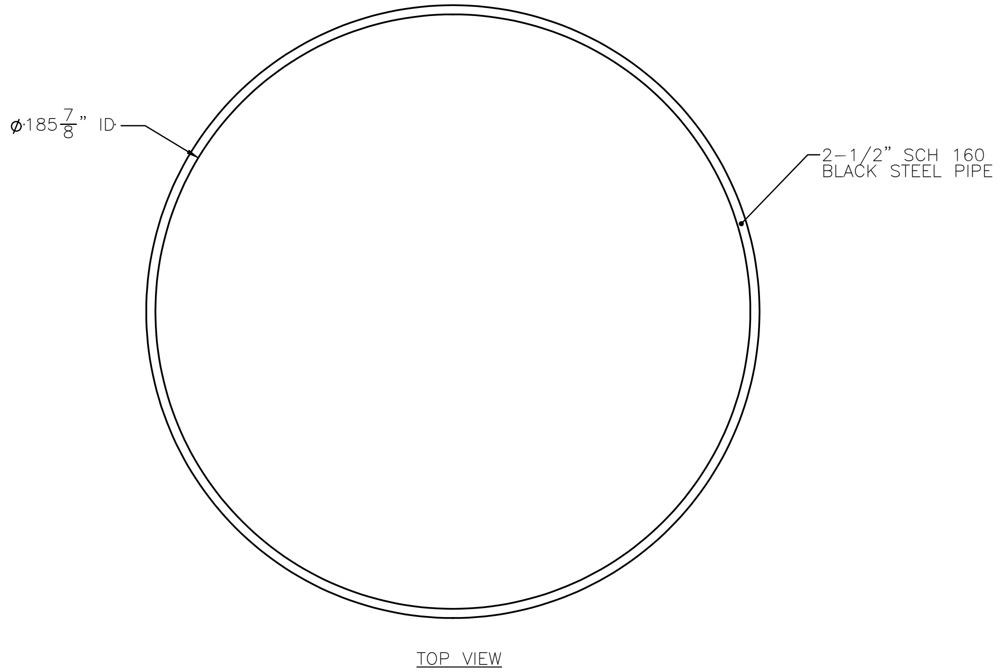
2/S50 BOTTOM GUIDE ASSEMBLY: PART 8
SCALE 1 : 4



3/S50 BOTTOM GUIDE ASSEMBLY: PART 9
SCALE 1 : 4



4/S50 BOTTOM GUIDE ASSEMBLY: PART 10
SCALE 1 : 4



5/S50 BOTTOM GUIDE ASSEMBLY: PART 11
SCALE 1 : 30

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

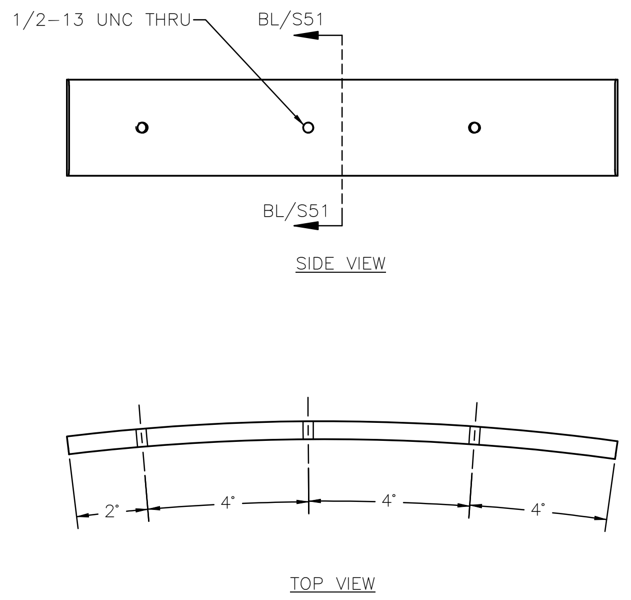
BOTTOM GUIDE FRAME
ASSEMBLY PARTS IV

MAKAI
OCEAN ENGINEERING, INC.

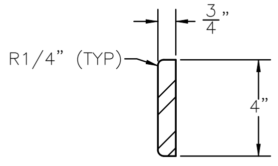
DESIGNED: N. REESE
SUBMITTED:
DRAWN: N. REESE
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
DRAWING NO. S50
MANAGER-CHIEF ENGINEER
DATE

JOB NO. 15706

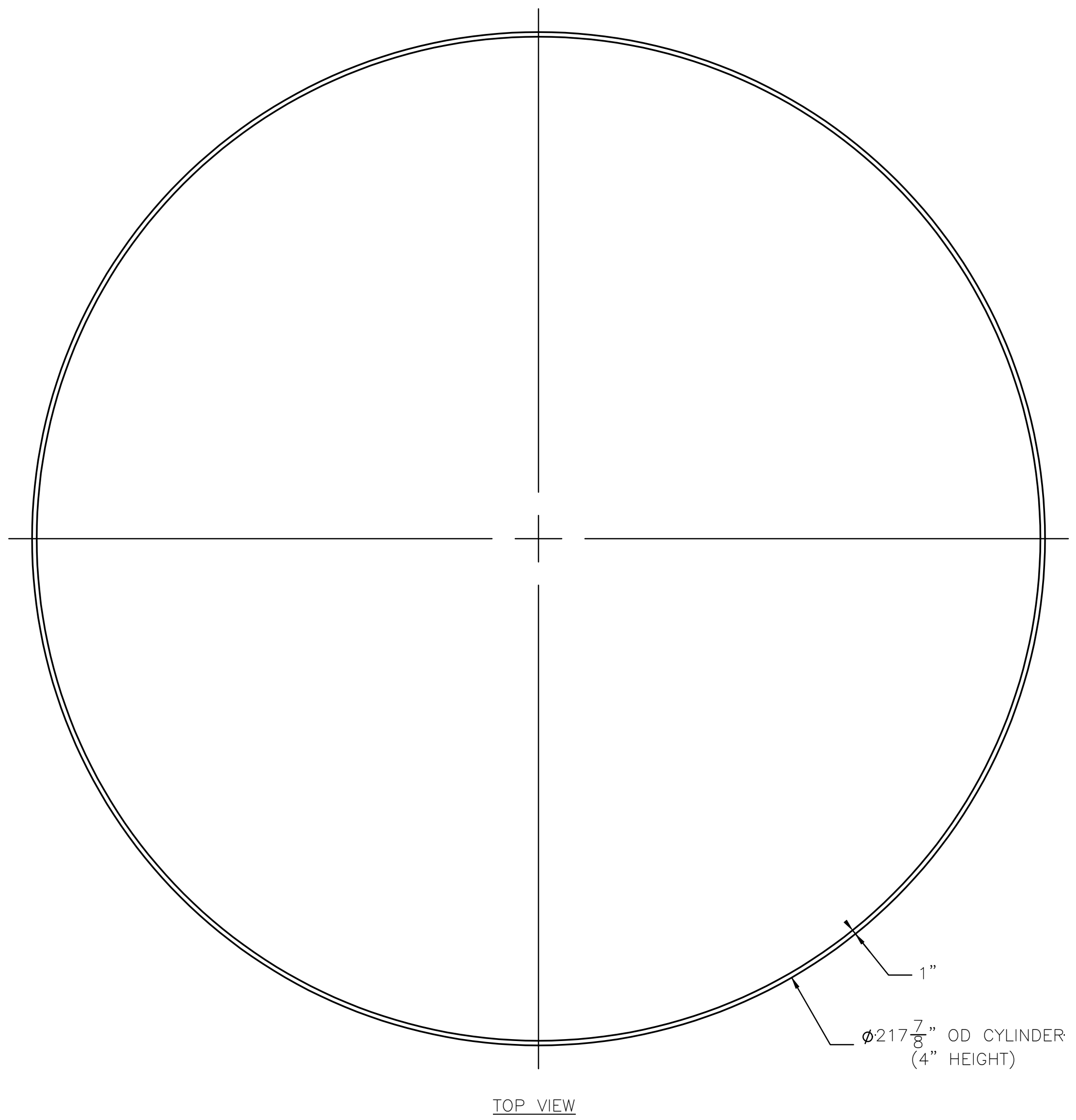
SHEET NO. 52 OF 61



1/S51 BOTTOM GUIDE ASSEMBLY: PART 12
SCALE 1 : 4



SECTION BL/S51-BL/S51
SCALE 1 : 4



2/S51 BOTTOM GUIDE ASSEMBLY: PART 13
SCALE 1 : 20

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

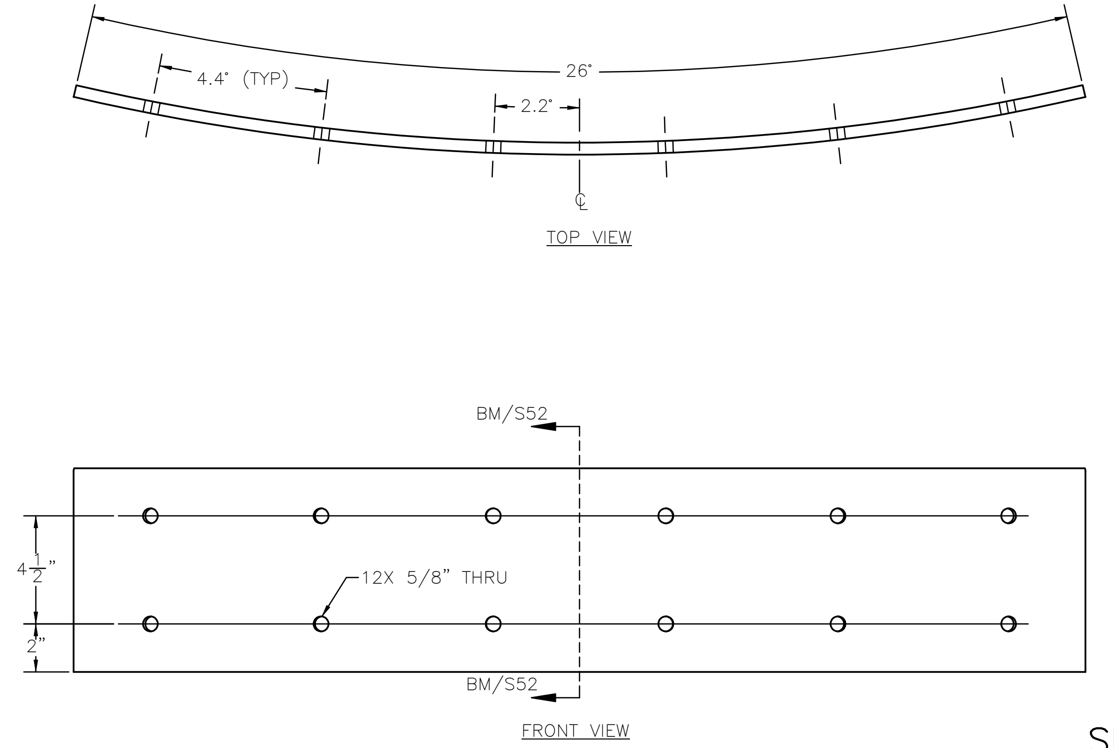
NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

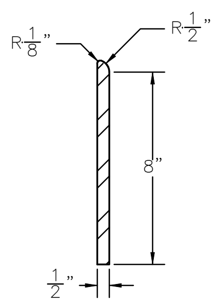
LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

BOTTOM GUIDE FRAME
ASSEMBLY PARTS V

MAKAI
OCEAN ENGINEERING, INC.

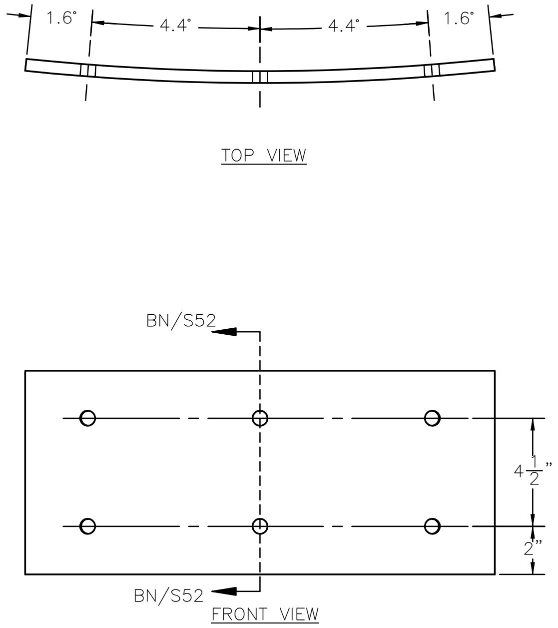
DESIGNED: N. REESE
SUBMITTED:
DRAWN: N. REESE
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER-CHIEF ENGINEER
DATE
DRAWING NO. S51
JOB NO. 15706
SHEET NO. 53 OF 61

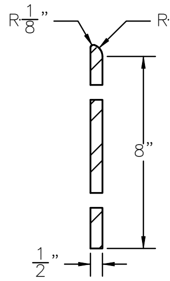




SECTION BM/S52-BM/S52
SCALE 1 : 4

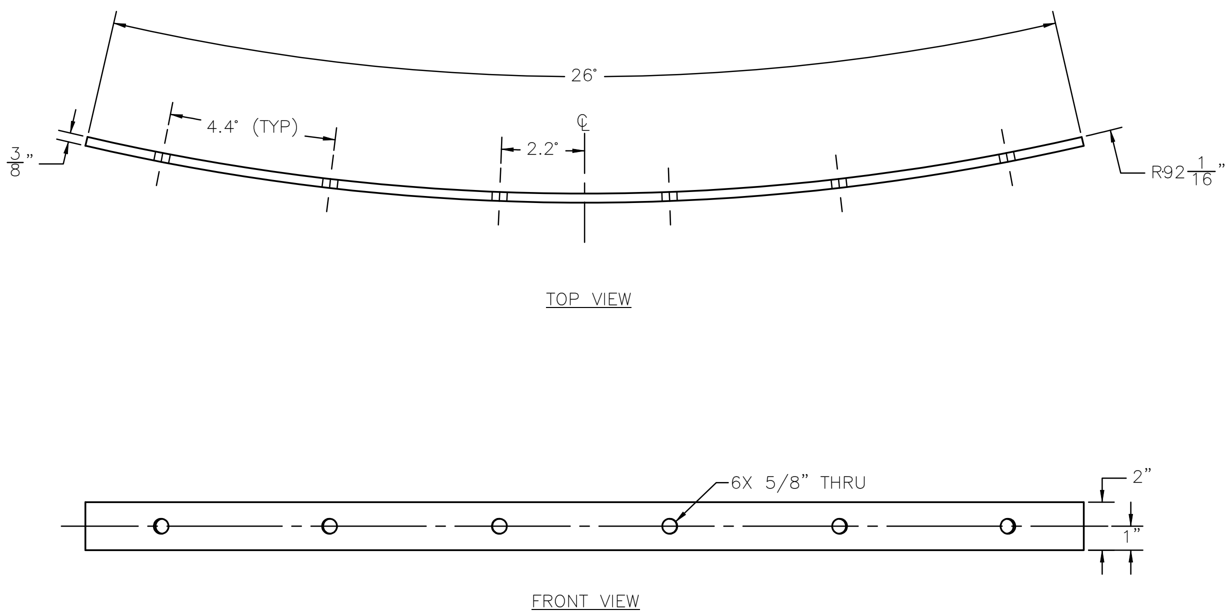
1/S52 BOTTOM GUIDE LOWER SLIDE LAYER CLAMP
SCALE 1 : 4



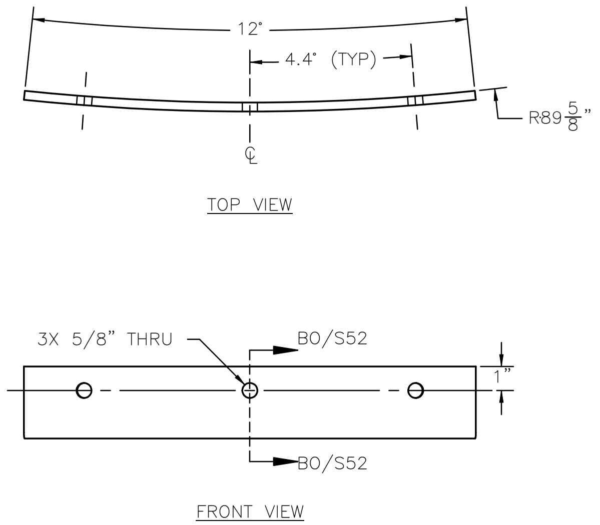


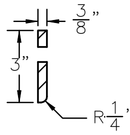
SECTION BN/S52-BN/S52
SCALE 1 : 4

2/S52 BOTTOM GUIDE UPPER SLIDE LAYER CLAMP
SCALE 1 : 4



3/S52 BOTTOM GUIDE WATER BAG CLAMP
SCALE 1 : 4





SECTION BO/S52-BO/S52
SCALE 1 : 4

4/S52 BOTTOM GUIDE GEL BAG CLAMP
SCALE 1 : 4

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

BOTTOM GUIDE SLIDE LAYER,
GEL BAG, AND WATERBED CLAMPS

MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR	SUBMITTED:
DRAWN: A. LANDHERR	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED:	DRAWING NO. S52

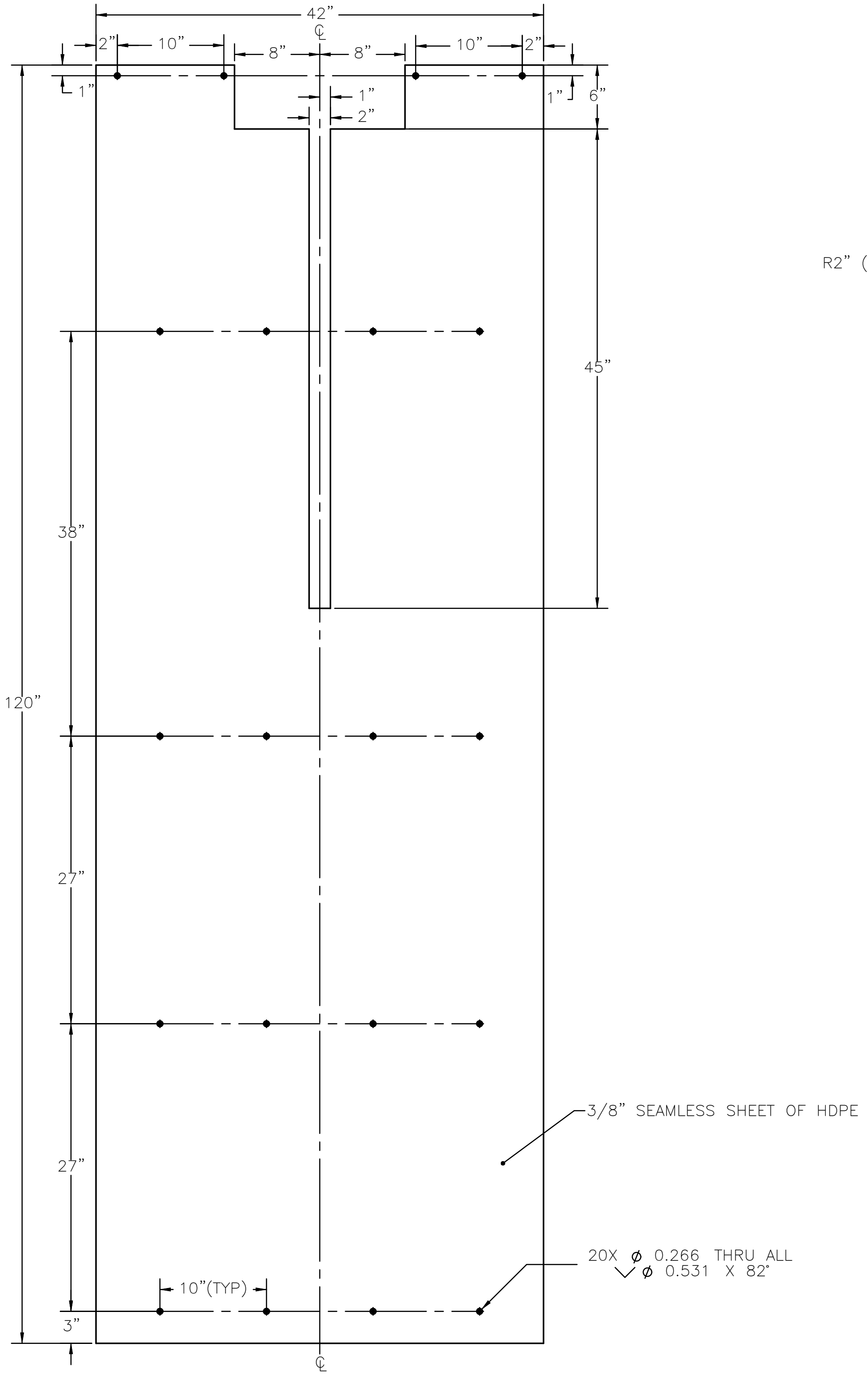
MANAGER-CHIEF ENGINEER DATE

JOB NO. 15706

SHEET NO. 54 OF 61

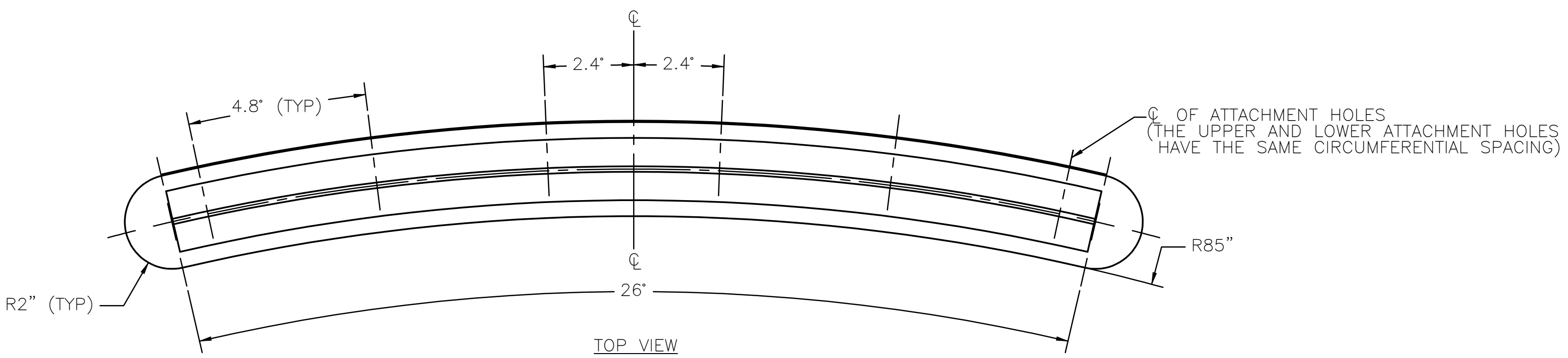
NOTES:

1. BEAD TO PREVENT PULLOUT FROM CLAMP

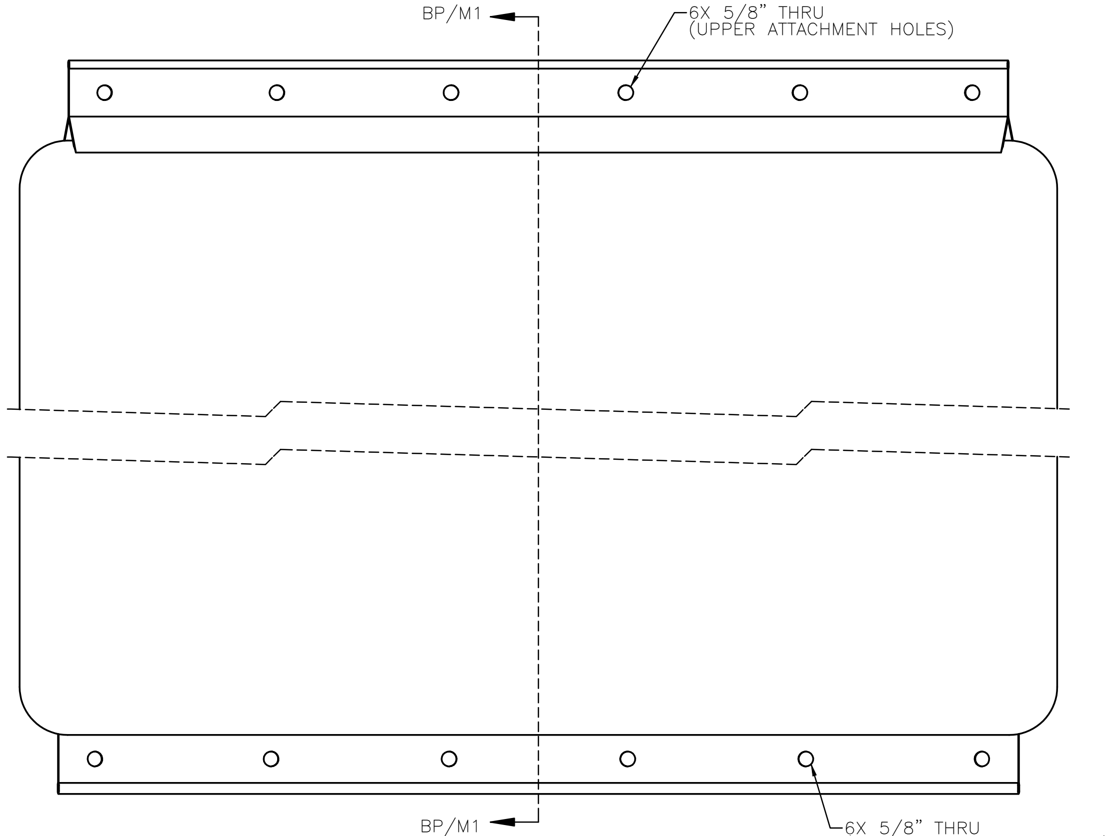


TOP VIEW

1/M1 SLIDE SHEET
SCALE 1 : 8

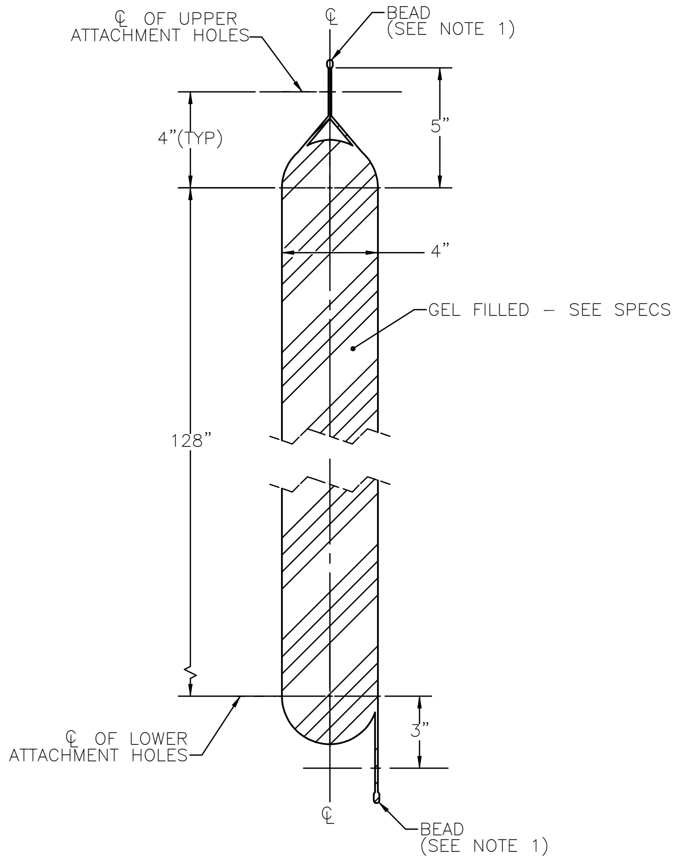


TOP VIEW



FRONT VIEW

2/M1 GRIPPER GEL BAG
SCALE 1 : 4



SECTION BP/M1–BP/M1
SCALE 1 : 4

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110-4121

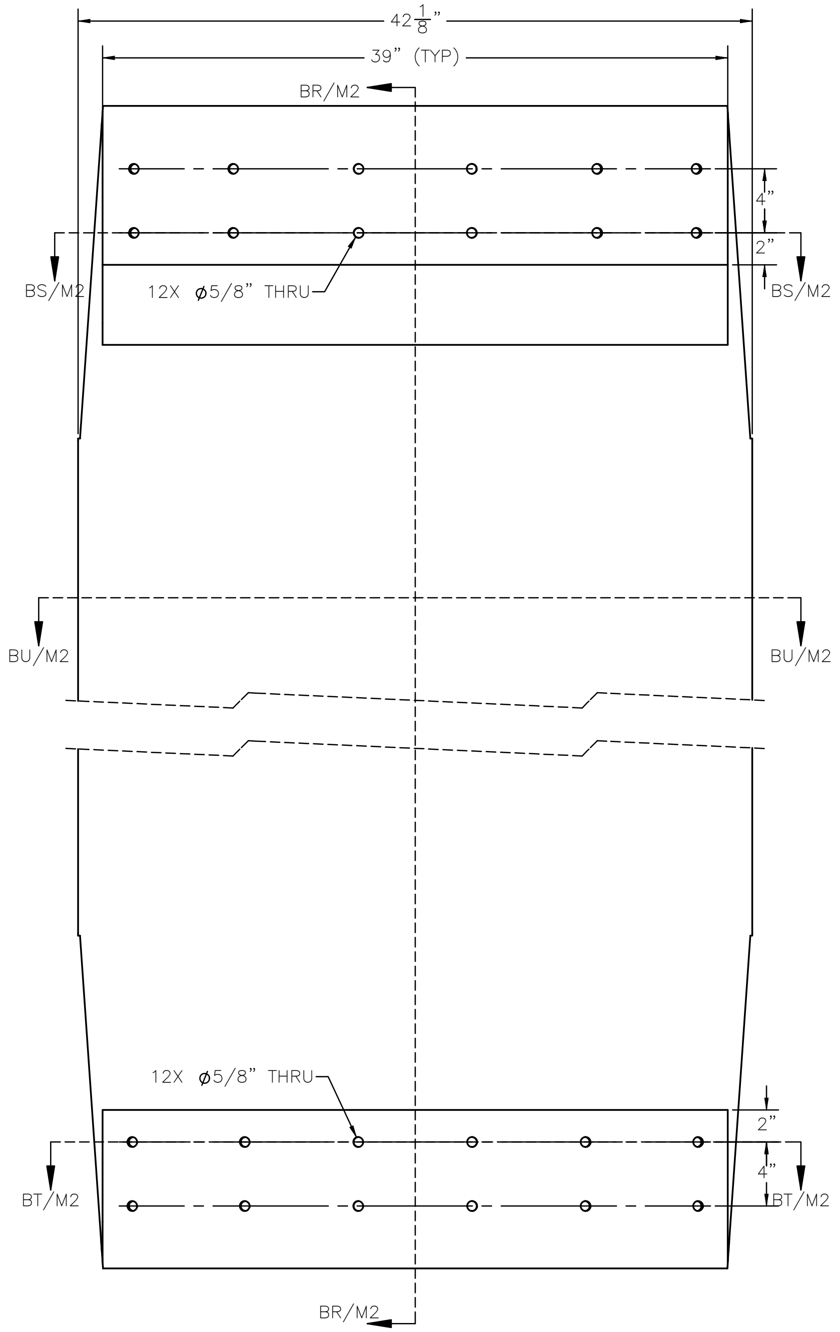
SLIDE SHEET AND GRIPPER GEL BAG

MAKAI
OCEAN ENGINEERING, INC.

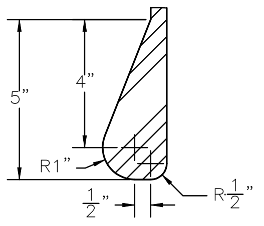
DESIGNED: A. LANDHERR SUBMITTED:
DRAWN: A. LANDHERR DATE: 9/18/2010
CHECKED: D. JENSEN SCALE: SHOWN
APPROVED: DRAWING NO.
M1
MANAGER–CHIEF ENGINEER DATE

JOB NO. 15706

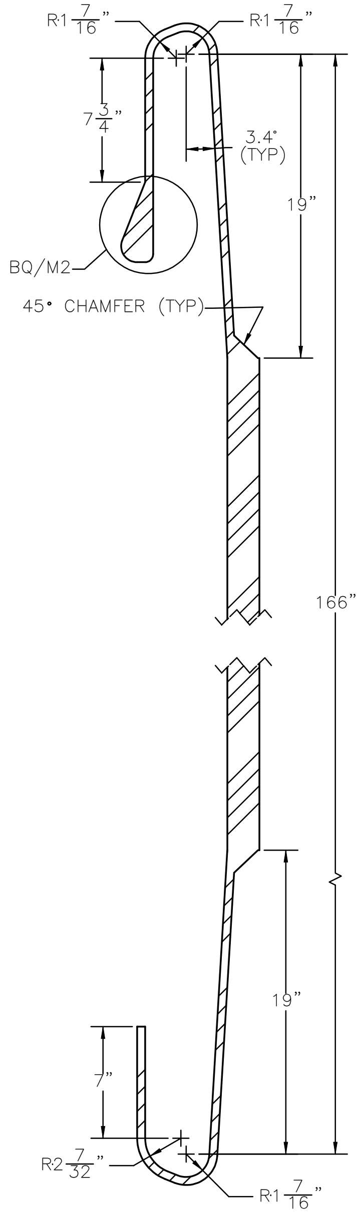
SHEET NO. 55 OF 61



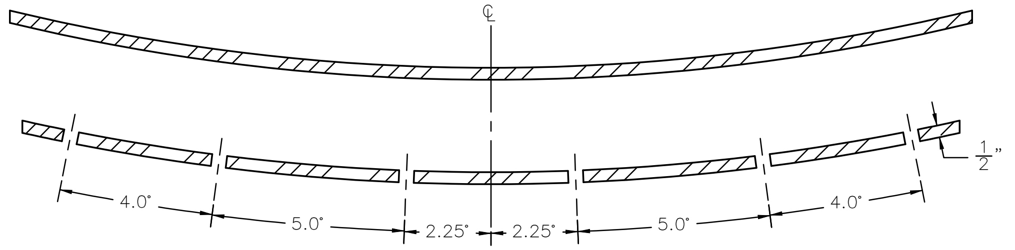
1/M2 FRICTION LAYER
SCALE 1 : 6



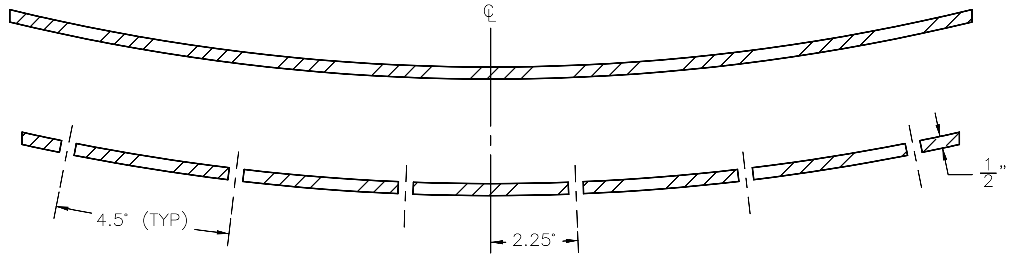
DETAIL BQ/M2
SCALE 1 : 3



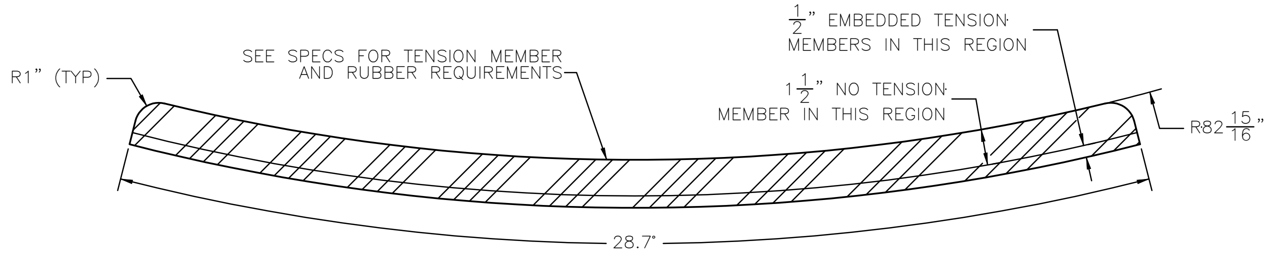
SECTION BR/M2–BR/M2
SCALE 1 : 6



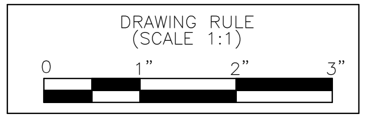
SECTION BS/M2–BS/M2
SCALE 1 : 4



SECTION BT/M2–BT/M2
SCALE 1 : 4



SECTION BU/M2–BU/M2
SCALE 1 : 4



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN
9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

FRICTION LAYER

MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR	SUBMITTED:
DRAWN: A. LANDHERR	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED:	DRAWING NO. M2

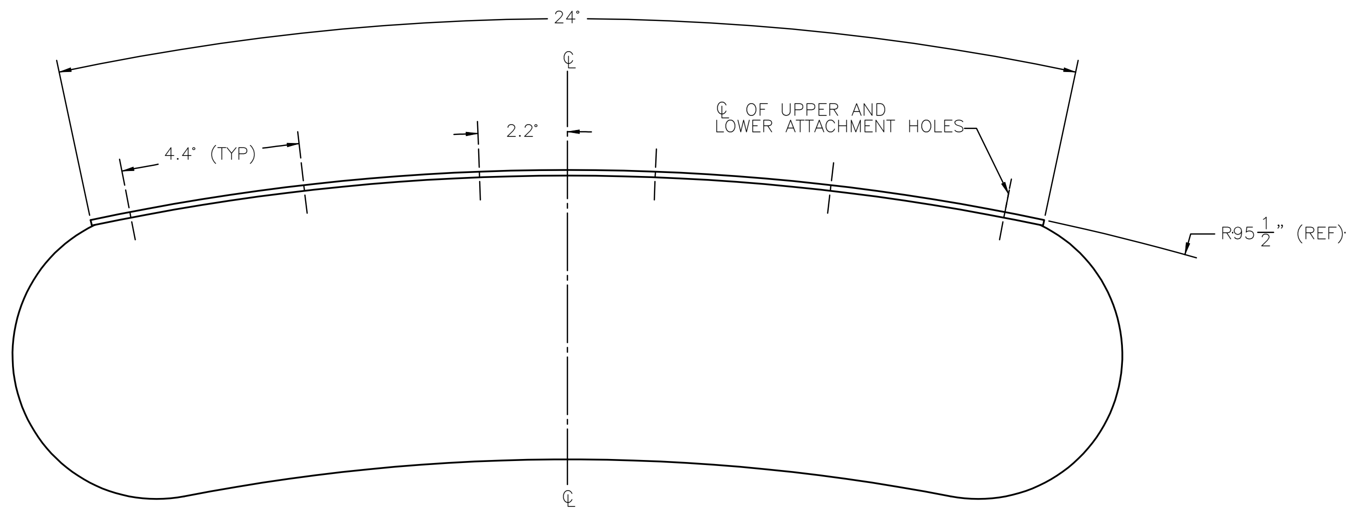
MANAGER–CHIEF ENGINEER
DATE

JOB NO. 15706

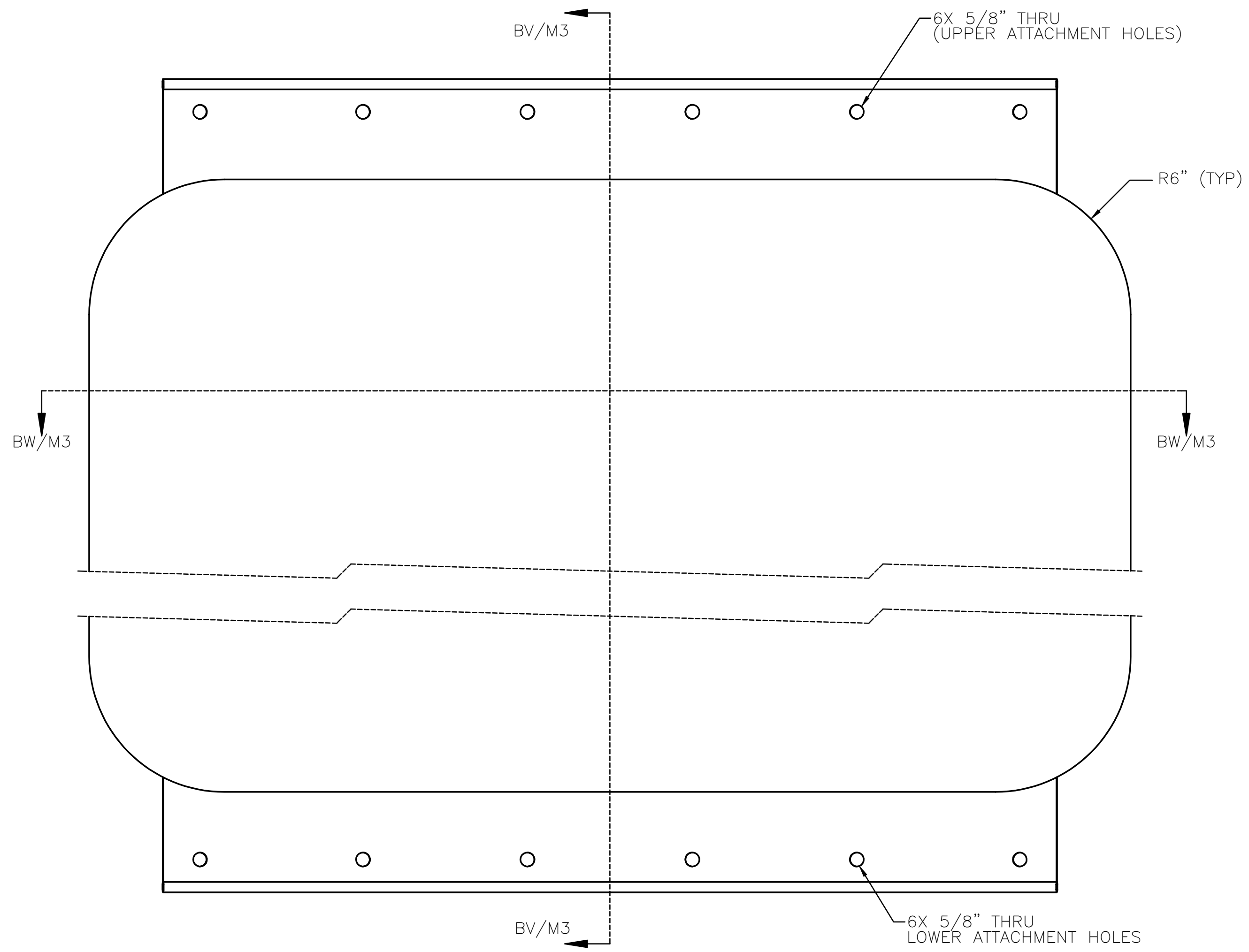
SHEET NO. 56 OF 61

NOTES:

1. BEAD TO PREVENT PULLOUT FROM CLAMP

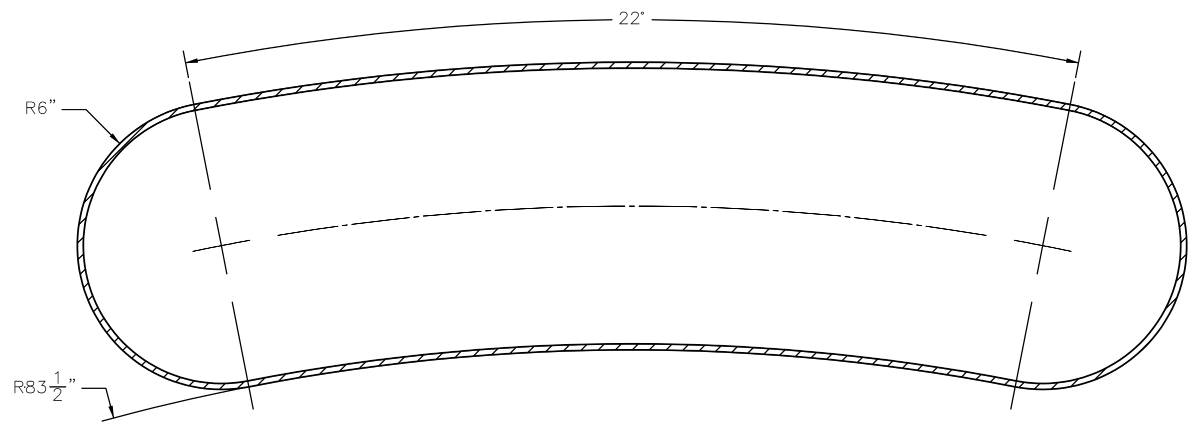


TOP VIEW

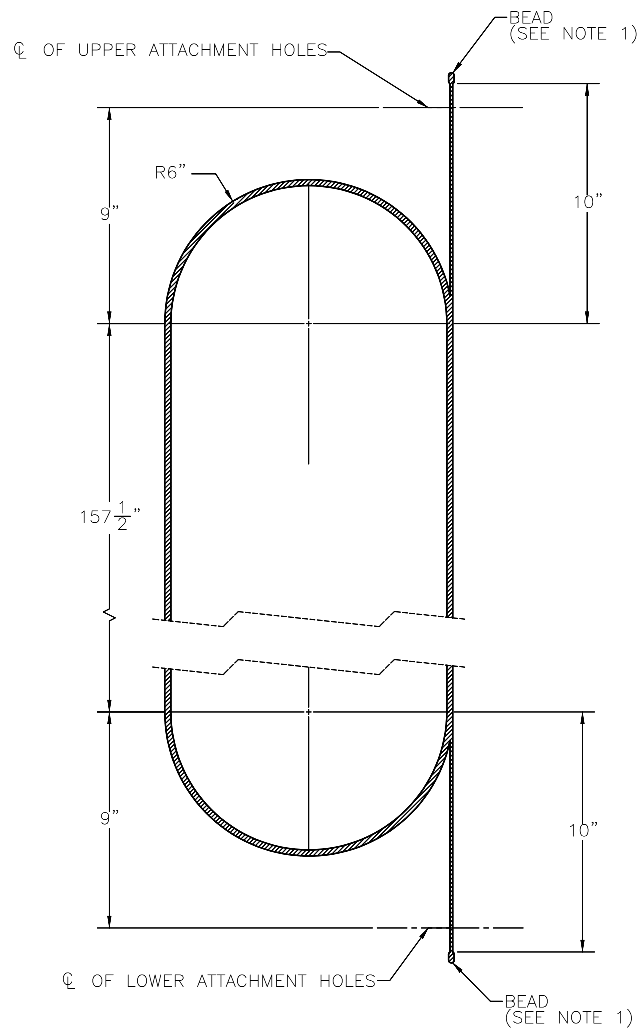


FRONT VIEW

1/M3 TOP GUIDE WATER BAG
SCALE 1 : 4



SECTION BW/M3–BW/M3
SCALE 1 : 4



SECTION BV/M3–BV/M3
SCALE 1 : 4

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD MANASSAS, VA 20110-4121

TOP GUIDE WATER BAG

MAKAI
OCEAN ENGINEERING, INC.

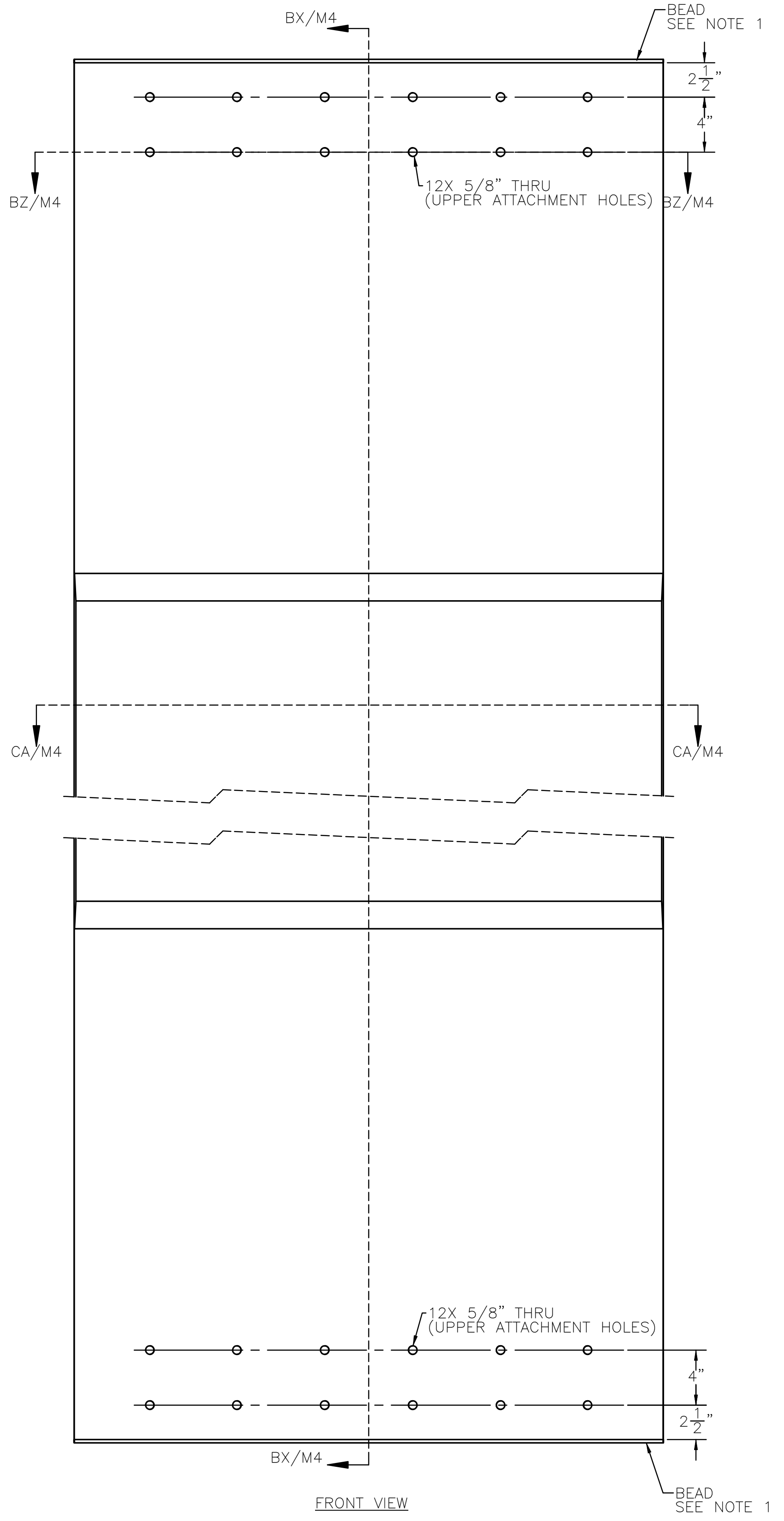
DESIGNED: A. LANDHERR	SUBMITTED:
DRAWN: A. LANDHERR	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED:	DRAWING NO. M3
MANAGER–CHIEF ENGINEER DATE	

JOB NO. 15706

SHEET NO. 57 OF 61

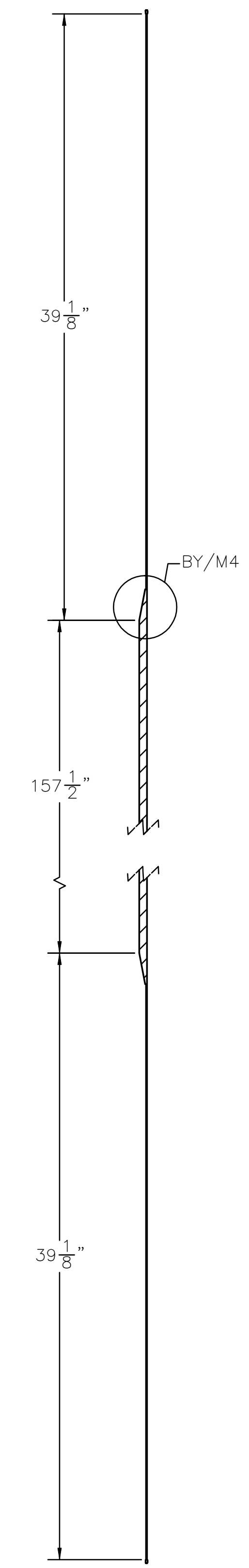
NOTES:

1. BEAD TO PREVENT PULLOUT FROM CLAMP

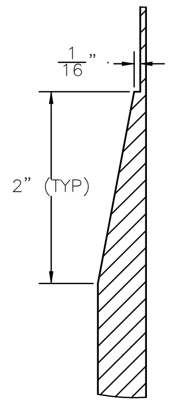


FRONT VIEW

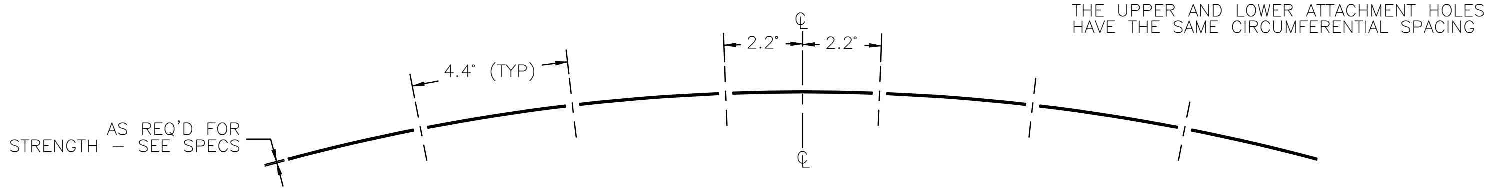
1/M4 TOP GUIDE SLIDE LAYER
SCALE 1 : 6



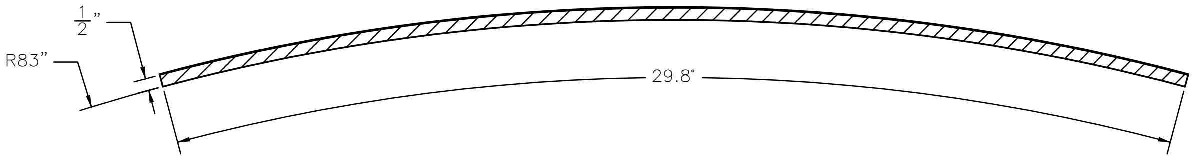
SECTION BX/M4–BX/M4
SCALE 1 : 6



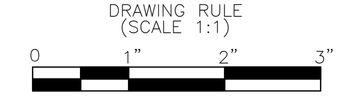
DETAIL BY/M4
SCALE 1 : 1



SECTION BZ/M4–BZ/M4
SCALE 1 : 4



SECTION CA/M4–CA/M4
SCALE 1 : 4



DRAWING RULE
(SCALE 1:1)

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

TOP GUIDE SLIDE LAYER

MAKAI
OCEAN ENGINEERING, INC.

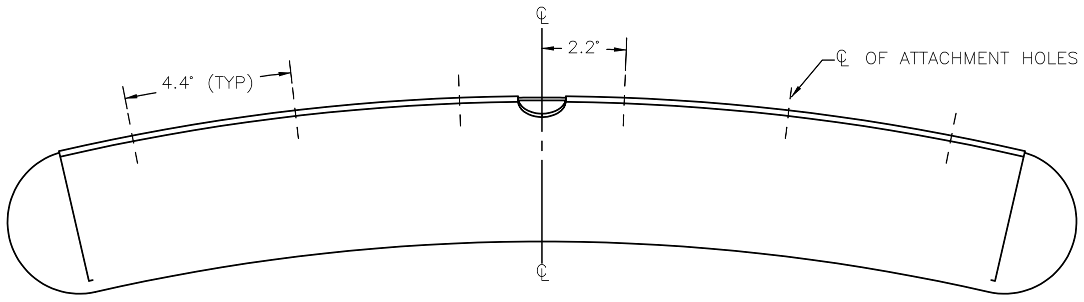
DESIGNED: A. LANDHERR	SUBMITTED:
DRAWN: A. LANDHERR	DATE: 9/18/2010
CHECKED: D. JENSEN	SCALE: SHOWN
APPROVED: MANAGER–CHIEF ENGINEER DATE	DRAWING NO. M4

JOB NO. 15706

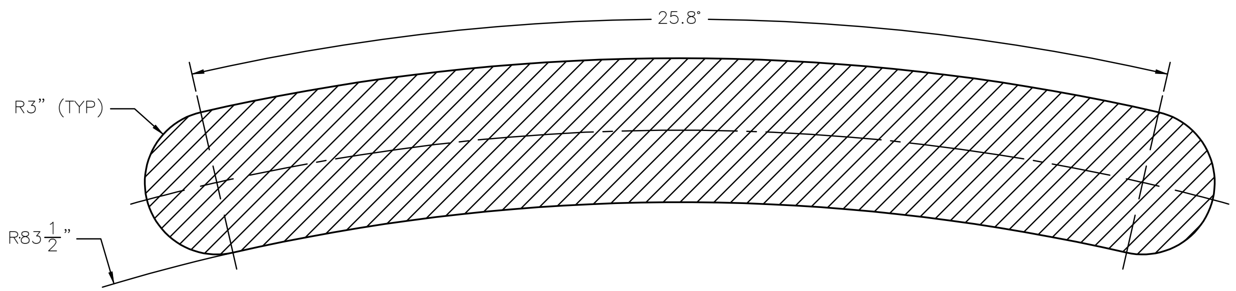
SHEET NO. 58 OF 61

NOTES:

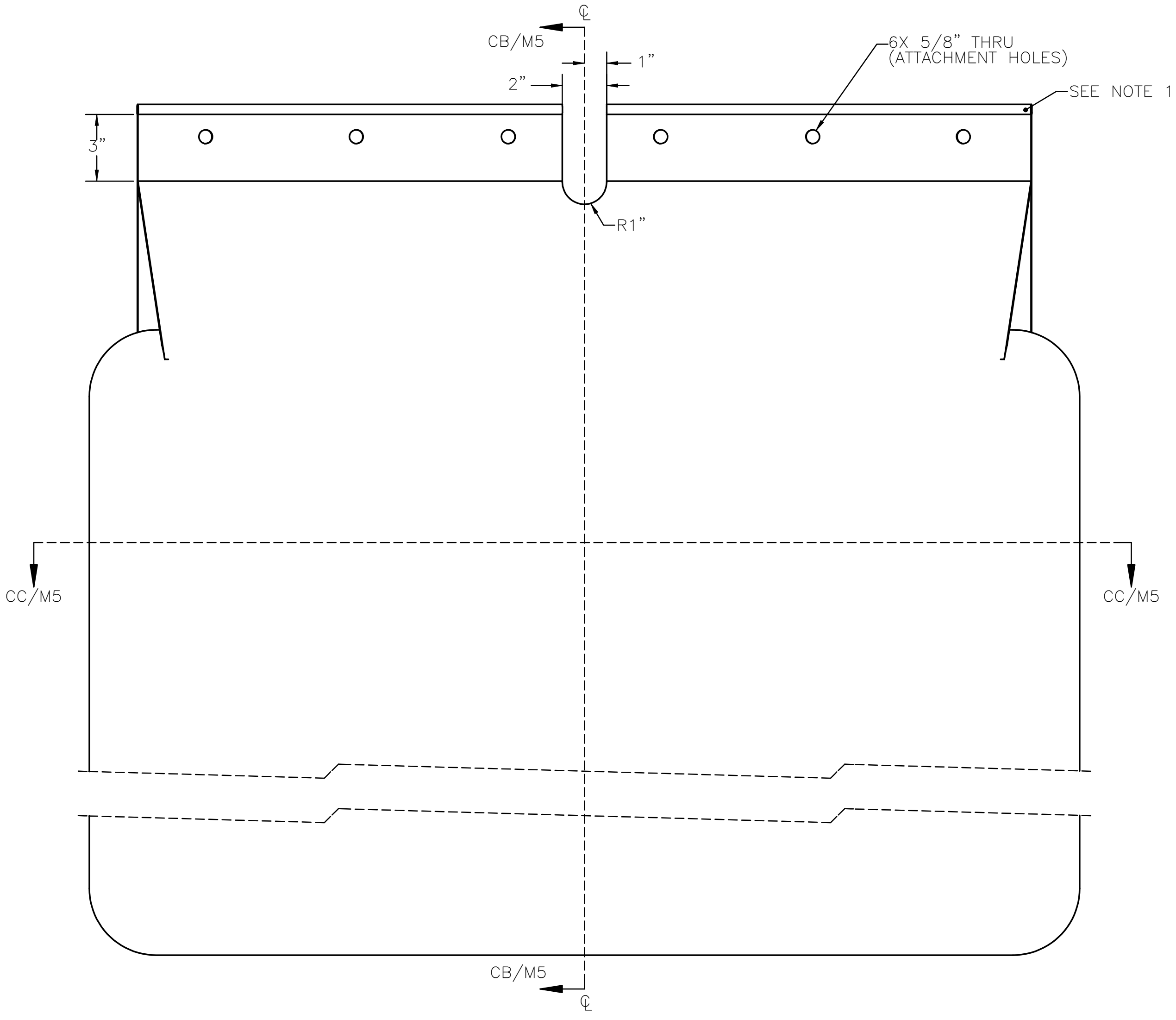
1. BEAD TO PREVENT PULLOUT FROM CLAMP



TOP VIEW

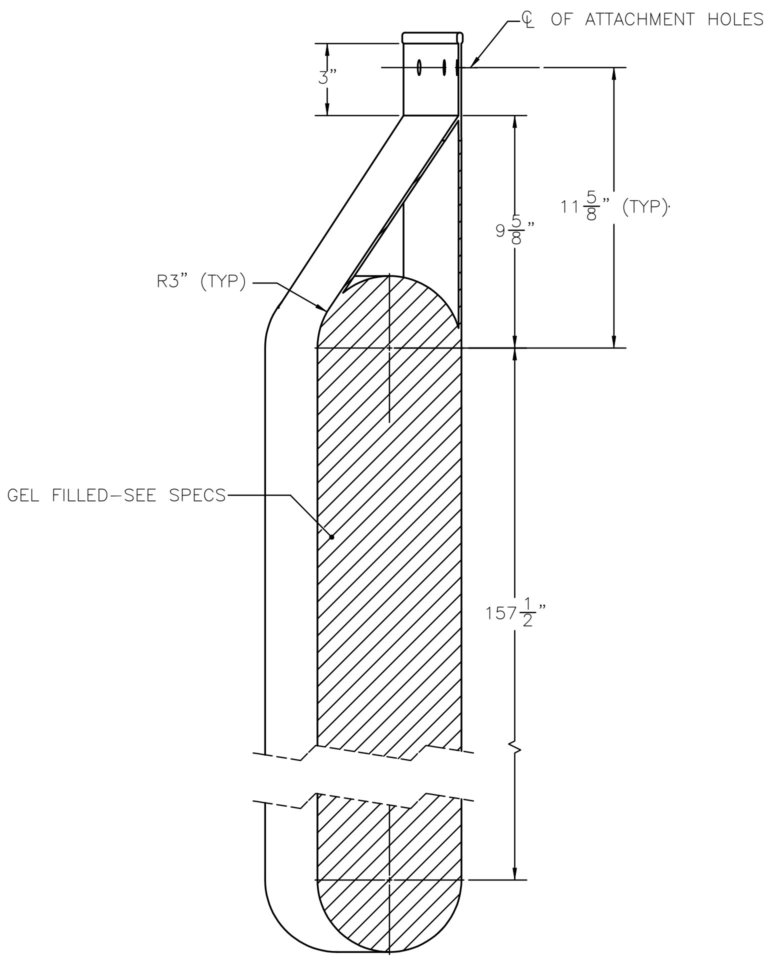


SECTION CC/M5–CC/M5
SCALE 1 : 4

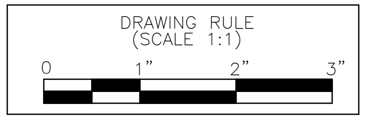


FRONT VIEW

1/M5 GUIDE GEL BAG
SCALE 1 : 4



SECTION CB/M5–CB/M5
SCALE 1 : 4



REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

BOTTOM GUIDE GEL BAG

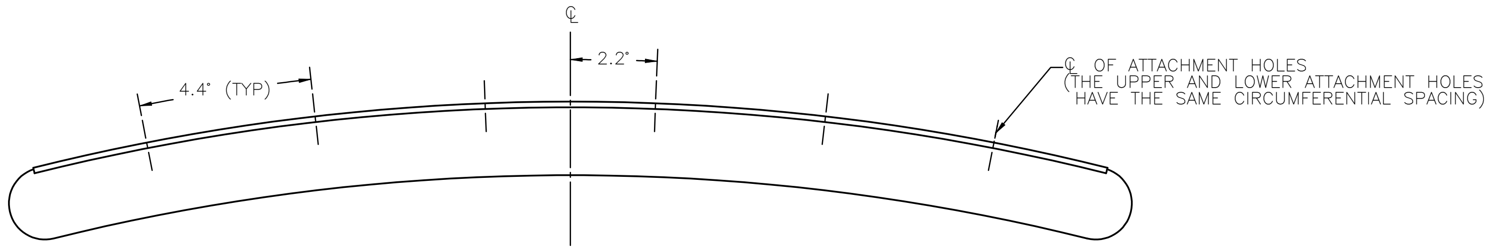
MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER–CHIEF ENGINEER
DATE
DRAWING NO. M5

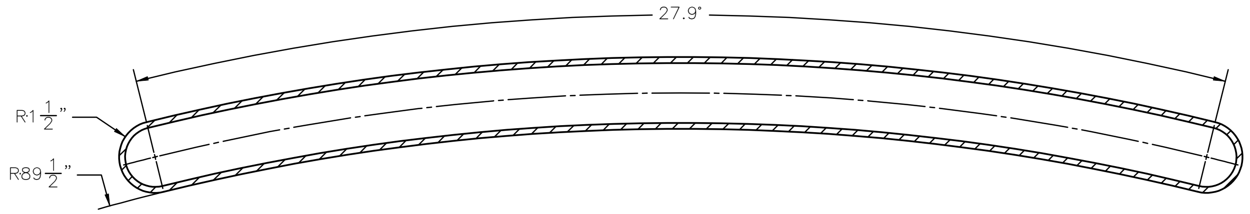
JOB NO. 15706
SHEET NO. 59 OF 61

NOTES:

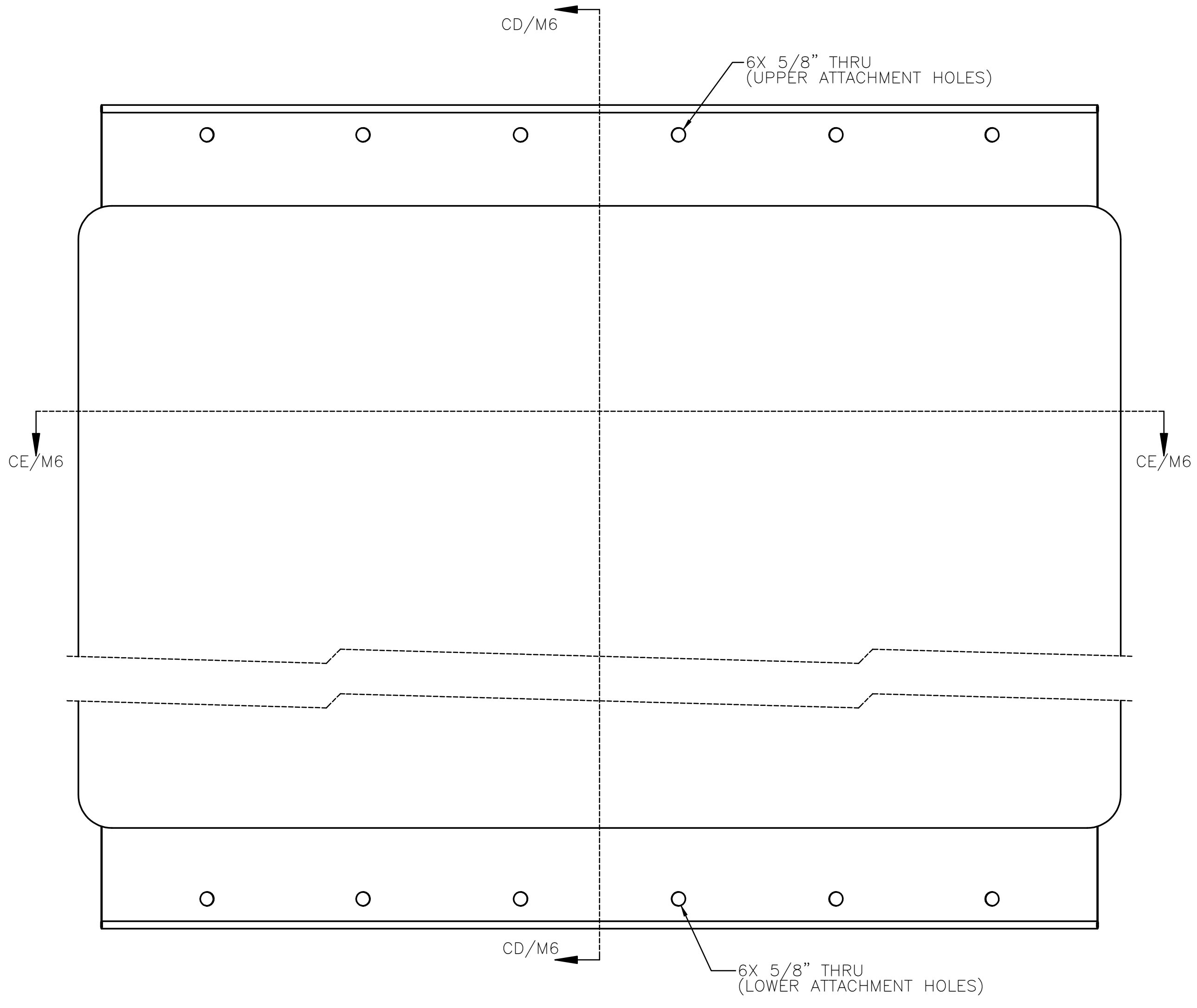
1. BEAD TO PREVENT PULLOUT FROM CLAMP



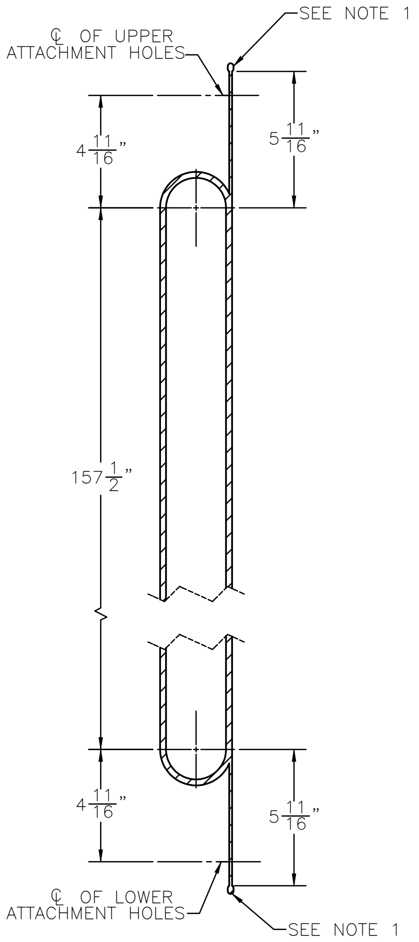
TOP VIEW



SECTION CE/M6–CE/M6
SCALE 1 : 4



FRONT VIEW



SECTION CD/M6–CD/M6
SCALE 1 : 4

1/M6 BOTTOM GUIDE WATERBED
SCALE 1 : 4

DRAWING RULE
(SCALE 1:1)
0 1" 2" 3"

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD MANASSAS, VA 20110–4121

BOTTOM GUIDE WATER BAG

MAKAI
OCEAN ENGINEERING, INC.

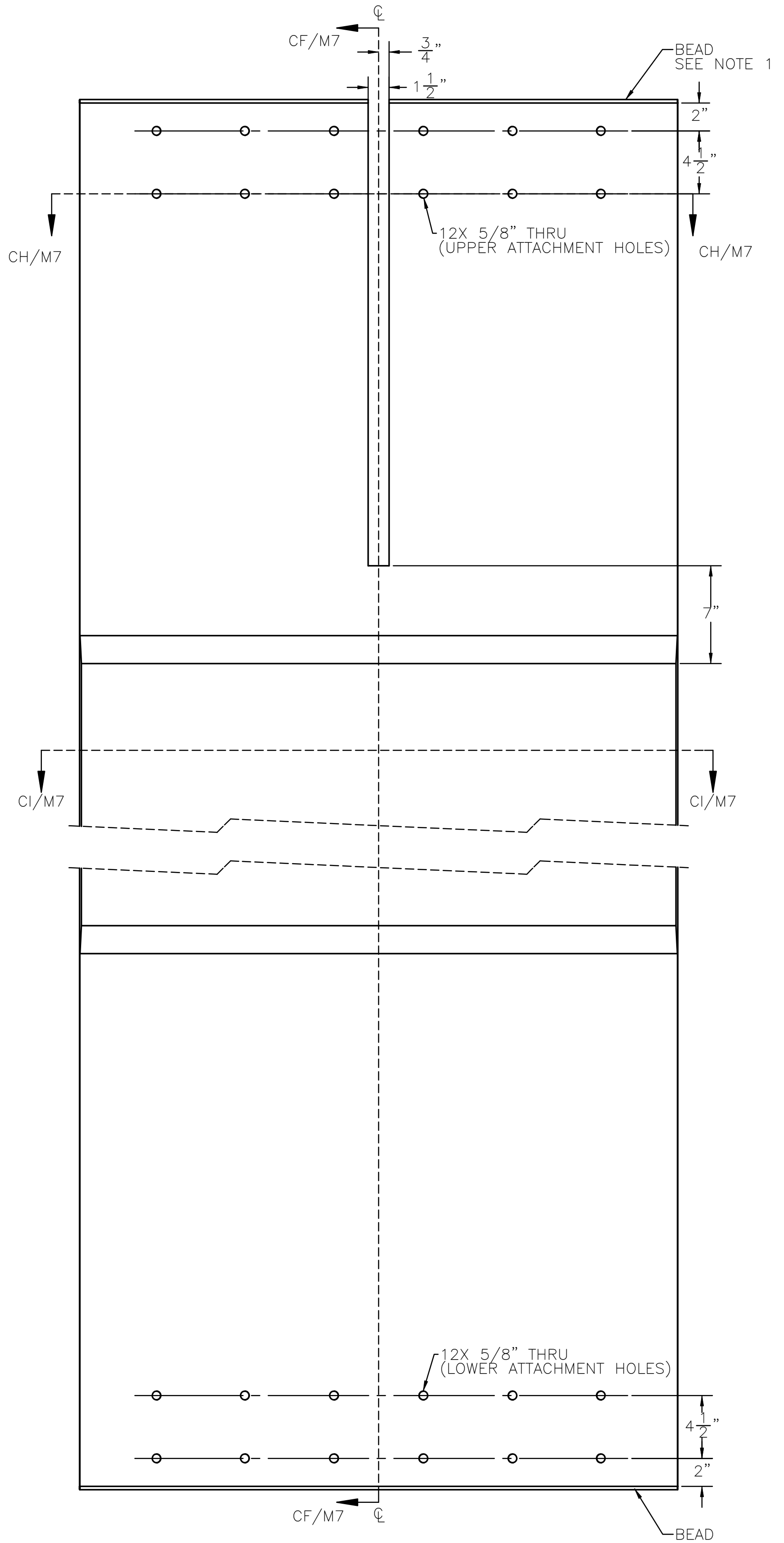
DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
MANAGER–CHIEF ENGINEER
DATE
DRAWING NO. M6

JOB NO. 15706

SHEET NO. 60 OF 61

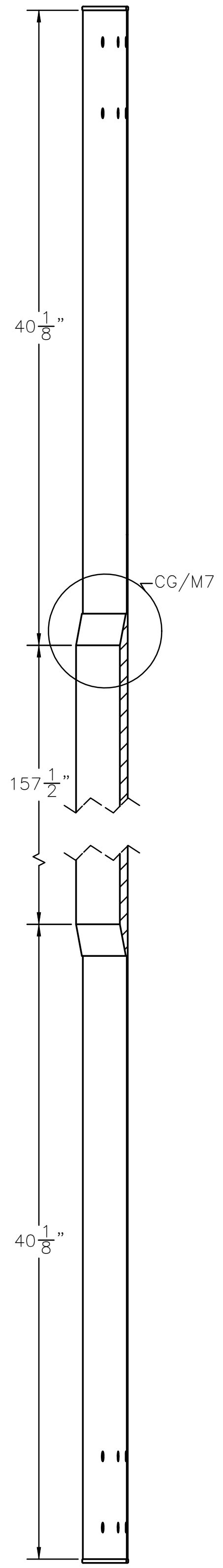
NOTES:

1. BEAD TO PREVENT PULLOUT FROM CLAMP

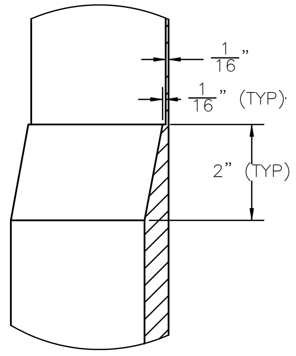


FRONT VIEW

1/M7 BOTTOM GUIDE SLIDE LAYER
SCALE 1 : 6

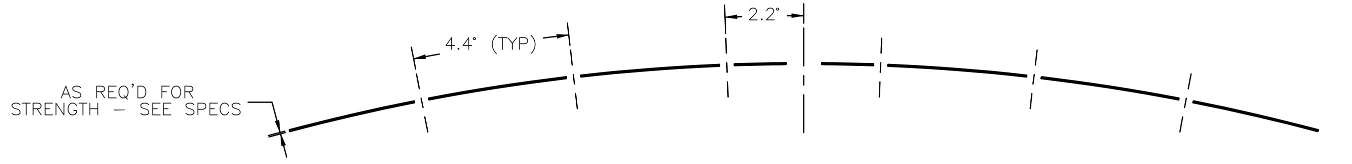


SECTION CF/M7–CF/M7
SCALE 1 : 6

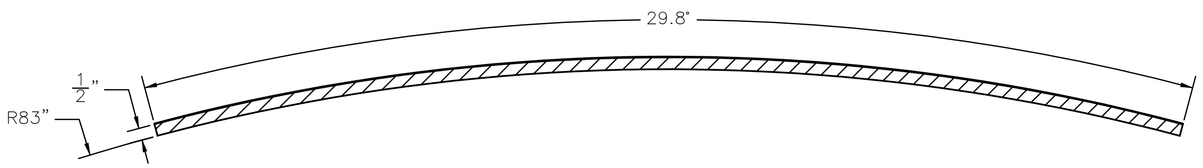


DETAIL CG/M7
SCALE 1 : 2

THE UPPER AND LOWER ATTACHMENT HOLES HAVE THE SAME CIRCUMFERENTIAL SPACING



SECTION CH/M7–CH/M7
SCALE 1 : 4



SECTION CI/M7–CI/M7
SCALE 1 : 4

DRAWING RULE
(SCALE 1:1)

REVISION NO.	SYM.	DESCRIPTION	SHT./OF	DATE	APPROVED

NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

LOCKHEED MARTIN 9255 WELLINGTON ROAD
MANASSAS, VA 20110–4121

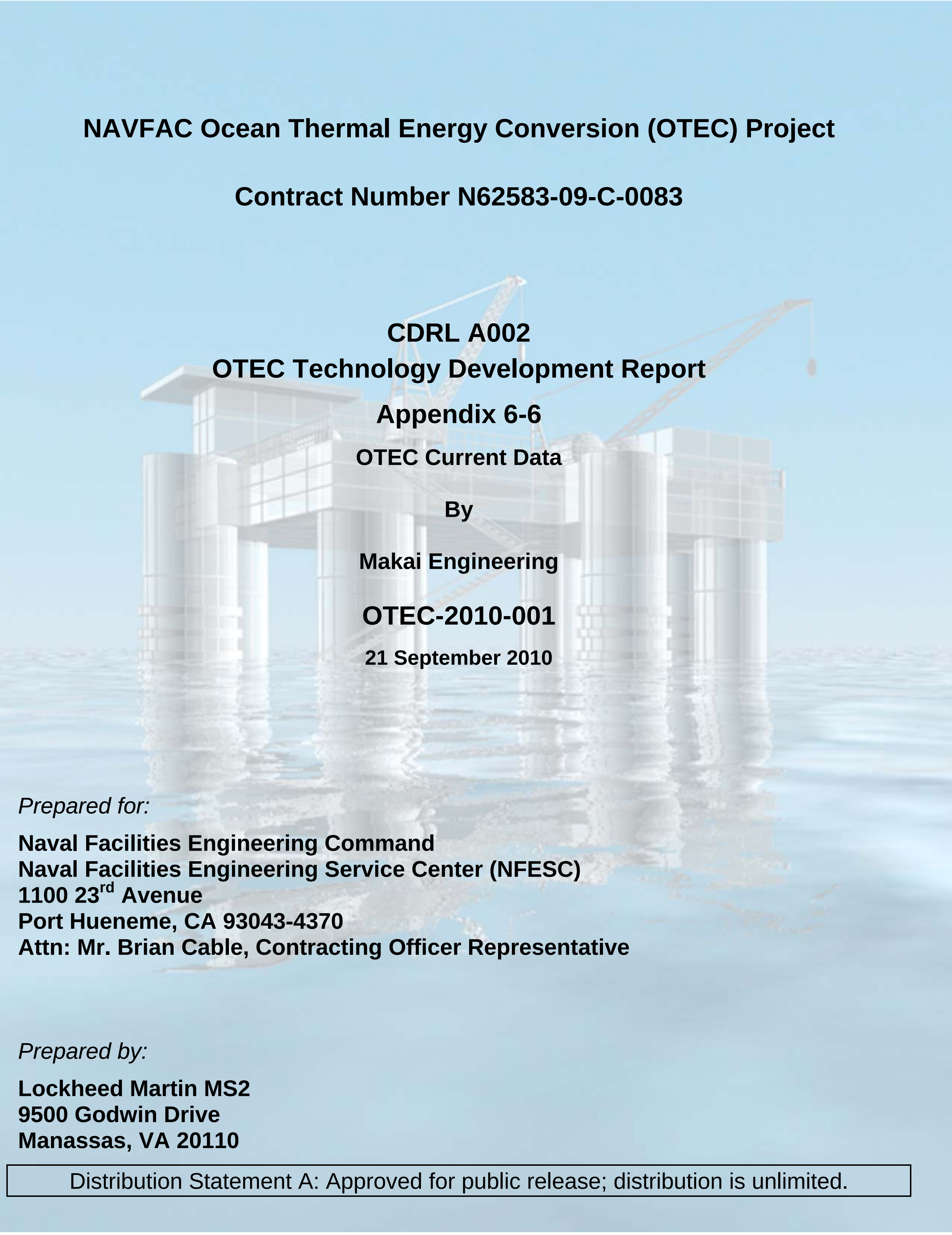
BOTTOM GUIDE SLIDE LAYER

MAKAI
OCEAN ENGINEERING, INC.

DESIGNED: A. LANDHERR
SUBMITTED:
DRAWN: A. LANDHERR
DATE: 9/18/2010
CHECKED: D. JENSEN
SCALE: SHOWN
APPROVED:
DRAWING NO. M7
MANAGER–CHIEF ENGINEER
DATE

JOB NO. 15706

SHEET NO. 61 OF 61



NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report
Appendix 6-6
OTEC Current Data

By

Makai Engineering

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
Naval Facilities Engineering Service Center (NFESC)
1100 23rd Avenue
Port Hueneme, CA 93043-4370
Attn: Mr. Brian Cable, Contracting Officer Representative

Prepared by:

Lockheed Martin MS2
9500 Godwin Drive
Manassas, VA 20110

OTEC current data

1.1 CURRENTS

Makai obtained shallow (<400m) current data from Hawaii Ocean Time-Series (HOTS) and deep current data from Wyrtki. The geographical locations of the current data are shown in Figure 14.

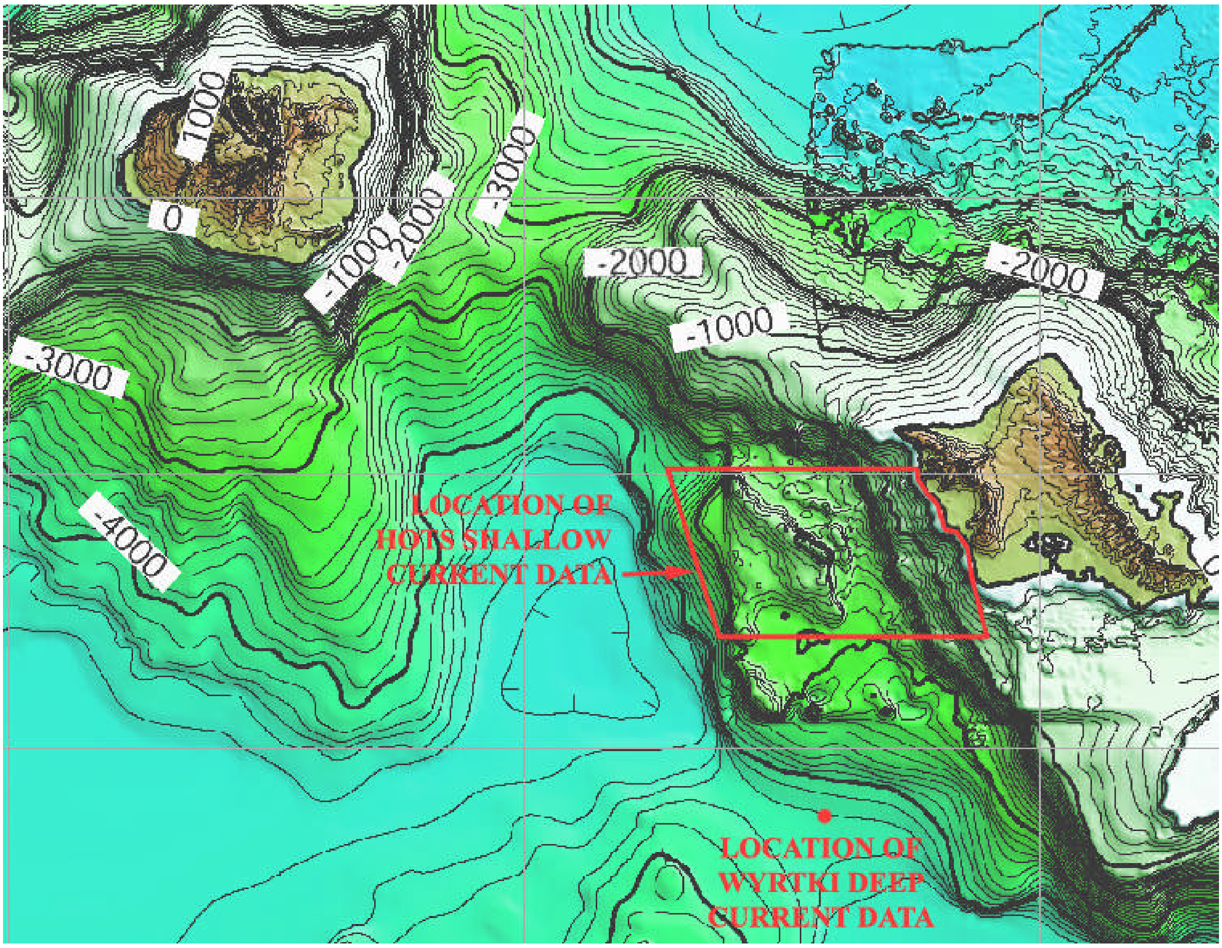


Figure 1: Geographical location of current data

The current data from HOTS was analyzed to determine the maximum currents encountered at a particular depth. The maximum velocities are shown in **Error! Reference source not found.Error! Reference source not found.**5.

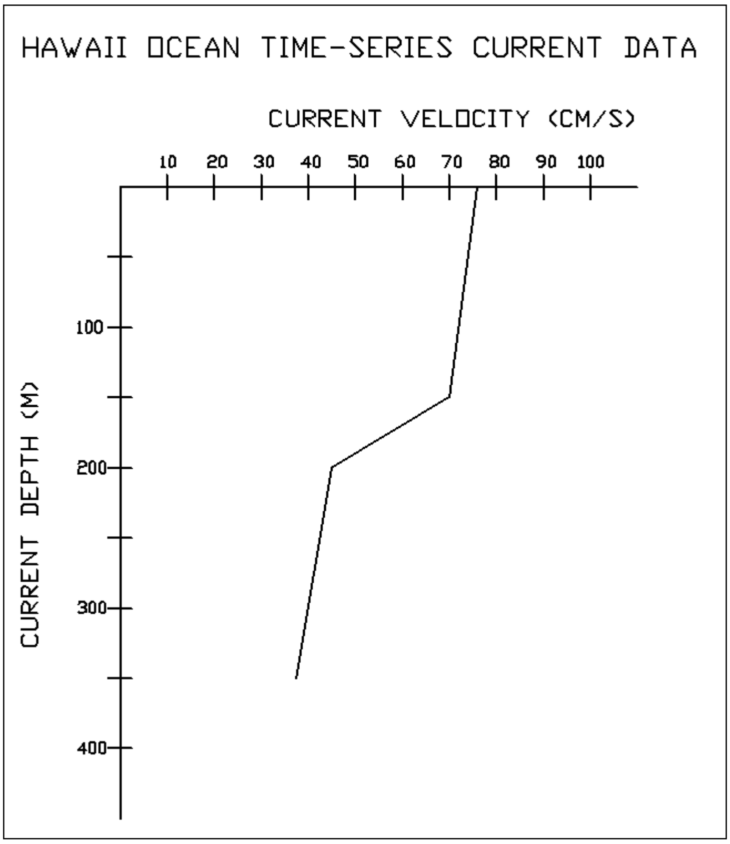


Figure 2: HOTS current data

Wyrtki has collected deep current data, taken from 1985 to 1987 at 20° 49.50’N, 158° 24.60’W. The bottom depth is 4210 m, and the current data was obtained from a depth of 4143m. The maximum current recorded at this location was 19.67 cm/s.

Data from the OTEC Cold Water Pipe At-Sea Test Program is provided in **Error! Reference source not found.Error! Reference source not found.**6. These data were collected by Noda And Associates in 1980 and 1981. The worst case velocity corresponds closely with the data from HOTS.

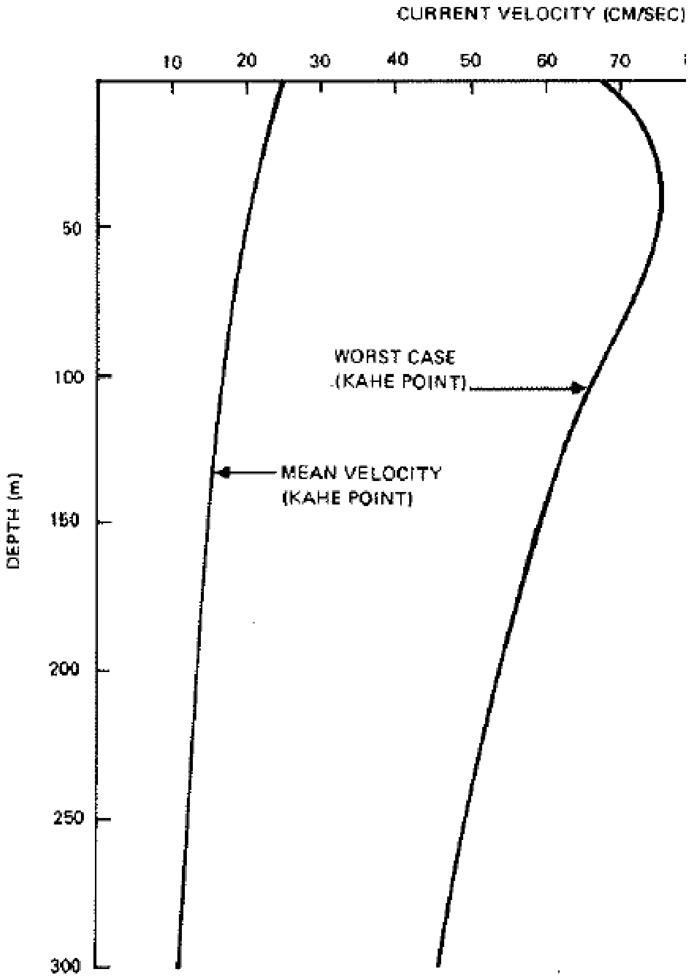


Figure 3: Kahe Point current data

1.1.1 Persistence and variability

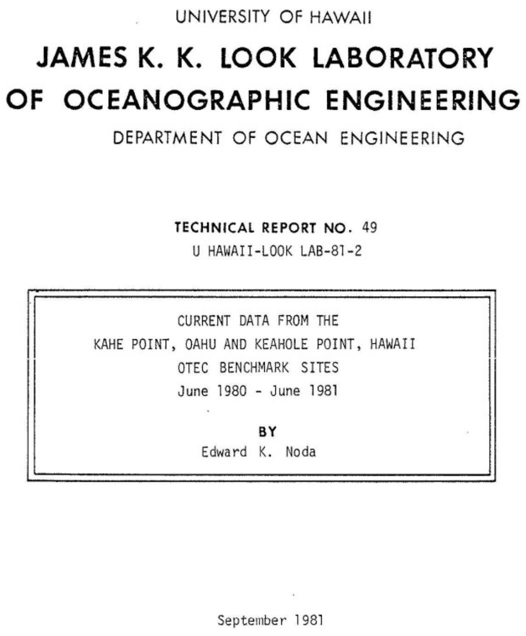
In order to understand current variability at Kahe, we looked into the data records from the data collected off Kahe in 1980 and 81. How likely are we to see the maximum currents? What drives the maximum currents? Is the maximum at one depth occur at the same time as the maximum at another depth? How persistent are the maximum currents?

We can get a partial understanding of these answers by looking at Noda's data. Several pages of results are provided in the following pages. High currents occurred on May 5, 1981.

- For most, but not all depths, the peak currents for the period occur at the same time. Therefore we can conclude that the peak currents give above will not necessarily all occur at the same time.
- The currents are definitely tidal driven. Strong currents are followed in hours by much milder values. For the gripper, we will not have strong persistent currents. Therefore we do not have to move pipe during strong currents – we can wait.

- Currents should be predictable – although the very high peaks may have other factors other than tides. However, the peak value for the day and the prediction of when the currents will drop should be easy.

Current Criteria to be based on West Oahu. Best historical data available is from:



UNIVERSITY OF HAWAII

JAMES K. K. LOOK LABORATORY
OF OCEANOGRAPHIC ENGINEERING

DEPARTMENT OF OCEAN ENGINEERING

TECHNICAL REPORT NO. 49
U HAWAII-LOOK LAB-81-2

CURRENT DATA FROM THE
KAHE POINT, OAHU AND KEAHOLE POINT, HAWAII
OTEC BENCHMARK SITES
June 1980 - June 1981

BY
Edward K. Noda

September 1981

Figure 4: Noda report cover

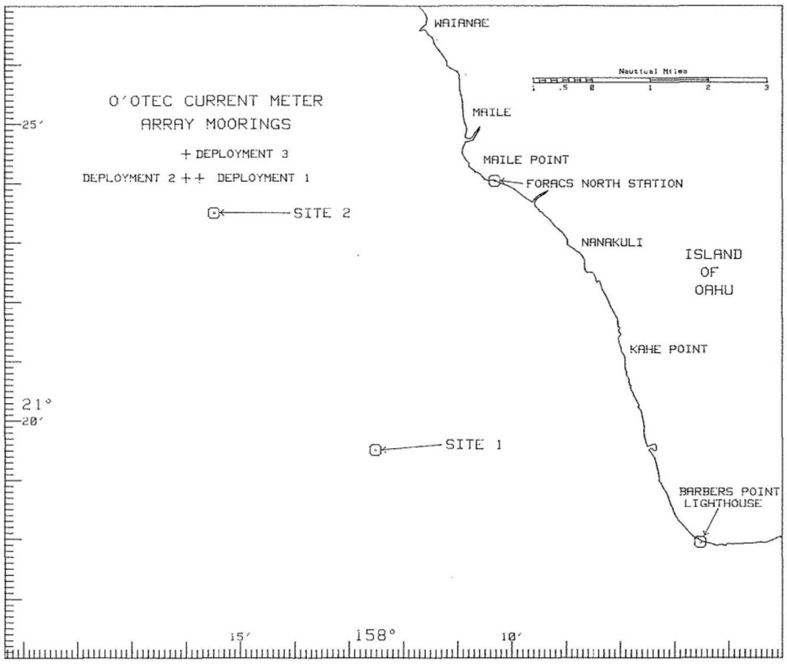


Figure 2-1: O'OTEC CURRENT METER ARRAY MOORING, KAHE POINT, OAHU

Figure 5: Data collected at deployment 1, 2, 3).

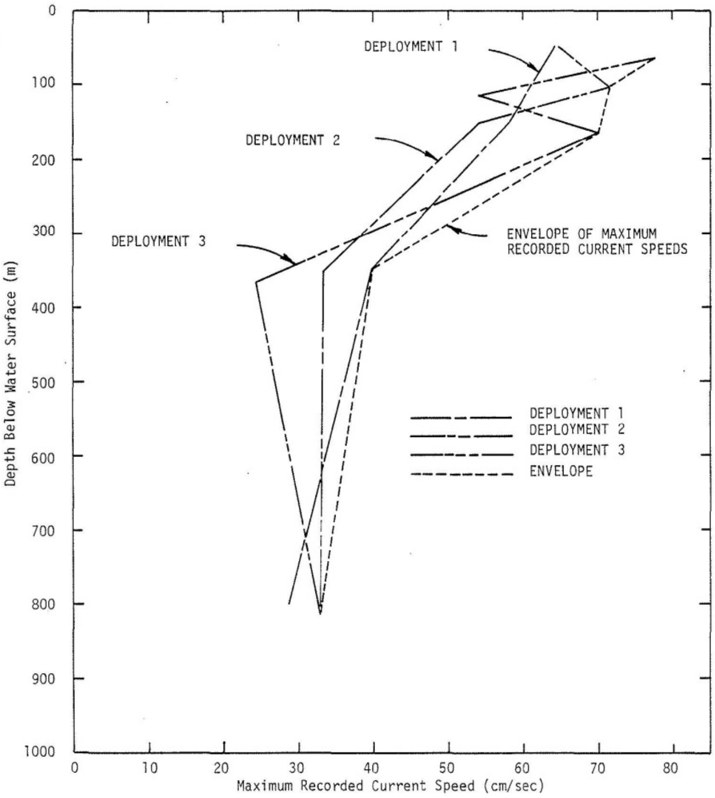
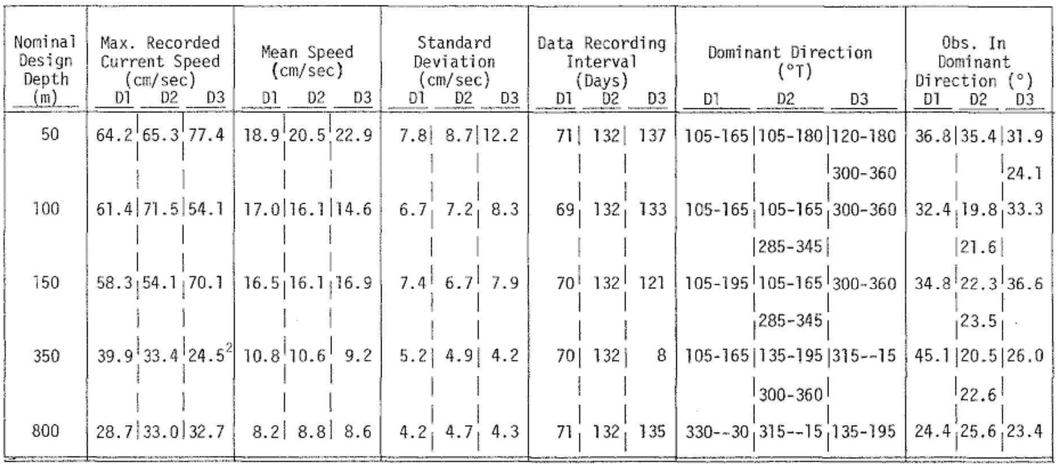


Figure 6: ***Maximum current levels measured by Noda.***



Nominal Design Depth (m)	Max. Recorded Current Speed (cm/sec)			Mean Speed (cm/sec)			Standard Deviation (cm/sec)			Data Recording Interval (Days)			Dominant Direction (°T)			Obs. In Dominant Direction (°)		
	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
50	64.2	65.3	77.4	18.9	20.5	22.9	7.8	8.7	12.2	71	132	137	105-165	105-180	120-180	36.8	35.4	31.9
															300-360			24.1
100	61.4	71.5	54.1	17.0	16.1	14.6	6.7	7.2	8.3	69	132	133	105-165	105-165	300-360	32.4	19.8	33.3
														285-345			21.6	
150	58.3	54.1	70.1	16.5	16.1	16.9	7.4	6.7	7.9	70	132	121	105-195	105-165	300-360	34.8	22.3	36.6
														285-345			23.5	
350	39.9	33.4	24.5^2	10.8	10.6	9.2	5.2	4.9	4.2	70	132	8	105-165	135-195	315--15	45.1	20.5	26.0
														300-360			22.6	
800	28.7	33.0	32.7	8.2	8.8	8.6	4.2	4.7	4.3	71	132	135	330--30	315--15	135-195	24.4	25.6	23.4

NOTES 1) D1 = Deployment 1, D2 = Deployment 2, D3 = Deployment 3
2) Deployment 3, Current Meter at 350m recorded data for only 1 week

Figure 7: ***Summary of data collect by Noda: max, mean, sigma, durations, directions.***

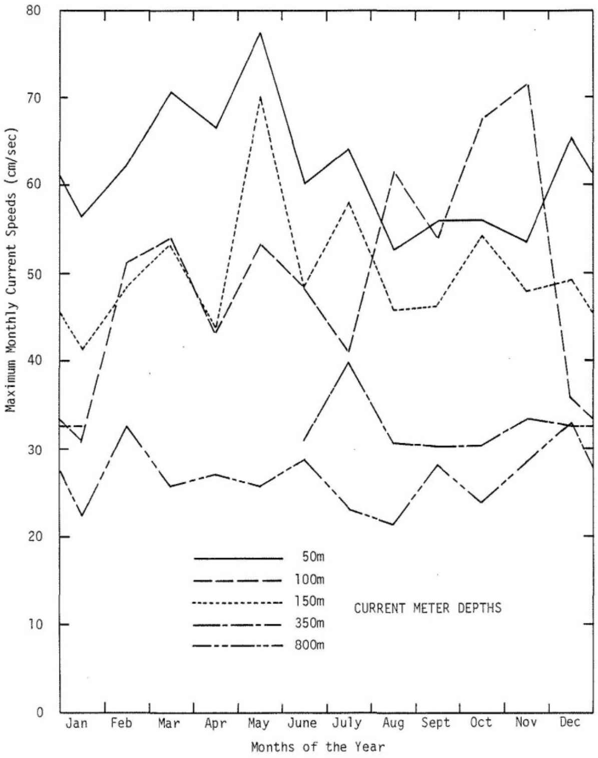


Figure 8: ***Max monthly currents at each depth. Note maximum currents for the five depths are not necessarily all in the same month – but many do occur at the same time. May was a***

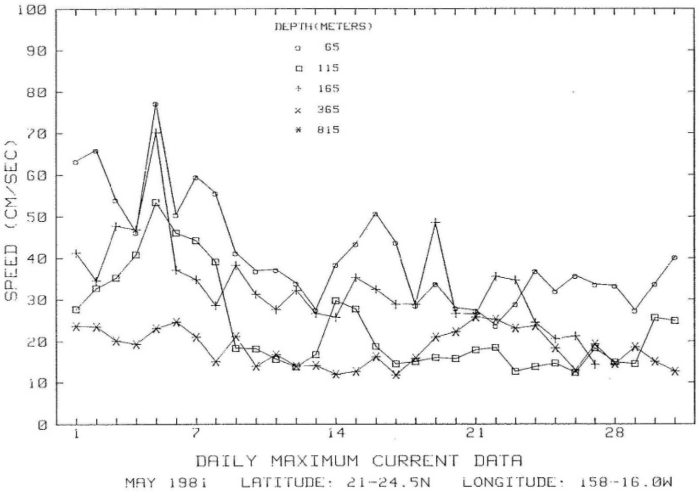


Figure C11: KAHE POINT DAILY MAXIMUM CURRENT SPEED
May 1981

Figure 9: ***Max currents for May, 1981. Max currents occur on May 5in shallow water but not necessarily in deep water. Currents were not measured at 365m in May.***

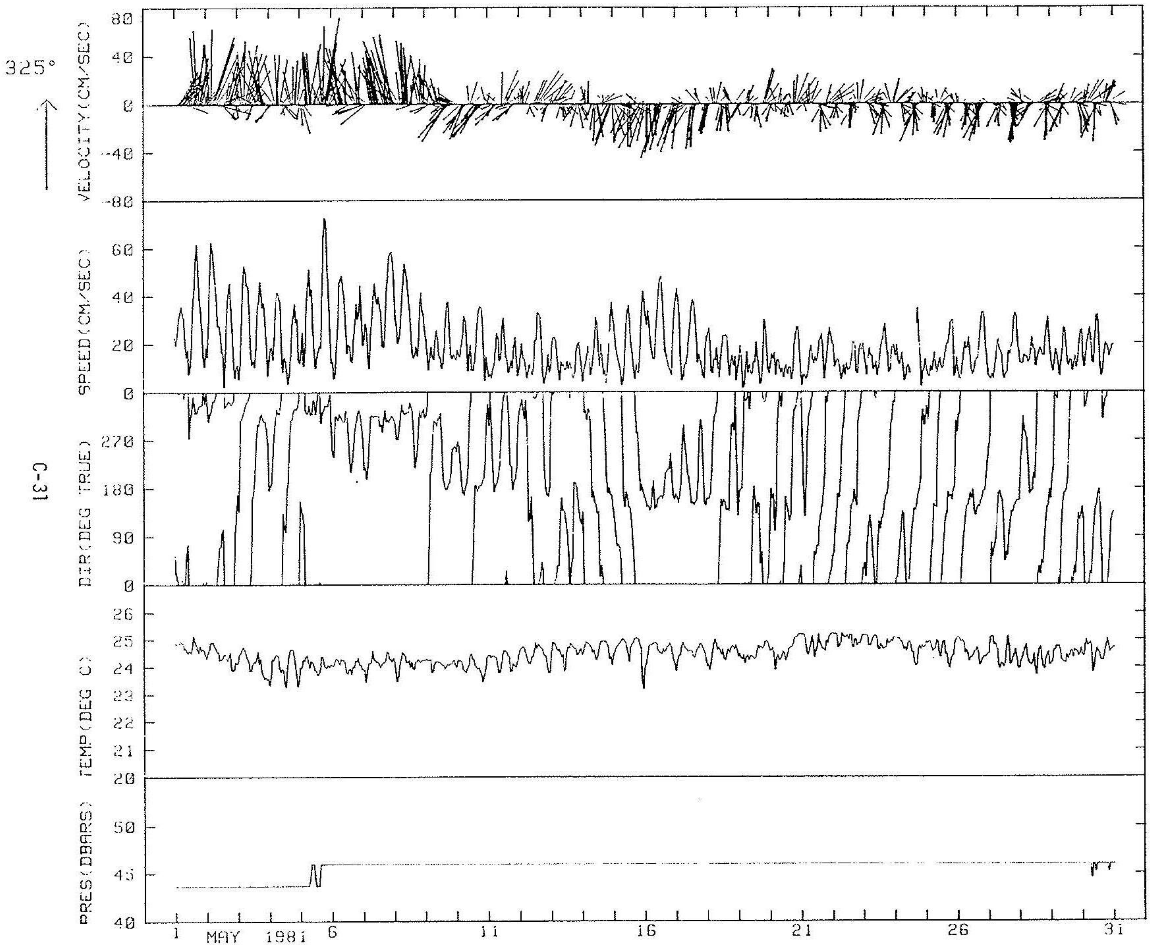


Figure 10: ***Currents at 65m depth in May. Note current strength is tidally driven. High peaks are soon followed by much lower values.***

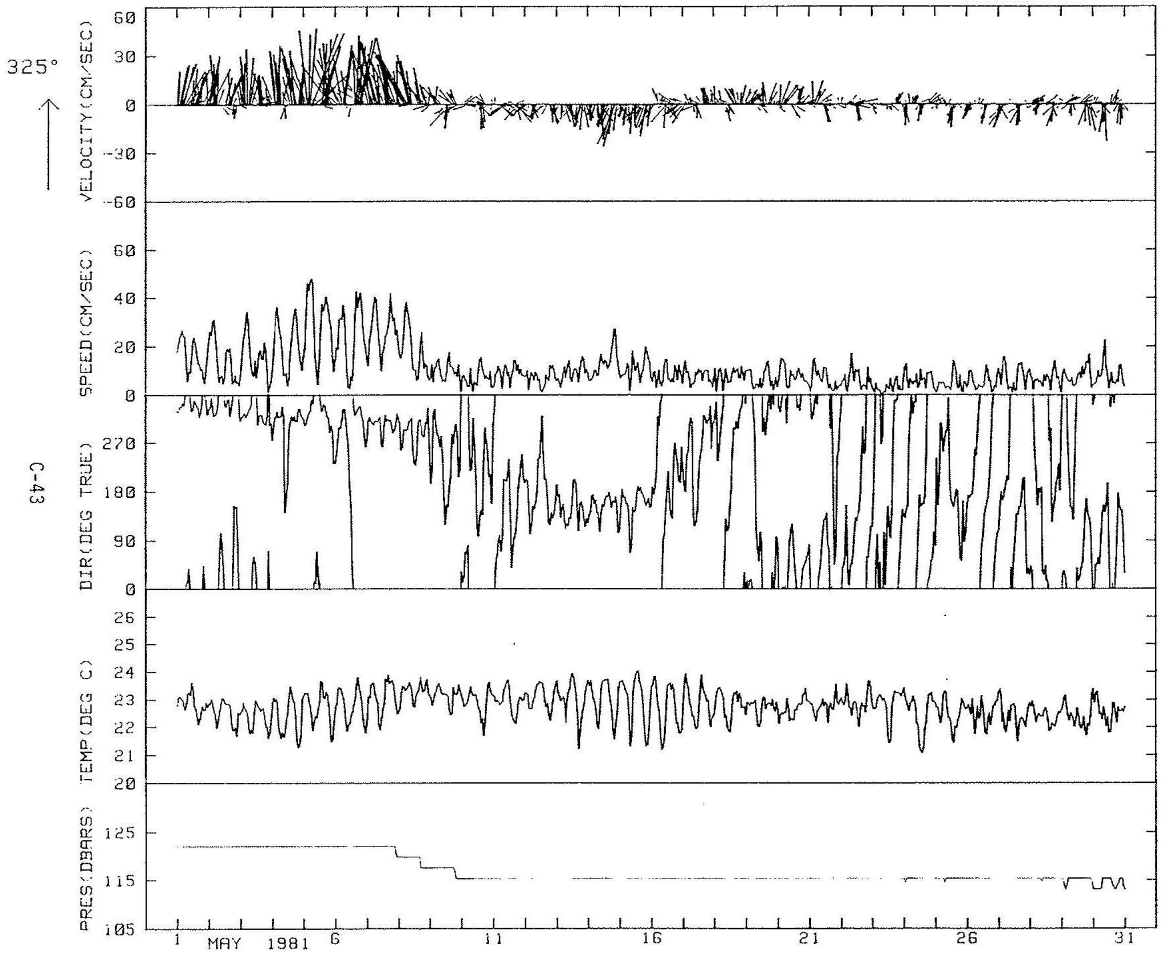


Figure 11: Currents at 115m depth in May. Peak activity at beginning of the month, May 5th is peak current. Tidal cycles.

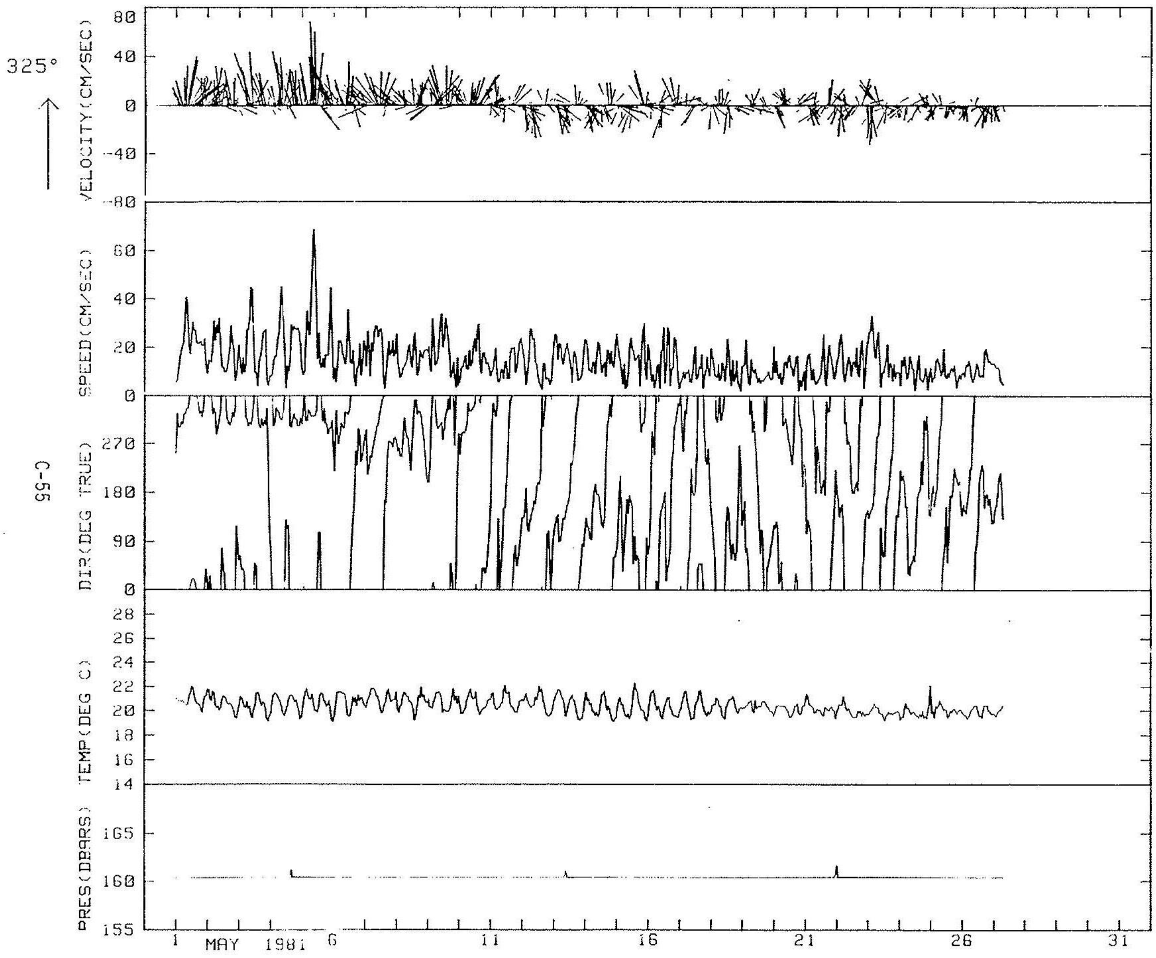


Figure 12: May currents at 165m depth. Peak at May 5th.

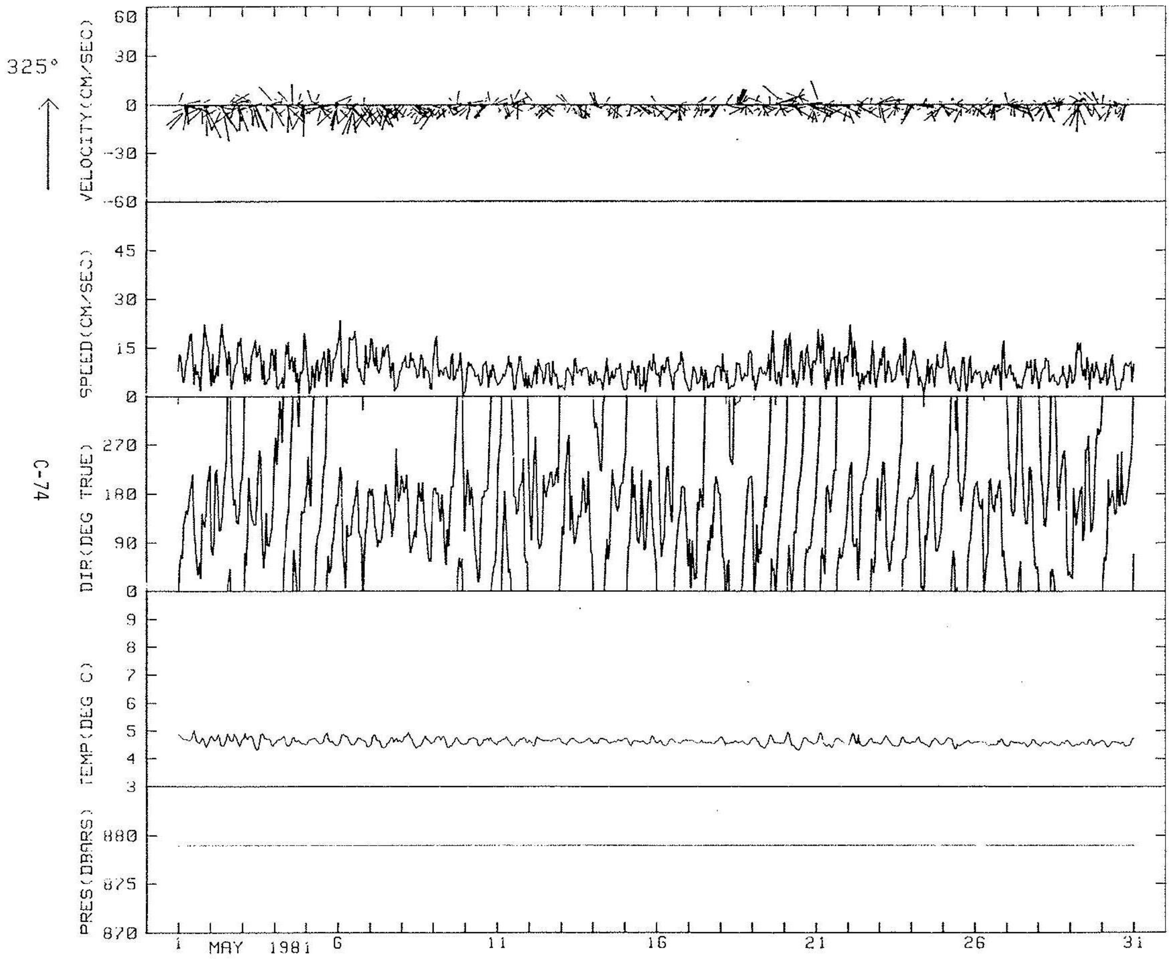


Figure 13: **Currents at 815m depth for May. Higher current activity at beginning of the month.**

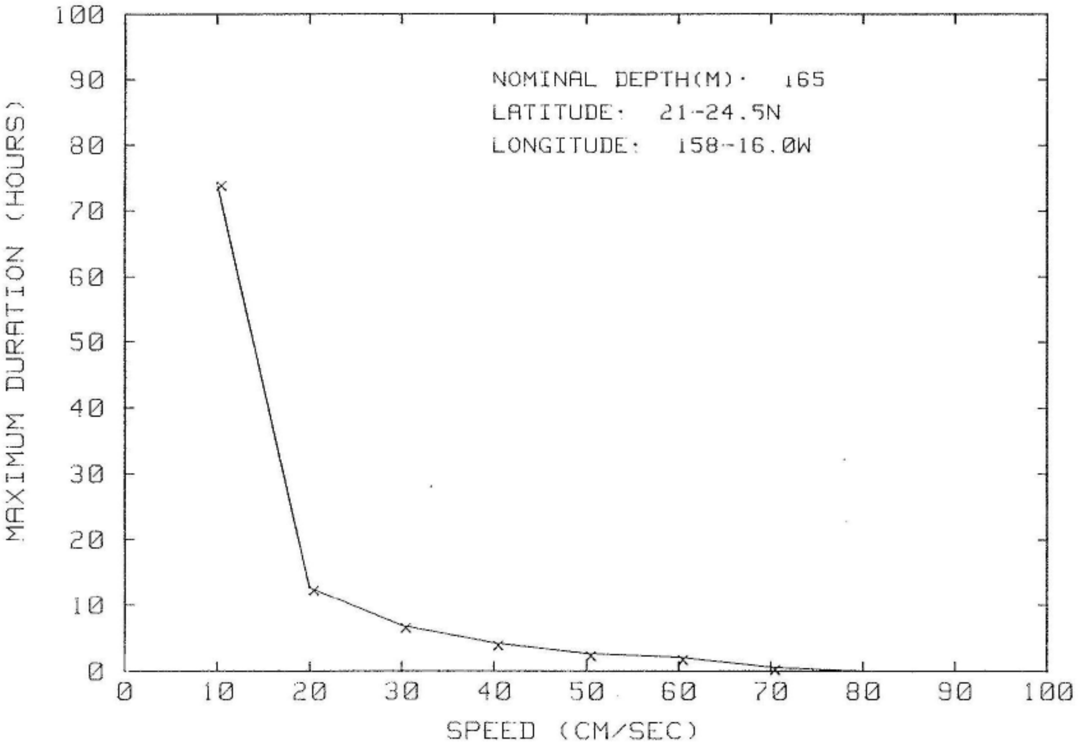
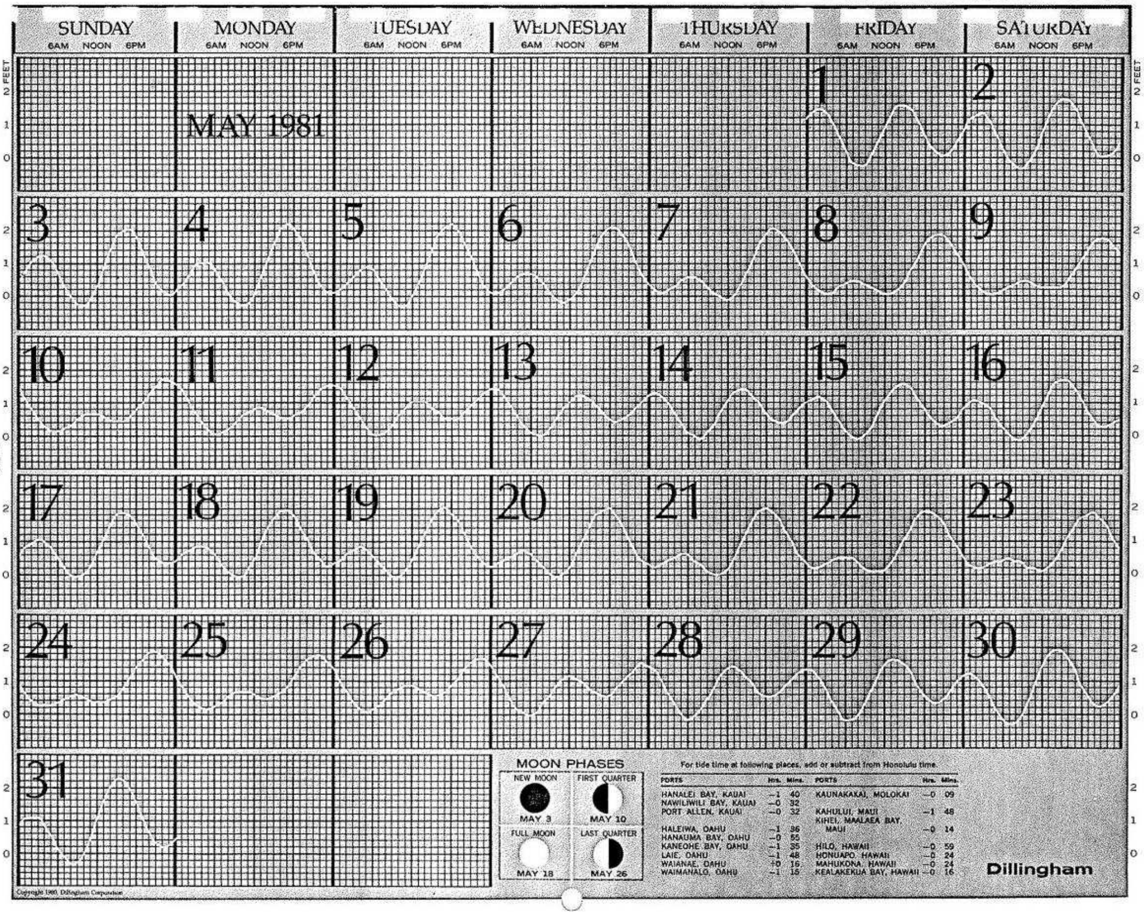


FIGURE C30: PERSISTENCE OF CURRENT SPEED FROM:
(HST) 1315 JAN 27 1981 TO 735 MAY 27 1981

Figure 14: ***Typical persistence curve. Very high currents are not persistent for more than a few hours.***

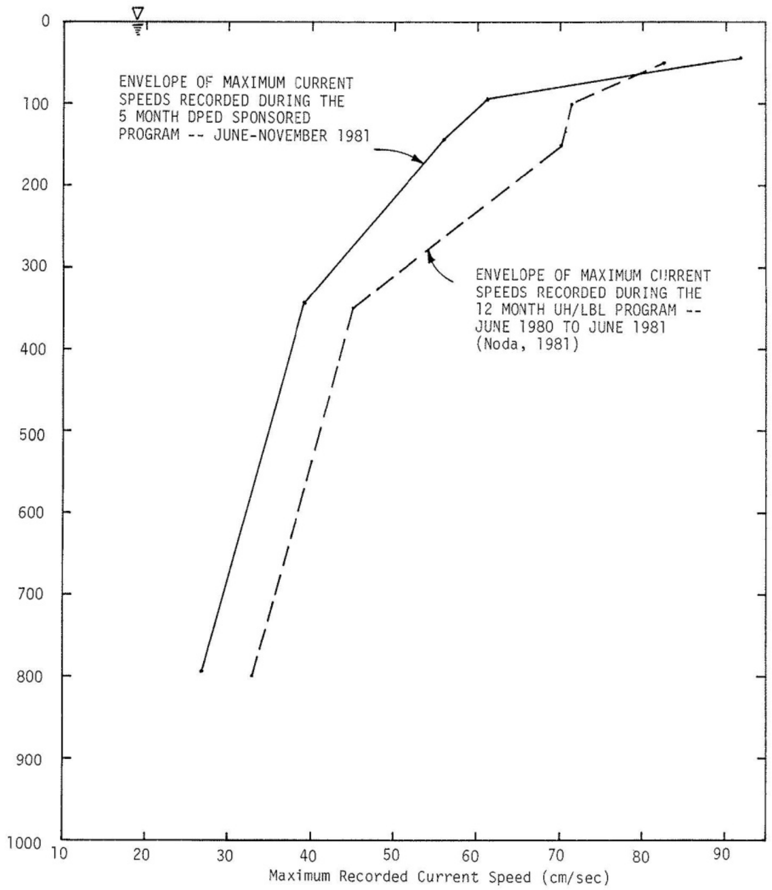


For tide time at following places, add or subtract from Honolulu time.

PORTS	Hrs.	Mins.	PORTS	Hrs.	Mins.
HANALEI BAY, KAUAI	−1	40	KAUNAKAKAI, MOLOKAI	−0	09
NAWILIWILI BAY, KAUAI	−0	32			
PORT ALLEN, KAUAI	−0	32	KAHULUI, MAUI	−1	48
HALEIWA, OAHU	−1	36	KIHEI, MAALAEA BAY, MAUI	−0	14
HANAUMA BAY, OAHU	−0	55			
KANEOHE BAY, OAHU	−1	35	HILO, HAWAII	−0	59
LAIE, OAHU	−1	48	HONUAPO, HAWAII	−0	24
WAIANAE, OAHU	+0	16	MAHUKONA, HAWAII	−0	24
WAIMANALO, OAHU	−1	15	KEALAKEKUA BAY, HAWAII	−0	16

Figure 15: ***Tidal cycles for May, 1981.***

Noda extended his measurements for another 5 months under a contract with the State of Hawaii from June-November, 1981. The following are from his State of Hawaii report of August, 1982. Except for the surface currents, his maximum currents for all other depths were recorded during the prior study period. (note that there is an error in this graph, the maximum recorded current at 350m is



ENVELOPE OF MAXIMUM CURRENT SPEEDS RECORDED DURING THE 5 MONTH DPED SPONSORED PROGRAM -- JUNE-NOVEMBER 1981

ENVELOPE OF MAXIMUM CURRENT SPEEDS RECORDED DURING THE 12 MONTH UH/LBL PROGRAM -- JUNE 1980 TO JUNE 1981 (Noda, 1981)

Figure 16: ***The envelop or the maximum record current velocities at the Kahe Point OTEC benchmark site.***

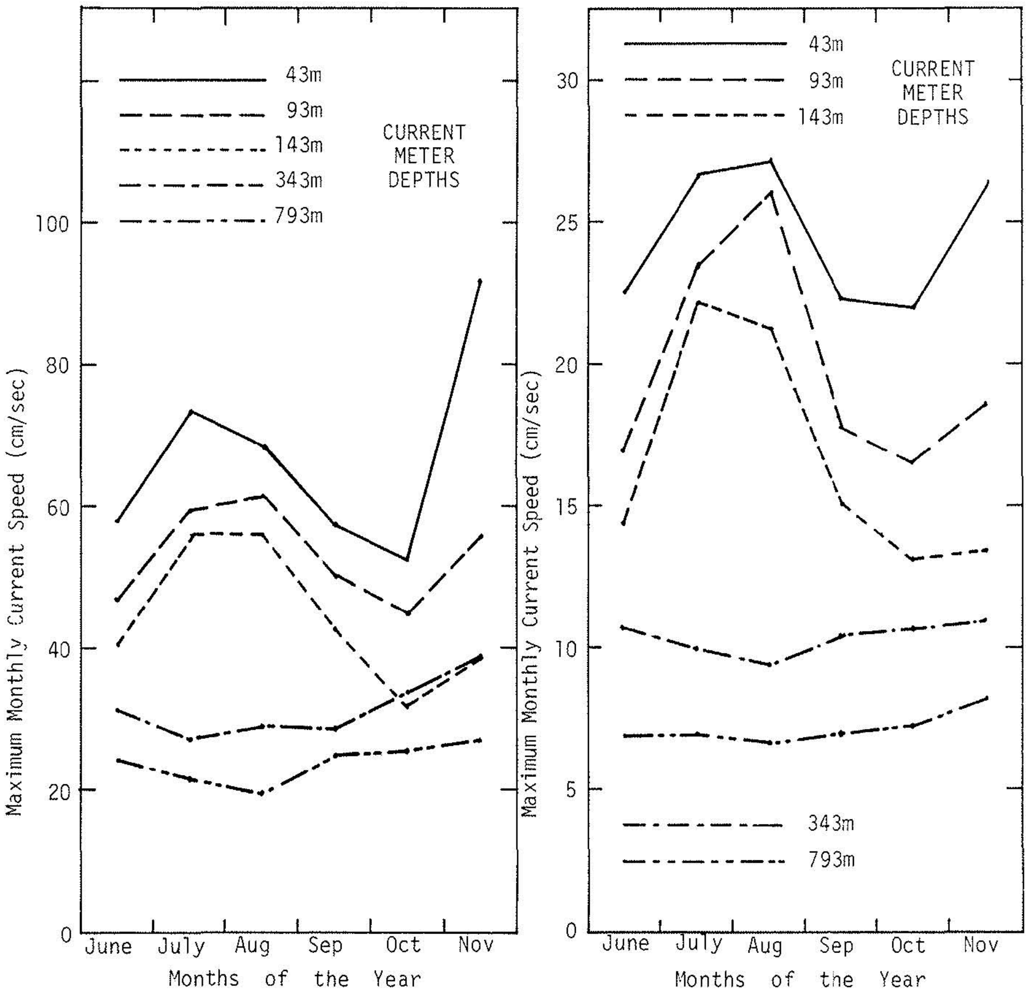


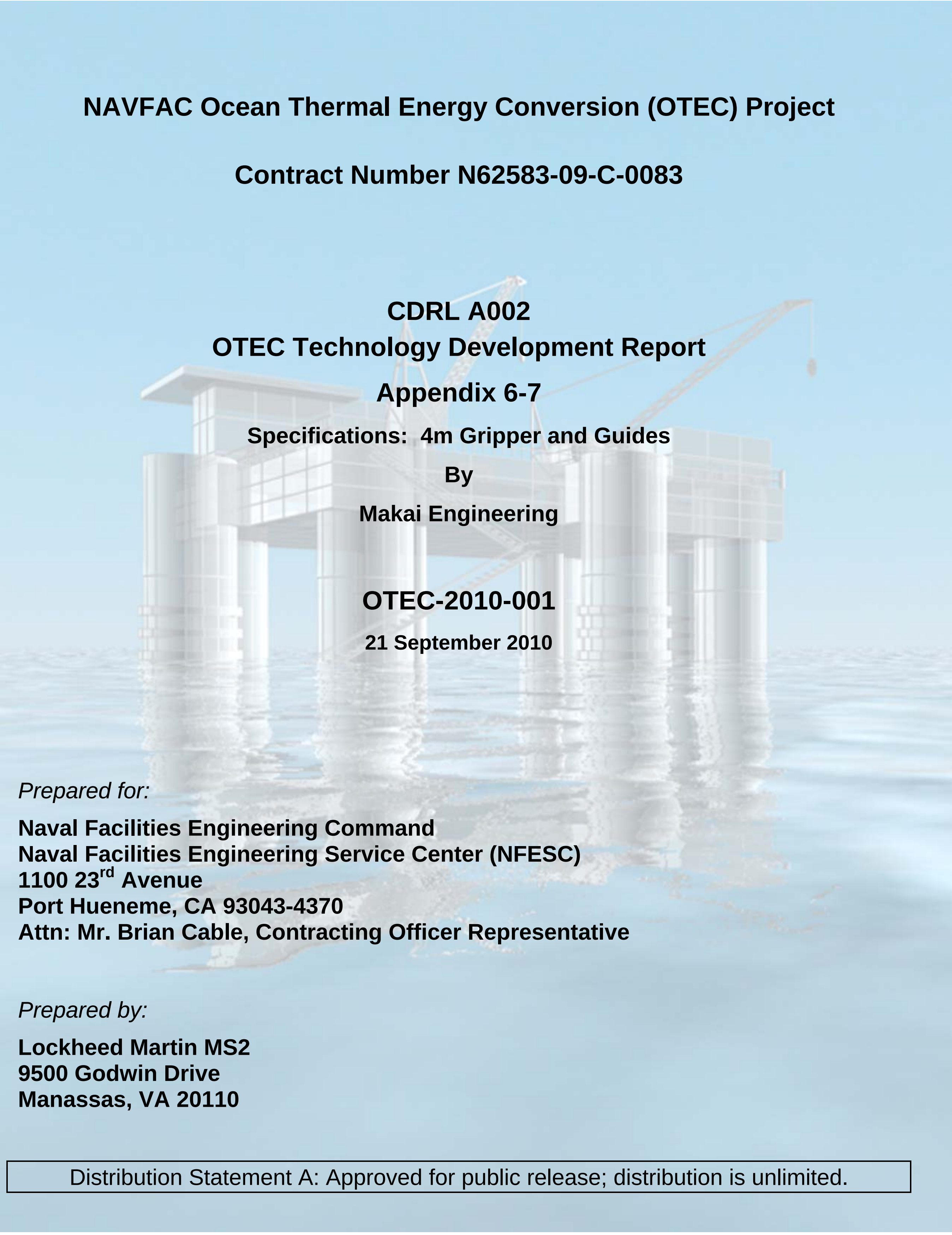
Figure 17: ***Maximum (left) and mean (right) monthly current speeds recorded at the Kahe Point OTEC benchmark site during June to November 1981.***

John Halkyard Proposed environmental Table:

Table 1 Proposed Design Environments for Gripper Design

	100 Year Cyclone	Max Current for CWP Design	90% Operational (Kahe Hindcast)	90% Operational (Kaneohe Hindcast)	10-yr Sea (Kahe)	10-yr Swell (Kaneohe)
Case ID	**100YrWave**	**MaxCurrent**	**Op90Kahe**	**Op90Kaneohe**	**10YrSea**	**10YrSwell**
Hs, m	10.2	6	1.6	3.0	4.4	5.6
Tp, sec	12	12	13.9	11.1	8.6	12.4
Spectrum, Jonswap gamma	2	3	4	1.0	1	3
Uw, m/sec (1-hr ave)	34.9	15	10	10	15.7	16
Uc, m/sec @ surface	1.4	.75	.55	.55	.55	.55
Uc, m/sec @ 50m	1.0	.75	.57	.57	.57	.57
Uc, m/sec @ 100 m	0.2	Interpolate	.48	.48	.48	.48
Uc, m/sec @ 150 m	0.2	.55	.41	.41	.41	.41
Uc, m/sec @ 200 m	0.2	.50	.38	.38	.38	.38
Uc, m/sec @ 300 m	0.2	Interpolate	.3	.3	.3	.3
Uc, m/sec @ 1000 m	0.2	0.2	0.2	0.2	0.2	0.2

Note: Design profile is envelope data from Noda data. For operational case I have used mean+2*sigma assuming “worst” is mean+ 3*sigma.



NAVFAC Ocean Thermal Energy Conversion (OTEC) Project

Contract Number N62583-09-C-0083

CDRL A002
OTEC Technology Development Report
Appendix 6-7
Specifications: 4m Gripper and Guides

By

Makai Engineering

OTEC-2010-001

21 September 2010

Prepared for:

Naval Facilities Engineering Command
Naval Facilities Engineering Service Center (NFESC)
1100 23rd Avenue
Port Hueneme, CA 93043-4370
Attn: Mr. Brian Cable, Contracting Officer Representative

Prepared by:

Lockheed Martin MS2
9500 Godwin Drive
Manassas, VA 20110

SPECIFICATIONS – 4m Gripper & Guides

Preface to Technical Specifications

The specification sections that follow apply to the fabrication and assembly of the gripper and guide assemblies for the 4m diameter OTEC pipe handling system. The supplied specification sections are the technical sections (Division 2-16 of the Construction Specifications Institute Master Format). Division 1 General Requirements would need to be added to the supplied specifications sections together with appropriate bid documents in order to properly guide the fabrication and assembly of these components.

TABLE OF CONTENTS

DIVISION 5 - METALS

SECTION 05500 – METAL FABRICATIONS

PART 1 - GENERAL

1.01 SUMMARY

A. Section Includes:

1. Provisions for the fabrication of welded steel gripper assemblies, guide assemblies and all other supporting brackets, pads, and appurtenances.
2. Provisions for all types of metallic fasteners and other hardware used in this project.
3. Provisions for HDPE sheet products used on surface of Pipe Gripper wedge assemblies.

B. Related Sections:

1. Section 09900 - Painting

1.02 GENERAL REQUIREMENTS

Furnish all labor and materials required to complete all metal work as indicated on the drawings and specified herein. Coordinate work with all trades.

1.03 SUBMITTALS

The following submittals are called for in this section and shall adhere to the content and format requirements stated in SECTION 01300:

1. Shop drawings. See Paragraph 3.01 A.
2. Welder certificates signed by Contractor certifying that welders comply with requirements of Paragraph 1.06 C
3. Welding Procedures: Provide written welding procedure specification (WPS) document per AWS Code requirements.

1.04 REFERENCE SPECIFICATIONS

The following publications of the issues listed below or a more recent publication of the same issue form a part of this specification to the extent indicated by the included references to these publications. These publications are referenced in this document by their basic designation number shown below:

A. American Society for Testing and Materials (ASTM):

A36	Structural Steel
A123	Zinc (Hot-Galvanized) Coatings on Iron and Steel Products
A153	Zinc Coating (Hot Dip) On Iron and Steel Hardware
A307	Specification for Carbon Steel Bolts and Studs, 60,000 PSI Tensile Strength
A563	Carbon and Alloy Steel Nuts
A780	Practice for Repair of Damaged and Uncoated Areas of Hot-Dip Galvanized Coatings
D1248	Polyethylene Plastics Extrusion for Wire and Cable
D3350	Polyethylene Pipe and Fittings Materials
F844	Washers, Steel, Plain (Flat), Unhardened for General Use.

B. American Welding Society (AWS)

D1.1	A Structural Welding Code Steel

C. Military Specification (Mil. Spec.)

MIL-A-18001	Anodes, Corrosion Preventative, Zinc; Slab, Disc and Rod Shaped.

D. National Fire Protection Association (NFPA)

101	Life Safety Code

E. Naval Facilities Engineering Command (NAVFAC).

P-307	Management Of Weight Handling Equipment

EM 385-1-1 Safety and Health Requirements Manual

1.05 ORDER OF PRECEDENCE

In the event of a conflict between the text of this specification and the references cited herein, the text of this specification shall take precedence.

1.06 QUALITY ASSURANCE

A. Codes and Standards: Comply with provisions of the following, except as otherwise indicated. Where conflicts occur, comply with the more stringent requirements.

1. AWS D1.1
2. NFPA 101

B. Fabricator Qualifications: Use a firm experienced in successfully producing metal fabrications similar in size and complexity to those shown on the drawings with a minimum of 5 years of documented experience and with sufficient production capacity to produce required units without causing delay in work.

C. Qualify welding processes and welding operators in accordance with AWS D1.1. Provide certification that welders to be employed in work have satisfactorily passed AWS qualification tests within the previous 12 months. If recertification of welders is required, retesting will be Contractor's responsibility.

D. Use of damaged items is prohibited except by specific authorization of the Construction Manager.

E. Shop Assembly:

Fabricated items shall be entirely assembled and tested in the shop to the fullest extent possible to verify proper form, fit and function prior to shipping or prior to installation into the supporting structure. Notify Construction Manager of assembly schedule at least 7 days prior first assembly operations.

1.07 SAFETY:

A. The Occupational Safety and Health Law is applicable to the fabricator and Contractor with regard to the work specified in this Section.

B. Contractor and Fabricator shall follow NAVFAC P-307 crane operation safety hazard.

C. Contractor and Fabricator shall follow NAVFAC EM 385-1-1 safety and health requirements manual.

1.08 DELIVERY, STORAGE AND HANDLING

A. Store materials to permit easy access for inspection and identification.

B. Keep steel members off ground, using pallets, platforms or other supports. Protect steel members from corrosion and deterioration.

C. Do not store materials on structure in a manner that might cause distortion or damage to member or supporting structures.

D. Repair or replace damaged materials or structures as directed.

PART 2 - PRODUCTS

2.01 MATERIALS

A. Structural Steel: Use ASTM A36 steel or equal for all plate, bar and shapes where called for on the plans.

B. Standard Bolts, Nuts and Washers: All bolts and nuts called for in Plans shall be standard bolts and nuts and shall conform to the requirements that follow: Bolts and nuts shall be threaded with American National Coarse thread series.

1. Bolts shall conform to ASTM A307, Grade B or SAE Grade 2. Bolt heads shall be hex heads unless otherwise specified on the Plans.
2. Threaded Rods: ASTM F1554, Grade 36.
3. Nuts shall conform to ASTM A563, Grade A, heavy hex nuts or SAE grade 2 heavy hex nuts.
4. Washers shall conform to ASTM F844

All nuts, bolts, rods and washers shall be hot-dip galvanized as per ASTM A153.

C. Welding Materials: AWS D1.1; Welding electrodes shall be low hydrogen type electrodes compatible with the type of steel welded.

1. An E70 electrode shall be used for all Carbon Steel to Carbon Steel welds.

Weld materials shall match or exceed the base metal in strength

D. High Density Polyethylene Pad

Use high density polyethylene in conformance with ASTM D1248, type IV, Class A, Category 4 with cell classification of 42662A per ASTM D3350. Density shall be 0.95 gm/cm3 and hardness of Shore D 69 or better. Submit sample and associated material specification for approval prior to purchase.

E. Corrosion Preventative Zinc Anodes

All sacrificial zinc anodes shall have a metal composition that is in accordance with U.S. Mil. Spec. A 18001 or better. All zinc anodes shall have a net zinc weight equal to or greater than that called for on the plans and shall be cast around a galvanized steel strap that runs through the length of the anode. Zinc anodes that are mounted against a steel surface shall be standard hull anodes with the steel straps placed off center in the zinc. All other anodes shall have the steel strap centered in the zinc mass. Some anodes require custom steel straps which shall conform to the dimensional details shown on the drawings. All steel straps shall be hot-dip galvanized per ASTM A153 after fabrication and before applying zinc. All anodes shall be supplied by a single manufacturer. Approved supplier is: Harbor Island Supply, Seattle, Washington, 206-628-0413 or others supplying an equal product.

F. Galvanizing Repair Paint:

1. Shall be high zinc dust content paint conforming to ASTM A780 and shall contain a minimum of 94% zinc dust by weight.

PART 3 - EXECUTION

3.01 PREPARATION

A. Shop Drawings:

Submit detailed shop drawings for all fabricated metal components for approval prior to commencing fabrication. Drawings shall include plans, elevations, sections and details of metal fabrications and their connections.

3.02 WELDED CONNECTIONS

A. Welded Connections: Make by direct-current electric arc welding process in hands of certified welders, American Welding Society, (AWS) Structural Welding Code, AWS D1.1 or equivalent.

B. In-General Connections: Unless otherwise indicated by weld symbols on the drawings develop the full strength of members connected and welds shall be continuous; allow no path for seawater to penetrate between the two welded members.

3.03 FABRICATION AND ASSEMBLY

A. Contractor shall verify all dimensions before proceeding and obtain omitted measurements from the Construction Manager for all work required to be accurately fitted to other construction. The Contractor shall be responsible for the accuracy of the finished product.

B. All work shall be fabricated true to shape, size, and tolerances as indicated on the drawings with straight lines, square corners, or smooth bends; free from twists, kinks, warps, dents, and other imperfections.

C. "Fabrication" shall include all operations such as forming, welding, bending, drilling, punching, shearing and any other necessary machine operations. Work shall be fabricated complete or in the largest sections practicable for transport and field assembly. All provisions for field assembly shall be completed in the shop.

D. All welded construction shall comply with appropriate provisions of AWS D1.1 Code.

1. Assemble and weld built-up sections by methods which will prevent warping.

2. Use welding procedures and sequences that prevent locked-in stresses or distortions.

E. All connections will be subject to the Construction Manager review

F. Insofar as practicable, fitting and assembly of the work shall be done in the shop. Work that cannot be permanently shop assembled shall be completely assembled, marked, and disassembled before shipment, to ensure proper assembly in the field.

3.04 FINISH

A. All steel fabrications that can be shall be galvanized after fabrication. It is anticipated that the Pipe Gripper Outer Frames and Pipe Guide Outer Frames will be too large to be hot dip galvanized. These items shall be painted following the requirements of Section 09900.

B. Galvanizing shall be in accordance with ASTM A123 and ASTM A153. "Fabrication" shall include all operations, such as shearing, punching, bending, forming, welding, grinding, drilling, or smoothing. All items that are galvanized shall be smooth and free from projections, barbs, and icicles resulting from the galvanizing process.

C. For those items to be galvanized, the only exception to the galvanize after fabrication requirement is for zinc anodes that are welded to a galvanized steel tabs or the galvanized steel structure for underwater components. Welded connections to zinc anodes need not be galvanized after welding. Instead, the weld area and surrounding heat affected area shall be treated as surfaces to repair per paragraph 3.04 C

D. Galvanized Coating Repair and Touchup: Cleaning and touchup of galvanized coating shall be in accordance with ASTM A780. Thickness of applied galvanizing repair paint shall be not less than coating thickness required by ASTM A123 or A153 as applicable. Touch-up of galvanized surfaces with aerosol spray, silver paint, bright paint, brite paint, or aluminum paints is not acceptable.

3.05 DEMONSTRATION

A. Gripper Assemblies: After fabrication and galvanizing and painting operations are complete, the gripper assemblies shall be fully assembled in the shop or at another designated location. Demonstrate that gripper wedges operate smoothly as intended without binding, galling or hanging up. Installation guidance and tolerances on sliding action of gripper wedges are detailed on the drawings and shall be strictly followed.

END OF SECTION

DIVISION 9 – FINISHES

SECTION 09900 – PAINTING

PART 1 - GENERAL

1.01 SUMMARY

A. Section Includes:

Provisions for preparation and painting of completed steel fabrications too large to be hot dip galvanized, i.e. Pipe Gripper Outer Frame Assemblies and Pipe Guide Outer Frame Assemblies.

B. Related Sections:

1. Section 05500 – Metal Fabrications

1.02 GENERAL REQUIREMENTS

Furnish all labor, materials and equipment required to complete the required preparation and painting called for in the plans and specified herein. Coordinate work with all trades.

1.03 GUARANTEE

A one year guarantee which commences on the date of acceptance against failure of all coatings shall be provided. Failure of any coating during the guarantee period shall be grounds for refund of all coating costs associated with the item on which the failure occurred. Repair by the Contractor shall not be an option unless the item has not yet been put in service.

1.04 REFERENCE SPECIFICATIONS

The following publications of the issues listed below or a more recent publication of the same issue form a part of this specification to the extent indicated by the included references to these publications. These publications are referenced in this document by their basic designation number shown below:

A. Steel Structures Paint Council (SSPC)

SP10-63T	Near White Metal Blast Cleaning

VIS-1	Guide and Reference Photographs for Steel Surfaces Prepared by Dry Abrasive Blast Cleaning
VIS-2	Standard Method of Evaluating Degree of Rusting on Painted Steel Surfaces

Unless otherwise specified, all work and materials for the preparation and coating of all metal surfaces shall conform to the applicable requirements specified in the *Steel Structures Painting Manual, Volume 2, Systems and Specifications*, latest edition.

1.05 ORDER OF PRECEDENCE

In the event of a conflict between the text of this specification and the references cited herein, the text of this specification shall take precedence.

1.06 QUALITY ASSURANCE

Evaluation of surface preparation for ferrous metal will be based upon SSPC-VIS 1 and VIS 2. To facilitate inspection, the Contractor shall, on the first day of sandblasting operations, sandblast metal panels to the degree called for in this Section. After mutually agreeing that a specific panel meets the requirements of the Specification, the panel shall be initialed by the Contractor and Engineer and then coated with a clear non-yelling finish. Panels shall be maintained and utilized by the Engineer throughout the duration of sandblasting operations.

1.07 ENVIRONMENTAL COMPLIANCE

Contractor shall comply with all current federal, state and local environmental laws and regulations, including, but not limited to the laws and regulations of the US Environmental Protection Agency (USEPA).

1.08 SUBMITTALS

The following submittals are called for in this section and shall adhere to the content and format requirements stated in SECTION 01300:

A. Samples

For compliance with these Specifications, the Contractor shall prepare and submit three paint and protective coating samples of the finish to be used on the steel fabrications. These samples shall include all coats of the specified finish. Submit to Engineer for review. The samples shall be clearly marked with the manufacturer’s name and product identification and shall be submitted in sufficient time to allow for review, and if necessary, resubmittal without causing delay of the Work.

B. Coating Materials List

The Contractor shall provide a copy of the paint and coating materials list with indicates the manufacturer and paint number for approval at the time of submittal of the samples required herein.

C. Product Data Sheets and Material Safety Data Sheets

Contractor shall submit paint and coatings material manufacturers' printed technical data sheets for products intended for use. Data sheets shall fully describe material as to its intended use, make-up, recommended surface preparation and application conditions, primers, materials mixing and application (recommended dry mil thickness), precautions, safety and maintenance cleaning directions.

1.09 PROTECTION OF WORK

The Contractor shall be responsible for any and all damage to his Work or the work of others during the time his Work is in progress.

1.10 RIGHT OF REJECTION

The Engineer shall have the right to reject all material or Work that is unsatisfactory and require the replacement of either or both at the expense of the Contractor.

PART 2 - PRODUCTS

2.01 MATERIALS

A. General

1. Surfaces to receive paint protective coating materials as herein specified shall be coated in conformance with the applicable coating systems specified herein. All materials specified by name and/or manufacturer or selected for use under these Specifications shall be delived unopened at the job site in their original containers and shall not be opened until inspected by the Engineer. Whenever a manufacturer's brand name is specified, it is intended to define the general type and quality of paint or coating desired. Other coatings or paints of equal quality may be used subject to Engineer's approval. In so.far as is possible, all paint and coating materials shall be provided by a single source supplier.

B. Paint and Coating Materials

1. Paint and protective coatings materials shall be sealed in containers that plainly show the designated name, formula, batch number, color, date of manufacture, manufacturer's directions and name of manufacturer, all of which shall be plainly legible at the time of use. Pigmented paints shall be furnished in containers not larger than five gallons.
2. Compatibility: Only compatible materials shall be used in the Work. Particular attention shall be directed to compatibility of primers and finish coats. If necessary, subject to review of the Engineer, a compatible barrier coat shall be applied between all existing prime coats and subsequent field coats to ensure compatibility.
3. Colors: All colors and shades of colrs of all coats of paints and protective coating materials shall be as selected by the Engineer. Each coat shall be of a slightly different shade, as directed by Engineer, to facilitate inspection of surface coverage of each coat.
4. Surface Preparation: All metal surfaces shall be field sandblasted in accordance with SSPC-SP10. An anchor profile of no less than 2 mils, as determined by a profile comparator, shall be attained. Weld surface, edges and sharp corners shall be ground to a curve and all weld splatter removed, and all welds neutralized with thinner.
5. Application: Application shall be instruct conformance with the manufacturer's printed recommendations. All sharp edges, nuts, bolts or other items difficult to coat shall receive a brush-applied coat of the specified coating prior to application of each coat.
6. Coating System: Except as otherwise noted, the prime coat shall have minimum dry film thickness of 8mils and the final coat 8 mils. The total system shall have minimum dry film thickness of 16 mils.
    a. Carboline System: Primer – Carboguard 890

       Final – Carboguard 890

PART 3 - EXECUTION

3.01 PREPARATION FOR PAINTING AND PROTECTIVE COATING

A. All surfaces to receive paint and protective coatings shall be cleaned as specified herein prior to application of coating materials. The Contractor shall examine all surfaces to be coated, and shall correct all surface defects before application of any coating material. Beginning the Work of this Section without reporting unsuitable conditions to the Engineer constitutes acceptance of conditions by the Contractor. Any required removal, repair, or replacement of the Work caused by unsuitable conditions shall be done at no additional cost to the Engineer.

B. Items Not To Be Coated

Hardware, hardware accessories, nameplate data tags, machined surfaces and similar items in contact with coated surfaces not to be coated shall be removed or masked prior to surface preparation and painting operations. Following completion of coating of each piece, removed items shall be reinstalled. Such removal and installation shall be done by workmen skilled in the trades involved.

C. Sandblasting

1. All sandblasting shall be done in strict accordance with the referenced specifications of the Steel Structures Painting Council.

2. When items are to be shop primed or shop primed and finish coated in the shop, surface preparation shall be as specified in this Section. The Engineer shall have the right to witness, inspect, and reject any sandblasting done in the shop.

3. When sandblasting is done in the field, care shall be taken to prevent damage to structures and equipment. Pumps, motors, and other equipment shall be shielded, covered, or otherwise protected to prevent the entrance of sand. No sandblasting may begin before the Engineer inspects and reviews the protective measures.

4. After sandblasting, dust and spent sand shall be removed from the surfaces by brushing or vacuum cleaning.

3.02 APPLICATION

A. Manufacturer's Recommendations

Unless otherwise specified herein, the paint and coating manufacturer's printed recommendations and instructions for thinning, mixing, handling, applying, and protection of his coating materials; for preparation of surfaces for coating; and for all other procedures relative to coating shall be strictly observed. No substitutions or other deviations shall be permitted without written permission of the Engineer.

B. Delivery and Storage

Materials shall be delivered in manufacturer's original, sealed containers, with labels and tags intact. Coating containers shall be opened only when required for use. Coatings shall be mixed only in the presence of the Engineer. Coating shall be thoroughly stirred or agitated to uniformly smooth consistency and prepared and handled in a manner to prevent deterioration and inclusion of foreign matter. Unless otherwise specified or reviewed, no materials shall be reduced, changed, or used except in accordance with the manufacturer's label or tag on container.

C. Safety Requirements

1. Contractor shall follow NAVFAC EM 385-1-1 safety and health requirements manual.

2. The Occupational Safety and Health Act is applicable to the Contractor with regard to the work specified in this Section.

   a. Protective Equipment. Respirators shall be worn by all persons engaged in, and assisting in, spray painting. In addition, workers engaged in or near the Work during sandblasting shall wear eye and face protection devices meeting the requirements of ANSI Z87.l latest revision, and approved OSHA Regulations for sandblasting operations and approved air-purifying, half-mask or mouthpiece respirator with appropriate filter.

   b. Ventilation. Where ventilation is used to control potential exposure to workers as set forth in OSHA Regulations for Construction, ventilation shall be adequate to reduce the concentration of the air contaminant to the degree that a hazard to the worker does not exist. Methods of ventilation shall meet the requirements set forth in ANSI Z9.2, latest revision.

   c. Sound Levels. Whenever the occupational noise exposure exceeds the maximum allowable sound levels as set forth in OSHA Regulations for Construction, ear protective devices shall be furnished and used. Ear protective devices inserted in the ear shall be fitted or determined individually, by competent persons. Plain cotton is not an acceptable protective device.

   d. Storage and mixing of coating materials shall be performed only in those areas specifically designated for these activities.

    e. Cloths and cotton waste that might constitute a fire hazard shall be placed in closed metal containers or destroyed at the end of each work day.

D. Storage, Mixing, And Thinning

Paint and coating materials shall be protected from exposure to cold weather, and shall be thoroughly stirred, strained, and kept at a uniform consistency during application. Materials of different manufacturers shall not be mixed together. Packaged materials may be thinned immediately prior to application in accordance with the manufacturer's directions.

E. Workmanship

1. Skilled craftsmen and experienced supervision shall be used on all Work.
2. All paint and coatings shall be applied in a workmanlike manner so as to produce an even film of specified uniform thickness. Edges, corners, crevices, and joints shall receive special attention to ensure that they have been thoroughly cleaned and that they receive an adequate thickness of paint. The finished surfaces shall be free from runs, drops, ridges, waves, laps, brush marks, and variations in color, texture, and finish. The hiding shall be so complete that the addition of another coat of paint would not increase the hiding. All coats shall be applied so as to produce a film of uniform thickness. Special attention shall be given to ensure that edges, corners, crevices, welds, and similar areas receive a film thickness equivalent to adjacent areas, and installations shall be protected by the use of drop cloths or other approved precautionary measures.

F. Application of Field Coatings

1. Except where in conflict with the manufacturer's printed instructions, or where otherwise specified herein, the Contractor may use brush, roller, air spray, or so-called airless spray application; however, any spray painting must first have the approval of the Engineer. Areas inaccessible to spray coating or rolling shall be coated by brushing or other suitable means.
2. The Contractor shall give special attention to the Work to ensure that edges, corners, crevices, welds, bolts, and other areas, as determined by the Engineer, receive a film thickness at least equivalent to that of adjacent coated surfaces.
3. All protective coating materials shall be applied in strict accordance with the manufacturer's printed instructions.

4. Prime coat shall be applied to all clean surfaces within a four hour period of the cleaning, and prior to deterioration or oxidation of the surface, and in accordance with the manufacturer's recommendations. Drift from sandblasting procedures shall not be allowed to settle on freshly painted surfaces.

5. All coatings shall be applied in dry and dust-free environment, and unless otherwise directed by the Engineer, shall not be applied when the air temperature or the temperature of the surface to be painted is outside the range of 50 degrees F to 90 degrees F.

6. Each coat shall be applied evenly, at the proper consistency, and free of brush marks, sags, runs, and other evidence of poor workmanship. Care shall be exercised to avoid lapping paint on glass or hardware. Coatings shall be sharply cut to lines. Finished coated surfaces shall be free from defects or blemishes. Protective coverings shall be used to protect floors,

7. fixtures, and equipment. Care shall be exercised to prevent paint from being spattered onto surfaces from which such paint cannot be removed satisfactorily. Surfaces from which paint cannot be removed satisfactorily shall be painted or repainted as required to produce a finish satisfactory to the Engineer. Whenever two (2) coats of a dark colored paint are specified, the two (2) coatings shall be of a contrasting color.

8. Interior surfaces and all contact surfaces inaccessible after assembly, shall be coated before erection; however, no structural friction connections or high tensile bolts and nuts shall be painted before erection. Areas damaged during erection shall be hand or power-tool cleaned and recoated with prime coat.

9. Touch-up of all surfaces shall be performed after installation.

10. All surfaces to be coated shall be clean and dry at the time of application.

G. Time of Coating

1. Sufficient time shall be allowed to elapse between successive coats to permit satisfactory recoating, but, once commenced, the entire coating operation shall be completed without delay. No additional coating of any structure, equipment, or other item designated to be painted shall be undertaken without specific permission of the Engineer until the previous coating has been completed for the entire structure, piece of equipment, or other item.

2. Piping shall not be finish coated until it has been pressure-tested and approved.

H. Thickness of Coating. The dry film mil-thickness specified shall be achieved and verified for each coat.

3.03 TESTING AND INSPECTION

A. Inspection Devices. The Contractor shall furnish, until final acceptance of coating and painting, inspection devices in good working condition for detection of holidays and measurement of dry-film thickness of coatings and paints. The Contractor shall also furnish U.S. Department of Commerce, National Bureau of Standards certified thickness calibration plates to test the accuracy of dry-film thickness gauge and certified instrumentation to test accuracy. Dry-film thickness gauges shall be made available for the Inspector's use at all times until final acceptance of application. Holiday detection devices shall be operated in the presence of the Inspector. Inspection devices shall be operated in accordance with the manufacturer's instructions at the direction of the Engineer or the Engineer's Representative.

B. The Contractor shall conduct film thickness measurements and electrical inspection of the coated surfaces with equipment furnished by him and shall recoat and repair as necessary for compliance with the Specifications.

C. After repaired and recoated ferrous metals areas have cured, final inspection tests will be conducted by the Engineer or the Engineer's Representative. Coating thicknesses specified in mils on ferrous substrates will be measured with a nondestructive magnetic type dry-film thickness gauge such as the Elcometer, manufactured by Gardner Laboratories, Inc. Discontinuities, voids and pinholes in the coatings will be determined with a nondestructive type electrical holiday detector. Epoxy coatings and other thin film coatings will be checked for discontinuities and voids with a low voltage detector of the wet-sponge type, such as Model Ml as manufactured by Tinker and Rasor. Use a non-sudsing type wetting agent, such as Kodak Photo-Flo, which shall be added to the water prior to wetting the sponge. All pinholes shall be marked, repaired in accordance with the manufacturer's printed recommendations and retested. No pinholes or other irregularities will be permitted. Wide film thickness discrepancies shall be measured and verified with a micrometer or other approved measuring instrument. Coatings not in compliance with the Specifications will not be acceptable and shall be replaced and re-inspected at Contractor's expense until the Specifications are met.

D. Warranty Inspection. Warranty inspection shall be conducted during the tenth month following completion of all coating and painting Work. Coating costs for all defective Work shall be refunded to the Owner, or if the item has not yet been put into service is shall be repaired in accordance with this Specification and to the satisfaction of the Engineer or his appointed representative.

3.04 CLEAN UP

A. Upon completion of the Work, staging, scaffolding, and containers shall be removed from the site or destroyed in an approved manner. Paint spots, oil, or stains upon adjacent surfaces shall be removed.

B. The Contractor shall clean the site in accordance with the requirements for "Cleaning Up" in the General Conditions.

END OF SECTION

DIVISION 11 - EQUIPMENT

SECTION 11501 – SPECIAL COMPONENTS AND BAGS

PART 1 - GENERAL

1.01 SUMMARY

A. Section Includes:

1. Provisions for rubber friction layers (Pipe Gripper Assemblies);
2. Provisions for gel bags (Pipe Gripper and Pipe Guide Assemblies);
3. Provisions for water bags (Pipe Guide Assemblies);
4. Provisions for low friction layer (Pipe Guide Assemblies);

1.02 GENERAL REQUIREMENTS

Furnish all labor, materials and equipment required to complete all fabrication, testing and assembly work of all components listed in Paragraph 1.01 A based on the drawings and requirements specified herein. This specification provides performance specifications for these components.

1.03 SUBMITTALS

The following submittals are called for in this section and shall adhere to the content and format requirements stated in SECTION 01300:

1. Shop drawings.
2. Component Samples.
3. Test Plans
4. Test Results

1.04 REFERENCE SPECIFICATIONS

The following publications of the issues listed below or a more recent publication of the same issue form a part of this specification to the extent indicated by the included references to these publications. These publications are referenced in this document by their basic designation number shown below:

A. American Society for Testing and Materials (ASTM):

D412	Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension

1.05 ORDER OF PRECEDENCE

In the event of a conflict between the text of this specification and the references cited herein, the text of this specification shall take precedence.

1.06 QUALITY ASSURANCE

A. Manufacturer’s Qualifications:

1. Friction Layers: Rubber friction layer fabricator shall have a minimum of 5 years experienced in fabrication of custom rubber products containing embedded steel, Kevlar or other cordage products for reinforcement. Fabricator shall have facilities with equipment of the size and capacity to fabricate the rubber friction layer components without delaying the project schedule. Submit fabricator’s experience record, product line information, name and resume of lead technical representative and contact information to the Engineer with bid documents.
2. Gel Bags and Water bags: Use a firm experienced in successfully producing waterproof bags of similar complexity and in sizes comparable to those shown on the drawings with a minimum of 5 years of documented experience. Submit fabricator’s experience record, product line information, name and resume of lead technical representative and contact information to the Engineer with bid documents.
3. Low Friction Guide Fabric: Use a firm experienced in successfully producing fabric of the type, style and size comparable to those shown on the drawings with a minimum of 5 years of documented experience. Submit fabricator’s experience record, product line information, name and resume of lead technical representative and contact information to the Engineer with bid documents.

1.07 DELIVERY, STORAGE AND HANDLING

A. Store materials to permit easy access for inspection and identification.

B. Store manufactured elements in a manner to protect them from deterioration.

C. All damaged units shall be replaced as directed.

PART 2 - PRODUCTS

2.01 MANUFACTURED UNITS

A. Rubber Friction Layer

1. Design Requirements:
    a. Contractor and his selected rubber fabricator shall be responsible for detailed design, fabrication and delivery of the rubber friction layer components to be used in the OTEC pipe gripper assemblies.
    b. Fabricator shall work out design based on Performance Requirements (below) and shall submit detailed shop drawings, supporting material specifications, samples and test data as required.
2. Performance Requirements:

a. The overall function of the rubber friction layer within the OTEC pipe gripper is to contact the pipeline uniformly, and when subjected to a uniform interfacial pressure of 50 psi, provide the high friction surface needed to securely support the entire weight of the Fiberglass Reinforced Plastic (FRP) OTEC pipe.

b. Dimensions: Match dimensional requirements shown in the drawings. Friction layers shall be preformed to match the outer radius of the OTEC pipe and shall be fabricated and cured in the final shape.

c. Friction Layer Design Concept:

   (i) Since the gel pad behind the friction layer transmits normal pressure but does not transmit shear load, all the frictional force between the pipe and the friction layer ends up as tension at the top of the friction layer.

   (ii) The vertical tension is carried by Kevlar or steel tension members embedded in the rubber. These tension members take the entire vertical tensile load and provide high vertical stiffness with very low elongation. Kevlar is the preferred strength member.

   (iii) The rubber friction layer in direct contact with the pipeline is unreinforced for the first 1.5” of thickness. The outer 0.5” of the friction layer has embedded tension layers with uniform distribution and strength over the full width and height of the friction layer.

d. Expected Loading (all per inch loads refer to per inch of circumference measured at outer pipe diameter)

   (i) The OTEC pipeline’s maximum weight is 651,880 lbs.

   (ii) Vertical Tension: Linearly varies from 200 lbs/inch at the bottom of the friction layer to 2500 lbs/inch max at the top

   (iii) Normal radial Pressure: 50 psi

   (iv) Horizontal Tension: 500 lbs/inch

e. Desired Safety Factors

   (i) Vertical tension at yield: Minimum 14,000 lbs/inch

   (ii) Horizontal tension safety factor: 2 = 1000 lbs/inch

f. Elasticity: Performance is based on the stiffness of the friction layer reinforcement. Maximum elasticity is 0.2% strain at 1550 lbs/inch load.

g. Operate in marine environment (seawater spray) without degradation for a minimum a one year operational life.

h. Rubber Compound: shall have the following additional characteristics:

(i)	Tensile strength:	3400 psi	ASTM D412
(ii)	Elongation:	580%	ASTM D412
(iii)	300% Modulus:	1375 psi	ASTM D412
(iv)	Durometer:	63±5	Shore A Scale

    i. Attachment: A reliable termination of the tension layer at the top of the friction layer is required to support expected tension loads. The drawings indicate a concept in which the tension members are wrapped about a horizontal bar and clamped secure with the whole termination coated in rubber. A similar design is used at the bottom of the friction layer. The termination design may be modified by the rubber manufacturer subject to the approval of the Engineer. Include alternate design in shop drawing submittal.

  3. Products

    a. Rubber: Use Natural Rubber Compound 1195D from Stockton Rubber of Linden, CA (209) 887-1172 or proven equal. If Contractor intends to use alternate rubber compounds in rubber friction layer, submit minimum of 3 each 6-inch square by 1” thick samples to Engineer for testing and approval before incorporation of different rubber into the friction layer design.

    b. Tension members: Steel, Kevlar, or Carbon Fiber are acceptable tension members. Placement and fiber diameter shall not significantly restrict flexibility of the rubber friction layer. Submit designs and samples to Engineer for approval.

B. Gel Bags

  1. Purpose:

    a. The OTEC pipe Gripper assemblies each have 12 frictional layers in contact with the pipe and outside of each of these layers is a Gripper Gel Bag. The purpose of this soft gel bag is to act as a “waterbed” and to evenly distribute the gripper assembly’s force over the surface of the FRP OTEC pipeline being held.

    b. At each of the 12 water bag positions in the lower pipe guide, two bags: one water bag and a second one that is gel filled, have been used. The Guide Gel Bag provides protection to the pipe to keep it from contacting additional steel framing members that are positioned relative close to the pipe and which could contact the pipe if a water bag alone was used.

  2. Design Requirements:

a. Contractor and his selected gel bag fabricator shall be responsible for detailed design, fabrication and delivery of the gel bag components to be used in the OTEC pipe gripper assemblies.

b. Fabricator shall work out design based on Performance Requirements (below) and shall submit detailed shop drawings, supporting material specifications, samples and test data as required.

3. Performance Requirements:

a. Functional Requirements: The gel bags in the gripper assemblies shall:

   (i) consist of a waterproof fabric outer layer and a gel interior,

   (ii) be waterproof – at seams and throughout the fabric such that no gel can extrude through the fabric or at the seams,

   (iii) adhere to the gel and support the gel to maintain its shape when the gripper wedges are retracted and the bag is not loaded in compression,

   (iv) provide attachment tabs in locations indicated on the drawings for connecting the pad to the face of the steel wedge.

   (v) transfer the squeezing force from the steel wedges, which when activated, provide a radial force to the back of the friction layer. The force is distributed over the surface of the pipe as an even pressure.

   (vi) withstand operational abrasion between the steel face of the gripper inner wedge surface and the back of the friction layer.

   (vii) when filled, constrain the gel such that the radial stiffness of the filled containment bag is high based on a nearly incompressible gel and a low elasticity outer surface layer.

b. Gel bag shall be fabricated from a waterproof fabric and shall have waterproof seams so no leakage or gel extrusion occurs at 50 psi working pressure. The gel bag fabric shall be able to sustain a maximum pressure of 100 psi without leakage or damage.

c. Filled gel bag’s overall specific gravity shall equal approximately 1.

d. Vertical tension: Gel and bag combination shall support its own weight when not compressed and the gel shall not flow to the bottom of the bag.

e. Gripper Gel Bag Fabric tension: 500 lbs/inch design minimum in all directions, (100 lbs/inch working) for the 4” thick Gripper Gel Bags.

f. Guide Gel Bag Fabric tension: 750 lbs/inch design minimum in all directions, (150 lbs/inch working) for the 6” thick Guide Gel Bags.

g. Fabric elasticity: The elasticity of the bag layer shall be less than or equal to nylon fabric at the above design loads.

h. Gel bags shall operate in a marine environment (seawater spray) without degradation for a minimum one year operational life.

4. Products

a. Gel: The gel bag shall contain a very low shear strength urethane that flows around pipe irregularities and pipe surface distortion. Use a polyurethane gel with a Shore OO hardness value of between 1 and 5 and modulus of elasticity of 0.5 psi. Ideal samples have been produced using Northstar Polymer SAI-1 polyurethane gel using the following mixing ratio (by weight.)

Part A	Part B	Plasticizer
1	8	5

Use this polyurethane gel from Northstar Polymers LLC of Minneapolis, MN (612-721-2911) or an approved equal. In all cases, submit minimum six fully cured gel samples (1-1/4 inch diameter x 1-1/2” tall cylindrical samples) to Engineer for approval prior to purchasing gel.

b. Fabric layer: The fabric layer can be rubber or polyurethane coated woven nylon fabric or suppliers recommended equivalent to meet the above criteria.

C. Water Bags

1. Purpose:

a. The OTEC pipe guide assemblies each have an inner circumferential pressure distribution layer made up of 12 separate water filled bags covered by a separate low friction layer fabric surface. The purpose of this soft bag is to act as a “waterbed” and to evenly distribute the guide assembly’s force over the surface of the FRP OTEC pipeline passing through it. The low friction layer fabric overlaying these bags (next section) allows the pipe to slide through the guide without dragging on the bags. The upper and lower guide water bags are different dimensions.

2. Design Requirements:

a. Contractor and his selected water bag fabricator shall be responsible for detailed design, fabrication and delivery of the waterbed and gel bag components to be used in the OTEC pipe guide assemblies.

b. Fabricator shall work out design based on Performance Requirements (below) and shall submit detailed shop drawings, supporting material specifications, samples and test data as required.

3. Performance Requirements

   a. The Water bags (waterbed type and gel filled type) shall meet the same performance requirements as the gel bags described in paragraph 1.06 B.2 except for additions and modifications included below:

      (i) Water bags shall provide a uniform radial pressure on the pipeline,.

      (ii) The water bags shall water that flows around pipe wall irregularities.

      (iii) The water bags shall operate in a marine environment (underwater, 82' deep max) and with seawater inside and without degradation for a minimum one year operational life.

      (iv) The water bag is a water-filled bladder that allows bag volume adjustment by means of a set of valved ports on the bag. The pad thickness can be adjusted and made snug on the pipeline.

         - The water fill and volume adjustment valve shall be at the bottom of each water bag going through the steel guide frame as shown on the drawings.
         - One or more manually operated vent ports shall be located at the top of each water bag so air can be purged from the bag.

      (v) The water bag outer layer shall be nylon or other fabric that: provides an attachment tabs in locations indicated on the drawings for connecting the bag to the steel guide frame.

      (vi) The water bag working pressure shall be 50 psi. Bags shall be safe at 200 psi sudden burst pressure at the filled thickness dimensions shown in the drawings and when sandwiched between Guide and Guide Fabric as shown in the drawings .

      (vii) Bag fabric tension: The fabric and seams shall have a factor of at least 5 on the working loads specified below.

         - Upper Guides: max 200 lbs/inch working for 8" thick upper water bags;
         - Lower Guides: max 50 lbs/inch working for 2" thick lower guide water filled

      (viii) Fabric elasticity: The elasticity of the bag layer shall be less than or equal to nylon fabric at the above design loads.

4. Products:

        a. Fabric layer: The fabric layer can be rubber or polyurethane coated woven nylon fabric or suppliers recommended equivalent to meet the above criteria.

D. <u>Guide Slide Layer</u>

1. Purpose
    a. The overall function of the Guide Slide Layer is to serve as a low-friction and high-abrasion layer covering the Guide Water bags. This layer is in direct contact with the FRP pipeline and is submerged in seawater.
    b. Contact the pipeline uniformly and provide a low friction surface underwater within the Guides.
    c. Operate in seawater without degradation – lifetime one year.
    d. Withstand the abrasion as the pipe slips over the surface.
    e. Withstand the tension resulting from the accumulated friction forces.
    f. Flexible to flow over bumps and irregularities in the pipeline.
2. Design Requirements:
    a. Contractor and his selected guide fabric fabricator shall be responsible for detailed design, fabrication and delivery of the low friction guide fabric components to be used in the OTEC pipe guide assemblies.
    b. Fabricator shall work out design based on performance requirements (below) and shall submit detailed shop drawings, supporting material specifications, samples and test data as required.
3. Performance Requirements
    a. Guide fabric shall be manufactured to the dimensions and shall be provided with the attachment mechanisms shown on the drawings.
    b. Dimensions per the drawings – upper and lower guide glide layers are different.
    c. Glide layers shall be formed and molded to fit the shape as shown on the drawings.
    d. Thickness: as needed for abrasion and strength - 0.5” anticipated.
    e. Normal pressure: 2-10 psi normal, 50 psi max
    f. Desired Coefficient of friction: < 0.2 FRP on guide underwater; see testing and products below.
    g. Vertical tension: maximum 1800 lbs/inch.
    h. Vertical tension at yield: 5x safety factor –9000 lbs/inch

    i. Horizontal tension: 500 lbs/inch working; 2x safety factor = 1000 lbs/inch design.

4. Products:
   a. Low Friction Guide Fabric: A polyurethane or hard rubber coated fabric with reinforcement with Kevlar fibers shall be used or an approved equal.
   b. Contractor shall submit minimum of 3 each 6-inch square samples to Engineer for testing and approval before incorporation into the design. Engineer will verify whether the coating has a coefficient of friction, when wet, of 0.2 or less on the FRP pipeline.

PART 3 - EXECUTION

3.01 PREPARATION

A. Shop Drawings:

Submit detailed shop drawings for all manufactured items for approval prior to commencing fabrication.

B. Samples:

Submit samples of all components to be used in manufactured items specified in this section together with manufacturer’s data sheets. Obtain Engineer’s approval before incorporating any components into manufactured items.

C. Fabrication

1. Gel Bag
   a. Supplier shall fill the gel bag with gel as follows:
      (i) The bag shall be completely evacuated with a vacuum pump prior to adding liquid gel compound.
      (ii) The bag shall be placed in a curved form with an inner and outer radius wall representing the final assembly walls of the gripper or guides and the pipe. These walls will restrict and make uniform the thickness of the gel bag.
      (iii) Apply a vacuum to the liquid gel mixture to eliminate all bubbles from the polyurethane.
      (iv) Fill the bag at a minimum of 4 psi liquid polyurethane and leave that pressure as the gel cures.
      (v) There shall be no air pockets in the gel-filled bag.

D. Tests

1. Friction Layer

   a. Supplier shall manufacture and test a 2' wide x 10' long sample representative of the friction layer with a design beaded termination at either end for (1) withstanding 10,000 lbs vertical tension / inch of width; (2) demonstrate ability to carry 125 psi surface shear without separation in the rubber and tension member layers; (3) 500 lbs/inch horizontal tension – all without permanent damage or deformation. Supplier shall also demonstrate that the elasticity of the sample is less than or equal to 0.5% strain at 1550 lbs/inch of sample width and vertically pull test the sample to failure to demonstrate the failure mode.

2. Gel Bag
   a. Supplier shall demonstrate on a sample of the fabric that the fabric meets the tension and elasticity needs of these specifications.
   b. Supplier shall test and demonstrate the fabric's and seam's ability to withstand leaks at the pressures specified.
   c. Supplier shall inflate each completed bag with air prior to adding gel and perform a leak test with soapy water.
   d. Supplier shall vertically support one completed bag to demonstrate gel adhesion and vertical support tabs.
3. Water Bag
   a. Supplier shall demonstrate on a sample of the fabric that the fabric meets the tension and elasticity needs of these specifications.
   b. Supplier shall test and demonstrate the fabric's and seam's ability to withstand leaks at the pressures specified.
   c. Supplier shall inflate each completed bag with air and perform a leak test with soapy water.
4. Glide Layer
   a. Supplier shall manufacture and test a 2' wide x 10' long sample representative of the glide layer with a design beaded termination at either end for (1) withstanding 7,500 lbs vertical tension / inch of width; (2) demonstrate ability to carry 125 psi surface shear without separation in the coating and tension member layers; (3) 500 lbs/inch horizontal tension – all without permanent damage or deformation. The supplier shall also vertically pull test the sample to failure to demonstrate the failure mode.

END OF SECTION

DIVISION 13 – SPECIAL CONSTRUCTION

SECTION 13400 – INDUSTRIAL AND PROCESS CONTROL SYSTEMS

PART 1 - GENERAL

1.01 SUMMARY

A. Section Includes:

1. Provisions for hydraulic (fluid power) systems used as OTEC pipe gripper controls;
2. Provisions for computerized controls and associated instruments;

1.02 GENERAL REQUIREMENTS

Furnish all labor, materials and equipment required to complete the design, component selection and installation of all hydraulic-fluid power controls, instrumentation and control system hardware and software as indicated on the drawings and specified herein. This shall include software debugging, demonstration of proper control system operation and training of Owner's operating workforce. Coordinate work with all trades.

1.03 SUBMITTALS

The following submittals are called for in this section and shall adhere to the content and format requirements stated in SECTION 01300:

1. Qualifications of personnel
2. Shop Drawings
3. Component specifications, details and catalog cuts
4. Control logic program flow and final programming
5. Control screen and description of the user interface

1.04 QUALITY ASSURANCE

A. Qualifications:

1. Fluid Power System Designer: Contractor shall employ an individual who is a recognized authority in fluid power circuit design, implementation, testing and trouble-shooting. This Fluid Power System Designer shall

have full responsibility for the design, component selection, oversight of fabrication and assembly, testing, troubleshooting and subsequent corrections as necessary for all hydraulic power circuits used in this project.

   a. The Fluid Power System Designer may be an employee of the Contractor, a consulting firm or individual consultant, but in all cases the Designer shall have the following minimum qualifications:

      (i) Registered Professional Engineer

      (ii) Minimum of 8 years of work experience as a fluid power circuit designer/developer, or 4 years work experience in fluid power circuit design and an additional 8 or more years experience in related technical positions in fluid power and motion control industry.

      (iii) Certification by the International Fluid Power Society (IFPS) as Fluid Power Engineer (preferred) or at minimum as Fluid Power Specialist.

   b. Submit qualifications and experience record together with contact information for fluid power design consultant for approval with bid documents.

2. Control System Designer/Integrator: Contractor shall employ a control system designer/integrator who is highly experienced and industry certified at the highest level in control system design and in control software programming. This individual shall have full responsibility for designing, specifying components, implementing, assembling and testing the control system for the OTEC pipe grippers and guides. He shall remain on task through testing, troubleshooting, subsequent corrections of the control system and training of Owner's personnel in operation of same.

   a. The Control System Designer/Integrator may be an employee of the Contractor, a consulting firm or individual consultant, but in all cases shall have demonstrated skills and experience in the following areas:

      (i) control systems design, programming, and systems integration with a strong understanding of open loop and closed loop control systems,

      (ii) electrical circuit design, control systems integration and architectures, PLC's, and motion control systems,

        - (iii) Development of process control applications utilizing Programmable Logic Controllers (PLC), Distributed Control Systems(DCS), Human Machine Interfaces (HMI) and Supervisory Control and Data Acquisition systems (Scada),
        - (iv) specification, selection and integration of instruments to meet control system needs,
        - (v) ability to troubleshoot equipment and process problems through process experimentation and data analysis,
        - (vi) and ability to work with the Fluid Power System Designer and provide system integration role for the entire control system.
    - b. Submit qualifications and experience record together with contact information for the Control System Designer/Integrator for approval with bid documents.

1.05 SYSTEM DESCRIPTION

A. Design Requirements – Overall Control System

1. This section describes the requirements for the design of the entire control system and the application programming (in general terms) required for the Work.
2. The Control System shall include:
    - a. the complete fluid power system design together with all required materials and equipment such as valves, rams, sensors, hoses, manifolds and appurtenances needed for its proper operation,
    - b. and the control system which is made up the programmable logic controller (PLC), input/output (I/O) equipment, operator interface (SCADA) equipment, all networking and communication equipment and devices, accessories, programming, and appurtenances required for its proper operation.
3. The control system shall be designed, coordinated, and supplied by a single approved Control System Designer/Integrator working in conjunction with an approved Fluid Power System Designer.
4. The control system shall be consist of PLC and SCADA operator interface graphic display application programs and hardware needed to direct the

fluid power components to perform the functional requirements specified and described in this Section and attached Appendices.

5. The Contractor shall guarantee the suitability of the complete control system to meet the functional control requirements for the OTEC pipe gripper control system with high reliability.

6. The Control System Designer/Integrator and the Fluid Power System Designer shall direct and oversee the purchase, assembly and onboard installation of their respective instrumentation and control components and shall troubleshoot and repair any deficiencies in the system until the Engineer is satisfied that it meets the control requirements stated in this Section.

B. Performance Requirements

1. An illustrated explanation of the overall operational goals and stepwise performance of the OTEC pipe gripper control system are included in Appendix 1 of these specifications. This document includes:

    a. An introduction of the gripper components and their location.

    b. An introduction of the various pressure sensors and positional sensors to be used to provide feedback within the gripper control system,

    c. Fluid power circuit definitions with identification of the valves, cylinders and sensors preliminary selected for use by the Designer.

    d. and a detailed 13 step description of a complete cycling of the two grippers and lowering hydraulics needed to safely and controllably lower the OTEC pipe.

2. Appendix 1 shall be the primary guidance to the detailed technical design of the OTEC pipe gripper control system including the fluid power systems.

3. The primary electronic control system components will be housed in an air conditioned space control room on board a floating semi-submersible platform at sea. The control system PLC, computers and other IC components shall be ruggedly constructed to withstand motions, vibrations and accelerations associated with vessels at sea.

4. Sensors, wiring and fluid powered rams, valves and circuit components not located with the control room shall be selected to operate in a marine

environment (seawater spray and, in some cases, underwater) without degradation for at minimum a two year operational life.

5. The control system shall be complete including all required sensors, field preamplifiers, signal conditioners, offset and span adjustments, amplifiers, transducers, transmitters, control devices, engineering units conversions and algorithms for desired applications and shall maintain the specified end-to-end process control loop accuracy from sensor to display and final control element.

1.06 DELIVERY, STORAGE AND HANDLING

A. Store materials to permit easy access for inspection and identification.

B. Store manufactured elements in a manner to protect them from deterioration.

C. All damaged units shall be replaced as directed.

PART 2 - PRODUCTS

2.01 EQUIPMENT

A. General

1. Use equipment meeting the recognized U.S. or international standards and manufactured as a standard product by an established equipment manufacturer in that industry.

2. Equipment shall be suitable for the environmental conditions (corrosive, seawater spray, submerged) in which it will be used.

3. Items of the same type and purpose shall be identical and supplied by the same manufacturer. Wherever possible units of the same type of equipment shall be products of a single manufacturer.

4. Submit complete product details (together with shop drawing submittal, see Paragraph 3.01 A.) for Engineer’s approval prior to purchase.

B. Fluid Power Equipment

1. The fluid power components identified in Appendix 1 shall be regarded as suggested equipment. The Fluid Power System Designer shall take full responsibility for the specification and selection of the components required to achieve the desired system functionality and reliability.

2. Use fluid power equipment meeting the recognized standards published by the National Fluid Power Association and manufactured as a standard product by an established fluid power equipment manufacturer.

3. Hydraulic power units shall be electrically powered by vessel electric power system. Coordinate voltage and power requirements with platform designer.

C. Instruments and Control System Equipment

1. The instruments identified in Appendix 1 shall be regarded as suggested equipment. The Control System Designer or Fluid Power System Designer (as appropriate) shall take full responsibility for the specification and selection of the components required to achieve the desired system functionality and reliability.

2. Control equipment shall be powered by vessel electric power system with local transformers included as needed for signal transmission and subsystem operation. Connecting conductors shall be suitable for installed service with due consideration of shielding requirements. Enclosures shall be NEMA rated for appropriate service conditions.

PART 3 - EXECUTION

3.01 PREPARATION

A. Shop Drawings:

Submit detailed shop drawings containing complete wiring, piping, schematic, flow diagrams and other details required to demonstrate that the control system has been coordinated and will properly function as a unit. Pipe and Instrumentation Drawing (P&ID) prepared using device symbols recognized by the Instrument Society of America shall be prepared as required. Include in the drawings, as appropriate: produce specific catalog cuts, a drawing index, a list of symbols, valve schedules and instrument schedules.

B. Control Logic and programming:

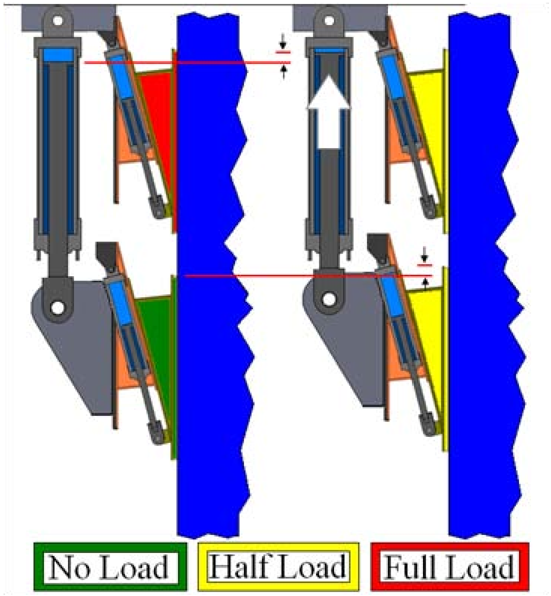
1. Submit detailed flow diagrams and logic diagrams for the control circuit prior to programming.

2. Submit detailed user interface plans and the layout of the control panel prior to programming.

3. Submit all program and source information used in the development and implementation of the control code.

END OF SECTION

13. Load Lower Wedges



- Action:
  - Retract Lifting Cylinders to share the lifting load between the upper and lower gripper during fabrication of the next OTEC pipe section.
- Feedback:
  - Primary: Lifting Cylinder Pressure Sensors – PSB1-PSB6.
  - Secondary: movement of lifting cylinders.
  - Visual confirmation and inspection of lower and upper grippers: all wedges equally engaged.
- Control Logic:
  - Control of VE-1 with feedback from PSB-1 through PSB-6. Raise OTEC pipe very short distance until weight carried by the lower gripper – measured by average of PSB-1 through PSB-6 – equals half the weight of the OTEC pipe plus the weight of the lower gripper. Pressure sensors are redundant and all in parallel. Discard any incorrect values.
  - Record distance cylinders have retracted – compare to prior values as check.

Gripper Lowering Sequence	Unload Upper Wedges	Disengage Upper Wedge	Retract Upper Wedge	Lowering Pipe	Extending Upper Wedge	Engaging Upper Wedge	Unload Lower Wedges	Disengage Lower Wedge	Retract Lower Wedge	Raising Lower Gripper	Extending Lower Wedge	Engaging Lower Wedge	Load Lower Wedges
Action:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Upper Wedge	Engaged	**Retract**	**Retract**	Retracted	**Extend**	**Engage**	Engaged	Engaged	Engaged	Engaged	Engaged	Engaged	Engaged
	Unload	**Disengage**				**Extend**	**Load**	Load	Load	Load	Load	Load	**1/2 load**
Lower Wedge	Engaged	Engaged	Engaged	Engaged	Engaged	Engaged	Engaged	**Retract**	**Retract**	Retracted	**Extend**	**Engaged**	Engaged
	Load	Load	Load	Load	Load	Load	**Unload**	**Disengage**				**Extend**	**1/2 load**
Pipe	**Up very small**	**Up Small**		**Lower**		**Down Small**	**Down very small**	**Down small**				**Up small**	**Up very small**
Upper Wedge Movement	X	**Retract till P drops**	**Retract tlll stop**	X	**Extend to contact**	**Extend to get 50 psi**	X	X	X	X	X	X	X
Upper Pad P	50 psi	**2 psi**	0 psi	0 psi	**2 psi**	**50 psi**	50 psi	50 psi	50 psi	50 psi	50 psi	50 psi	50 psi
Lifting Cylinders	**Small Up to shift load**	**Up - Follow Wedge**	X	**Lower most of way**	X	**Down - follow Wedge**	**Small Down shift load**	**Down - follow Wedge**	X	**Raise to top, level, lower sm**	X	**Up - Follow Wedge**	**Small Up to shift load**
dP Lifting Cylinder	**to 100%**	100%	100%	100%	100%	100%	**to 0%**	0%	0%	0%	0%	0%	**to 50%**
Gimbal Mode?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**No**	No	No	**Yes**	Yes
Lower Wedge Movement	X	X	X	X	X	X	X	**Retract till P drops**	**Retract tlll stop**	X	**Extend to contact**	**Extend to get 50 psi**	X
Lower Pad P	50 psi	50 psi	50 psi	50 psi	50 psi	50 psi	50 psi	**2 psi**	0 psi	0 psi	**2 psi**	**50 psi**	50 psi

Red designates change

Yellow coordinated movement with pad pressure

Tan - Pressure feedback

Figure 9. Summary Table of Gripper Lowering Sequence

APPENDIX 1

Operational Goals and Stepwise Performance of the OTEC Pipe Gripper Control System

1 Control System

1.1 Goals

The primary goals of the Gripper control system include the following:

1. Reliably support the OTEC pipe weight during all stages of fabrication.
    a. The final OTEC pipe length is 3280ft (1000m)
2. Reliably hold the OTEC pipe in shear currents, wave loads, and bending moments due to pipe fabrication platform motion.
    a. Support OTEC pipe fabrication operations in 90% swell and wave conditions
3. Accurately control the vertical placement of the OTEC pipe
    a. Pipe is fabricated incrementally in ~11m segments
    b. Raise or lower and adjust pipe position accurately
    c. Hold, raise and lower the OTEC pipe from any point along its length
4. Do not damage the OTEC pipe
    a. Do not crush or collapse the OTEC pipe.
    b. Contact OTEC pipe with a uniform pressure; nominal 50 psi or less
5. Accommodate contingencies
    a. Be reversible

The control system operates the wedges and the lifting rams used in conjunction with the two grippers. The most critical portion of the gripper control is the hand-off of the OTEC pipe load from one gripper to another and the engaging and disengaging of the grippers onto the pipe.

Figure 1 illustrates the engagement and disengagement of the lower gripper. The wedges are driven by the wedge ram. To have the wedge pad move radially inward and outward (and not up and down as it squeezes along the pipe), both the lifting rams and the wedge rams are moved together. The control system has feedback from every ram and can synchronize the movement of any ram combinations. Similarly, Figure 2 shows the engagement and disengagement of the upper gripper. Note that this operation involves the vertical movement of the OTEC pipe since the lower griper is supporting the load during this operation.

1.2 Requirements, Sequencing

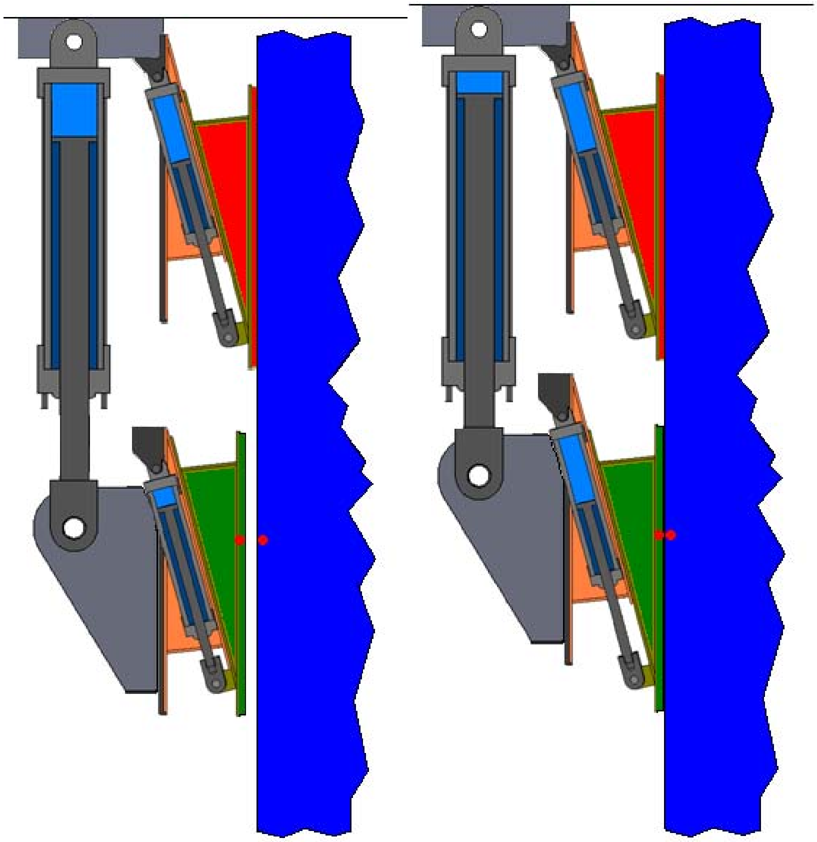


Figure 1. Motion of both the lifting rams and the lower wedge rams to engage and disengage the lower gripper.

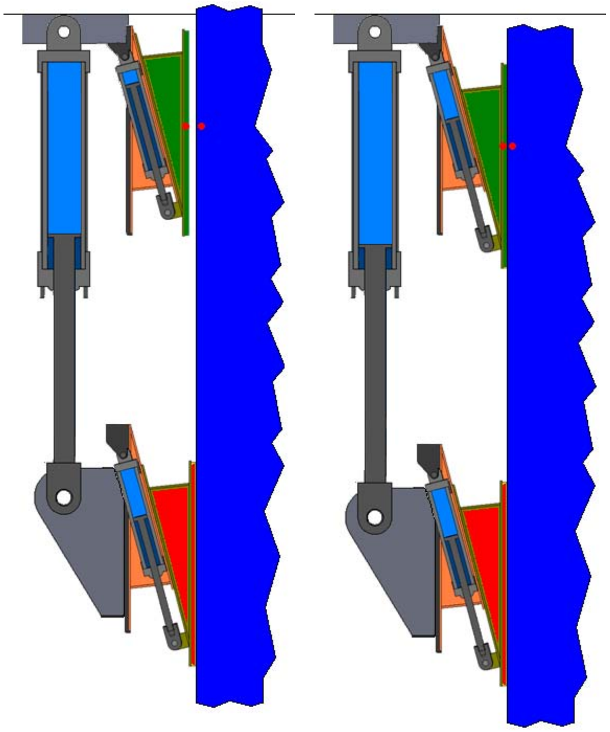


Figure 2. Motion of both the lifting rams and the upper wedge rams to engage and disengage the upper gripper. Note that the OTEC pipe moves in this operation.

The sequence shown above is repeated many times during the pipe fabrication process. It will take 180 each 5.5m strokes to lower a 1000m long pipeline. The hand-over cycle is illustrated in Figure 3. A more detailed description of this multi-step process is provided beginning in Paragraph 1.4.2.

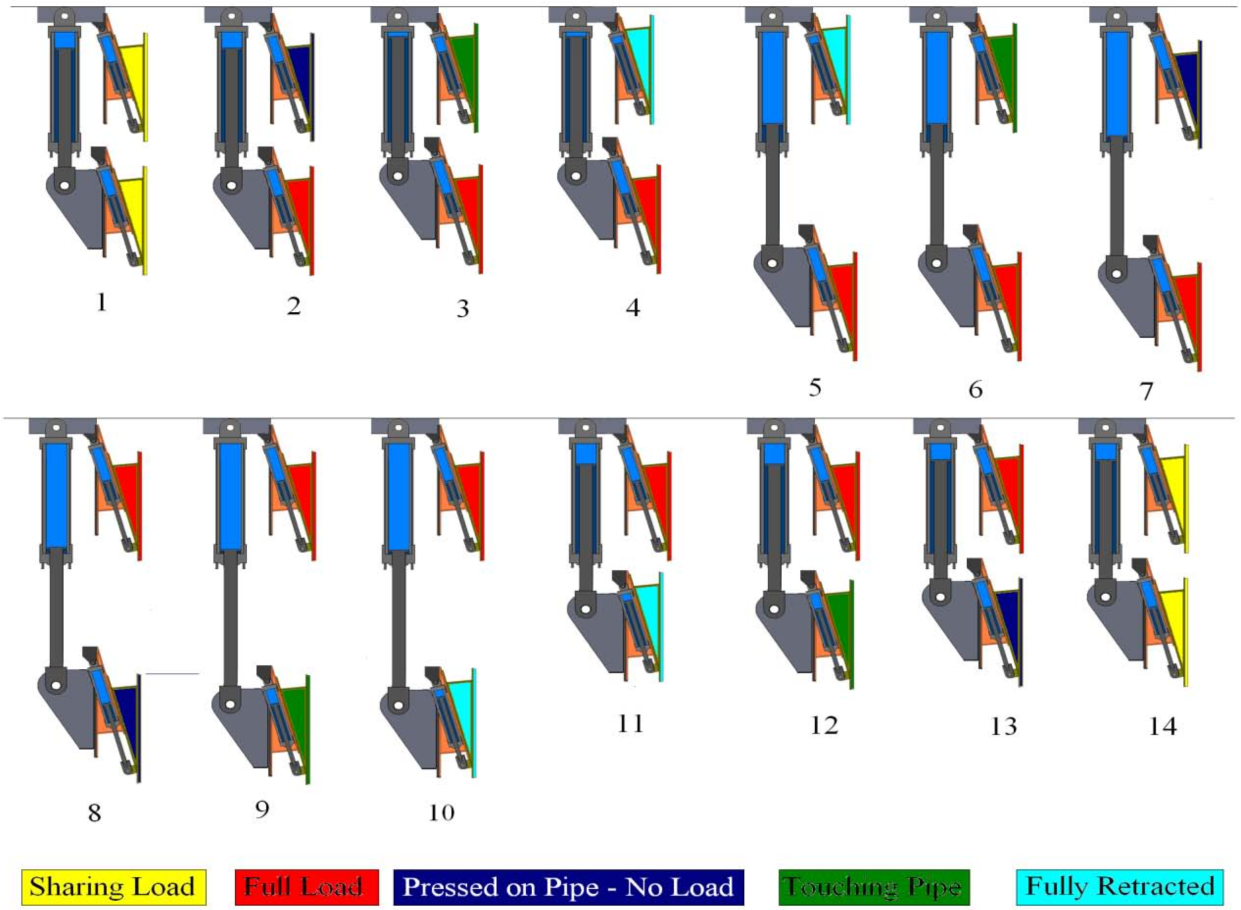


Figure 3. **Hand-off sequence between grippers (see above color legend to determine condition of upper and lower wedges as the process proceeds).**

1.3 Component and Sensor Definition and Location

1.3.1 Components – See Figure 4

- Upper Wedge – Inner steel wedge located on the Upper Gripper. Moves radially in toward the pipe at an angle.
- Lower Wedge – Inner steel wedge located on the Lower Gripper. Moves radially in toward the pipe at an angle.
- Upper Wedge Gel Bag – Bag containing soft polyurethane gel. Located on the Upper Wedge.
- Lower Wedge Gel Bag – Bag containing soft polyurethane gel. Located on the Lower Wedge.
- Upper Wedge Cylinder – Hydraulic cylinder that moves the inner wedge. Located on the Upper Wedge.
- Lower Wedge Cylinder – Hydraulic cylinder that moves the inner wedge. Located on the Lower Wedge.
- Lifting Cylinders – Hydraulic cylinders that raise or lower the Lower Gripper.

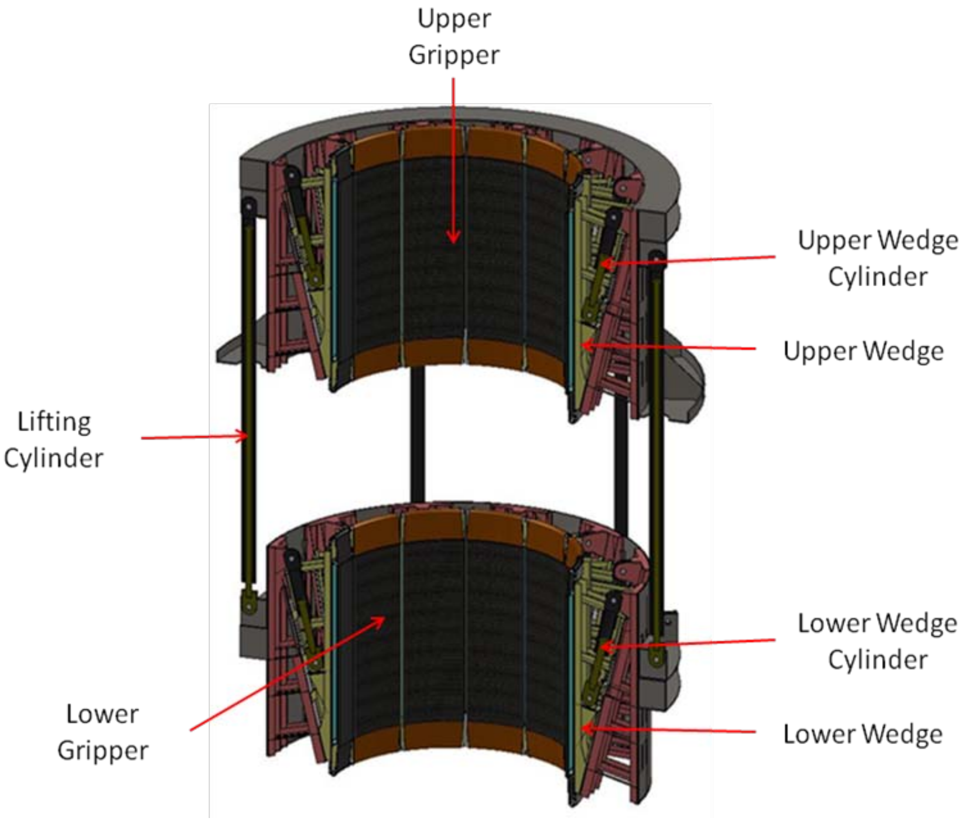


Figure 4 Components

1.3.2 Sensors – See Figure 5

- Upper Wedge Gel Pressure Sensors – Sensors measuring the pressure in the Upper Wedge Gel Bag. One per bag.
- Lower Wedge Gel Pressure Sensors – Sensors measuring the pressure in the Upper Wedge Gel Bag. One per bag.
- Lifting Cylinder Position Sensors – Internal position transducers in the Lifting Cylinders. One per cylinder – 6 total.
- Upper Wedge Cylinder Position Sensors – Internal position transducers in the Upper Wedge Cylinders – 12 total, one per wedge cylinder.
- Lower Wedge Cylinder Position Sensors – Internal position transducers in the Lower Wedge Cylinders– 12 total, one per wedge cylinder.
- Lifting Cylinder Pressure Sensors – Pressure transducers in the Lifting Cylinders rod side manifold – three total all in parallel (redundant)
- Lifting Cylinder Pressure Sensors – Pressure transducers in the Lifting Cylinders piston end side manifold – two total all in parallel (redundant)
- Upper Wedge Cylinder Pressure Sensors – Pressure transducers in the Upper Wedge Cylinders – 12 total one each cylinder, piston side
- Lower Wedge Cylinder Pressure Sensors – Pressure transducers in the Lower Wedge Cylinders– 12 total one each cylinder, piston side

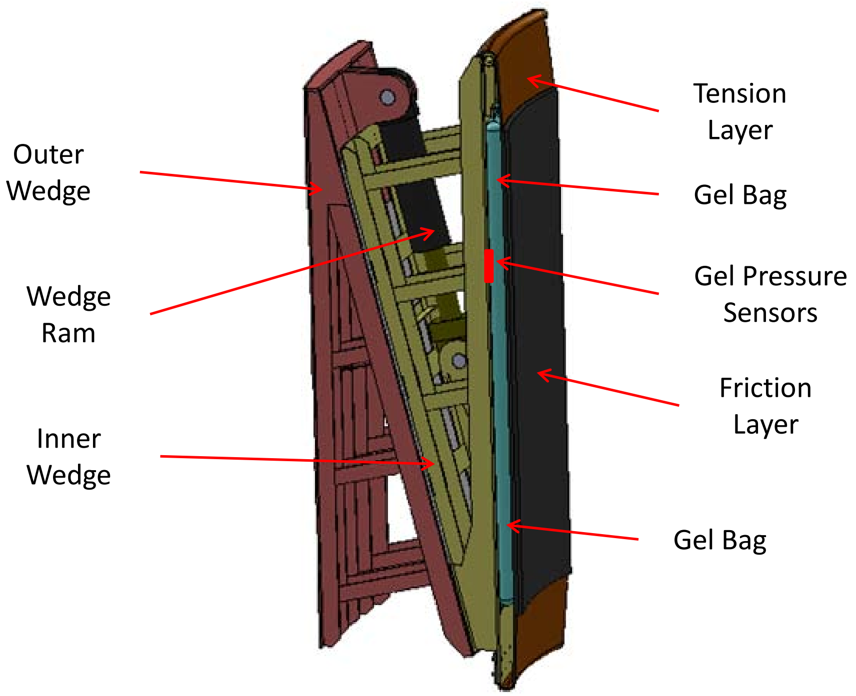


Figure 5 Sensor locations

1.4 Basic Control

Each hydraulic ram used for actuation of the various gripper functions is individually controlled with a servo proportional valve and position feedback from a built-in position sensor in the ram. Thus, any ram can be very accurately positioned at any position and can be moved at any desired velocity, and important for this system, rams can be moved in parallel with a high level of control. Figure 6 illustrates the basic relationship between all the rams and the PLC.

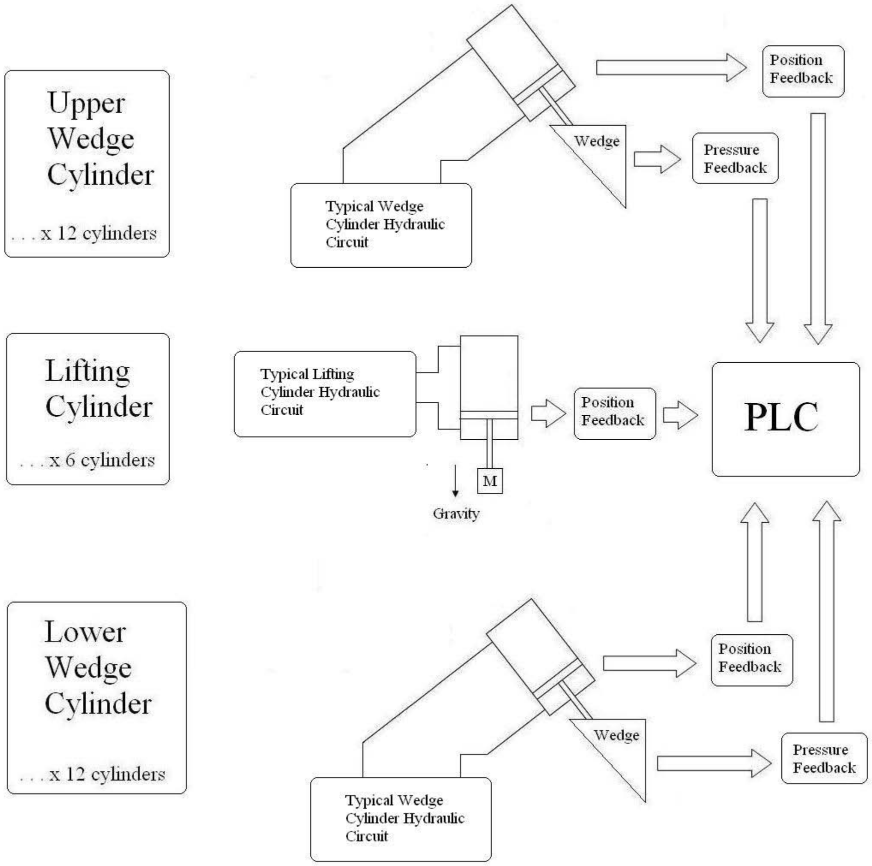


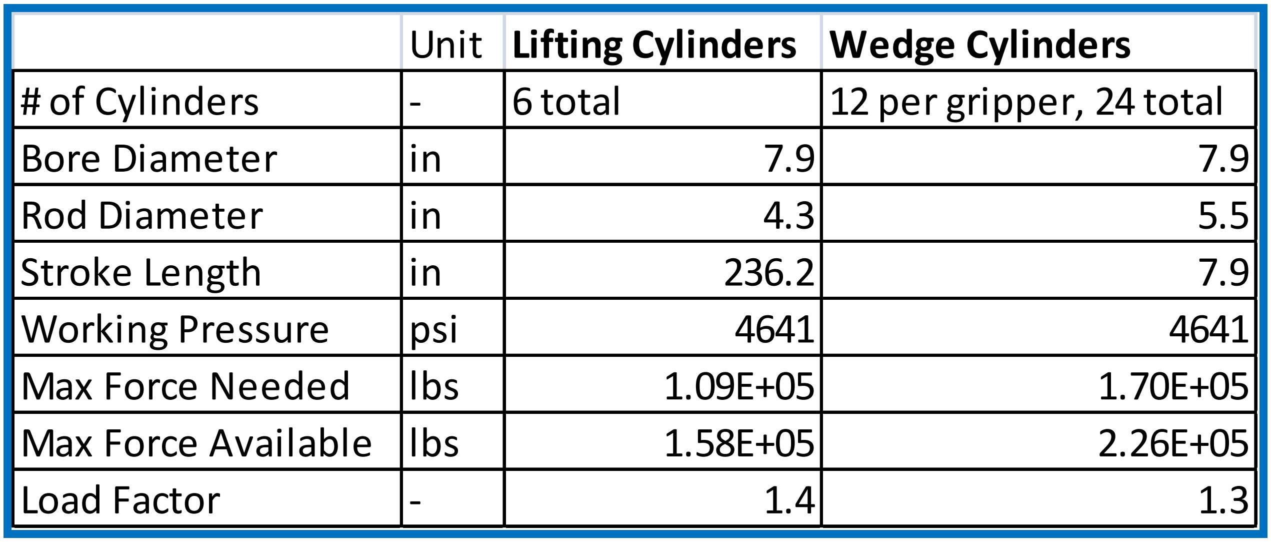
Figure 6 Basic hydraulic schematic for the Gripper system

1.4.1 Hydraulics (Fluid Power System)

The hydraulic system that has been conceptually developed for the 4m gripper system is described here.

There is a common hydraulic power supply operating at 5000 psi. The hydraulic fluid is either Lubritherm by Lubecorp Manufacturing Inc. or Power Flo by Tapco. Both are water soluble, environmentally friendly, and can be easily washed off the gripper pads to maintain gripper friction.

There are basically two hydraulic circuits: The first for the lifting cylinders and the second for the wedge cylinders. The characteristics of the two cylinder types used in these circuits are shown in Table 1. Both operate at a nominal 4650 psi. There are six lifting cylinders and 24 wedge cylinders; 12 on each gripper.



	Unit	**Lifting Cylinders**	**Wedge Cylinders**
# of Cylinders	-	6 total	12 per gripper, 24 total
Bore Diameter	in	7.9	7.9
Rod Diameter	in	4.3	5.5
Stroke Length	in	236.2	7.9
Working Pressure	psi	4641	4641
Max Force Needed	lbs	1.09E+05	1.70E+05
Max Force Available	lbs	1.58E+05	2.26E+05
Load Factor	-	1.4	1.3

Table 1: Lifting and Wedge Cylinder characteristics.

Figure 7 is the schematic for the lifting cylinders. This schematic has the following features:

- Three cylinders are shown in this diagram, but there are a total of 6 lifting cylinders attached to the lower gripper – used for raising and lowering the OTEC pipe.
- Each cylinder has a differential pressure sensor between the two ports. This is the most critical pressure measurement used in the control circuit. This pressure is used to determine the OTEC pipe load on the lower gripper. When the pressure corresponds to the total weight, the full load of the OTEC pipe is being carried by the lower gripper. The absence of an OTEC pipe load verifies for the control system that the upper gripper is supporting the OTEC pipe.
- Each cylinder has a gun-drilled rod to house an internal, magnetostrictive position sensor to provide accurate position feedback.
- There are two operational modes for these cylinders. (1) “No OTEC pipe Mode” which is used for lowering and raising the lower gripper when it is not attached to the OTEC Pipe and (2) “Gimbal Mode” when the lower gripper is engaged on the OTEC pipe.
- In No OTEC Pipe Mode, the six cylinders are all individually controlled by the directional proportional valves VD-1 through VD-6.
- In No OTEC Pipe Mode, the weight of the lower gripper is offset by the six counter balance valves VF-1 through VF-6. These valves prevent the lowering of the lower gripper when the hydraulic system fails.
- In Gimbal Mode, all the cylinders are operated from a common manifold such that the pressure is balanced on all cylinders and the gripper (which is clamped onto the pipe when in Gimbal Mode) can easily tilt and follow any tilting in the OTEC pipe due to dynamics. Hydraulic fluid can easily flow from one cylinder to another to balance pressures. The pressure sensors will all read identical values in Gimbal Mode.

- In Gimbal Mode, the six cylinders are all controlled together through a single directional proportional valve, VC-1.
- In Gimbal Mode, a counter balance valve, VE-1, offsets the total weight of the fully fabricated (1000m long) OTEC pipe. If hydraulic power fails – this valve prevents the OTEC pipe from lowering.
- The two-position solenoid actuated directional valves VG-1 through VG-6 and valves VH-1 through VH-6 are used for switching between No OTEC Pipe Mode and Gimbal Mode. The normal, unpowered position of all these valves is in the Gimbal Mode.

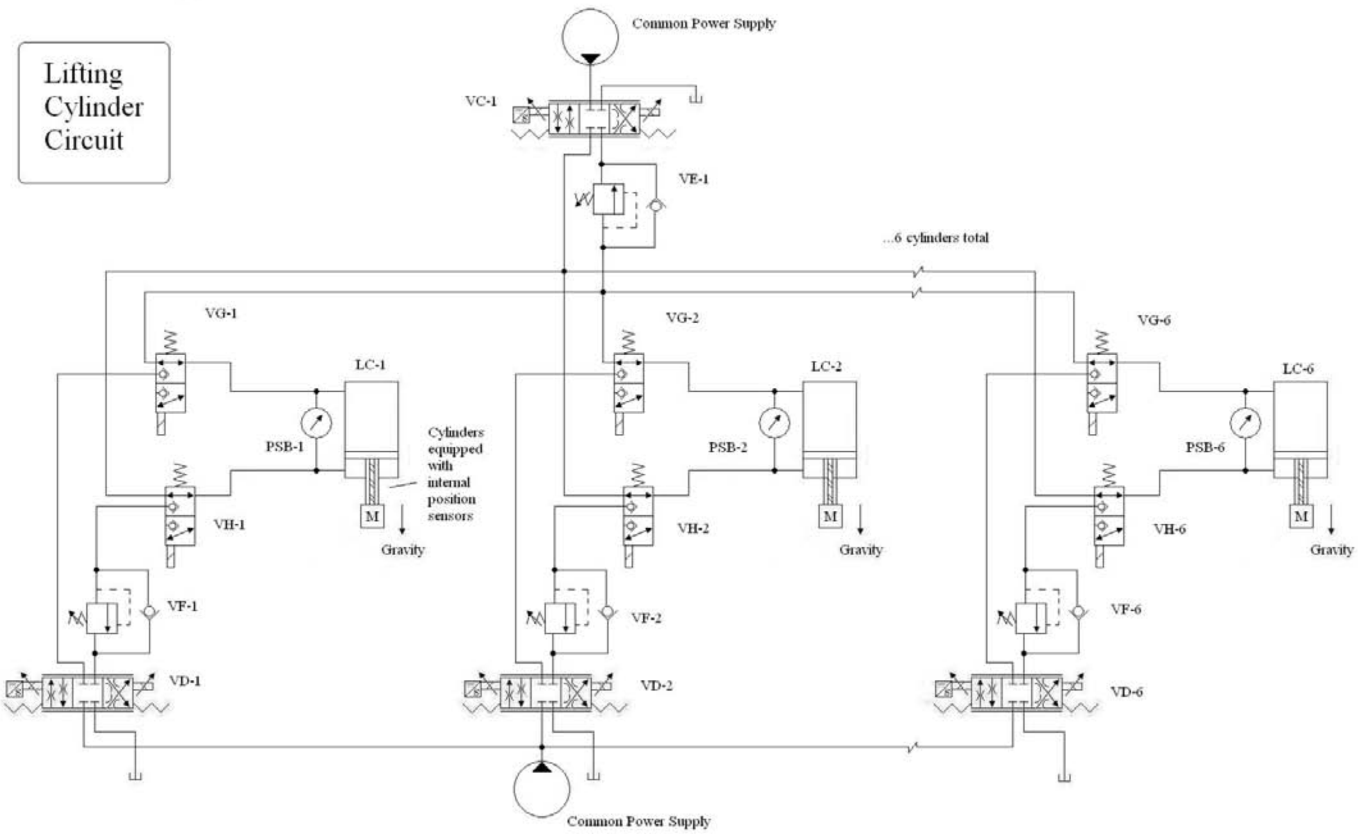


Figure 7: Hydraulic Schematic for the Lifting Cylinders

Figure 8 is the schematic for the wedge cylinders. This schematic has the following features:

- One cylinder is shown in the diagram. There are 24 such cylinders, 12 on each gripper.
- Each cylinder has a differential pressure sensor between the two ports. This pressure is used to determine the driving force for setting and unsetting the wedges, checking the centering of the OTEC pipe within the gripper, and detecting whether there are any changes in the OTEC pipe or the Gripper pads during operations.
- Each cylinder has a gun-drilled rod to house an internal, magnetostrictive position sensor to provide accurate position feedback
- The position of each wedge is controlled via the PLC using the directional proportional valves VA-1 through VA-24 and feedback from the magneto-restrictive position sensors.

- When the wedges are set against the OTEC pipe, VB-1 valve is closed. This solenoid actuated valve prevents the wedge from retracting and is normally closed.

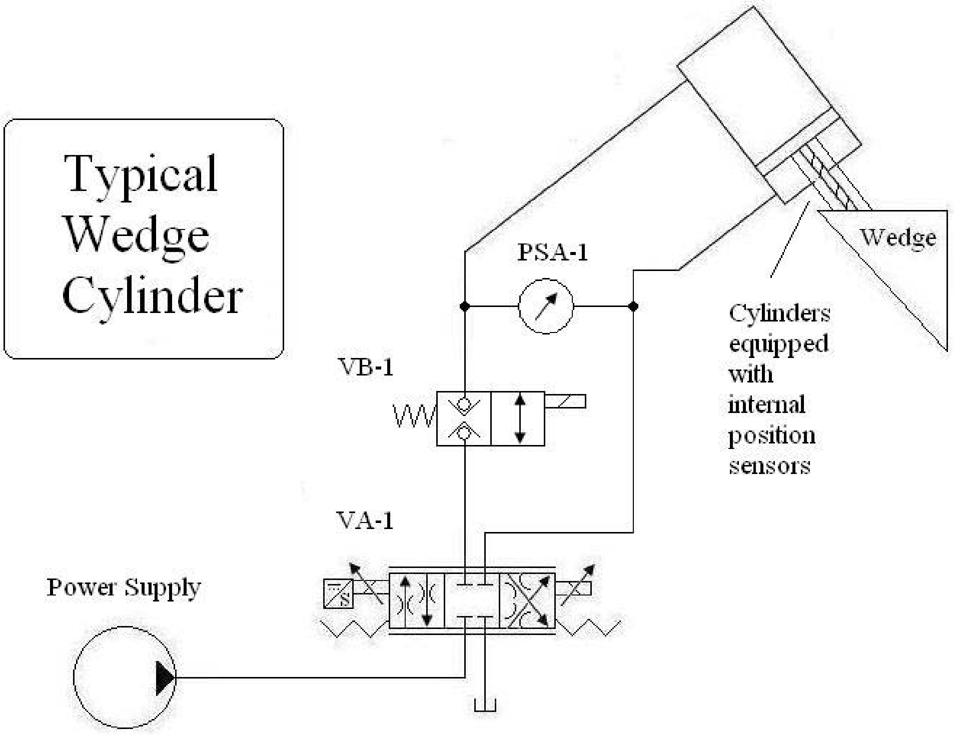


Figure 8: Hydraulic Schematic for the Wedge Cylinders.

For these hydraulic circuits, the following have been selected:

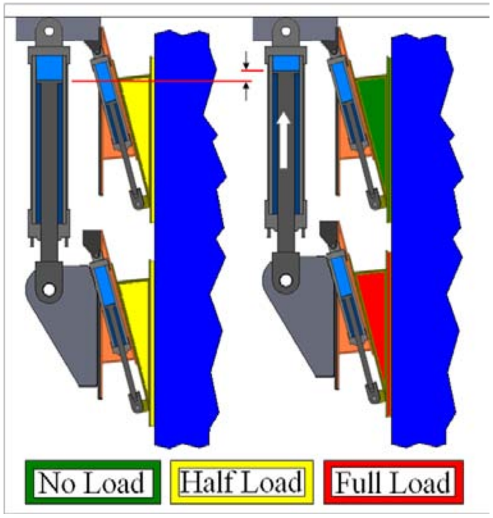
- VA – Direct operated, four-way, three-position, proportional directional flow control valve. Parker Series D1FP or equivalent.
- VB – Direct acting, two-way, two-position, solenoid operated directional poppet valve. Sun Series DTDA-XHN or equivalent.
- VC – Direct operated, four-way, three-position, proportional directional flow control valve. Parker Series D1FP or equivalent.
- VD – Direct operated, four-way, three-position, proportional directional flow control valve. Parker Series D1FP or equivalent.
- VE – Counterbalance valve. Sun Series CBAB or equivalent.
- VF – Counterbalance valve. Sun Series CBAB or equivalent.
- VG – Direct acting, three-way, two-position, solenoid operated directional valve. Sun Series DWDA or equivalent.
- VH – Direct acting, three-way, two-position, solenoid operated directional valve. Sun Series DWDA or equivalent.
- Large bore Hydrowa cylinders made by Eaton Hydraulics

- Spherical rod ends used for both wedge and lifting cylinders
- Gun-drilled cylinders will house internal, magnetostrictive position sensors to provide position feedback
- Operating time full length of lowering cylinder: 2 minutes fastest moving pipe, 1 minute without pipe.
- Operating time full length of wedge cylinder: one minute while engaging.
- Acceleration of lowering cylinders when engaged on OTEC pipe: < 0.05g

1.4.2 Gripper Lowering Steps and Control Logic

This section contains a description of the 13 steps needed to move through one complete gripper cycle. For each step, a description is provided of the **Action** required in the step, the **Feedback** provided, and the **Logic** required within the PLC. The starting point is when both grippers have been holding the pipe equally (sharing the load); the Lifting Cylinders are in the Gimbal Mode; an OTEC pipe section has been completed, and the OTEC pipe is ready to be lowered. Reference is made to cylinders, valves and sensors in the in the hydraulic schematics in Figure 7 and Figure 8. A summary table showing the status and action of each major component used to control the gripper cycling is shown in Figure 9.

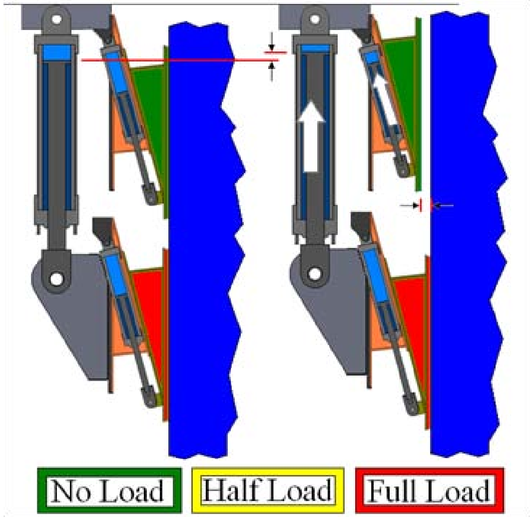
1. Unload Upper Wedges



⇧

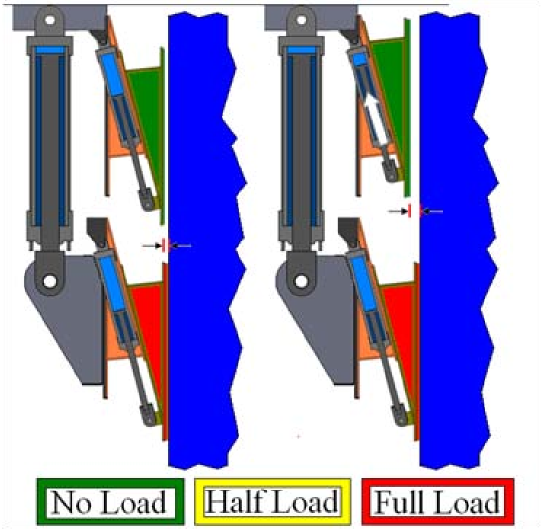
- Action:
    - Retract Lifting Cylinders to transfer the OTEC pipe load entirely to the lower Gripper
- Feedback:
    - Primary: Lifting Cylinder Pressure Sensors – PSB1-PSB6.
    - Secondary: movement of lifting cylinders.
    - Visual confirmation and inspection of lower gripper: all wedges equally engaged.
- Control Logic:
    - Control of VE-1 with feedback from PSB-1 through PSB-6. Raise OTEC pipe very short distance until weight carried by the lower gripper – measured by average of PSB-1 through PSB-6 – equals the weight of the OTEC pipe plus the weight of the lower gripper. Pressure sensors are redundant and all in parallel. Discard any incorrect values.
    - Weight of the OTEC pipe of prior cycle measure in Step 4. Know weight added with each fabrication increment by prior cycle measurements. Therefore, fairly accurate pressure can be computed for the weight of the OTEC pipe plus the weight of the lower gripper assembly.
    - Record distance cylinders have retracted – compare to prior values as check.

2. Disengage Upper Wedge Cylinders



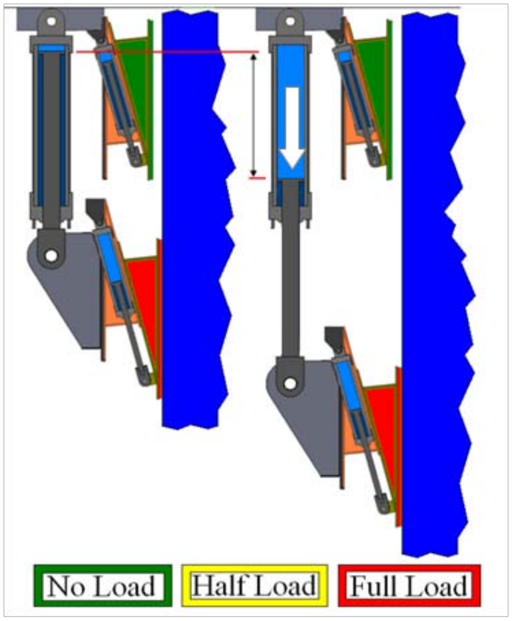
- Action:
  - Retract Lifting Cylinders
  - Retract Upper Wedge Cylinders
  - Upper wedge pads move radially outward from pipe & pressure drops.
- Feedback:
  - Lifting & Upper Wedge Cylinder Position.
  - Upper Wedge Gel Pressure.
  - Visual confirmation that the wedges are just touching the OTEC pipe
- Control Logic:
  - Open the VB valves by energizing them on all the upper gripper wedge cylinders.
  - Raise the OTEC pipe by retracting the lifting cylinders at a slow but fixed speed.
  - Monitor motion of the lifting cylinders.
  - Retract wedge cylinders in upper gripper at fixed ratio to movement of the lifting cylinders. All wedge cylinders retracted in parallel: pads move radially from the OTEC pipe.
  - Monitor the gel pad pressures (12 sensors). When pressures drop to less than 2 psi, stop retracting the lifting cylinders.
  - Log distance traveled each cylinder and compare to prior values as a check.

3. Retract Upper Wedge Cylinders



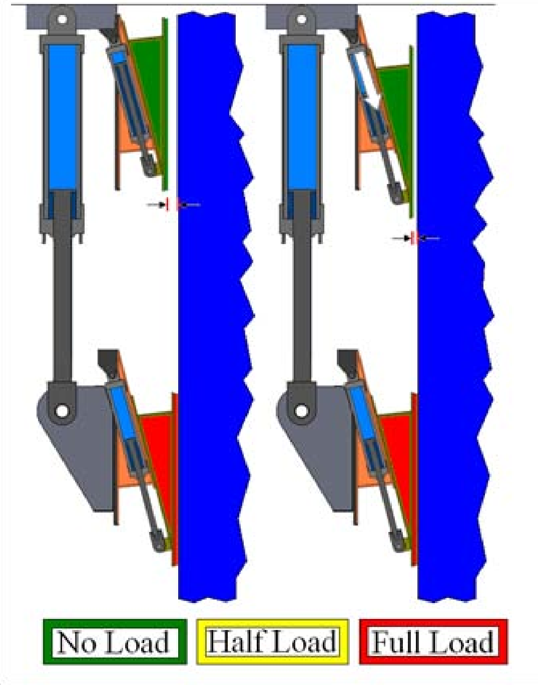
- Action:
    - Retract Upper Wedge Cylinders to build clearance between the OTEC pipe and the upper wedge pads
- Feedback:
    - Upper Wedge Cylinder Position Sensors.
    - Visual confirmation that all wedges retracted.
- Control Logic:
    - Move all upper wedge cylinders in parallel; they are no longer in contact with the OTEC pipe. You are building clearance between the pads and the OTEC pipe.
    - Feedback is the position sensor on each wedge cylinder.
    - Each cylinder has a home location based on a prior survey of all the pads such that each wedge has moved a fixed distance from a perfectly centered and circular pipeline. Due to construction tolerances, each cylinder has a different home position. Retract the cylinders in parallel to this home location.
    - Close the VB valves by de-energizing them on all the upper gripper wedge cylinders.

4. Lowering Pipe



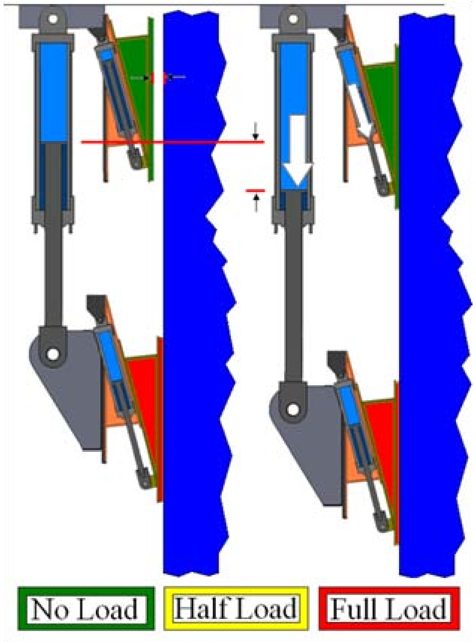
- Action:
  - Extend Lifting Cylinders to lower the OTEC pipe
- Feedback:
  - Lifting Cylinder Position Sensors
  - Lifting Cylinder Pressure Sensors
  - Manual check of pipe movement above deck
  - Manually confirm upper gripper free of OTEC pipe
- Control Logic:
  - Keep acceleration low at <0.05g
  - Accelerate slowly to uniform speed.
  - Move downward slowly, 2 minutes minimum time to lower. Use feedback from average of all 6 cylinder position sensors.
  - Confirm that the same load is being carried by the Lower Gripper for the entire stroke.
  - Log the weight of the OTEC pipe – it is free of the upper gripper and the measurement is accurate.
  - Decelerate slowly to stop 10” short of the end of the lifting cylinders – or just 4” above desired stop position for the fabrication process above deck – whichever comes first.

5. Extending Upper Wedge Cylinders



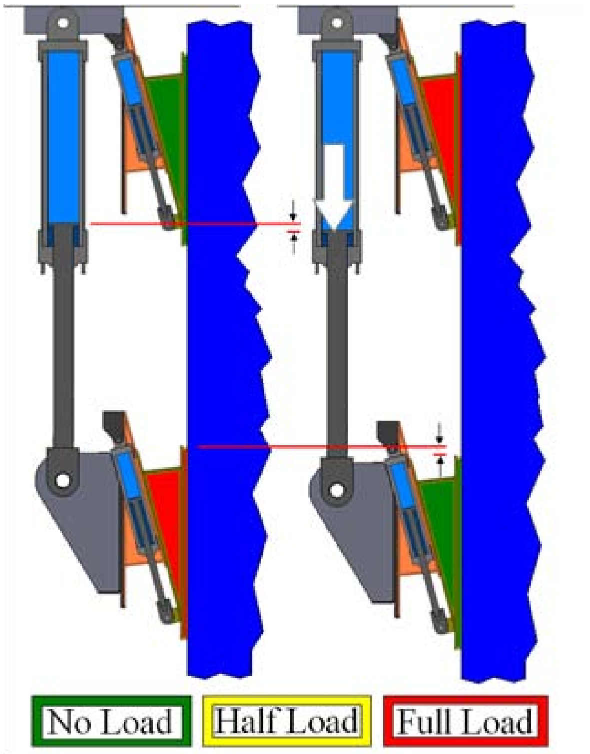
- Action:
  - Extend Upper Wedge Cylinders to almost or just contact the OTEC pipe
- Feedback:
  - Upper Wedge Cylinder Position Sensors.
  - Upper Wedge Gel Pressure Sensors.
  - Visual check upper wedges extended
- Control Logic:
  - Open the VB valves by energizing them on all the upper gripper wedge cylinders.
  - Extend all 12 upper gripper wedge cylinders identically and in parallel, stopping just short of contacting the OTEC pipe.
  - If any wedge pad pressure starts to rise – the OTEC pipe has been contacted on that side – stop the extension of all upper wedge cylinders.
  - All wedges should have moved equal amount from their home positions.
  - Log distances and compare to prior cycles for check.

6. Engaging Upper Wedge Cylinders



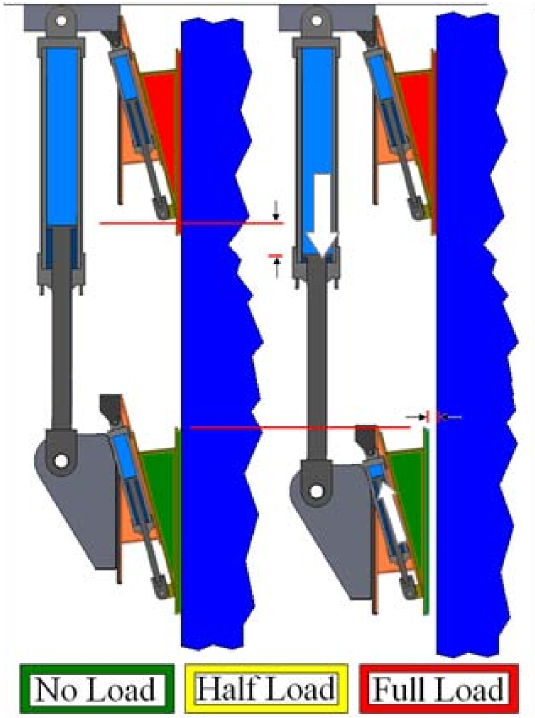
- Action:
  - Extend Upper Wedge Cylinders
  - Extend Lifting Cylinders
  - Upper pads squeeze on the pipeline by moving radially inward.
- Feedback:
  - Lifting & Upper Wedge Cylinder Position Sensors – Verifies that these two sets of cylinders are moving according to a fixed ratio.
  - Upper Wedge Gel Pressure Sensors.
- Control Logic:
  - Lower the OTEC pipe by extending the lifting cylinders at a slow but fixed speed.
  - Monitor motion of the lifting cylinders.
  - Extend wedge cylinders in upper gripper at fixed ratio to movement of the lifting cylinders. All wedge cylinders extended equally and in parallel: pads move radially toward the OTEC pipe.
  - Monitor the gel pad pressures (12 sensors). When pressures reach an average 50 psi, stop the cylinder extension.
  - Confirm that all pad sensors are nearly at 50 psi and pressure distribution from one pad to the next around the gripper is uniformly varying if not constant.
  - Close the VB valves by de-energizing them on all the upper gripper wedge cylinders.
  - Log distance traveled each cylinder and compare to prior values as a check.

7. Unload Lower Wedges



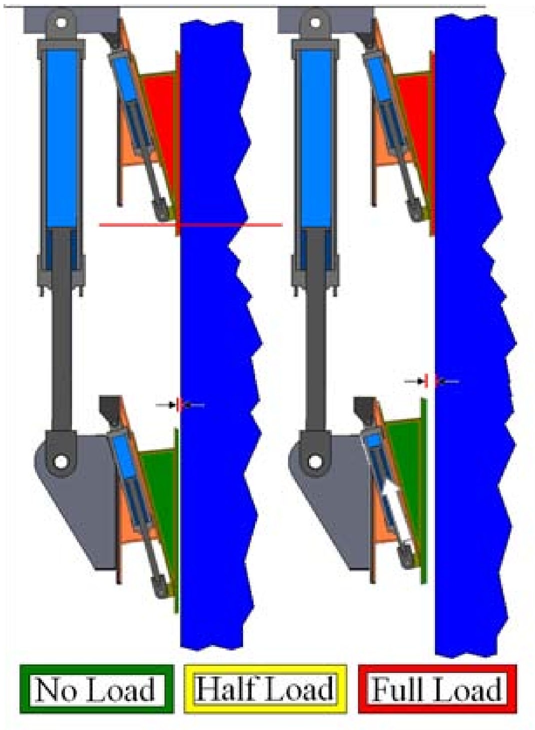
- Action:
  - Extend Lifting Cylinders to transfer the OTEC pipe load entirely to the upper Gripper
- Feedback:
  - Primary: Lifting Cylinder Pressure Sensors – PSB1-PSB6.
  - Secondary: movement of lifting cylinders.
  - Visual confirmation and inspection of upper gripper: all wedges equally engaged.
- Control Logic:
  - Control of VE-1 with feedback from PSB-1 through PSB-6. Lower OTEC pipe very short distance until weight carried by the lower gripper – measured by average of PSB-1 through PSB-6 – equals the weight of the lower gripper only. Pressure sensors are redundant and all in parallel. Discard any inconsistent values.
  - Upper gripper is holding the OTEC pipe
  - Record distance cylinders have retracted – compare to prior values as check.

8. Disengage Lower Wedge Cylinders



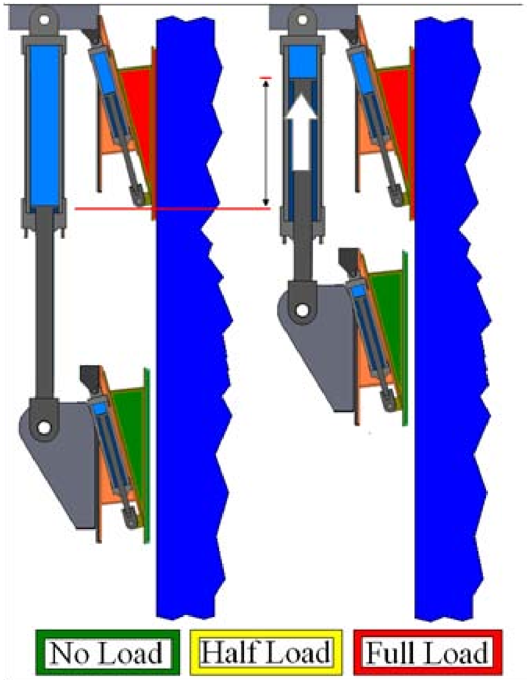
- Action:
    - Extend Lifting Cylinders
    - Retract Lower Wedge Cylinders
    - Lower wedge pads move radially outward from pipe pressure drops.
- Feedback:
    - Lifting & Upper Wedge Cylinder Position Sensors.
    - Lower Wedge Gel Pressure Sensors
    - Visual confirmation that the wedges are just touching the OTEC pipe
- Control Logic:
    - Open the VB valves by energizing them on all the lower gripper wedge cylinders.
    - Lower the OTEC pipe by extending the lifting cylinders at a slow but fixed speed.
    - Monitor motion of the lifting cylinders.
    - Retract wedge cylinders in lower gripper at fixed ratio to movement of the lifting cylinders. All wedge cylinders retracted in parallel: pads move radially from the OTEC pipe.
    - Monitor the gel pad pressures (12 sensors). When pressures drop to less than 2 psi, stop extending the lifting cylinders.
    - Switch the Lifting Cylinders from the Gimbal Mode to the No OTEC pipe Mode by energizing solenoids VG-1 through VG-6 and solenoids VH-1 through VH-6.
    - Log distance traveled each cylinder and compare to prior values as a check.

9. Retract Lower Wedge Cylinders



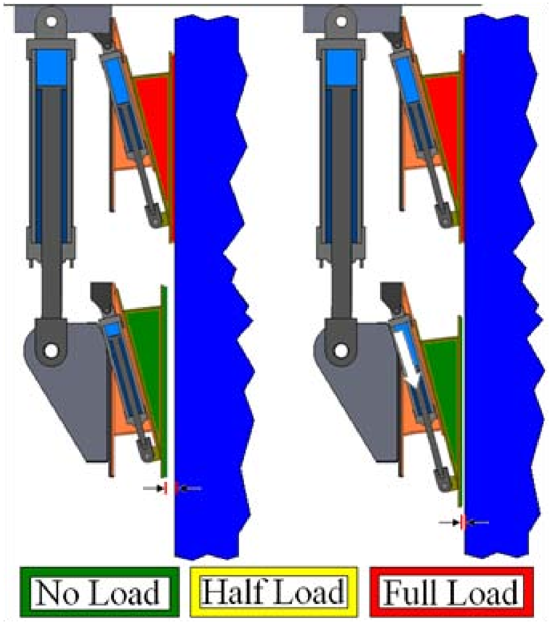
- Action:
    - Retract Lower Wedge Cylinders to build clearance between the OTEC pipe and the lower wedge pads
- Feedback:
    - Lower Wedge Cylinder Position Sensors.
    - Visual confirmation that all wedges retracted.
- Control Logic:
    - Move all lower wedge cylinders in parallel; they are no longer in contact with the OTEC pipe. You are building clearance between the pads and the OTEC pipe.
    - Feedback is the position sensor on each wedge cylinder.
    - Each cylinder has a home location based on a prior survey of all the pads such that each wedge has moved a fixed distance from a perfectly centered and circular pipeline. Due to construction tolerances, each cylinder has a different home position. Retract the cylinders in parallel to this home location.
    - Close the VB valves by de-energizing them on all the lower gripper wedge cylinders.

10. Raising Lower Gripper



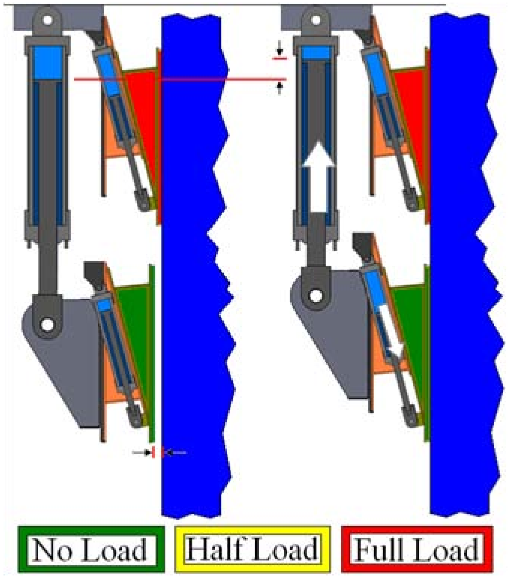
- Action:
    - Retract Lifting Cylinders to raise the lower gripper for another lowering cycle.
- Feedback:
    - Lifting Cylinder Position Sensors
    - Lifting Cylinder Pressure.
- Control Logic:
    - By operating Proportional Control Valves VF-1 through VF-6, raise the lifting cylinders all in parallel.
    - Monitor hydraulic pressures in the lifting cylinders to confirm there is no OTEC pipe drag on the lower gripper.
    - Move all the way up. Level the lower gripper by fully retracting all 6 lowering rams.
    - Lower each lifting cylinder 6”

11. Extending Lower Wedge Cylinders



- Action:
  - Extend Lower Wedge Cylinders to almost or just contact the OTEC pipe
- Feedback:
  - Lower Wedge Cylinder Position Sensors.
  - Lower Wedge Gel Pressure Sensors.
  - Visual check Lower wedges extended
- Control Logic:
  - Open the VB valves by energizing them on all the lower gripper wedge cylinders.
  - Extend all 12 Lower gripper wedge cylinders identically and in parallel.
  - Stop the extension when the average of the lower pad pressures equals 4psi.
  - All wedges should have moved an equal amount from their home positions.
  - Switch the Lifting Cylinders from the No OTEC pipe Mode to the Gimbal Mode by de-energizing solenoids VG-1 through VG-6 and solenoids VH-1 through VH-6.
  - Lower gripper is lightly engaged on the OTEC pipe and is freely moving in Gimbal Mode.
  - Log distances and compare to prior cycles for check.

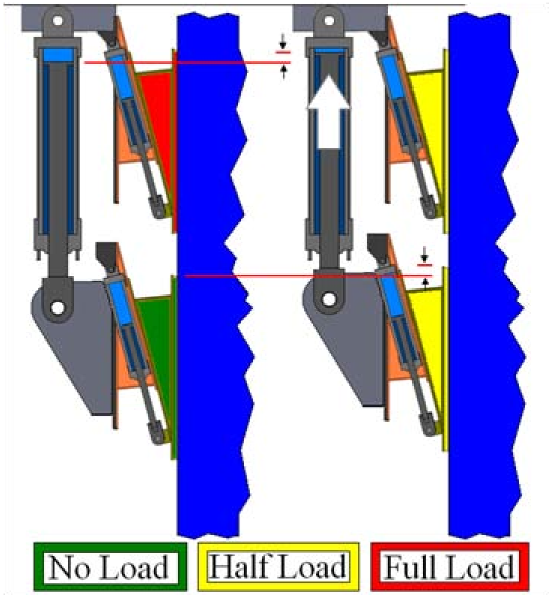
12. Engaging Lower Wedge Cylinders



- Action:
  - Extend Lower Wedge Cylinders
  - Retract Lifting Cylinders
  - Lower pads squeeze on the pipeline by moving radially inward.
- Feedback:
  - Lifting & Lower Wedge Cylinder Position Sensors – Verifies that these two sets of cylinders are moving according to a fixed ratio.
  - Lower Wedge Gel Pressure Sensors.
- Control Logic:
  - Raise the OTEC pipe slightly by retracting the lifting cylinders at a slow but fixed speed.
  - Monitor motion of the lifting cylinders.
  - Extend wedge cylinders in lower gripper at fixed ratio to movement of the lifting cylinders. All wedge cylinders extended equally and in parallel: pads move radially toward the OTEC pipe.
  - Monitor the gel pad pressures (12 sensors). When pressures reach an average 50 psi, stop the cylinder extension.
  - Confirm that all pad sensors are nearly at 50 psi and pressure distribution from one pad to the next around the gripper is uniformly varying if not constant.
  - Log distance traveled each cylinder and compare to prior values as a check.
  - Close the VB valves by de-energizing them on all the lower gripper wedge cylinders.

If the pipe is to be further lowered, then proceed to step 1 for another cycle. If the pipe is now at its position for fabricating another OTEC pipe section, proceed to step 13.

13. Load Lower Wedges



- Action:
  - Retract Lifting Cylinders to share the lifting load between the upper and lower gripper during fabrication of the next OTEC pipe section.
- Feedback:
  - Primary: Lifting Cylinder Pressure Sensors – PSB1-PSB6.
  - Secondary: movement of lifting cylinders.
  - Visual confirmation and inspection of lower and upper grippers: all wedges equally engaged.
- Control Logic:
  - Control of VE-1 with feedback from PSB-1 through PSB-6. Raise OTEC pipe very short distance until weight carried by the lower gripper – measured by average of PSB-1 through PSB-6 – equals half the weight of the OTEC pipe plus the weight of the lower gripper. Pressure sensors are redundant and all in parallel. Discard any incorrect values.
  - Record distance cylinders have retracted – compare to prior values as check.

Gripper Lowering Sequence	Unload Upper Wedges	Disengage Upper Wedge	Retract Upper Wedge	Lowering Pipe	Extending Upper Wedge	Engaging Upper Wedge	Unload Lower Wedges	Disengage Lower Wedge	Retract Lower Wedge	Raising Lower Gripper	Extending Lower Wedge	Engaging Lower Wedge	Load Lower Wedges
Action:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Upper Wedge	Engaged	**Retract**	**Retract**	Retracted	**Extend**	**Engage**	Engaged	Engaged	Engaged	Engaged	Engaged	Engaged	Engaged
	Unload	**Disengage**				**Extend**	**Load**	Load	Load	Load	Load	Load	**1/2 load**
Lower Wedge	Engaged	Engaged	Engaged	Engaged	Engaged	Engaged	Engaged	**Retract**	**Retract**	Retracted	**Extend**	**Engaged**	Engaged
	Load	Load	Load	Load	Load	Load	**Unload**	**Disengage**				**Extend**	**1/2 load**
Pipe	**Up very small**	**Up Small**		**Lower**		**Down Small**	**Down very small**	**Down small**				**Up small**	**Up very small**
Upper Wedge Movement	X	**Retract till P drops**	**Retract tlll stop**	X	**Extend to contact**	**Extend to get 50 psi**	X	X	X	X	X	X	X
Upper Pad P	50 psi	**2 psi**	0 psi	0 psi	**2 psi**	**50 psi**	50 psi	50 psi	50 psi	50 psi	50 psi	50 psi	50 psi
Lifting Cylinders	**Small Up to shift load**	**Up - Follow Wedge**	X	**Lower most of way**	X	**Down - follow Wedge**	**Small Down shift load**	**Down - follow Wedge**	X	**Raise to top, level, lower sm**	X	**Up - Follow Wedge**	**Small Up to shift load**
dP Lifting Cylinder	**to 100%**	100%	100%	100%	100%	100%	**to 0%**	0%	0%	0%	0%	0%	**to 50%**
Gimbal Mode?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**No**	No	No	**Yes**	Yes
Lower Wedge Movement	X	X	X	X	X	X	X	**Retract till P drops**	**Retract tlll stop**	X	**Extend to contact**	**Extend to get 50 psi**	X
Lower Pad P	50 psi	50 psi	50 psi	50 psi	50 psi	50 psi	50 psi	**2 psi**	0 psi	0 psi	**2 psi**	**50 psi**	50 psi

Red designates change

Yellow coordinated movement with pad pressure

Tan - Pressure feedback

Figure 9. Summary Table of Gripper Lowering Sequence