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REVIEW OF THE STRUCTURAL INTEGRITY OF THE ARMY FLOATING MODULAR CAUSEWAY PIER

by

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EXECUTIVE SUMMARY

The structural integrity of the U. S. Army's floating modular causeway pier was evaluated. Specific areas of concern included the adequacy of the Anchor Mooring System, the flexor and shear connector interfaces, and a proposed 120-ft long by 88-ft wide pierhead. Findings from this study indicate that the Anchor Mooring System is adequate for the proposed pier configurations, the 120-ft long pierhead is inadequate in seas greater than sea state 3, and limitations should be placed on berthing Army watercraft during certain longshore currents and at minimum water depths.

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INTRODUCTION

Problem Statement

The U. S. Army is replacing their Navy Lightered (NL) causeway lighterage assets with the Modular Causeway Section (MCS) system. The modularity of the MCS system is allowing the Army to redefine the shapes and sizes of the various platforms required for ship to shore transfer of cargo. Because of this modularity, the Army has realized the need for guidelines to limit overall platform shape and size. During the transition between the NL and MCS systems, the Army also wishes to validate that certain hardware designed for the NL system can be used with the MCS system.

Objective

It is the objective of this study to evaluate the integrity of the Army's Causeway Pier, specifically the adequacy of the Anchor Mooring System (AMS), the flexor and shear connector interfaces, and the pierhead.

Purpose

Several pier configurations (Figure 1 through Figure 3) were submitted by the U. S. Army Aviation and Troop Command (ATCOM) to the Naval Facilities Engineering Service Center (NFESC) (formerly Naval Civil Engineering Laboratory (NCEL)) for review[1] due to concerns at ATCOM that the Army users were constructing large MCS platforms that would experience increased loads on the MCS hardware and AMS.

Background

The MCS (Figure 4) is a U. S. Army container-compatible causeway system which can be transported in an ISOPAK configuration (Figure 5) by containerships and handled by standard commercial or military container equipment. An MCS consists of six raked pontoons (20- by 8- by 4½-ft) and three box-end pontoons (40- by 8- by 4½-ft). The pontoons are designed with an integral connection system, allowing for repeated assembly and disassembly of modular platforms. When assembled, the MCS is nominally 80-ft long by 24-ft wide.

Assembled causeway sections can be end-connected to form causeway ferries and piers. The end connection system consists of flexors and shear connectors (Figure 6). The shear connectors are pipe and socket devices on the causeway ends that absorb shear and compression forces. The flexors are designed to work in tension, holding the causeway sections together, but still allowing relative pitch motion between the sections. The flexors extend from a stowed position in the end pontoons into identical receivers in connecting pontoons. The flexors are secured in place with guillotine sockets at each end.

As the Army replaces their NL causeway system assets with this new MCS system, field users are using the MCS' modularity to redefine existing platform shapes and sizes. Recent

[1] Facsimile from ATCOM AMSAT-W-TA to NCEL Code L65/Kane dated 24 Jul 92

exercises have seen the MCS pontoons used to assemble a Roll-On/Roll-Off (RO/RO) platform (two 80- by 72-ft sections end connected), a High Sea State Container Transfer System (HISEACOTS) (160- by 56-ft), and an air cushion supported platform (80- by 24-ft) equipped with the Pontoon Air Cushion Kit (PACK). Even traditional roles such as floating causeway ferries and piers have undergone change. A double-wide causeway ferry (two 80- by 48-ft sections, end connected) was demonstrated during JLOTS-III to transport 40-ft containers. Several new configurations have also been tested to increase the efficiency of operation on the floating causeway pier. All of the pier configurations have one thing in common—a large semi-rigid platform (up to 120- by 88-ft) at the end. Access to the pierhead from the beach would be from single or dual roadways. An offshore section would be end connected to the seaward end of the pierhead. Vessels that could offload cargo on this floating causeway pier would include causeway ferries, the various Landing Crafts, Utility (LCU's), and the Logistics Support Vessel (LSV).

As no guidance was provided to the Army for assembling other than standard (24- by 80-ft) MCS', concern has been raised as to the integrity of these new platforms.

Scope of the Investigation

NFESC was retained by ATCOM[2,3,4] to determine the end connector (flexor and shear) loading on the offshore section, suitability of the AMS and the structural integrity of the 120- by 88-ft pierhead.

Plan of Treatment

The plan of treatment was to determine berthing, mooring, and environmental loading on offshore section during operating conditions and analyze allowable loading of the end connector system (flexor and shear). The environmental loading on the pierhead for operating and survival conditions, as well as for the AMS, was determined to verify integrity of pier and suitability of AMS. The structural integrity of a 120- by 88-ft pierhead was determined by analyzing a finite element model of the pontoon and pin/guillotine connection system, and comparing dynamic loads to an acceptable pin loading.

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[2] Ltr from ATCOM AMSAT-W-TA (70-17b) to NCEL Code L65 of 27 Aug 92
[3] Ltr from NCEL (Ser L65/0997) to ATCOM of 10 Dec 92
[4] Memo from ATCOM AMSAT-W-TA (70-17b) to NCEL Code L65 of 4 Jan 93

APPROACH

System Requirements

The requirements to be considered during this analysis for the causeway pier can be divided into two categories: (1) environmental condition requirements and (2) causeway requirements.

Environmental Condition Requirements:

- Normal operations will occur in sea state 2 or below, and limited operating capability is expected during sea state 3. The pier should survive sea state 5.
- Maximum expected current during normal operations is a 4-kt cross current.
- Maximum tide range of 7-ft.
- Windloads can be calculated using side area of one vehicle per causeway section for Sea State 2 or below. This ratio of vehicles per section will be lower during Sea State 3 due to limited operations.

Sea states were assumed to be those of a fully arisen sea as defined by the Pierson-Moskowitz Sea Spectrum[5].

Causeway Requirements:

- The seaward end of the causeway must reach a water depth of 12 ft. This depth was chosen to accommodate the draft of an LSV.
- Causeway length will not exceed 1500-ft (16 roadway sections, 120-ft pierhead, and 80-ft offshore section).

End Connector Loading - Offshore Section

An offshore section is located seaward of the causeway pierhead and serves as both a cargo discharge point and a berthing pier for Army lighters. The section(s) seaward of the pierhead is connected to the pier with flexor and shear connectors and is not supported directly by an anchoring system. It is the structural integrity of this flexor joint, between the pierhead and offshore section, that is in question.

Flexor and Shear Connector Strength

Because of the lack of MCS design data, it was assumed that the strength of the MCS flexor causeway connection system is equivalent to that of the NL P-8 pontoon-flexor causeway connection system (Figure 6), which is capable of resisting[6]:

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[5] Pierson-Moskowitz Sea Spectrum, Table G-1, Joint Pub 4-01.6, Joint Tactics, Techniques, and Procedures for Joint Logistics Over the Shore, 22 Aug 1991, p G-2.

1. Cyclic tensile forces up to 50-kip per flexor with a period of 7 seconds and ±7 degrees of flexing (e.g., wave-induced loads to the system during transit in a seaway up to sea state 3).
2. Noncyclic tensile forces up to 300-kip per flexor (e.g., loads induced by causeway beaching and retrieving maneuvering).
3. Vertical forces up to 100-kip per pair of pipe/socket connectors.

For a causeway section seaward of the pierhead, the primary loading concern is the ability of the connection interface to resist a horizontal moment applied during the berthing process and while a watercraft is moored alongside. These loads would be considered in the same category as paragraph 2 above.

The connection system interface would therefore be capable of withstanding a horizontal moment of 5,250 ft-kip (300-kip x 17.5-ft (the distance between the flexor centerline and furthest shear connector where rotation would be resisted)).

Berthing Impact

One of the most significant loads the causeway section(s) seaward of the pierhead will experience is the impact load from a berthing watercraft. This load will depend primarily on the displacement of the watercraft and its approach velocity. The procedures for calculating berthing force as well as the results for both an LSV and LCU-2000 are provided as part of Appendix A. The results indicate that forces as large as 126-kip can be experienced (representing an LSV with an approach velocity of 1.5-ft/s (0.9-kt)). To calculate the moment on the connection system that this load would create, the point of contact of the watercraft with the pier must be known. For an LSV, it would be reasonable to expect the point of impact to be approximately 80-ft from where the ramp would be placed on deck. For a pierhead configuration that uses 20-ft raked pairs alongside the seaward sections, this point of impact would be approximately 100-ft from the connection interface (20-ft (ramp at mid-point of 20-ft raked pairs) plus 80-ft). With this moment arm, a moment of 12,600 ft-kip (126-kip x 100-ft) would be experienced. It can be clearly seen that this moment exceeds the 5,250 ft-kip capability determined in the previous section.

By reducing the approach velocity of an LSV to 1.0-ft/s (0.6-kt), the impact force is greatly reduced. This force acting over the same moment arm would create a moment of 5,590 ft-kip (55.9-kip x 100-ft), which still exceeds the allowable moment on the connection system.

Because neither the pier configuration nor the requirement to dock an LSV alongside a causeway pier is likely to change, extreme care should be exercised during when berthing an LSV to the pier. Measures that can be exercised include dropping the LSV's bow anchor prior to approach in higher wave and current environments, and docking at the seaward end of the offshore section(s) thereby avoiding the impact.

The berthing force for an LCU-2000 is considerably smaller than that of the LSV. At an approach velocity of 1.5-ft/s (0.9-kt), the berthing force is 33.0-kip. This force acting over a

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[6] Hatch, W. G. (1985). Development of P-8 Pontoon-Flexor End Connector System for Navy Pontoon Causeway Equipment, Naval Civil Engineering Laboratory, Technical Note N-1727. Port Hueneme, CA, July 1985, p. 25.

moment arm of 100-ft would create a moment of 3,330 ft-kip (33.0-kip x 100-ft), which is less than the capability of the connection system (5,250 ft-kip). The approach velocity of an LCU-2000 could be increased to 1.89-ft/s (1.12-kt) to equal the horizontal moment capability of the connection system.

Loads while Watercraft Moored Alongside

The wind and current loads for watercraft moored alongside the offshore section(s) are also presented in Appendix A. The wind load calculated for an LSV (4,307-lb) is almost insignificant when compared to the current loads (e.g., from Appendix A, Figure A-1: 320,000-lb for an LSV in 15-ft water depth in a 4-kt cross current).

As stated earlier, the end connection system between the pierhead and offshore sections can resist a horizontal moment of 5,250 ft-kip. This equates to a capability to withstand a 43.75-kip (5,250 ft-kip/120-ft[7]) combined current and wind load acting on a watercraft moored alongside the offshore section(s). Operating conditions exist that are both within and exceeding this load range. For example, if an LSV were moored alongside the pier in a 2-kt cross current at high tide (25-ft water depth), the current load on the LSV would be 33-kip (Figure A-1). When combined with the wind load, the total load would still be less than the 43.75-kip allowed. However, given the same vessel and cross current, but changing from a high to low tide, the combined load would greatly exceed the allowed load [80-kip (Figure A-1) + 4.3-kip > 43.75-kip].

Because the LCU-2000 generates less lateral wind and current load, broader operations can be conducted; however, the connection system could still be damaged in higher current conditions and when multiple craft are moored alongside the offshore sections. Two LCU-2000's could be accommodated at the pierhead (one each side of the offshore sections) at low tide if the current was less than 2-kt (2 x 19-kip < 43.75-kip) and wind loads were negligible. Only one LCU could be accommodated at low tide if the current were to reach 3-kt (43-kip current load ≅ 43.75-kip allowed).

As mentioned earlier, the impact of the current and wind loads could be reduced if the watercraft were to make use of their bow anchors prior to approaching the causeway pier and while alongside.

Mooring System Loads

The AMS was originally designed for a NL causeway pier with a single discharge point at the seaward end. This discharge point could accommodate a Tank Landing Ship (LST) as well as other landing craft. Because of the similar size and draft of the NL and MCS systems, no changes to the AMS, other than interface hardware would be expected; however, the Army has adopted a new pier configuration to handle multiple discharge points. This new pier configuration, which makes use of a larger pierhead, will experience greater current and wind loading at the pierhead due to the new lighterage discharge points.

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[7] The 120-ft moment arm is an approximation based on likely mooring points for both an LSV and LCU-2000.

The procedure for calculating the mooring loads on the causeway pier as well as results of the analysis are provided in Appendix B. Using this data as well as the environmental loads on the different watercraft generated in Appendix A, the suitability of the AMS can be determined.

The AMS makes use the of 2K NAVMOOR anchors in single and tandem configurations. Their holding capacity are as follows[8]:

	single	tandem
mud	48-kip	120-kip
sand	60-kip	150-kip

It should be noted that these values represent "set" anchors. The drag distance required to reach maximum capacity is variable and dependent upon soil density. For a sand seafloor, the drag distance ranges from 8 to 13 fluke lengths to achieve maximum capacity and about 3 fluke lengths to achieve the safe capacity (50% of maximum).[9] The 2K NAVMOOR anchor fluke length is 5-ft, which means the anchor would have to be dragged approximately 40- to 65-ft to achieve maximum capacity. Unfortunately, existing Army watercraft and procedures do not allow for the anchors to be pre-set in this manner.

As shown in Appendix B, in SS5 survival conditions (assuming no craft moored at the pierhead) a load of 108-kip could be experienced on a causeway section approximately half-way along the pier length. This estimate is conservative since diminishing wave heights along the pier's length caused by breaking waves weren't considered. The analysis is also conservative by selecting a beam sea condition, something unlikely because of wave refraction. "Refraction simply means bending. As waves move into shoaling water the friction of the bottom causes them to slow down, and those in the shallowest water move the slowest. Since different segments of the wave front are traveling in different depths of water, the crests bend and wave direction constantly changes. Thus the wave fronts tend to become roughly parallel to the underwater contours."[10] If refraction was considered and a still conservative approaching wave angle of 45° was used, the drift force component could be reduced to 66-kip, resulting in a combined load of 81-kip per section. Even given the conservative environmental load of 108-kip, the existing anchor arrangement would be sufficient along the roadway. Because the offshore section(s) are unsupported by mooring legs, the loads acting on them must be taken up by the mooring legs at the pierhead. Each of the pierhead configurations provided for analysis (Figure 1 through Figure 3) show two tandem NAVMOOR anchor legs on the pierhead. These anchors could hold against a force of 240-kip to 300-kip. For two unanchored offshore sections plus the pierhead (3 x 81-kip = 243-kip), the two tandem anchor legs will just prove adequate.

The mooring system must also withstand the additional load placed on the causeway pier by moored vessels. As shown in the previous section, the maximum load the connection system could support from a lighter moored alongside the offshore section(s) was less than 50-kip. The

[8] Johnson, B. A. (1987). Design of Mooring System for Army Floating Causeway Pier, Naval Civil Engineering Laboratory, Technical Memorandum M-42-87-05. Port Hueneme, CA, Jan. 1987, p. 13

[9] Taylor, R. (1987). The NAVMOOR Anchor, Naval Civil Engineering Laboratory, Techdata Sheet 87-05. Port Hueneme, CA, May 1987.

[10] Bascom, W. (1980). Waves and Beaches, pp. 78-79.

maximum environmental loads per causeway section in SS3 operating conditions is approximately 31-kip. Adding the vessel load (50-kip) to the environmental loads on the pierhead (3 x 31-kip), results in a load of approximately 143-kip, which is less than the 240-kip to 300-kip capacity of the two tandem anchor mooring legs at the pierhead.

Based on the results of this analysis, the AMS should prove sufficient for the new Army causeway pier configurations.

Structural Integrity of Pierhead

The MCS pontoons with their integral connection system give field users the capability of assembling semi-rigid platforms of various sizes and shapes. Though platforms of large sizes can be assembled, consideration must be given to the limits of the pontoon's pin and guillotine connection system. From a structural engineering viewpoint, platforms assembled from MCS pontoons are not rigid. The pin and guillotine connection system is fabricated with a given tolerance to allow for the easy assembly of platforms. Past experience at NFESC with the prototype of the MCS system has shown that large cyclic loading can be experienced in the pin and guillotine system due to the looseness of the connection. As no guidance has been provided for other than the construction of standard 24- by 80-ft causeway sections, a review of the larger pierheads was conducted.

As the largest platform is likely to generate the greatest internal loads, the 120- by 88-ft pierhead was selected for analysis. The internal structural loads were calculated using the diffraction theory program, MORA, for operating and survival conditions. Experience suggests that the results of this type of linear theory analysis yields good results for small-amplitude waves; however, it is unclear where nonlinear effects would become significant. The procedures and results of the analysis are provided in Appendix C.

The loads of interest are from a vertical plane at the midship of the platform. From Appendix C, Figure C-13, the largest moment that the 88- by 120-ft pierhead is expected to experience is 8,575,000 ft-lb. Along this plane of maximum moment the pierhead is held together with 22 pins along the bottom and 22 along the top. The vertical distance between the centers of the top and bottom pins is 47-in. At SS5 the load on one pin is:

$$P_s = (8{,}575{,}000 \text{ ft-lb}) / [(47\text{-in} \times 1\text{-ft}/12\text{-in})\ (22 \text{ pins})] = 99{,}516 \text{ lbs/pin}$$

This load is well within the 75-ton tensile rating of the pin; however, since the pin is subjected to a cyclic load from passing waves, additional issues such as fatigue need to be addressed. Dynamic impact load was not a concern because the period of the fluctuating load cycle is on the order of several seconds.

Based on previous experience with the prototype and fielded MCS systems, it was felt that the component most likely to fail would be the male lock pin. A fatigue analysis of the pin was conducted to evaluate its endurance over a number of cycles (see Appendix D). A S-N diagram for the male lock pin was plotted (Appendix D, Figure D-2). From this diagram, it can be seen that the SS5 pin load calculated above will cause failure of the pin after 24,000 load cycles in a 120- by 88-ft platform. This equates to less than a 2-day (approximately 40-hr) storm duration. Even if the storm were to not last 40-hrs, permanent damage to the pin would have occurred, resulting in a lower endurance limit and earlier failure under less stress at a later date. For example, prior to the SS5 conditions, the pins would have theoretically lasted infinitely long because the stress on a pin during SS3 conditions is less than that of the endurance limit (10,472 psi < 11,160 psi); however, after a 15-hr SS5 storm, the modified endurance limit for the damaged pins is 7,700 psi. If the pins were then subjected to SS3 conditions, they would fail in less than 3-wks time. Appendix D provides further information on cumulative fatigue damage.

FINDINGS

For an LSV, approach velocities greater than approximately 1-ft/s (0.6-kt) during berthing creates an impact load which exceeds the offshore section flexor/shear connection system capability.

For an LCU-2000, approach velocities greater than approximately 1.9-ft/s (1.1-kt) during berthing creates an impact load which exceeds the offshore section flexor/shear connection system capability.

The ability to moor watercraft alongside the sections seaward of the pierhead is highly dependent upon the current load, which increases significantly as the draft of the watercraft approaches the available water depth.

- For an LSV, at low tide only a 1-kt cross current is acceptable. In a 2-kt cross current, a minimum water depth of 25-ft is required.
- For an LCU-2000, at low tide a 2.5-kt cross current is acceptable. In a 3-kt cross current, the minimum water depth required is 15-ft; 3.5-kt / 20-ft; and 4.0-kt / 25-ft.
- For two LCU-2000's, at low tide a 1.5-kt cross current is acceptable. In a 2.0-kt cross current, the minimum water depth required is 15-ft, and a 2.5-kt current requires 20-ft.

The existing AMS design is adequate for the roadway sections.

Two tandem anchor mooring legs are required on each side of the pierhead.

The results of the fatigue analysis indicates that fatigue must be considered when evaluating pierhead survivability (i.e., when compared to the pin's rated load, the environmental load did not cause failure; however, applying the same load over thousands of cycles caused the pin to fail).

The stress on the MCS male lock pins of a 120- by 88-ft pierhead during SS3 conditions is slightly less than the pins' endurance limit. During SS5 conditions, the stress exceeds the pins' endurance limit, meaning the pins have a finite fatigue life when (and after) being exposed to SS5 conditions.

RECOMMENDATIONS

Inform watercraft operators of affect of impact velocity on pierhead and develop/follow operational procedures to limit berthing impact force.

Develop procedures to determine under what water depth and cross current conditions it is advisable to moor LSV's and LCU-2000's at the pierhead

Use watercrafts' anchoring and bow thruster capabilities to reduce berthing impact force and mooring loads on the pierhead.

Consider other pierhead arrangements to increase moment capability between pierhead and offshore sections.

Use two tandem anchor mooring legs on each side of the pierhead.

Do not assemble and operate a 120-ft long pierhead where seas greater than SS3 are expected.

Develop and implement a program to determine pin life, periodic inspection and replacement criteria.

Perform statistically meaningful experimental tests to determine the fatigue strength and endurance limit mean and standard deviation of the male lock pin. Then determine the value of cyclic stress that would require periodic inspection.

Very little experimental data is available in the literature for shallow-draft barge motions of the type considered here. In view of this, certain well-designed model tests including measurements of both motions and loads would be warranted.

ACKNOWLEDGMENTS

The following NFESC personnel assisted greatly in the completion of this report: Mr. Billy Karrh (structural engineering); Rob Johnston and John Norbutas (finite element modeling and fatigue analysis); Tom Lin (mooring analysis); and Dan McCambridge (berthing analysis). Dr. C. J. Garrison of C. J. Garrison and Associates is acknowledged for performing the hydrodynamic analysis. NFESC would also like to thank Mr. Steve Woolery of USA TRANSCOM for the opportunity to perform this work and the patience shown during its execution.

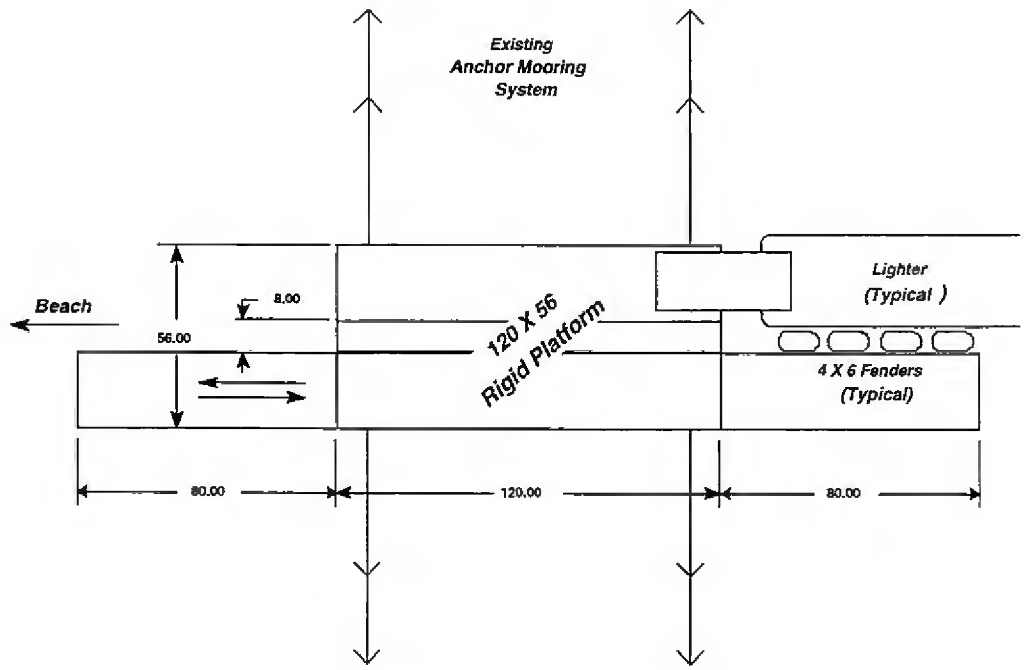

Figure 1. Single Pierhead, Single Roadway

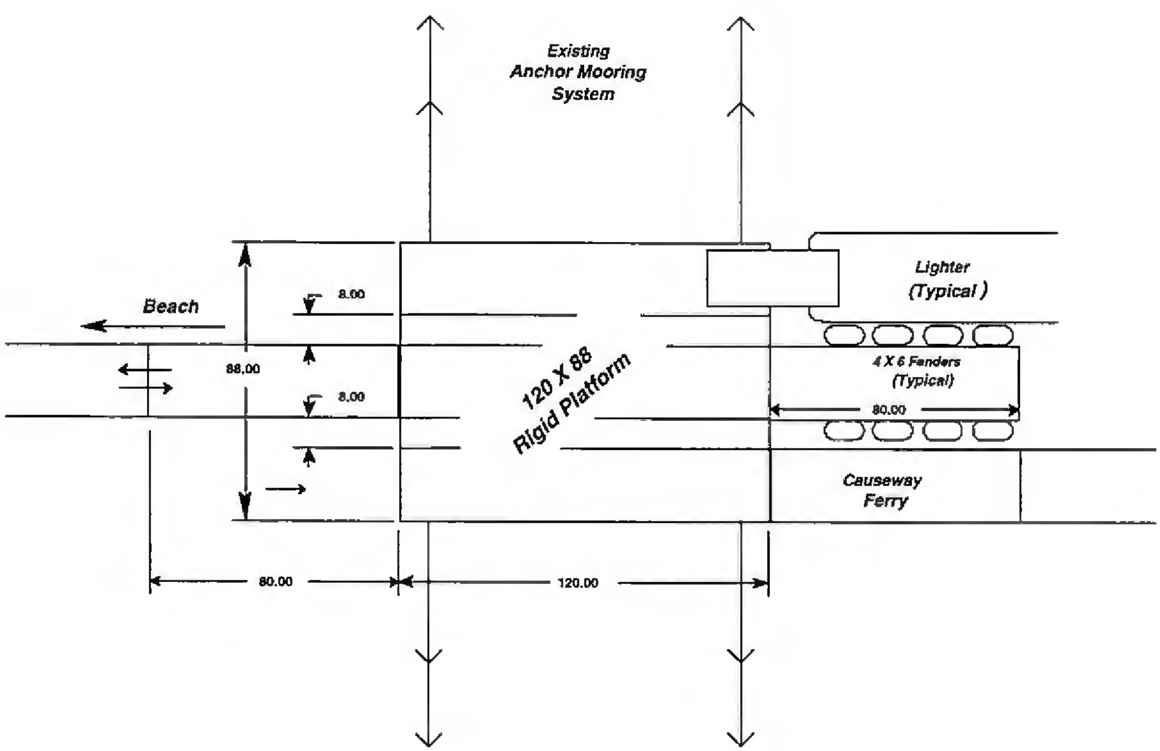

Figure 2. Dual Pierhead, Single Roadway

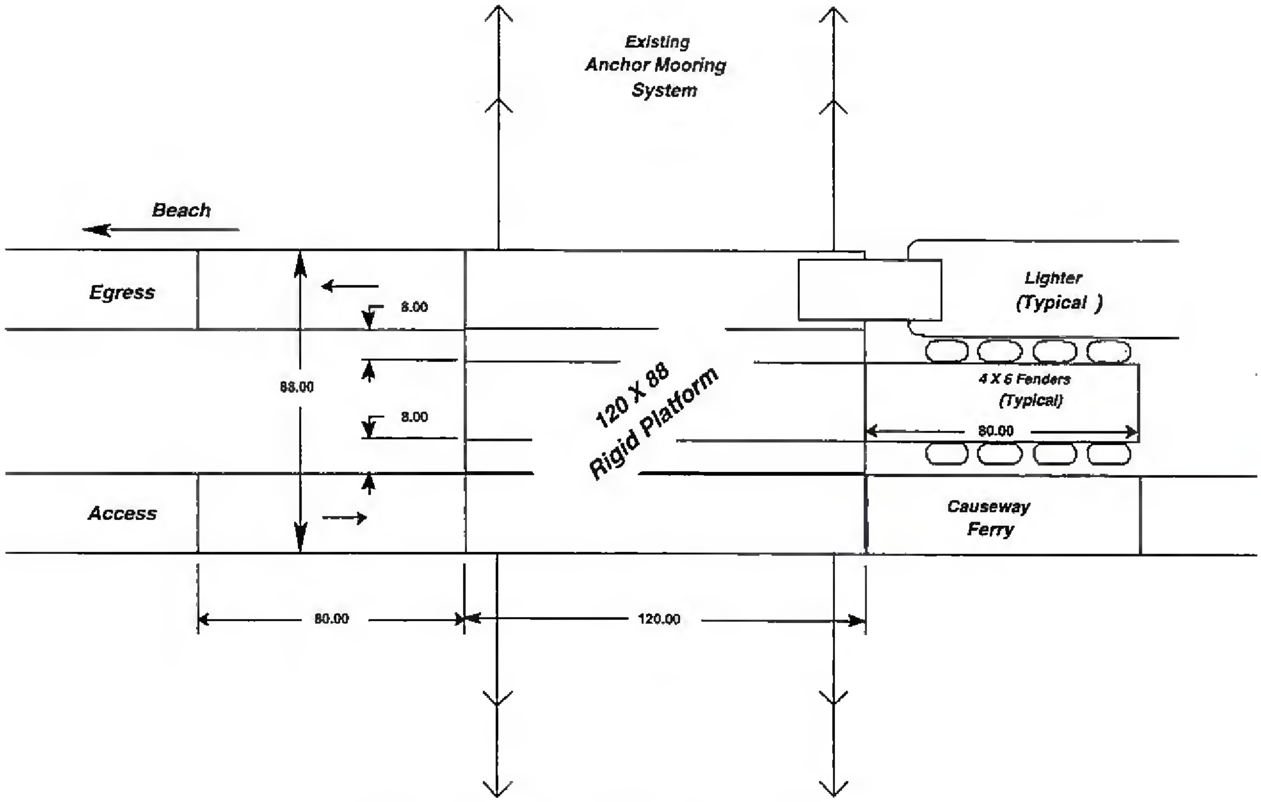

Figure 3. Dual Pierhead, Dual Roadway

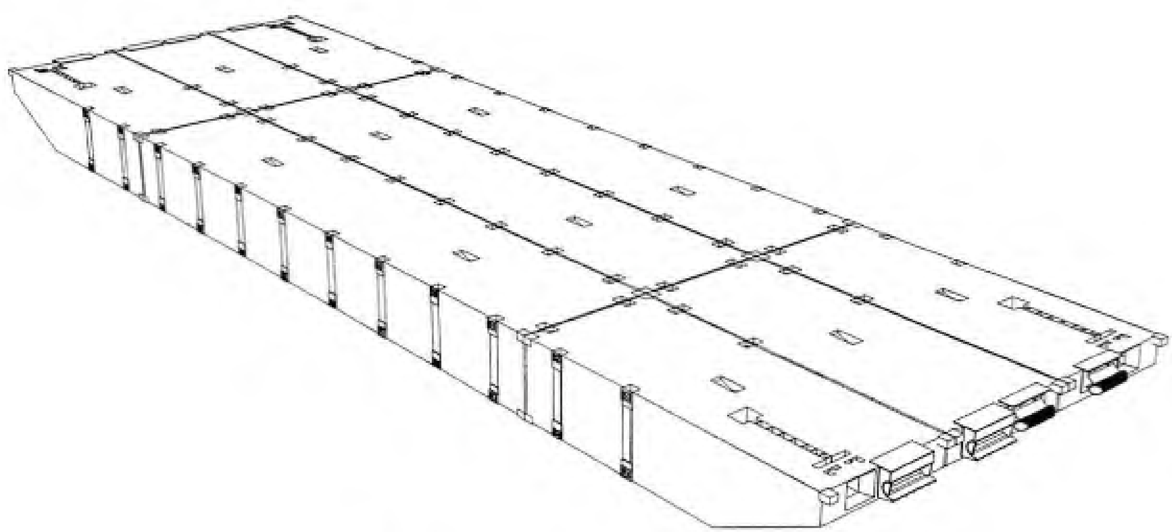

Figure 4. Modular Causeway Section (MCS)

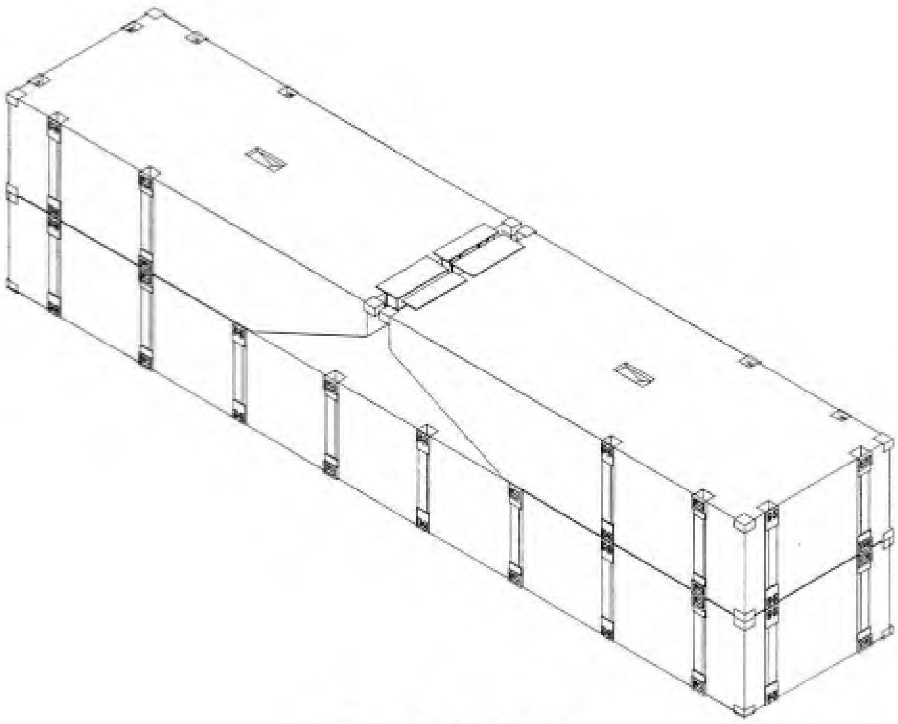

Figure 5. ISOPAK

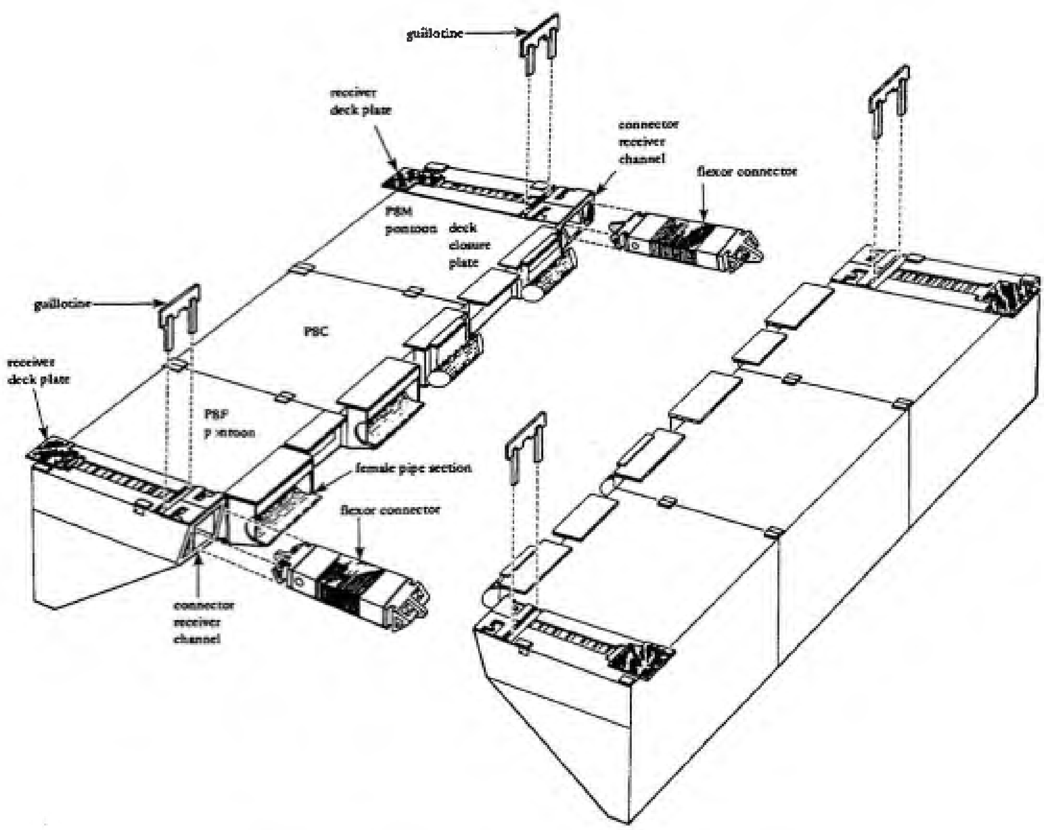

Figure 6. Flexor and Shear Connector Interface

Appendix A. Offshore Section Loading Calculation

This appendix addresses the loading on an offshore section that is located seaward of the causeway pierhead and serves as both a cargo discharge point and a berthing pier for Army lighters. The section seaward of the pierhead is connected to the pier with FLEXOR and Shear connectors and is not supported directly by an anchoring system.

The recommended analysis procedure requires the forces on this offshore section due to the impact load of the berthing vessel and the wind, waves and current acting on the berthed vessel. Wind, waves and current each produce a steady state force. These forces are evaluated individually and summed to get the total steady state environmental force. The energy absorbed and the force developed by a berthing lighter is based on factors such as the form of the lighter, water depth, berthing velocity, difficulty of the approach, angle of approach, maneuvering space, and location of the pier. The most significant of these factors is the approach velocity, since berthing energy is a function of the square of the normal component of the approach velocity. By doubling the design value of the approach velocity, the lighter's kinetic energy is quadrupled.

The wind and current loads are calculated using procedures established in the Naval Facilities Engineering Command (NAVFAC) Design Manual (DM) 26.5, Fleet Moorings, Basic Criteria and Planning Guidelines, June 1985. The berthing loads are calculated using procedures established in the Military Handbook for Piers and Wharves (MIL-HDBK-1025/1).

Wind Load Calculation

Lateral wind load is determined using the following equation:

$$F_{yw} = \tfrac{1}{2}\,\rho_a\,V_w^2\,A_y\,C_{yw}\,f_{yw}(\theta_w)$$

where

- F_{yw} = lateral wind load, in pounds
- ρ_a = mass density of air = 0.00237 slugs/ft^3 at 68°F
- V_w = wind velocity, in feet per second
- A_y = lateral projected area of ship, in square feet
- C_{yw} = lateral wind-force drag coefficient
- $f_{yw}(\theta_w)$ = shape function for lateral load = $[(\sin\theta_w - (\sin 5\theta_w)/20) / (1 - 1/20)]$
- θ_w = wind angle

The lateral wind-force drag coefficient depends upon the hull and superstructure of the vessel:

$$C_{yw} = 0.92\,[(V_S/V_R)^2 A_S + (V_H/V_R)^2 A_H] / A_y$$

where

- V_S/V_R = average normalized wind velocity over superstructure
- V_R = reference wind velocity at 33.33 feet above sea level
- A_S = lateral projected area of superstructure only, in sq. ft.
- V_H/V_R = average normalized wind velocity over hull

A_H = lateral projected area of hull only, in sq. ft.
A_y = lateral projected area of ship, in sq. ft.

The values of V_S/V_R and V_H/V_R are determined using the following equations

$$V_S/V_R = (h_S/h_R)^{1/7}$$
$$V_H/V_R = (h_H/h_R)^{1/7}$$

where

h_S = average height of superstructure, in feet
h_R = reference height of wind speed (33.33 ft)
h_H = average height of hull, in feet

For an LSV (see Appendix E for LSV characteristics):

$V_S/V_R = (h_S/h_R)^{1/7} = (36 \text{ ft} / 33.33 \text{ ft})^{1/7} = 1.011$
$V_H/V_R = (h_H/h_R)^{1/7} = (12 \text{ ft} / 33.33 \text{ ft})^{1/7} = 0.864$

The lateral wind-force drag coefficient can now be calculated as:

$$\begin{aligned} C_{yw} &= 0.92\,[(V_S/V_R)^2 A_S + (V_H/V_R)^2 A_H] / A_y \\ &= 0.92\,[(1.011)^2\, 960 \text{ ft2} + (0.864)^2\, 5933 \text{ ft2}] / 6893 \text{ ft2} \\ &= 0.722 \end{aligned}$$

For $\theta_w = 90°$, and V_w = 16 kt (27.024 ft/s), the lateral wind load on an LSV is:

$$\begin{aligned} F_{yw} &= \tfrac{1}{2}\, \rho_a V_w^2 A_y C_{yw} f_{yw}(\theta_w) \\ &= \tfrac{1}{2}\,(0.00237 \text{ slugs/ft3})\,(27.024 \text{ ft/s})^2\,(6893 \text{ ft2})\,(0.722)\,(1) \\ &= 4{,}307 \text{ lb} \end{aligned}$$

Current Load Calculation

The Lateral current load is determined from the following equation:

$$F_{yc} = \tfrac{1}{2}\, \rho_w V_c^2 L_{wL} T C_{yc} \sin\theta_c$$

where

F_{yc} = lateral current load, in pounds
ρ_w = mass density of water = 2 slugs/ft^3 for sea water
V_c = current velocity, in feet per second
L_{wL} = vessel waterline length, in feet
T = vessel draft, in feet
C_{yc} = lateral current-force drag coefficient
θ_c = current angle

The lateral current-force drag coefficient is given by:

$$C_{yc} = C_{yc}|_{\infty} + (C_{yc}|_1 - C_{yc}|_{\infty})\, e^{-k(wd/T - 1)}$$

where

C_{yc}	=	lateral current-force drag coefficient
$C_{yc}\vert_{\infty}$	=	limiting value of lateral current-force drag coefficient for large values of wd/T
$C_{yc}\vert_1$	=	limiting value of lateral current-force drag coefficient for wd/T = 1
e	=	2.718
k	=	coefficient
wd	=	water depth, in feet
T	=	vessel draft, in feet

Values of $C_{yc}|_{\infty}$ are given in NAVFAC DM26.5 Figure 56 as a function of L_{wL}/B and vessel block coefficient, ϕ. For an LSV (L_{wL}/B = 255.4 ft / 60.0 ft = 4.26 and ϕ = 0.80), $C_{yc}|_{\infty}$ = 0.58.

Values of $C_{yc}|_1$ are given in NAVFAC DM26.5 Figure 57 as a function of $C_p\, L_{wL} / T^{1/2}$, where C_p is the prismatic coefficient. For an LSV ($C_p\, L_{wL} / T^{1/2}$ = (0.80)(255.4 ft)/(12.0 ft)$^{1/2}$ = 59.0), $C_{yc}|_1$ =3.60.

The value of the coefficient, k, is given in NAVFAC DM26.5 Figure 58 as a function of ϕ and the vessel hull shape (either block-shaped or normal ship-shaped). For an LSV (block-shaped hull form and ϕ = 0.80), k = 1.7.

It is important to note that the lateral current-force drag coefficient varies with water depth. As water depth decreases, the current load will increase. The maximum water depth at the pierhead is determined by lighterage draft, tide range and wave height plus a minimum clearance between the lighter bottom and seafloor to reduce damage to the hull from grounding (this will vary depending on the preference of the vessel operator). For an LSV:

$$\begin{aligned} wd_{max} &= T + \text{tide} + \text{wave trough} + \text{clearance} \\ &= 12.0\text{ ft} + 7\text{-ft} + 6\text{-ft}/2 + 3\text{-ft} \\ &= 25\text{-ft} \end{aligned}$$

The minimum water depth to consider is equal to the draft of the lighter plus the ground clearance:

$$\begin{aligned} wd_{min} &= T + \text{clearance} \\ &= 12.0\text{ ft} + 3\text{ ft} \\ &= 15\text{-ft} \end{aligned}$$

With this information, all of the data required to calculate C_{yc} and F_{yc} is available.

$$\begin{aligned} C_{yc} &= C_{yc}|_{\infty} + (C_{yc}|_1 - C_{yc}|_{\infty})\, e^{-k(wd/T - 1)} \\ &= 0.58 + (3.60 - 0.58)\, e^{-1.7\,(wd/12 - 1)} \end{aligned}$$

for wd = 12-ft, C_{yc} = 3.60
for wd = 15-ft, C_{yc} = 2.55

for wd = 20-ft, C_{yc} = 1.55
for wd = 25-ft, C_{yc} = 1.06

For these water depths, the lateral current load on the LSV as a function of current is provided in Figure A-1.

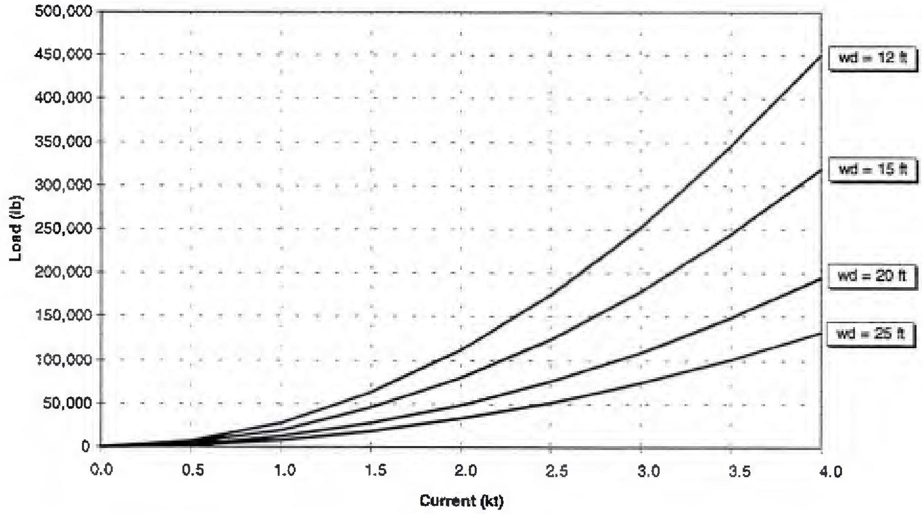

Figure A-1. Lateral Current Load for an Army LSV (Draft = 12 ft)

These same calculations can be repeated for an LCU-2000. Using:

$C_{yc}|_{\infty}$ = 0.54 from NAVFAC DM26.5 Figure 56, where L_{wL}/B = 3.57 (156 ft/42.0 ft) and ϕ = 0.69
$C_{yc}|_{1}$ = 2.6 from NAVFAC DM26.5 Figure 57, where $C_p\, L_{wL} / T^{1/2}$ = 36.9 ((0.69)(156 ft)/(8.5 ft)$^{1/2}$)
k = 1.1 from NAVFAC DM26.5 Figure 58, where ϕ = 0.69 and using block-shaped hull form

the lateral current load on the LCU-2000 is calculated and provided as a function of current in Figure A-2:

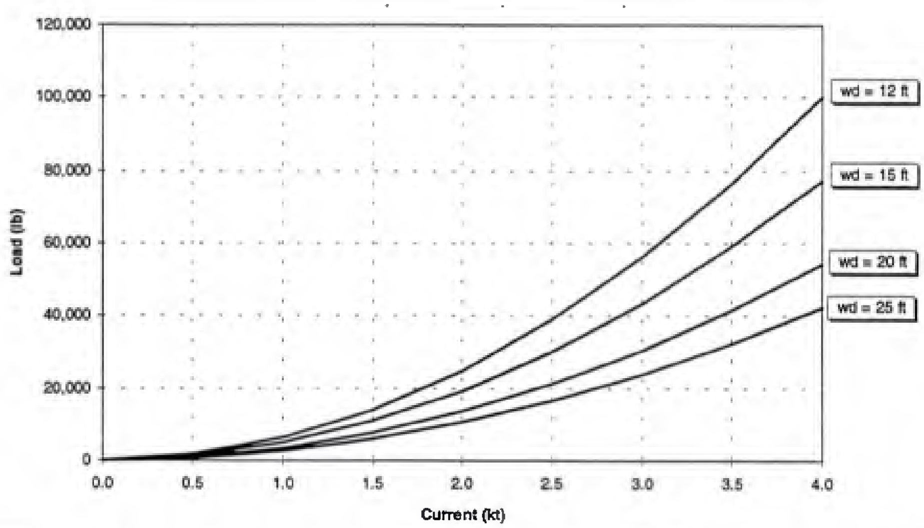

Figure A-2. Lateral Current Load for an Army LCU-2000 (Draft = 8.5 ft)

Berthing Force Calculation

Berthing energy was calculated using the kinetic method as described in Section 5 of the Military Handbook for Piers and Wharves (MIL-HDBK-1025/1). When the displacement tonnage of the watercraft is known, the energy equation can be written as:

$$E_{ship} = \frac{1}{2}\frac{W}{g}v^2$$

where

E_{ship} = Berthing energy of ship (ft-lbs)
W = Weight of ship (lbs)
g = Acceleration due to gravity (32 ft/s^2)
v_n = Berthing velocity normal to berth (ft/s)

Several references were consulted to determine a suitable berthing velocity. It should be noted that the kinetic energy of the berthing vessel is a function of the square of the normal component of its approach velocity. Thus, the kinetic energy as well as the resultant force on the berthing structure are sensitive to changes in approach velocity. By doubling the design value of the approach velocity, the vessel's kinetic energy is quadrupled. Design values used for the approach velocity normal to the berth generally vary from 0.25 to 1.50 ft/s, depending on the size of the ship being docked and the tug assistance that is employed. Figure 44 of MIL-HDBK-1025/1 provides a berthing velocity of approximately 1.0 ft/s for a 5,000 long ton displacement vessel berthing in exposed conditions. In moderate wind and heavy sea conditions, berthing velocity is estimated at 1.5 ft/s from Appendix 3, Table 1 of *Port Engineering* by Per Bruun. Because higher approach velocities should be anticipated when the berth is located in exposed waters and when vessels self-dock (i.e., no tug assistance), the more conservative estimate was selected.

Given the LSV characteristics (Appendix E) and estimated berthing velocity, berthing energy of the LSV was calculated as:

$$E_{ship} = \frac{1}{2}\frac{W}{g}v^2 = \frac{1}{2}\frac{9{,}406 kips}{32\,ft/s^2}(1.5\frac{ft}{s})^2 = 330.7 \text{ ft-kip}$$

for v_n = 1.0 ft/s, E_{ship} = 147.0 ft-kip
for v_n = 0.5 ft/s, E_{ship} = 36.7 ft-kip

There are other factors that modify the actual energy to be absorbed by the causeway pier and fendering system. The expression can be written as:

$$E_{fender} = C_b C_m E_{ship}$$

where

E_{fender} = Energy to be absorbed by fender system
C_b = Berthing coefficient = $C_e C_g C_d C_c$
C_m = Effective or virtual mass coefficient

and

C_e = Eccentricity coefficient
C_g = Geometric coefficient
C_d = Deformation coefficient
C_c = Configuration coefficient

The coefficients that determine the berthing coefficient, C_b, are briefly discussed below. The eccentricity coefficient, C_e, accounts for rotation of the vessel around the contact point which dissipates part of the vessel's energy. Values of C_e typically are between 0.4 and 0.7. A value of 0.4 was chosen from Figure 43 of MIL-HDBK-1025/1. The geometric coefficient, C_g, depends upon the geometric configuration of the ship at the point of impact. Generally, 0.95 is recommended for the impact point at or beyond the quarter points of the vessel, and was selected for this analysis. The deformation coefficient, C_d, accounts for energy dissipated due to ship deformation. A coefficient of 1.0 was chosen since little or no deformation of the vessel is expected. The configuration coefficient, C_c, accounts for the difference between an open pier or wharf and a solid pier or wharf. The Army pier is considered an open pier, with a coefficient of 1.0. For this analysis, the berthing coefficient is:

$$C_b = C_e C_g C_d C_c = (0.4)\,(0.95)\,(1.0)\,(1.0) = 0.38$$

When a vessel approaches a pier, the berthing impact is induced not only by the mass of the moving vessel, but also by the water mass moving along with the ship. The effective mass or virtual mass coefficient, C_m, accounts for this "added" mass. Its value should be a minimum of 1.5 and need not exceed 2.0. It can be calculated as:

$$C_m = 1 + 2\frac{T}{B} = 1 + (2)\,(12.0\text{ ft} / 60.0\text{ ft}) = 1.4 < 1.5\text{, therefore select 1.5 as value}$$

The actual energy of an LSV berthing alongside a pier can now be calculated as

$$E_{fender} = C_b C_m E_{ship} = (0.38)\,(1.5)\,(330.7\text{ ft-kip}) = 188.5\text{ ft-kip}$$

for v_n = 1.0 ft/s, E_{fender} = 83.8 ft-kip
for v_n = 0.5 ft/s, E_{fender} = 20.9 ft-kip

The force, F, on the pier/fender can be calculated from this energy. The work, W, done by the pier/fender to bring the ship to rest is equal to the kinetic energy applied to the fender. Assuming the fender compressing 18 inches (approximately 50% compression on a 3-ft diameter SEA GUARD fender):

$$W_{pier/fender} = E_{fender} = F_{pier/fender}\,(dist\ pier\,/\,fender\ move)$$

$$F_{pier/fender} = \frac{E_{fender}}{dist\ pier\,/\,fender\ move} = \frac{188.5 ft - kips}{1.5 ft} = 125.7\text{ kip}$$

for v_n = 1.0 ft/s, $F_{pier/fender}$ = 55.9 kip for $v_n = 0.5$ ft/s, $F_{pier/fender} = 13.9$ kip

These same calculations can be repeated to find the berthing force of an LCU-2000 (vessel characteristics from Appendix F). The results are presented below:

LCU-2000			
v_n (ft/s)	E_{ship} (ft-kip)	E_{fender} (ft-kip)	$F_{pier/fender}$ (kip)
1.5	86.8	49.5	33.0
1.0	38.6	22.0	14.7
0.5	9.6	5.5	3.6

Appendix B. Anchor Mooring System Review

The procedures established in NCEL Technical Memorandum M-42-87-05, Design of Mooring System for Army Floating Causeway Pier, with minor modifications by Dr. Tom Lin of the Amphibious Systems Division (Code ESC31) at NFESC, were used to calculate the environmental loads for this study. The significant environmental loads to be analyzed include current and drift force. When the waves hit the causeway pier, they are partly reflected and partly transmitted. This results in a fluctuating force on the causeway with a non-zero mean which is referred to as a "drift force." The magnitude of the drift force depends on the height, period and direction of the waves impinging upon the causeway pier. These quantities depend on the height, period and direction of the waves in deep water long before they reach the causeway and on the variations in the seafloor between the deepwater area and the location of the pier. The wave direction in deepwater that will produce the maximum load on the causeway varies depending on the water depth at the point of interest on the causeway. The magnitude of the drift force is also affected by the pier itself and how it affects the waves which depends on water depth, causeway draft (which changes with load and position of load), and direction of wave travel.

The low profile of a floating causeway pier provides little opportunity for large windloads to be generated. As shown in TM M-42-87-05, the windloads were insignificant in comparison to the other environmental loadings acting on the pier. Therefore, wind loads were not considered in this analysis.

The slope of the beach and the submerged bottom can also vary widely around the world. Since the intended use of the floating causeway pier is on beaches with too shallow a bottom slope for lighters to operate in, the slope of interest are in the range of 1:50 to 1:250 (vertical:horizontal distances) or flatter. A beach slope of 1:68, calculated as follows, was used for this study to obtain the required minimum water depth (12-ft) for the given pier length (1500-ft) during sea state 3 operations

Beach slope = vertical:horizontal distances
Vertical Distance = water depth + tide + wave trough
Horizontal Distance = 1500-ft

Beach slope = (12-ft + 7-ft + 3-ft) : 1,500-ft
= 22-ft : 1,500-ft
= 1:68

The loads due to current were assumed to be perpendicular to the axis of the causeway. In accordance with TM M-42-87-05 the worst case drift force was also assumed perpendicular to the axis of the causeway and in the same direction as current to produce a total load of the worst possible case. For the calculation of the current loads, the following equation was used:

$$f_c = C_D\,(1 + K_d)\,A\,r\,V^2/2$$

where

f_c = unit load due to current (lb/linear foot)

C_D = drag coefficient
$(1 + K_d)$ = shallow water factor of drag coefficient
A = area (cross-sectional of submerged causeway) (ft^2)
r = density of seawater (lb/ft^3)
V = velocity of current (ft/sec)

For the calculation of the drift force loads, the following equation was used:

$$f_w = f\,H^2$$

where

f_w = unit force on causeway due to wave drift force (lb/linear-foot)
H = wave height at point of interest on causeway (feet)
f = drift force factor, f (a, d, T) (lb/ft^3)

and

a = wave angle (angle between wave crest and shoreline) at point of interest on causeway, f (a_o, d, T) (degrees)
a_o = wave angle (angle between wave crest and shoreline) in deep water (degrees)
d = water depth at point of interest on causeway (feet)
T = period of waves (second)

The total load (current plus drift force) on the 1500-ft causeway pier in a sea state 5 survival condition (12-ft wave height) is presented in Figure B-1 and in Table B-1.

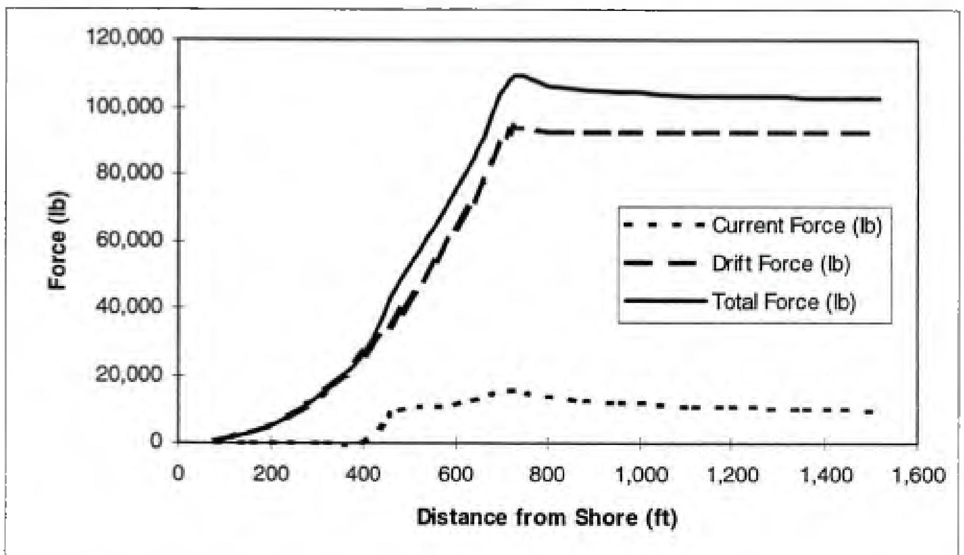

Figure B-1. Environmental loads on a 1500-ft single roadway causeway pier assuming a bottom slope of 1:68, tide range of 7 feet, cross current of 4-kt and a sea state 5.

Table B-1. Environmental loads on a 1500-ft single roadway causeway pier assuming a bottom slope of 1:68, tide range of 7 feet and a sea state 5.

```
INPUT DATA:

   NCASE = 1, FIXED BARGE; NCASE = 2,  FLOATING BARGE
   WDMAX   = WATER DEPTH AT PIER HEAD
   AL      = A BARGE LENGTH              SL    = SEAFLOOR SLOPE
   V1      = BEAM CURRENT, KNOT          T0    = DRAFT, FT
   NCASE   WDMAX  LENGTH   SLOPE     V1      T0     WAMP     PERI
       2    22.0    80.0     68.    4.0     2.2      6.0      6.8
```

OUTPUT DATA:

WATER DEPTH (FT)	DIST. FROM SHORE (FT)	CURRENT FORCE (LB)	DRIFT FORCE (LB)
.6	80.0	0.	321.
1.8	160.0	0.	2888.
2.9	240.0	0.	8022.
4.1	320.0	0.	15723.
5.3	400.0	0.	25992.
6.5	480.0	9395.	38827.
7.6	560.0	10568.	54230.
8.8	640.0	12682.	72199.
10.0	720.0	15296.	92736.
11.2	800.0	13450.	92736.
12.4	880.0	12363.	92736.
13.5	960.0	11693.	92736.
14.7	1040.0	11176.	92736.
15.9	1120.0	10777.	92736.
17.1	1200.0	10475.	92736.
18.2	1280.0	10253.	92736.
19.4	1360.0	10053.	92736.
20.6	1440.0	9870.	92736.
21.8	1520.0	9748.	92736.

Appendix C. Wave Loads on Pierhead

This study was carried out to evaluate the internal structural loads at certain imaginary cuts through the pierhead. The general configuration of the structure is shown in Figure C-1. The overall dimensions are 120 feet by 88 feet by 4.5 feet in depth. The structure was taken to float at equilibrium with a draft of 14 inches. The water depth was constant at 16.0 feet.

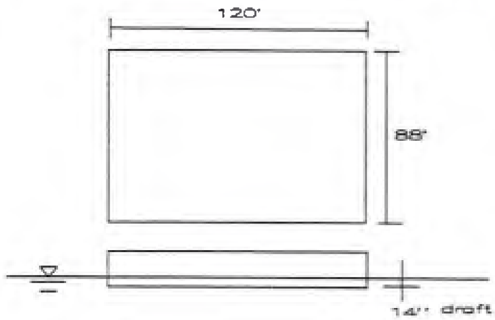

Figure C-1. Simplified Army Causeway Pierhead

The coordinates used to describe the loads are represented by rectangular coordinates with y pointing upward, x pointing in the direction of wave propagation (at zero wave direction) and z pointing in the beamwise direction. The structure was subjected to irregular waves at sea state 3 and 5.

Loads have been calculated at vertical-plane cuts through the structure at 20 feet from the end (cut B), at the center (cut A) and along the centerline of the structure (cut C) as shown in Figure C-2. The statistical values of all six components of the loads as well as the moment RAO are presented for the cuts. Figure C-2 defines the wave direction and the load component designation. The load components follow the right hand coordinates system at the cut with y being upward and z being transverse to the long dimension of the structure and x being parallel to the long dimension of the structure in all three cases. To simplify the analysis, the structure was considered to be free-floating without moorings and responding to the wave motion.

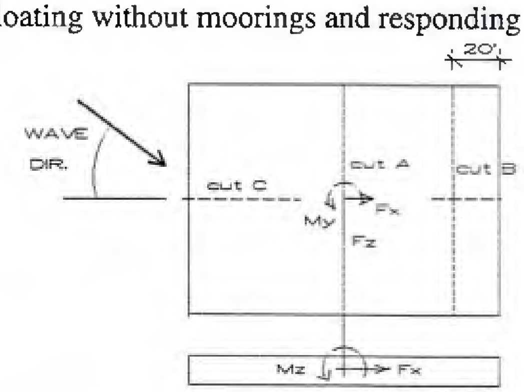

Figure C-2. Definition of Loads & Cuts

Methodology

Analysis of the wave loads at three different sections through the pier have been carried out using the computer program package, MORA (MORA User's Guide (1993), C. J. Garrison & Associates). In this program, three-dimensional diffraction theory is used to evaluate the hydrodynamic coefficients and eventually the Response Amplitude Operator (RAO) for the load components resolved into the principal axes at the imaginary cut. The origin of the axes used to resolve the loads is located at the center of cut. This load RAO information is then used in conjunction with the wave spectrum to obtain the statistical properties of the loads. As noted in the following, however, it is actually only the bending moment about a horizontal axis at the interface which is of primary interest since only this component is large and effective in generating the critical structural loads.

Numerical Hydrodynamic Analysis

The three dimensional diffraction theory analysis requires discretizing the immersed surface of the multi-module structure into a quadrilateral grid. The immersed surface of the structure is then represented by a surface source distribution uniformly distributed over each panel. The subdivision of the immersed surface must be sufficiently fine to obtain convergence of the numerical solution. The grid used to make the calculations is shown in Figure C-3 for the complete pier structure. A total of 516 source panels was used to represent the complete immersed surface.

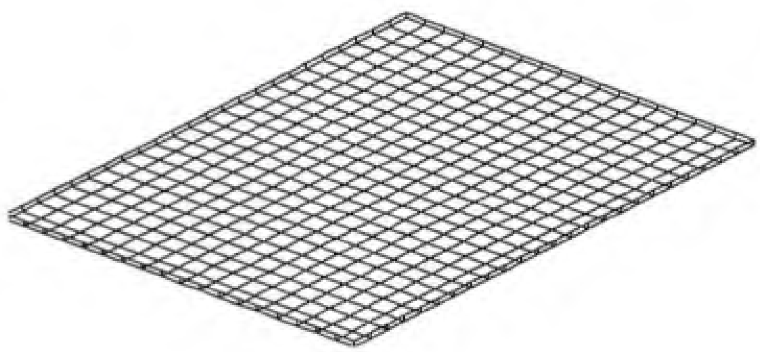

Figure C-3. Immersed Surface Grid

For purposes of evaluating the motions and loads, the mass distribution of the overall pierhead was needed. This was computed based on a 14.0 inch draft giving a displacement of 789.5 kip. The radii of gyration were estimated by assuming that the total mass of the module was uniformly distributed over the surface of the box-like form. That is, the module was approximated by a simple shell structure. The location of the center of gravity and moments of inertia corresponding to parts of the structure isolated by the cuts are listed in Table C-1. Section B, for example, refers to the part of the structure to the right of the cut B indicated in Figure C-1. The mass refers to this portion of the structure and the moments of inertia are about axes at the cut.

Table C-1. Mass Properties of Sections of Structure

SECTION	C.G. Dist. from center	Mass (slugs)	I_{xx} (slug-ft^2)	I_{yy} (slug-ft^2)	I_{zz} (slug-ft^2)
A	30.5	$1.227\ 10^4$	$0.8175\ 10^7$	$2.44\ 10^7$	$1.578\ 10^7$
B	50.97	$0.437\ 10^4$	$0.3087\ 10^7$	$.3764\ 10^7$	$0.714\ 10^6$
C	23.03	$1.227\ 10^4$	$0.8715\ 10^7$	$2.44\ 10^7$	$1.578\ 10^7$

Wave Spectra

There are two wave spectra which are considered in this report; an operational spectra and a survival spectra, characterized by an International Ship Structures Congress (ISSC) spectrum with significant wave height, H_s, and a peak frequency, f_0, as shown in Table C-2.

Table C-2. ISSC Wave Spectra

Sea State	H_s (ft)	f_0 (peak, Hz.)
3.0	3.3	0.18
5.0	10.0	0.11

The operational and survival spectra as defined above are plotted in Figure C-4 and Figure C-5, respectively.

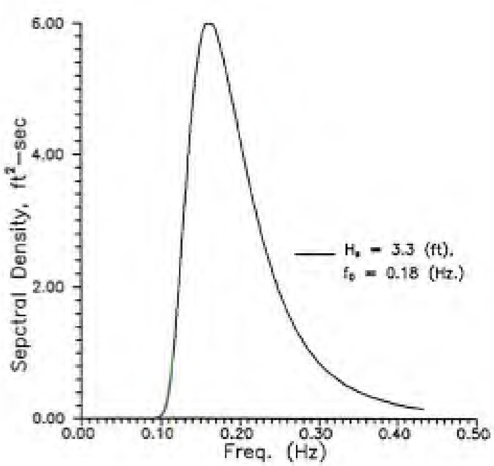

Figure C-4. Operational Wave Spectra; ISSC Spectra, Sea State 3.0

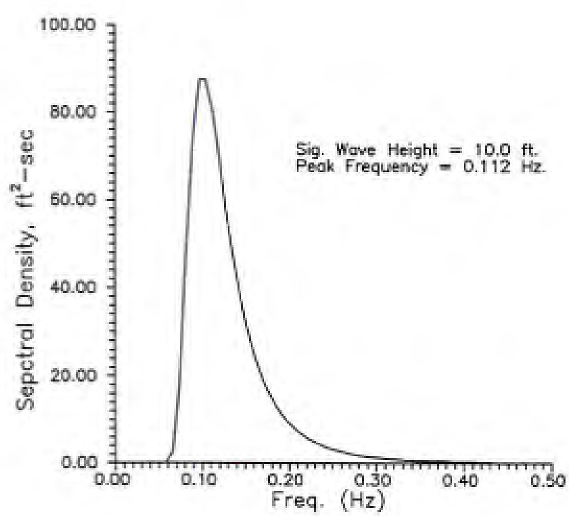

Figure C-5. Survival Wave Spectrum; ISSC Spectrum, Sea State 5

Load Components

The three components of force and three components of moment have been computed for each of the three sections identified as section A, B and C in Figure C-2. The loads have been computed corresponding to both the operational spectrum (sea state 3) and the survival spectrum (sea state 5). In all cases the loads have been computed as a function of wave direction as well as sea state. The input and output MORA data files for this analysis are provided beginning on page C-9 and C-14 respectively.

The load values shown in the figures represent significant loads. These are sometimes referred to as the average of the one third highest peak values. From a statistical viewpoint, the maximum value can be computed based on a Rayleigh distribution by multiplying the significant values by the factor $(LnN/2)^{1/2}$ where N denotes the total number of waves during the duration of exposure to the sea state in question.

The significant values of the force components at Cut A (transverse cut through the middle of the pier) are shown in Figure C-6 and Figure C-7 for sea state 3 and 5, respectively. The results appear very similar to each other with the exception that the magnitudes are greater, as expected, for sea state 5 compared to sea state 3.

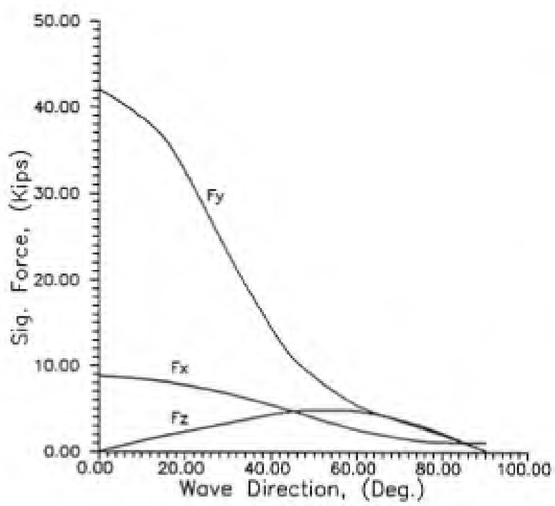

Figure C-6. Significant Loads at Cut A, SS3

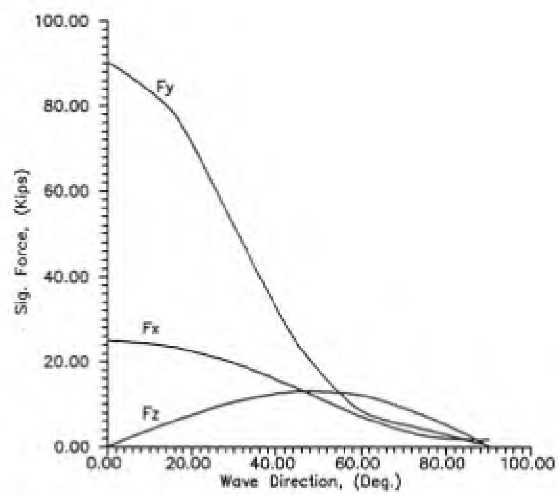

Figure C-7. Significant Loads at Cut A, SS5

Significant values of the force components at cut B (cut 20 ft. from the end) are shown in Figure C-8 and Figure C-9. The vertical "shear force" is found to be the greatest component as shown by the figures when the waves approach from the end where the cut is located (180 degrees).

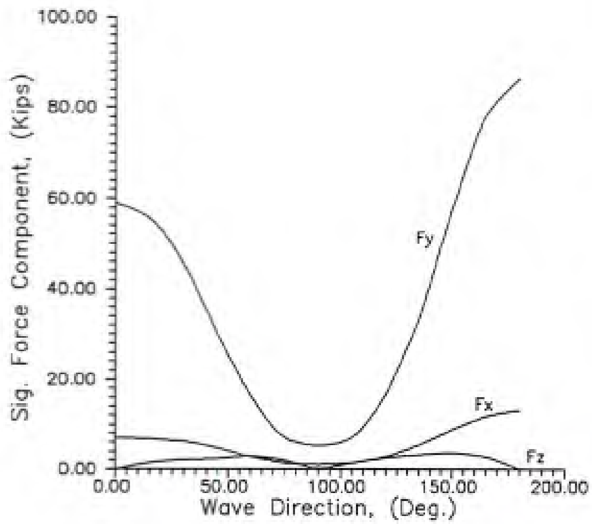

Figure C-8. Significant Loads at Cut B, SS3

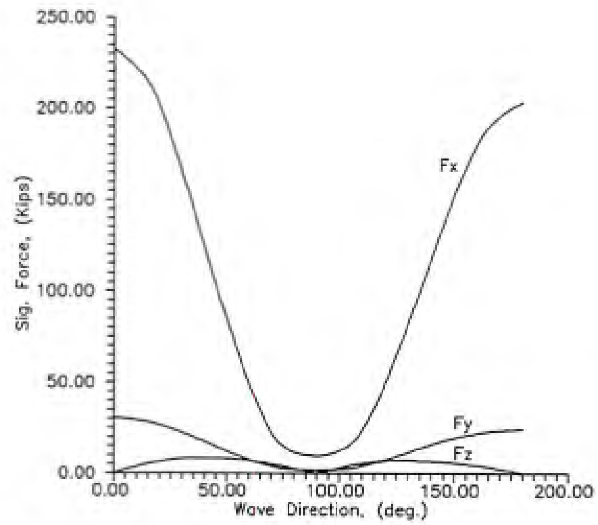

Figure C-9. Significant Loads at Cut B, SS5

Figure C-10 and Figure C-11 show the three components of the significant force at cut C (centerline cut). Here the vertical force which always represents the greatest component has its maximum value at wave direction of 90 degrees and, of course, is zero at zero degrees wave direction due to symmetry.

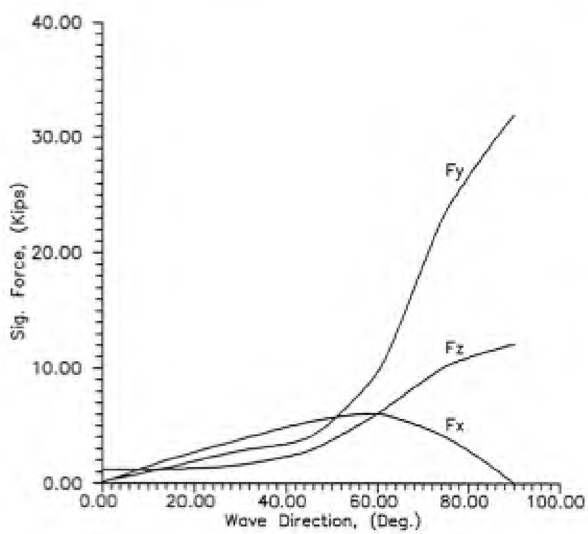

Figure C-10. Significant Loads at Cut C, SS3

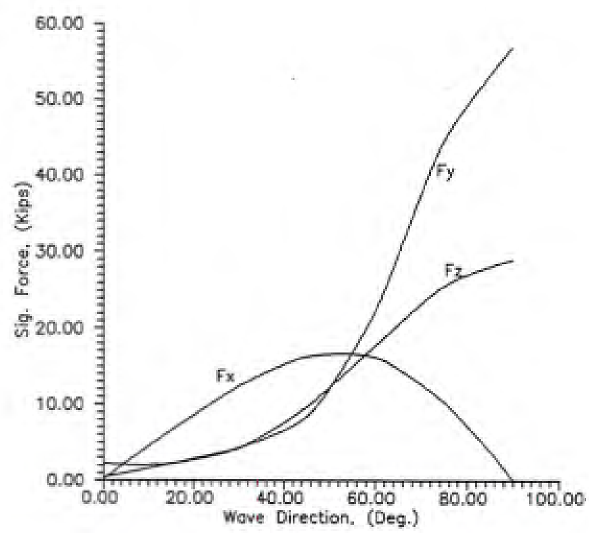

Figure C-11. Significant Loads at Cut C, SS5

The values of the significant moments at the cuts A, B and C are shown in Figure C-12 through Figure C-17. In the case of cut A described in Figure C-12 and Figure C-13 the values of Mx shows the largest peak, but this is somewhat misleading from the view point of resulting stresses within the structure. Even though Mx is large, its effect on the structure is minor since the sectional area through the structure available to resist this load component is very large. That is, there is a great deal of sectional area with large associated lever arm. The effect of My is also negligible in view of the fact that it is not only small but also has a large associated lever arm.

The most important load for cut A is Mz, the moment about a horizontal axis along the cut. Mz is large at zero wave direction and the lever arm of the sectional area or connector device, which ever provides the resistance, is small (only 2.25 feet maximum from the center of the section).

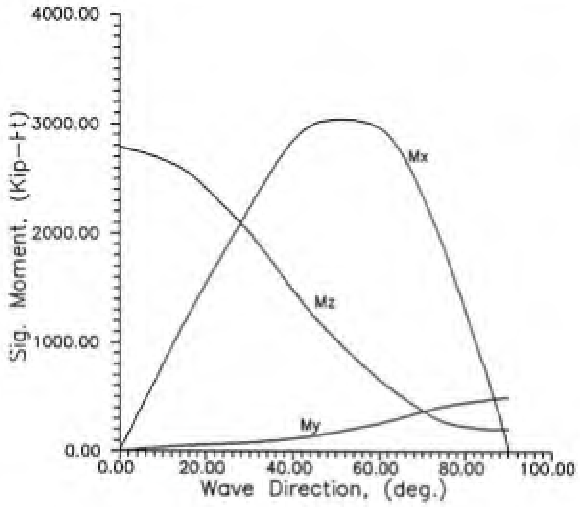

Figure C-12. Significant Moment at Cut A, SS3

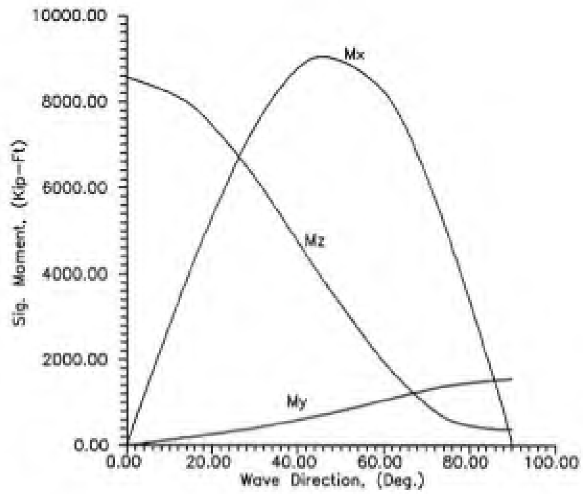

Figure C-13. Significant Moment at Cut A, SS5

The values of the significant moment at cut B (20 feet from the end of the structure) presented in Figure C-14 and Figure C-15 shows that Mx and Mz are both sizable. Here again, Mx is probably not of much importance but Mz is very important even though it is smaller in magnitude than Mx due to the fact that the vertical dimension of the structure is rather small (only 4.5 feet).

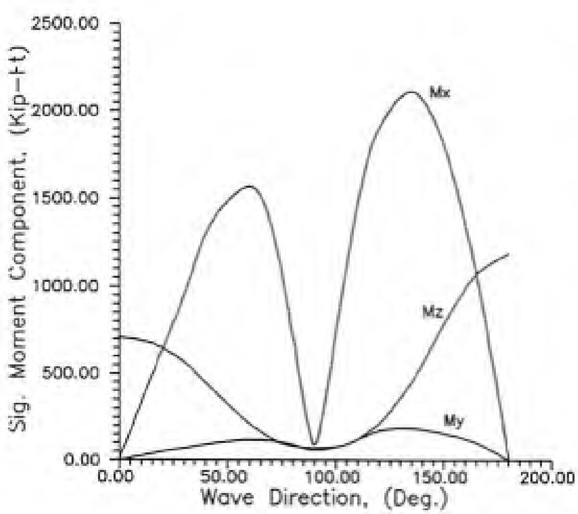

Figure C-14. Significant Moment at Cut B, SS3

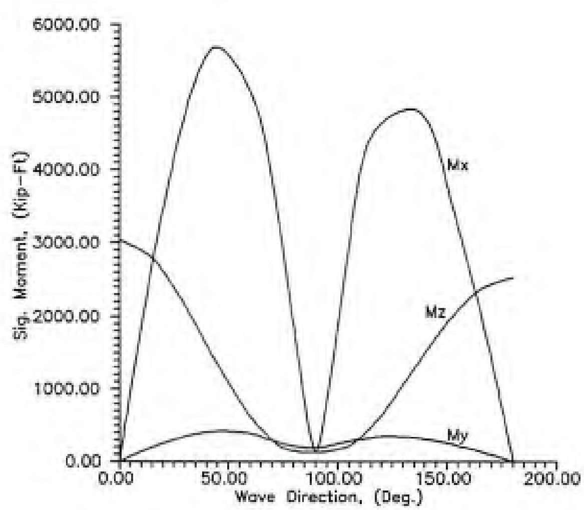

Figure C-15. Significant Moment at Cut B, SS 5

In Figure C-16 and Figure C-17 the significant moment components for cut C are presented. Cut C is perpendicular to cut A and B and is along the centerline of the structure. Thus, Mx (as opposed to Mz) is the most important moment component from the view point of structural resistance. In

Figure C-16 and Figure C-17 Mz is large but from the view point of the structure it is of little significance.

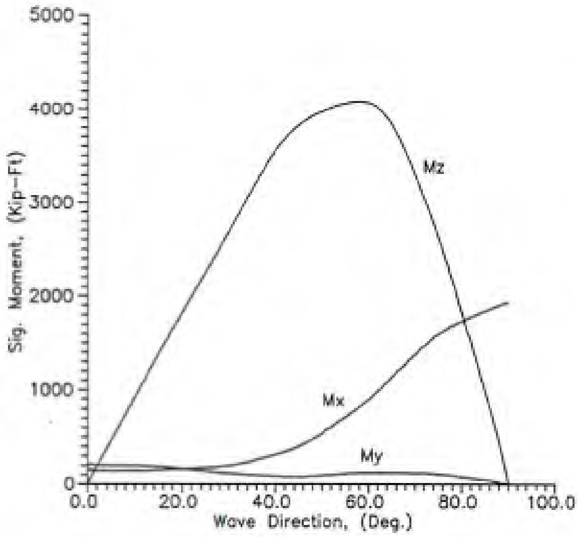

Figure C-16. Significant Moments at Cut C, SS3

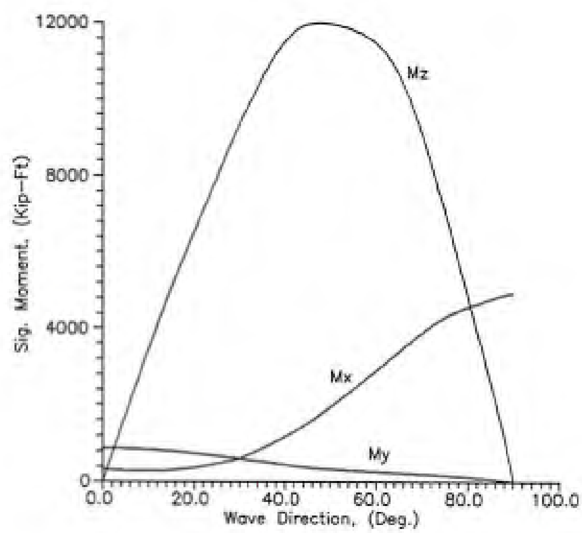

Figure C-17. Significant Moments at Cut C, SS5

Moment RAO

In Figure C-12 through Figure C-17 the significant values of the load components are presented. These values were obtained by use of the load RAO and spectral density functions. The results and configuration of the structure indicate that for cut A and B the significant value of Mz is the most important load component. Thus, the RAO's which were used to produce these figures showing significant load are presented in Figure C-18 and Figure C-19. The results indicate the variation of the moment per unit wave amplitude for 75 and 90 degrees wave direction. The figures generally show fairly large values of the RAO in the region of large wave spectral density. This results in large (significant) loads.

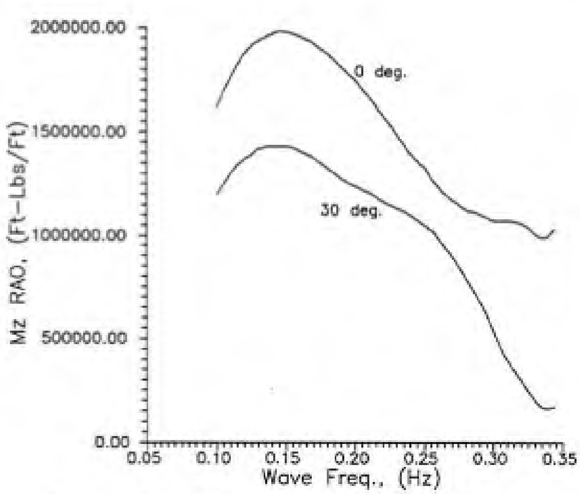

Figure C-18. Moment RAO at Cut A

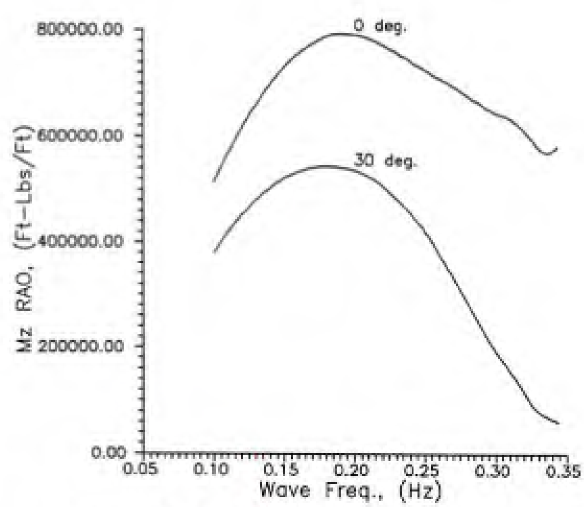

Figure C-19. Moment RAO at Cut B

In Figure C-20 the Mx moment RAO, for cut C is shown. The z-component is actually the largest moment component but the moment component Mx, which is maximum at 90 degrees, is the one of primary interest in the way that it effects the structure. Mx at this cut lies horizontally along the cut and represents the most critical component of load as it affects the structure.

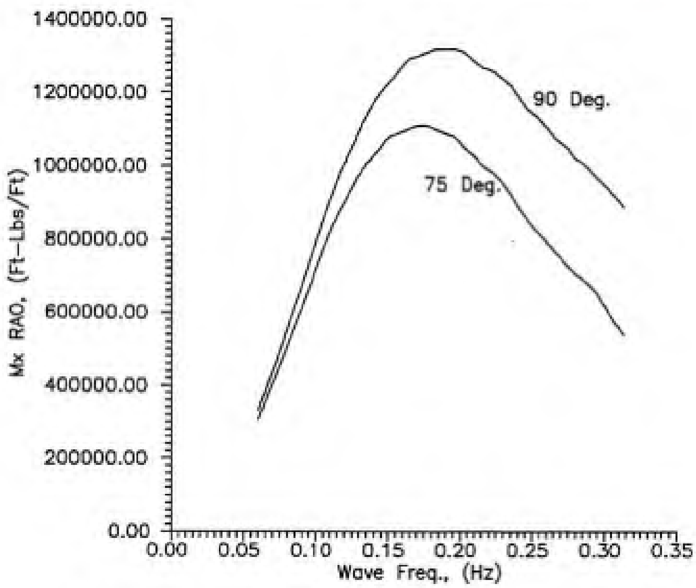

Figure C-20. Mx Moment RAO at Cut C

MORHAL INPUT FILE

```
Floating Pier - 120' x 88' x  1.167
     2   152   516     0
     0     1     5     1     0     1
     0     0     0     0     7     1
     16.0000      44.0000      2.0000     32.1740       .0000
      .0100   15.0000   4.0000   1.0830     .0000
  .245400E+05  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00
  .000000E+00  .245400E+05  .000000E+00  .000000E+00  .000000E+00  .000000E+00
  .000000E+00  .000000E+00  .245400E+05  .000000E+00  .000000E+00  .000000E+00
  .000000E+00  .000000E+00  .000000E+00  .174300E+08  .000000E+00  .000000E+00
  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .488000E+08  .000000E+00
  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .315700E+08
  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00
  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00
  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00
  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00
  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00
  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00  .000000E+00
       .0000      1.1670      .0000
    1     60.0000        .0000     44.0000
    2     60.0000        .0000       .0000
    3       .0000        .0000     44.0000
    4       .0000        .0000       .0000
    5     55.0000        .0000       .0000
    6     50.0000        .0000       .0000
    7     45.0000        .0000       .0000
    8     40.0000        .0000       .0000
    9     35.0000        .0000       .0000
   10     30.0000        .0000       .0000
   11     25.0000        .0000       .0000
   12     20.0000        .0000       .0000
   13     15.0000        .0000       .0000
   14     10.0000        .0000       .0000
   15      5.0000        .0000       .0000
   16     55.0000        .0000     44.0000
   17     50.0000        .0000     44.0000
   18     45.0000        .0000     44.0000
   19     40.0000        .0000     44.0000
   20     35.0000        .0000     44.0000
   21     30.0000        .0000     44.0000
   22     25.0000        .0000     44.0000
   23     20.0000        .0000     44.0000
   24     15.0000        .0000     44.0000
   25     10.0000        .0000     44.0000
   26      5.0000        .0000     44.0000
   27     60.0000        .0000     39.1111
   28     60.0000        .0000     34.2222
   29     60.0000        .0000     29.3333
   30     60.0000        .0000     24.4444
   31     60.0000        .0000     19.5556
   32     60.0000        .0000     14.6667
   33     60.0000        .0000      9.7778
   34     60.0000        .0000      4.8889
   35       .0000        .0000     39.1111
   36       .0000        .0000     34.2222
   37       .0000        .0000     29.3333
   38       .0000        .0000     24.4444
   39       .0000        .0000     19.5556
   40       .0000        .0000     14.6667
   41       .0000        .0000      9.7778
   42       .0000        .0000      4.8889
   43     55.0000        .0000      4.8889
   44     50.0000        .0000      4.8889
```

45	45.0000	.0000	4.8889
46	40.0000	.0000	4.8889
47	35.0000	.0000	4.8889
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50	20.0000	.0000	4.8889
51	15.0000	.0000	4.8889
52	10.0000	.0000	4.8889
53	5.0000	.0000	4.8889
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55	50.0000	.0000	9.7778
56	45.0000	.0000	9.7778
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58	35.0000	.0000	9.7778
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67	45.0000	.0000	14.6667
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75	5.0000	.0000	14.6667
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77	50.0000	.0000	19.5556
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82	25.0000	.0000	19.5556
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85	10.0000	.0000	19.5556
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105	20.0000	.0000	29.3333
106	15.0000	.0000	29.3333
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108	5.0000	.0000	29.3333
109	55.0000	.0000	34.2222

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142	55.0000	1.1670	44.0000
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148	60.0000	1.1670	19.5556
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150	60.0000	1.1670	9.7778
151	60.0000	1.1670	4.8889
152	60.0000	1.1670	.0000

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54	81	70	71	82
55	92	81	82	93
56	103	92	93	104
57	114	103	104	115
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66	102	91	92	103
67	113	102	103	114
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69	20	124	125	21
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79	19	123	124	20
80	19	20	138	139
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82	56	45	46	57
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85	89	78	79	90
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87	111	100	101	112

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94	77	66	67	78
95	88	77	78	89
96	99	88	89	100
97	110	99	100	111
98	121	110	111	122
99	17	121	122	18
100	17	18	140	141
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102	54	43	44	55
103	65	54	55	66
104	76	65	66	77
105	87	76	77	88
106	98	87	88	99
107	109	98	99	110
108	120	109	110	121
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112	54	33	34	43
113	65	32	33	54
114	76	31	32	65
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123	32	149	150	33
124	31	148	149	32
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MORHAL OUTPUT FILE

******HYDRODYNAMIC INPUT DATA******

ADDED MASS MATRIX

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.0000	7.8850	.0000	.0000	.0000	.0000
.0000	.0000	.0154	.0758	.0000	.0000
.0000	.0000	.1184	1.3660	.0000	.0000
.0000	.0000	.0000	.0000	.0069	.0000
-.1474	.0000	.0000	.0000	.0000	3.2990

FREQ.= .080

.0098	.0000	.0000	.0000	.0000	-.0748
.0000	6.3040	.0000	.0000	.0000	.0000
.0000	.0000	.0141	.0642	.0000	.0000
.0000	.0000	.1008	1.2220	.0000	.0000
.0000	.0000	.0000	.0000	.0071	.0000
-.1180	.0000	.0000	.0000	.0000	2.8580

FREQ.= .100

.0086	.0000	.0000	.0000	.0000	-.0565
.0000	5.3940	.0000	.0000	.0000	.0000
.0000	.0000	.0125	.0512	.0000	.0000
.0000	.0000	.0810	1.0630	.0000	.0000
.0000	.0000	.0000	.0000	.0073	.0000
-.0899	.0000	.0000	.0000	.0000	2.4430

FREQ.= .120

.0078	.0000	.0000	.0000	.0000	-.0416
.0000	4.8240	.0000	.0000	.0000	.0000
.0000	.0000	.0111	.0394	.0000	.0000
.0000	.0000	.0630	.9227	.0000	.0000
.0000	.0000	.0000	.0000	.0074	.0000
-.0672	.0000	.0000	.0000	.0000	2.1100

FREQ.= .140

.0071	.0000	.0000	.0000	.0000	-.0302
.0000	4.4450	.0000	.0000	.0000	.0000
.0000	.0000	.0099	.0296	.0000	.0000
.0000	.0000	.0482	.8106	.0000	.0000
.0000	.0000	.0000	.0000	.0076	.0000
-.0497	.0000	.0000	.0000	.0000	1.8580

FREQ.= .160

.0066	.0000	.0000	.0000	.0000	-.0213
.0000	4.1840	.0000	.0000	.0000	.0000
.0000	.0000	.0090	.0219	.0000	.0000
.0000	.0000	.0365	.7254	.0000	.0000
.0000	.0000	.0000	.0000	.0079	.0000
-.0363	.0000	.0000	.0000	.0000	1.6670

FREQ.= .180

.0062	.0000	.0000	.0000	.0000	-.0146
.0000	4.0070	.0000	.0000	.0000	.0000
.0000	.0000	.0083	.0160	.0000	.0000
.0000	.0000	.0276	.6618	.0000	.0000
.0000	.0000	.0000	.0000	.0080	.0000
-.0260	.0000	.0000	.0000	.0000	1.5220

FREQ.= .200

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.0000	.0000	.0078	.0114	.0000	.0000
.0000	.0000	.0208	.6145	.0000	.0000
.0000	.0000	.0000	.0000	.0081	.0000
-.0181	.0000	.0000	.0000	.0000	1.4100

FREQ.= .220

.0055	.0000	.0000	.0000	.0000	-.0055
.0000	3.8490	.0000	.0000	.0000	.0000
.0000	.0000	.0075	.0079	.0000	.0000
.0000	.0000	.0157	.5791	.0000	.0000
.0000	.0000	.0000	.0000	.0080	.0000
-.0124	.0000	.0000	.0000	.0000	1.3250

FREQ.= .240

.0053	.0000	.0000	.0000	.0000	-.0027
.0000	3.8510	.0000	.0000	.0000	.0000
.0000	.0000	.0072	.0052	.0000	.0000
.0000	.0000	.0116	.5527	.0000	.0000
.0000	.0000	.0000	.0000	.0078	.0000
-.0083	.0000	.0000	.0000	.0000	1.2650

FREQ.= .260

.0051	.0000	.0000	.0000	.0000	-.0006
.0000	3.8970	.0000	.0000	.0000	.0000
.0000	.0000	.0069	.0029	.0000	.0000
.0000	.0000	.0082	.5331	.0000	.0000
.0000	.0000	.0000	.0000	.0076	.0000
-.0053	.0000	.0000	.0000	.0000	1.2300

FREQ.= .280

.0049	.0000	.0000	.0000	.0000	.0013
.0000	3.9880	.0000	.0000	.0000	.0000
.0000	.0000	.0065	.0008	.0000	.0000
.0000	.0000	.0052	.5195	.0000	.0000
.0000	.0000	.0000	.0000	.0074	.0000
-.0026	.0000	.0000	.0000	.0000	1.2140

FREQ.= .300

.0047	.0000	.0000	.0000	.0000	.0030
.0000	4.1340	.0000	.0000	.0000	.0000
.0000	.0000	.0062	-.0010	.0000	.0000
.0000	.0000	.0027	.5120	.0000	.0000
.0000	.0000	.0000	.0000	.0071	.0000
-.0002	.0000	.0000	.0000	.0000	1.2130

FREQ.= .320

.0044	.0000	.0000	.0000	.0000	.0046

.0000	4.3500	.0000	.0000	.0000	.0000
.0000	.0000	.0059	-.0025	.0000	.0000
.0000	.0000	.0005	.5110	.0000	.0000
.0000	.0000	.0000	.0000	.0068	.0000
.0021	.0000	.0000	.0000	.0000	1.2240

FREQ.= .340

.0041	.0000	.0000	.0000	.0000	.0063
.0000	4.7080	.0000	.0000	.0000	.0000
.0000	.0000	.0055	-.0040	.0000	.0000
.0000	.0000	-.0016	.5164	.0000	.0000
.0000	.0000	.0000	.0000	.0065	.0000
.0045	.0000	.0000	.0000	.0000	1.2530

FREQ.= .360

.0039	.0000	.0000	.0000	.0000	.0079
.0000	5.1640	.0000	.0000	.0000	.0000
.0000	.0000	.0051	-.0055	.0000	.0000
.0000	.0000	-.0038	.5270	.0000	.0000
.0000	.0000	.0000	.0000	.0062	.0000
.0067	.0000	.0000	.0000	.0000	1.2960

DAMPING MATRIX

FREQ.= .060

.0037	.0000	.0000	.0000	.0000	-.0545
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.0000	.0000	.0046	.0354	.0000	.0000
.0000	.0000	.0543	.4191	.0000	.0000
.0000	.0000	.0000	.0000	.0001	.0000
-.0839	.0000	.0000	.0000	.0000	1.2210

FREQ.= .080

.0046	.0000	.0000	.0000	.0000	-.0664
.0000	8.1960	.0000	.0000	.0000	.0000
.0000	.0000	.0061	.0466	.0000	.0000
.0000	.0000	.0715	.5440	.0000	.0000
.0000	.0000	.0000	.0000	.0002	.0000
-.1022	.0000	.0000	.0000	.0000	1.4750

FREQ.= .100

.0049	.0000	.0000	.0000	.0000	-.0698
.0000	6.8510	.0000	.0000	.0000	.0000
.0000	.0000	.0070	.0521	.0000	.0000
.0000	.0000	.0799	.5976	.0000	.0000
.0000	.0000	.0000	.0000	.0003	.0000
-.1076	.0000	.0000	.0000	.0000	1.5370

FREQ.= .120

.0050	.0000	.0000	.0000	.0000	-.0684
.0000	5.8350	.0000	.0000	.0000	.0000
.0000	.0000	.0073	.0533	.0000	.0000
.0000	.0000	.0818	.5993	.0000	.0000
.0000	.0000	.0000	.0000	.0005	.0000
-.1056	.0000	.0000	.0000	.0000	1.4910

FREQ.= .140

.0049	.0000	.0000	.0000	.0000	-.0649
.0000	5.0410	.0000	.0000	.0000	.0000
.0000	.0000	.0073	.0520	.0000	.0000
.0000	.0000	.0798	.5716	.0000	.0000
.0000	.0000	.0000	.0000	.0007	.0000
-.1003	.0000	.0000	.0000	.0000	1.3980

FREQ.= .160

.0048	.0000	.0000	.0000	.0000	-.0605
.0000	4.3980	.0000	.0000	.0000	.0000
.0000	.0000	.0071	.0493	.0000	.0000
.0000	.0000	.0758	.5307	.0000	.0000
.0000	.0000	.0000	.0000	.0011	.0000
-.0936	.0000	.0000	.0000	.0000	1.2900

FREQ.= .180

.0048	.0000	.0000	.0000	.0000	-.0559
.0000	3.8610	.0000	.0000	.0000	.0000
.0000	.0000	.0069	.0461	.0000	.0000
.0000	.0000	.0710	.4861	.0000	.0000
.0000	.0000	.0000	.0000	.0015	.0000
-.0867	.0000	.0000	.0000	.0000	1.1800

FREQ.= .200

.0047	.0000	.0000	.0000	.0000	-.0513
.0000	3.4060	.0000	.0000	.0000	.0000
.0000	.0000	.0066	.0428	.0000	.0000
.0000	.0000	.0662	.4424	.0000	.0000
.0000	.0000	.0000	.0000	.0021	.0000
-.0797	.0000	.0000	.0000	.0000	1.0720

FREQ.= .220

.0047	.0000	.0000	.0000	.0000	-.0469
.0000	3.0210	.0000	.0000	.0000	.0000
.0000	.0000	.0065	.0397	.0000	.0000
.0000	.0000	.0616	.4014	.0000	.0000
.0000	.0000	.0000	.0000	.0026	.0000
-.0731	.0000	.0000	.0000	.0000	.9658

FREQ.= .240

.0046	.0000	.0000	.0000	.0000	-.0431
.0000	2.6970	.0000	.0000	.0000	.0000
.0000	.0000	.0065	.0370	.0000	.0000
.0000	.0000	.0576	.3636	.0000	.0000
.0000	.0000	.0000	.0000	.0030	.0000
-.0673	.0000	.0000	.0000	.0000	.8635

FREQ.= .260

.0046	.0000	.0000	.0000	.0000	-.0399
.0000	2.4290	.0000	.0000	.0000	.0000
.0000	.0000	.0065	.0346	.0000	.0000
.0000	.0000	.0542	.3287	.0000	.0000
.0000	.0000	.0000	.0000	.0034	.0000
-.0626	.0000	.0000	.0000	.0000	.7694

FREQ.= .280

.0046	.0000	.0000	.0000	.0000	-.0372
.0000	2.2080	.0000	.0000	.0000	.0000

.0000	.0000	.0066	.0325	.0000	.0000
.0000	.0000	.0510	.2960	.0000	.0000
.0000	.0000	.0000	.0000	.0038	.0000
-.0587	.0000	.0000	.0000	.0000	.6869

FREQ.= .300

.0047	.0000	.0000	.0000	.0000	-.0349
.0000	2.0300	.0000	.0000	.0000	.0000
.0000	.0000	.0066	.0304	.0000	.0000
.0000	.0000	.0481	.2653	.0000	.0000
.0000	.0000	.0000	.0000	.0042	.0000
-.0554	.0000	.0000	.0000	.0000	.6163

FREQ.= .320

.0048	.0000	.0000	.0000	.0000	-.0328
.0000	1.8980	.0000	.0000	.0000	.0000
.0000	.0000	.0066	.0286	.0000	.0000
.0000	.0000	.0455	.2375	.0000	.0000
.0000	.0000	.0000	.0000	.0045	.0000
-.0525	.0000	.0000	.0000	.0000	.5554

FREQ.= .340

.0049	.0000	.0000	.0000	.0000	-.0310
.0000	1.8520	.0000	.0000	.0000	.0000
.0000	.0000	.0067	.0270	.0000	.0000
.0000	.0000	.0433	.2142	.0000	.0000
.0000	.0000	.0000	.0000	.0048	.0000
-.0500	.0000	.0000	.0000	.0000	.5056

FREQ.= .360

.0048	.0000	.0000	.0000	.0000	-.0293
.0000	1.8250	.0000	.0000	.0000	.0000
.0000	.0000	.0067	.0254	.0000	.0000
.0000	.0000	.0410	.1929	.0000	.0000
.0000	.0000	.0000	.0000	.0051	.0000
-.0474	.0000	.0000	.0000	.0000	.4592

EXCITATION LOADS

FREQ.= .060

BETA = .000000

LOAD COMPONENTS:	.0827	3.6736	.0000	.0000	.0000	1.9012
PHASE ANGLES:	-1.6324	-.4831	.0000	.0000	.0000	1.5108

BETA = .261800

LOAD COMPONENTS:	.0805	3.6966	.0234	.2677	.0058	1.8385
PHASE ANGLES:	-1.6318	-.4831	-1.5890	-1.5896	3.1414	1.5109

BETA = .523600

LOAD COMPONENTS:	.0738	3.7584	.0457	.5288	.0098	1.6531
PHASE ANGLES:	-1.6302	-.4830	-1.5894	-1.5899	3.1414	1.5114

BETA = .785400

LOAD COMPONENTS:	.0619	3.8411	.0658	.7704	.0109	1.3546
PHASE ANGLES:	-1.6282	-.4829	-1.5901	-1.5903	3.1414	1.5121

BETA = 1.047000

LOAD COMPONENTS:	.0449	3.9215	.0820	.9714	.0091	.9610
PHASE ANGLES:	-1.6263	-.4827	-1.5908	-1.5907	3.1413	1.5127

BETA = 1.309000

LOAD COMPONENTS:	.0237	3.9790	.0925	1.1060	.0051	.4985
PHASE ANGLES:	-1.6249	-.4826	-1.5913	-1.5910	3.1413	1.5132

BETA = 1.571000

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LOAD COMPONENTS:      .0000    3.9997     .0961    1.1536     .0000     .0000
PHASE ANGLES:         .0000    -.4826   -1.5915   -1.5912     .0000    1.5033

 FREQ.=       .080

                          BETA =     .000000
LOAD COMPONENTS:      .0873    3.1056     .0000     .0000     .0000    2.0449
PHASE ANGLES:       -1.7620    -.7594     .0000     .0000     .0000    1.3895
                          BETA =     .261800
LOAD COMPONENTS:      .0857    3.1476     .0254     .2767     .0098    1.9796
PHASE ANGLES:       -1.7587    -.7583   -1.6514   -1.6572    3.1324    1.3900
                          BETA =     .523600
LOAD COMPONENTS:      .0803    3.2600     .0504     .5592     .0163    1.7847
PHASE ANGLES:       -1.7503    -.7554   -1.6535   -1.6579    3.1318    1.3913
                          BETA =     .785400
LOAD COMPONENTS:      .0693    3.4073     .0738     .8384     .0176    1.4664
PHASE ANGLES:       -1.7399    -.7519   -1.6566   -1.6589    3.1309    1.3930
                          BETA =    1.047000
LOAD COMPONENTS:      .0515    3.5471     .0931    1.0853     .0141    1.0419
PHASE ANGLES:       -1.7307    -.7489   -1.6598   -1.6599    3.1297    1.3947
                          BETA =    1.309000
LOAD COMPONENTS:      .0276    3.6445     .1059    1.2583     .0077     .5408
PHASE ANGLES:       -1.7246    -.7469   -1.6623   -1.6607    3.1288    1.3959
                          BETA =    1.571000
LOAD COMPONENTS:      .0000    3.6791     .1103    1.3208     .0000     .0000
PHASE ANGLES:         .0000    -.7462   -1.6632   -1.6609     .0000    1.4553

 FREQ.=       .100

                          BETA =     .000000
LOAD COMPONENTS:      .0839    2.5749     .0000     .0000     .0000    2.0275
PHASE ANGLES:       -1.9788   -1.0814     .0000     .0000     .0000    1.2009
                          BETA =     .261800
LOAD COMPONENTS:      .0835    2.6419     .0246     .2485     .0144    1.9663
PHASE ANGLES:       -1.9664   -1.0752   -1.7543   -1.7794    3.1046    1.2019
                          BETA =     .523600
LOAD COMPONENTS:      .0809    2.8190     .0501     .5224     .0233    1.7797
PHASE ANGLES:       -1.9365   -1.0604   -1.7599   -1.7791    3.1007    1.2044
                          BETA =     .785400
LOAD COMPONENTS:      .0726    3.0463     .0754     .8212     .0240    1.4668
PHASE ANGLES:       -1.9026   -1.0442   -1.7684   -1.7792    3.0940    1.2076
                          BETA =    1.047000
LOAD COMPONENTS:      .0557    3.2544     .0972    1.1072     .0181    1.0426
PHASE ANGLES:       -1.8749   -1.0317   -1.7781   -1.7797    3.0847    1.2106
                          BETA =    1.309000
LOAD COMPONENTS:      .0304    3.3934     .1118    1.3179     .0092     .5404
PHASE ANGLES:       -1.8576   -1.0243   -1.7859   -1.7802    3.0754    1.2127
                          BETA =    1.571000
LOAD COMPONENTS:      .0000    3.4412     .1169    1.3957     .0000     .0000
PHASE ANGLES:         .0000   -1.0220   -1.7890   -1.7804     .0000    1.1808

 FREQ.=       .120

                          BETA =     .000000
LOAD COMPONENTS:      .0772    2.0977     .0000     .0000     .0000    1.9244
PHASE ANGLES:       -2.2947   -1.4685     .0000     .0000     .0000     .9529
                          BETA =     .261800
LOAD COMPONENTS:      .0781    2.1889     .0213     .1934     .0193    1.8725
PHASE ANGLES:       -2.2598   -1.4470   -1.8981   -1.9764    3.0545     .9547
                          BETA =     .523600
LOAD COMPONENTS:      .0786    2.4312     .0458     .4380     .0303    1.7060
PHASE ANGLES:       -2.1798   -1.3990   -1.9054   -1.9648    3.0409     .9589
                          BETA =     .785400
LOAD COMPONENTS:      .0735    2.7382     .0727     .7454     .0294    1.4113
PHASE ANGLES:       -2.0977   -1.3528   -1.9201   -1.9543    3.0140     .9635
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                       BETA =     1.047000
LOAD COMPONENTS:     .0580    3.0080      .0970     1.0687      .0199     1.0004
PHASE ANGLES:      -2.0367   -1.3223    -1.9401    -1.9477     2.9688      .9667
                       BETA =     1.309000
LOAD COMPONENTS:     .0321    3.1767      .1134     1.3197      .0089      .5153
PHASE ANGLES:      -2.0012   -1.3074    -1.9582    -1.9445     2.9097      .9682
                       BETA =     1.571000
LOAD COMPONENTS:     .0000    3.2316      .1191     1.4145      .0000      .0000
PHASE ANGLES:        .0000   -1.3033    -1.9657    -1.9436      .0000      .5856

 FREQ.=       .140

                       BETA =      .000000
LOAD COMPONENTS:     .0717    1.7178      .0000      .0000      .0000     1.7776
PHASE ANGLES:      -2.7135   -1.9448      .0000      .0000      .0000      .6524
                       BETA =      .261800
LOAD COMPONENTS:     .0728    1.8166      .0157      .1249      .0244     1.7407
PHASE ANGLES:      -2.6380   -1.8883    -2.1159    -2.3324     2.9918      .6563
                       BETA =      .523600
LOAD COMPONENTS:     .0748    2.0956      .0380      .3270      .0374     1.6059
PHASE ANGLES:      -2.4706   -1.7702    -2.1001    -2.2520     2.9593      .6642
                       BETA =      .785400
LOAD COMPONENTS:     .0722    2.4632      .0666      .6348      .0338     1.3359
PHASE ANGLES:      -2.3116   -1.6705    -2.1075    -2.1930     2.8860      .6693
                       BETA =     1.047000
LOAD COMPONENTS:     .0582    2.7775      .0942      .9938      .0198      .9396
PHASE ANGLES:      -2.2047   -1.6172    -2.1367    -2.1606     2.7249      .6678
                       BETA =     1.309000
LOAD COMPONENTS:     .0323    2.9571      .1127     1.2861      .0073      .4768
PHASE ANGLES:      -2.1477   -1.5993    -2.1702    -2.1456     2.4148      .6622
                       BETA =     1.571000
LOAD COMPONENTS:     .0000    3.0103      .1190     1.3987      .0000      .0000
PHASE ANGLES:        .0000   -1.5965    -2.1852    -2.1414      .0000      .6952

 FREQ.=       .160

                       BETA =      .000000
LOAD COMPONENTS:     .0708    1.4883      .0000      .0000      .0000     1.6065
PHASE ANGLES:       3.0811   -2.5136      .0000      .0000      .0000      .2999
                       BETA =      .261800
LOAD COMPONENTS:     .0702    1.5531      .0088      .0715      .0292     1.5912
PHASE ANGLES:      -3.0805   -2.4038    -2.6077     3.1001     2.9289      .3108
                       BETA =      .523600
LOAD COMPONENTS:     .0705    1.7990      .0277      .2189      .0443     1.5014
PHASE ANGLES:      -2.7997   -2.1714    -2.3941    -2.7443     2.8715      .3304
                       BETA =      .785400
LOAD COMPONENTS:     .0686    2.1920      .0581      .5132      .0379     1.2623
PHASE ANGLES:      -2.5405   -1.9904    -2.3312    -2.5135     2.7227      .3363
                       BETA =     1.047000
LOAD COMPONENTS:     .0554    2.5392      .0895      .8992      .0198      .8763
PHASE ANGLES:      -2.3845   -1.9158    -2.3583    -2.4174     2.3011      .3177
                       BETA =     1.309000
LOAD COMPONENTS:     .0303    2.7244      .1106     1.2271      .0091      .4330
PHASE ANGLES:      -2.3126   -1.9095    -2.4141    -2.3794     1.4791      .2851
                       BETA =     1.571000
LOAD COMPONENTS:     .0000    2.7743      .1177     1.3548      .0000      .0000
PHASE ANGLES:        .0000   -1.9162    -2.4418    -2.3694      .0000      .2226

 FREQ.=       .180

                       BETA =      .000000
LOAD COMPONENTS:     .0745    1.4258      .0000      .0000      .0000     1.4250
PHASE ANGLES:       2.5813   -3.1201      .0000      .0000      .0000     -.1141
                       BETA =      .261800
LOAD COMPONENTS:     .0704    1.4094      .0072      .0863      .0322     1.4334
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PHASE ANGLES:	2.7306	-2.9729	2.3071	1.8904	2.8659	-.0830
BETA =	.523600					
LOAD COMPONENTS:	.0653	1.5203	.0176	.1600	.0499	1.3969
PHASE ANGLES:	3.1220	-2.6091	-2.9515	2.6847	2.7855	-.0297
BETA =	.785400					
LOAD COMPONENTS:	.0626	1.8879	.0479	.4020	.0419	1.1961
PHASE ANGLES:	-2.7849	-2.3124	-2.5916	-2.9350	2.5494	-.0186
BETA =	1.047000					
LOAD COMPONENTS:	.0498	2.2723	.0831	.7974	.0235	.8203
PHASE ANGLES:	-2.5929	-2.2197	-2.5955	-2.7167	1.8016	-.0784
BETA =	1.309000					
LOAD COMPONENTS:	.0260	2.4898	.1071	1.1485	.0174	.3952
PHASE ANGLES:	-2.5391	-2.2468	-2.6885	-2.6470	.9485	-.1838
BETA =	1.571000					
LOAD COMPONENTS:	.0000	2.5542	.1153	1.2856	.0000	.0000
PHASE ANGLES:	.0000	-2.2749	-2.7389	-2.6308	.0000	-.1399
FREQ.=	.200					
BETA =	.000000					
LOAD COMPONENTS:	.0803	1.4593	.0000	.0000	.0000	1.2581
PHASE ANGLES:	2.0977	2.5916	.0000	.0000	.0000	-.6066
BETA =	.261800					
LOAD COMPONENTS:	.0722	1.3589	.0143	.1327	.0316	1.2742
PHASE ANGLES:	2.2478	2.7297	1.5578	1.2454	2.7765	-.5319
BETA =	.523600					
LOAD COMPONENTS:	.0589	1.2594	.0146	.1792	.0525	1.2769
PHASE ANGLES:	2.7217	-3.1092	2.2908	1.7495	2.6922	-.4047
BETA =	.785400					
LOAD COMPONENTS:	.0542	1.5323	.0364	.3128	.0455	1.1222
PHASE ANGLES:	-3.0415	-2.6522	-2.8876	2.8143	2.3908	-.3766
BETA =	1.047000					
LOAD COMPONENTS:	.0424	1.9630	.0744	.6954	.0305	.7755
PHASE ANGLES:	-2.8452	-2.5358	-2.8381	-3.0532	1.4155	-.5118
BETA =	1.309000					
LOAD COMPONENTS:	.0207	2.2674	.1024	1.0581	.0287	.3846
PHASE ANGLES:	-2.9065	-2.6150	-2.9976	-2.9522	.6979	-.7495
BETA =	1.571000					
LOAD COMPONENTS:	.0000	2.3841	.1130	1.1987	.0000	.0000
PHASE ANGLES:	.0000	-2.6726	-3.0849	-2.9336	.0000	-.8606
FREQ.=	.220					
BETA =	.000000					
LOAD COMPONENTS:	.0850	1.4796	.0000	.0000	.0000	1.1431
PHASE ANGLES:	1.6212	2.0558	.0000	.0000	.0000	-1.1806
BETA =	.261800					
LOAD COMPONENTS:	.0741	1.3431	.0211	.1675	.0263	1.1246
PHASE ANGLES:	1.7530	2.1610	1.2488	.7822	2.5853	-1.0471
BETA =	.523600					
LOAD COMPONENTS:	.0513	1.0544	.0211	.2311	.0509	1.1142
PHASE ANGLES:	2.2545	2.5823	1.4807	1.0673	2.5668	-.7977
BETA =	.785400					
LOAD COMPONENTS:	.0432	1.1461	.0233	.2476	.0474	1.0100
PHASE ANGLES:	2.9784	-3.0427	3.0370	2.1502	2.2620	-.7314
BETA =	1.047000					
LOAD COMPONENTS:	.0343	1.6160	.0623	.5917	.0372	.7385
PHASE ANGLES:	3.1415	-2.8760	-3.0795	2.8648	1.1257	-.9711
BETA =	1.309000					
LOAD COMPONENTS:	.0175	2.0597	.0968	.9633	.0403	.4215
PHASE ANGLES:	2.7924	-3.0149	2.9377	2.9866	.4982	-1.3372
BETA =	1.571000					
LOAD COMPONENTS:	.0000	2.2685	.1130	1.1061	.0000	.0000
PHASE ANGLES:	.0000	-3.0999	2.8057	2.9976	.0000	-1.4214

FREQ.= .240

	BETA =	.000000				
LOAD COMPONENTS:	.0860	1.4306	.0000	.0000	.0000	1.0905
PHASE ANGLES:	1.1174	1.5045	.0000	.0000	.0000	-1.8027
	BETA =	.261800				
LOAD COMPONENTS:	.0748	1.3120	.0238	.1786	.0185	.9996
PHASE ANGLES:	1.2382	1.5931	.9988	.3126	2.0784	-1.6368
	BETA =	.523600				
LOAD COMPONENTS:	.0451	.9451	.0282	.2775	.0454	.8998
PHASE ANGLES:	1.6955	1.9243	1.0209	.5113	2.3804	-1.2411
	BETA =	.785400				
LOAD COMPONENTS:	.0300	.7814	.0101	.2162	.0464	.8389
PHASE ANGLES:	2.7127	2.7484	2.3544	1.3322	2.1734	-1.0995
	BETA =	1.047000				
LOAD COMPONENTS:	.0258	1.2492	.0467	.4792	.0409	.6971
PHASE ANGLES:	2.8198	3.0298	2.9633	2.4741	.8392	-1.4506
	BETA =	1.309000				
LOAD COMPONENTS:	.0186	1.8619	.0908	.8666	.0510	.4891
PHASE ANGLES:	2.1336	2.8336	2.5504	2.6051	.2810	-1.8591
	BETA =	1.571000				
LOAD COMPONENTS:	.0000	2.1886	.1157	1.0188	.0000	.0000
PHASE ANGLES:	.0000	2.7324	2.3859	2.5932	.0000	-2.0282

FREQ.= .260

	BETA =	.000000				
LOAD COMPONENTS:	.0831	1.3302	.0000	.0000	.0000	1.0633
PHASE ANGLES:	.5309	.8841	.0000	.0000	.0000	-2.4449
	BETA =	.261800				
LOAD COMPONENTS:	.0733	1.2399	.0210	.1666	.0184	.9115
PHASE ANGLES:	.6871	1.0000	.6694	-.2805	1.0783	-2.2967
	BETA =	.523600				
LOAD COMPONENTS:	.0418	.8966	.0314	.3026	.0370	.6692
PHASE ANGLES:	1.1025	1.2853	.6589	-.0152	2.1053	-1.7977
	BETA =	.785400				
LOAD COMPONENTS:	.0160	.4941	.0089	.2334	.0423	.6218
PHASE ANGLES:	2.4773	2.0816	.5066	.4978	2.1371	-1.5121
	BETA =	1.047000				
LOAD COMPONENTS:	.0162	.8853	.0292	.3542	.0415	.6402
PHASE ANGLES:	2.4938	2.5964	2.7410	2.0452	.4951	-1.9618
	BETA =	1.309000				
LOAD COMPONENTS:	.0223	1.6747	.0841	.7637	.0593	.5499
PHASE ANGLES:	1.6112	2.3574	2.1230	2.1871	.0281	-2.3364
	BETA =	1.571000				
LOAD COMPONENTS:	.0000	2.1261	.1192	.9413	.0000	.0000
PHASE ANGLES:	.0000	2.2574	1.9501	2.1361	.0000	-2.4931

FREQ.= .280

	BETA =	.000000				
LOAD COMPONENTS:	.0813	1.2356	.0000	.0000	.0000	1.0254
PHASE ANGLES:	-.1715	.1679	.0000	.0000	.0000	-3.1183
	BETA =	.261800				
LOAD COMPONENTS:	.0688	1.1235	.0149	.1559	.0286	.8613
PHASE ANGLES:	.0713	.3478	.0450	-1.0942	.3832	-3.0006
	BETA =	.523600				
LOAD COMPONENTS:	.0382	.8175	.0292	.2949	.0270	.4892
PHASE ANGLES:	.5752	.6916	.3161	-.5661	1.6892	-2.5314
	BETA =	.785400				
LOAD COMPONENTS:	.0042	.3176	.0160	.2689	.0366	.3923
PHASE ANGLES:	2.7860	1.1682	-.2338	-.1639	2.1701	-2.0009
	BETA =	1.047000				
LOAD COMPONENTS:	.0059	.5544	.0128	.2229	.0410	.5709
PHASE ANGLES:	2.1349	2.0706	2.7370	1.5307	.0963	-2.5229

BETA = 1.309000

LOAD COMPONENTS:	.0255	1.5065	.0765	.6490	.0632	.5871
PHASE ANGLES:	1.2118	1.8373	1.6503	1.7221	-.2866	-2.8260

BETA = 1.571000

LOAD COMPONENTS:	.0000	2.0614	.1208	.8746	.0000	.0000
PHASE ANGLES:	.0000	1.7541	1.4872	1.6246	.0000	-2.8318

FREQ.= .300

BETA = .000000

LOAD COMPONENTS:	.0841	1.1893	.0000	.0000	.0000	.9615
PHASE ANGLES:	-.9353	-.6289	.0000	.0000	.0000	2.4339

BETA = .261800

LOAD COMPONENTS:	.0630	.9924	.0137	.1718	.0375	.8145
PHASE ANGLES:	-.6425	-.4052	-1.0372	-1.9885	-.0576	2.5703

BETA = .523600

LOAD COMPONENTS:	.0297	.6625	.0213	.2529	.0184	.3947
PHASE ANGLES:	.1216	.0897	-.0247	-1.2180	.9102	2.9053

BETA = .785400

LOAD COMPONENTS:	.0078	.2470	.0176	.2706	.0327	.1778
PHASE ANGLES:	-2.1537	.0672	-.7045	-.7084	2.2814	-2.6352

BETA = 1.047000

LOAD COMPONENTS:	.0034	.2839	.0094	.1075	.0393	.4987
PHASE ANGLES:	-1.1074	1.3723	-2.3921	.7537	-.2870	-3.1286

BETA = 1.309000

LOAD COMPONENTS:	.0257	1.3560	.0684	.5296	.0630	.6014
PHASE ANGLES:	.8574	1.2827	1.1333	1.1814	-.7066	2.9287

BETA = 1.571000

LOAD COMPONENTS:	.0000	1.9809	.1195	.8204	.0000	.0000
PHASE ANGLES:	.0000	1.2103	.9740	1.0565	.0000	2.8447

FREQ.= .320

BETA = .000000

LOAD COMPONENTS:	.0864	1.1822	.0000	.0000	.0000	.8792
PHASE ANGLES:	-1.7197	-1.4673	.0000	.0000	.0000	1.6046

BETA = .261800

LOAD COMPONENTS:	.0585	.9087	.0183	.1954	.0381	.7153
PHASE ANGLES:	-1.4509	-1.2638	-1.8588	-2.8175	-.5230	1.8238

BETA = .523600

LOAD COMPONENTS:	.0172	.4582	.0090	.2057	.0219	.3261
PHASE ANGLES:	-.2692	-.6030	-.4053	-2.0867	-.1190	2.1131

BETA = .785400

LOAD COMPONENTS:	.0130	.2275	.0131	.2207	.0326	.0474
PHASE ANGLES:	-2.5492	-.9593	-1.1679	-1.2459	2.4026	1.4214

BETA = 1.047000

LOAD COMPONENTS:	.0087	.1084	.0195	.0546	.0338	.4143
PHASE ANGLES:	-1.6129	-.0190	-2.3134	-.9009	-.5979	2.5414

BETA = 1.309000

LOAD COMPONENTS:	.0223	1.1998	.0594	.4276	.0615	.5911
PHASE ANGLES:	.4646	.7028	.5952	.5457	-1.2458	2.3496

BETA = 1.571000

LOAD COMPONENTS:	.0000	1.8924	.1166	.7834	.0000	.0000
PHASE ANGLES:	.0000	.6108	.3824	.4335	.0000	2.1636

FREQ.= .340

BETA = .000000

LOAD COMPONENTS:	.0845	1.1677	.0000	.0000	.0000	.8347
PHASE ANGLES:	-2.5848	-2.3424	.0000	.0000	.0000	.6599

BETA = .261800

LOAD COMPONENTS:	.0552	.8807	.0193	.2046	.0316	.5876
PHASE ANGLES:	-2.2946	-2.1390	-2.4304	2.6363	-1.2782	.9270

BETA = .523600

LOAD COMPONENTS:	.0062	.2763	.0035	.1978	.0308	.2228

```
PHASE ANGLES:        -.1659   -1.5043    3.0626   -3.0841    -.5950    1.3645
                          BETA =     .785400
LOAD COMPONENTS:      .0145     .1823     .0038     .1365     .0338     .1608
PHASE ANGLES:        3.1195   -1.8980   -1.5230   -1.8451    2.4454    -.0365
                          BETA =    1.047000
LOAD COMPONENTS:      .0095     .1643     .0261     .0872     .0249     .2957
PHASE ANGLES:       -2.2086   -1.8598   -2.6837   -2.4646    -.7492    1.9229
                          BETA =    1.309000
LOAD COMPONENTS:      .0169    1.0295     .0473     .3535     .0608     .5603
PHASE ANGLES:        -.0251     .0895     .0472    -.1440   -1.8818    1.6997
                          BETA =    1.571000
LOAD COMPONENTS:      .0000    1.8407     .1161     .7654     .0000     .0000
PHASE ANGLES:         .0000    -.0522    -.2839    -.2219     .0000    1.5022

 FREQ.=      .360

                          BETA =     .000000
LOAD COMPONENTS:      .0838    1.1218     .0000     .0000     .0000     .8349
PHASE ANGLES:        2.7092    2.9593     .0000     .0000     .0000    -.3175
                          BETA =     .261800
LOAD COMPONENTS:      .0487     .7930     .0138     .1921     .0334     .5330
PHASE ANGLES:        3.1295   -3.0379    3.1376    1.6962   -2.3677    -.1078
                          BETA =     .523600
LOAD COMPONENTS:      .0078     .1657     .0077     .1936     .0314     .0940
PHASE ANGLES:         .5522   -2.7103    2.5930    2.3644    -.7972     .4861
                          BETA =     .785400
LOAD COMPONENTS:      .0124     .1189     .0077     .0446     .0312     .2106
PHASE ANGLES:        2.3420    3.0832     .9698   -2.6196    2.4227    -.7070
                          BETA =    1.047000
LOAD COMPONENTS:      .0078     .2317     .0258     .1318     .0187     .1554
PHASE ANGLES:       -2.9685   -2.7357    3.1333    2.9265    -.4998    1.2017
                          BETA =    1.309000
LOAD COMPONENTS:      .0112     .8316     .0324     .2822     .0620     .5201
PHASE ANGLES:        -.6676    -.5975    -.5389    -.8271   -2.5691     .9534
                          BETA =    1.571000
LOAD COMPONENTS:      .0000    1.8238     .1183     .7317     .0000     .0000
PHASE ANGLES:         .0000    -.7855    -.9908    -.8995     .0000     .6438
```

Appendix D. Fatigue Analysis

Because the MCS pin and guillotine system is subjected to a cyclic load from passing waves, a fatigue analysis of the male lock pin was conducted (dynamic impact load was not a concern because the period of the fluctuating load cycle is on the order of several seconds). The fatigue analysis of the pin involves the ultimate and yield strengths, and the endurance limit of the pin material. The endurance limit is the value of stress that the subject material may endure for an unlimited number of cycles. If the pin experiences stresses below its endurance limit, it will not fail; however, if stresses exceed the endurance limit, the pin will fail after a certain number of cycles—the number of cycles determined by an S-N diagram. If the pin is subjected to stresses above the endurance limit but for fewer than the number of cycles required to fail, the endurance limit for all subsequent cycles will be lower.

Material and Endurance Strength

Information provided by the Army to conduct this study did not include material properties of the male pin. Available references indicate that the pin material yield strength is 71,000 psi and ultimate strength, S_u, is 100,000 psi.

For steel with an ultimate strength less than 200,000 psi, the endurance strength, S'_e, equals 1/2 the ultimate strength.[1] For the male lock pin:

$$S'_e = 0.5\ S_u = 0.5\ (100{,}000\ \text{psi}) = 50{,}000\ \text{psi}$$

Endurance Limit

The endurance limit, the value of stress that the subject material may endure for an unlimited number of cycles, is determined from the endurance strength, S'_e, and modifying factors to reflect the actual conditions a pin must endure. The allowable stress for 1,000,000 cycles to infinity (endurance limit) for the male lock pin under a tension only fluctuating load is[2]:

$$S_e = k_a\, k_b\, k_c\, k_d\, k_e\, k_f\, S'_e$$

The values for the modifying factors are as follows:

Surface finish. For no surface finish, a surface finish factor $\mathbf{k_a} = 0.4$ is used (Shigley & Mischke, figure 13-7).

Relative size. For an axial loaded subject, a relative size factor $\mathbf{k_b} = 0.9$ is used (Shigley & Mischke, p. 13-15).

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[1] Joseph E. Shigley & Larry D. Mitchell, *Mechanical Engineering Design*, 4th ed., McGraw-Hill, New York, p. 276.
[2] Shigley, J. E., and Mischke, C. R. (1986). *Standard Handbook of Machine Design* (McGraw-Hill, New York), p. 13-11.

Reliability. For reliability of 50%, a reliability factor $\mathbf{k_c} = 1$ is used. This is not a true reliability analysis but it is a probability that a known (or assumed) stress will exceed the strength of a randomly selected component made from the pin material (8% standard deviation) (Shigley & Mischke, p. 13-19).

Temperature. For a temperature less than 600°F, temperature factor $\mathbf{k_d} = 1$ is used (Shigley & Mischke, p. 13-15).

Stress concentration. The stress concentration factor can be calculated using the following equation (Shigley & Mischke, p. 13-17):

$$\mathbf{k_e} = \frac{1}{1 + q \bullet (K_t - 1)}$$

where

k_e = stress concentration factor
q = notch sensitivity
K_t = stress concentration = S_{max} / S_{ave}

Notch sensitivity (**q**) of 100,000 psi steel for notch radius **r** = 0.04-in is **q** = 0.75. (Shigley & Mischke, fig. 13-12).

The maximum stress, S_{max}, was determined from a linear finite element analysis of the pin loaded with a 134,400 lb. tension load. The result of this analysis shows a maximum stress of S_{max} = 173,530 psi (see Figure D-1).

Given a cross sectional area for the pin of 3.103 in^2, the average stress on the pin can be calculated as:

S_{ave} = (134,400 lb) / (3.103 in2) = 43,313 psi

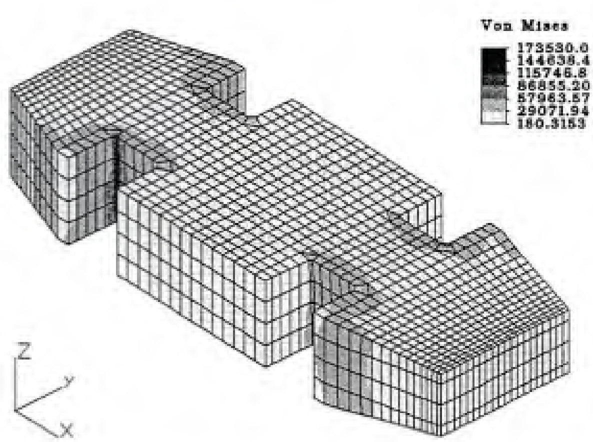

Figure D-1. Finite Element Model of MCS Male Lock Pin

The stress concentration factor can now be calculated:

$$k_e = \frac{1}{1 + q \bullet (K_t - 1)} = \frac{1}{1 + 0.75 \bullet (173{,}530 \text{ psi} / 43{,}313 \text{ psi}) - 1)} = 0.31$$

Miscellaneous. Because the load varies from 0 to some maximum instead of +/- some maximum, a miscellaneous factor of $\mathbf{k_f} = 2$ was selected. Factors not taken into consideration include corrosion and frettage.

With the modifying factors defined, the endurance limit is calculated as:

$$\begin{aligned} S_e &= k_a\, k_b\, k_c\, k_d\, k_e\, k_f\, S'_e \\ &= (0.4)\,(0.9)\,(1)\,(1)\,(0.31)\,(2)\,(50{,}000 \text{ psi}) \\ &= 11{,}160 \text{ psi} \end{aligned}$$

Short Life Endurance Stress

For allowable stress at 1,000 cycles, use $S_{1000} = 0.8S_u = 0.8$ (100,000 psi) = 80,000 psi (Shigley & Mitchell, p. 284).

S-N Diagram

With the short life endurance stress and endurance limit of the pin defined, an S-N diagram is created to determine fatigue strength as a function of number of loading cycles. Figure D-2 was created by drawing a line between the short life endurance stress at 1,000 cycles (80,000 psi) and the endurance limit at 1,000,000 cycles (11,160 psi).

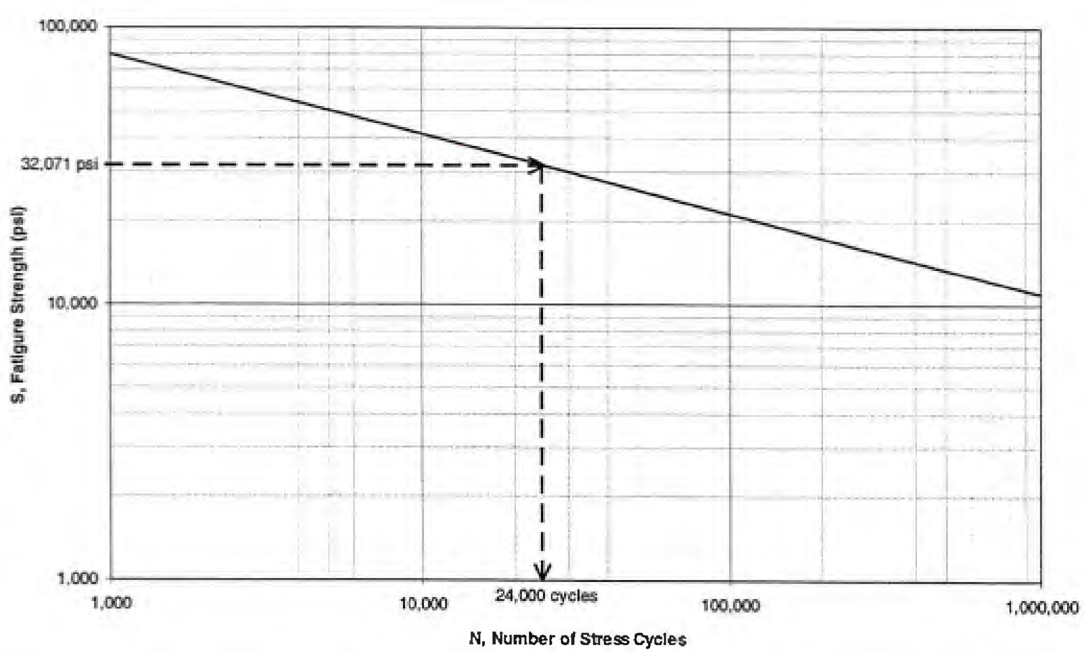

Figure D-2. Fatigue Strength vs. Number of Stress Cycles for MCS Male Lock Pin

Pin Loading

In service the male lock pins are subjected to a fluctuating load that varies from 0 to some maximum tensile load. From Appendix C, Figure C-13, the largest moment that the 88- by 120-ft pierhead is expected to experience in SS5 is 8,575,000 ft-lb. Along this plane of maximum moment the pierhead is held together with 22 pins along the bottom and 22 along the top. The vertical distance between the centers of the top and bottom pins is 47-in. At SS5 the load on one pin is:

$$P_s = (8{,}575{,}000 \text{ ft-lb}) / [(47\text{-in x } 1\text{-ft}/12\text{-in})(22 \text{ pins})] = 99{,}516 \text{ lbs/pin}$$

which gives a stress of P_s/a = 32,071 psi. From the S-N Diagram (Figure D-2), the corresponding number of stress cycles for this stress is 24,000 cycles. The period of the fluctuating load cycle depends on the sea state, but is on the order of several seconds. For a 6-sec wave period, the 24,000 cycles could be experienced in a little over 40-hrs.

In normal operating conditions (SS3), a maximum moment of 2,800,000 ft-lb is expected (Appendix C, Figure C-12). This relates to a tensile load on a pin of 32,495-lb, equating to a stress of 10,472 psi. Although this operational pin stress (10,472 psi) is lower than the pin endurance limit found above (11,160 psi), it must be kept in mind that calculated endurance limits are the mean value of a highly dispersed, or spread, set of possibilities. "This spread will occur even when the tensile strengths of a large number of specimens remain exactly the same." (Shigley & Mitchell, p. 275). In the absence of experimental procedures to find the true endurance limit and standard deviation of the pin, a standard deviation of 15% is suggested (Shigley & Mitchell, p. 276). This means that to ensure that 68% of the pins do not fail, the pin endurance limit should be lowered to 9,350 psi. To ensure that 95% of the pins do not fail, the endurance limit should be lowered to 7,500 psi; and to ensure that 99% of the pins do not fail, the endurance limit should be lowered to 6,050 pounds.

Cumulative Fatigue Damage

It would be easy to calculate the life of a pin for a single stress σ acting for n cycles; however, a causeway pier is exposed to quite a different environment—the magnitude and duration of the sea continually changes. The fatigue life must be estimated for a pin subjected to σ_1 for n_1 cycles, σ_2 for n_2 cycles, σ_3 for n_3 cycles, etc. (e.g., SS2 for 6-wks, SS5 for 15-hrs, SS3 for 25-days, etc.). If any of theses stresses exceeded the endurance limit, the pin would be damaged and the pin's subsequent endurance limit would have to be calculated. Shigley & Mitchell (p. 336) state that "Under these conditions... A search of the literature reveals that this problem has not been solved completely. Therefore the results obtained using [either Miner's[3] or Manson's[4] approach] should be employed as guides to indicate how [to] seek improvement. They should *never* be used to

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[3] Palmgren, A. (1924). "Die Lebensdauer von Kugellagern," ZVDI, vol. 68, 1924, pp. 339-341; Miner, M. A. (1945). "Cumulative Damage in Fatigue," *J. Appl. Mech.*, vol. 12, *Trans. ASME*, vol. 67, 1945, pp. A159-A164.

[4] Manson, S. S., et.al. (1965). "Further Investigation of a Relation for Cumulative Fatigue Damage in Bending," *Trans. ASME, J. Eng. Ind.*, ser. B, vol. 87, no. 1, Feb 1965, pp. 25-35.

obtain absolute values... [because] an approach consistently in agreement with experiment has not yet been reported." Given this constraint, we'll use Manson's method to estimate the endurance limit of a pin that has been overstressed for a finite number of cycles.

Using Manson's method, the log S-log N lines must be constructed in the same historical order in which the stresses occur. Using the above example (SS2 for 6-wks, SS5 for 15-hrs, SS3 for 25-days) a new S-N Diagram will be constructed. The log S-log N line for the undamaged material is the same as in Figure D-2. SS2 conditions do not result in stresses that exceed the original endurance limit; therefore, the endurance limit is unaffected and the original log S-log N line remains. SS5 conditions result in a stress (32,071 psi) that exceeds the pins' endurance limit (11,160 psi); therefore, we wish to find the new endurance limit $S'_{e,1}$ of the damaged pin. Figure D-2 shows that at 32,071 psi the pin has a life N_1 = 24,000 cycles, and consequently, after the application of this stress for n_1 = 9,000 cycles (15-hrs x 1-cycle/wave x 1-wave/6-sec x 3600-sec/hr), there are $N_1 - n_1$ = 15,000 cycles of life remaining. Through this point and through $0.8S_u$ at 10^3 cycles, we draw a heavy dashed line to meet $N = 10^6$ cycles and define the endurance limit $S'_{e,1}$ of the damaged material. From Figure D-3, it can be seen that the new endurance limit is approximately 7,700 psi.

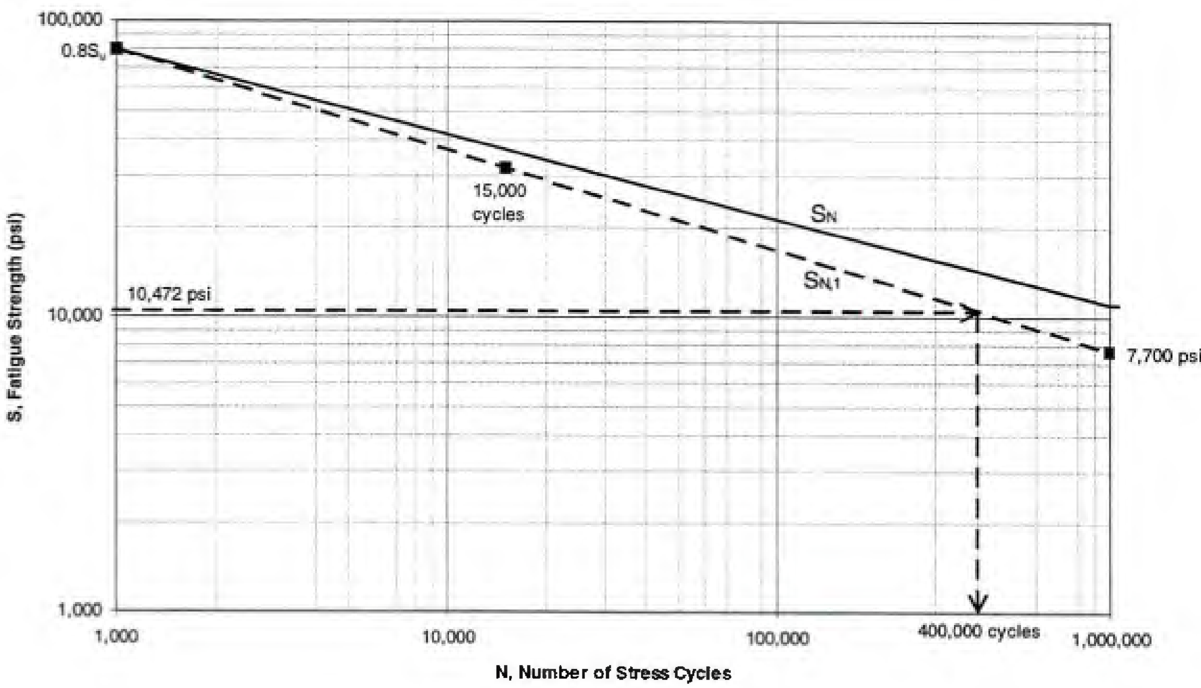
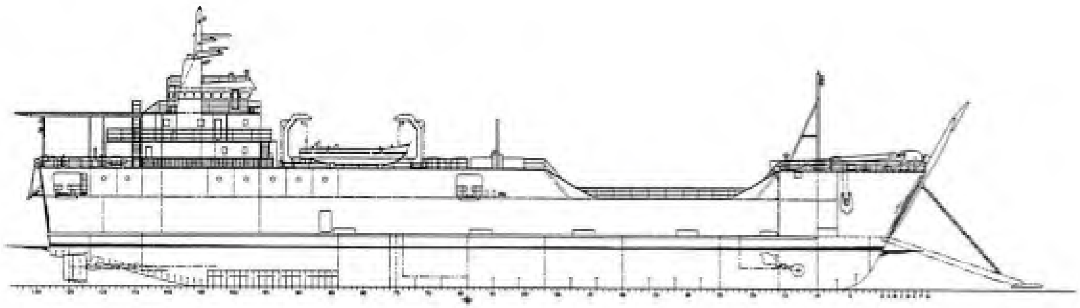


Figure D-3. Modified S-N Diagram

Using this modified S-N diagram, it can be seen that the stress for SS3 (10,472 psi) is no longer below the endurance limit (previously 11,160 psi, now modified to 7,700 psi). On this diagram, the number of cycles to failure for the SS3 stress is 400,000 cycles, which equates to 18.5-days of a 4-sec wave period. Though the pin did not fail during the SS5 storm, it could fail during what would be considered a normal operating environment (SS3).

Appendix E. Logistics Support Vessel (LSV) Characteristics



Characteristics obtained from Trinity Marine Group:

Displacement at design draft (D)	=	4,199 LT (9,406 kip)
Length overall (L)	=	272.75 ft
Length along waterline (L_{wL})	=	255.4 ft
Beam (B)	=	60.0 ft
Length between perpendicular (L_{pp})	=	256.0 ft
Location of CG	=	19.83 ft above keel and 127.75 ft aft of fwd pp
Draft, Design (T)	=	12.0 ft

Characteristics determined from drawing:

Lateral projected area of superstructure (A_S)	=	960 ft^2
Lateral projected area of hull (A_H)	=	5933 ft^2
Lateral projected area of ship (A_y)	=	6893 ft^2
Average height of superstructure (h_S)	=	36 ft
Average height of hull (h_H)	=	12 ft

Characteristics calculated:

Block Coefficient (ϕ) = 0.80

where ϕ = 35 D / (L_{wL} B T)

= 35 (4,199 LT) / (255.4 ft x 60.0 ft x 12.0 ft)

= 0.80

Midship Section Coefficient (C_m) $\cong$ 1

where C_m = (immersed area of midship section) / B T

$\cong$ 1

Prismatic Coefficient (C_p) = 0.80

where C_p = ϕ / C_m

Appendix F. Landing Craft, Utility 2000 (LCU-2000) Characteristics

Characteristics obtained from Jane's (1993-94):

Displacement at design draft (D)	=	1,102 LT (2,468 kip)
Length overall (L)	=	173.8 ft
Length along waterline (L_{wL})	=	156 ft
Beam (B)	=	42.0 ft
Draft, Design (T)	=	8.5 ft

Characteristics calculated:

Block Coefficient (ϕ) = 0.69

where $\phi = 35\,D / (L_{wL}\,B\,T)$

$= 35\,(1{,}102\text{ LT}) / (156\text{ ft} \times 42.0\text{ ft} \times 8.5\text{ ft})$

$= 0.69$

Midship Section Coefficient (C_m) $\cong$ 1

where $C_m =$ (immersed area of midship section) / B T

$\cong 1$

Prismatic Coefficient (C_p) = 0.69

where $C_p = \phi / C_m$