An Alternate Method for the Determination of Aircraft Carrier Limiting Displacement for Strength

by

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and

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ABSTRACT

Aircraft Carriers are currently exceeding design displacement limits, with minimal Service Life Allowance margin. Current aircraft carrier displacement limits are based primarily on structural strength criteria under very limited load and environment conditions. Traditional methods of determining hull girder displacement strength utilized an arbitrary safety factor of 15 percent which was allowed between the Calculated Primary Stress and the Design Primary Stress. The use of this safety factor and others has resulted in the establishment of a conservative displacement limit. This established displacement limit fails to provide an adequate margin of comfort for the addition of post construction weight to aircraft carrier hulls and does not provide an accurate indication of the actual hull girder displacement limit.

A first failure analysis of fifteen sections of the newest aircraft carrier design (CVN 77) was conducted. The results of this analysis along with output data from the Ship Hull Characteristic Program (SHCP) were utilized in forming an alternate method for determining the limiting displacement for strength for aircraft carriers. Although the present aircraft carrier displacement limit takes into account numerous other limitations, this process deals only with the hull girder displacement limit for strength. This study does not provide a specific number for the displacement limit for strength for aircraft carriers; however, it does show that the NIMITZ aircraft carrier hull is potentially capable of sustaining significant additional weight without exceeding established Maximum Allowable Bending Moment limits.

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To Delphina and Brandon

Cambridge, Massachusetts, June 2001

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1 Introduction

All NIMITZ Class aircraft carriers are approaching their limiting displacement for strength. This limiting displacement is due to calculated limitations based upon longitudinal strength. Traditionally, longitudinal strength has been determined by balancing the ship on a static wave. The ability to meet operational requirements using a static balance method is implicitly based on the historical success of the method.[1] Through the years, design practices and capability to assess the results of those practices have undergone significant change. United States aircraft carrier design, in particular, has improved significantly since its modest beginnings in the early 1940's. This thesis is motivated by the present condition of NIMITZ class aircraft carriers regarding limiting displacement for strength. In the following chapters, a fresh look will be taken into the parameters underlying longitudinal strength.

Table 1 shows the commissioned displacement of this class of warship, and the estimated current displacements, individually.

Table 1. CVN 68 Class Displacement.

SHIP	Delivery Displacement (LTONS)	Estimated Current Displacement (LTONS)
68	93,282	101,080
69	93,831	101,636
70	94,069	100,979
71	96,865	103,448
72	97,497	103,995
73	97,816	103,900
74	97,490	103,187
75	97,943	102,585

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[1] Sieve, M. W., Kihl, D. P., Ayyub, B. M., "Fatigue Design Guidance for Surface Ships, Draft," CARDEROCKDIV-U-SSM-65- / September 2000.

For example, using current practice in determining the limiting displacement for strength, an estimation of the CVN 68 limiting displacement would be as follows:

$$\Delta_L = (\sigma_{1L} / \sigma_{1C}) * \Delta_C$$

where: Δ_L = Limiting Displacement (long tons (LTON))

Δ_C = Contract Design Displacement (LTON)

σ_{1C} = Calculated Primary Stress (tons per square inch (tsi))

σ_{1L} = Limiting Primary Stress (tsi)

If we assume the following:

$$\Delta_L = (8.00 \text{ tsi} / 7.19 \text{ tsi}) * 93,282 \text{ LTON}$$

The estimated longitudinal displacement for strength would be: 103,790.82 LTON

The difference between Δ_L and Δ_C is 10508.82 LTON, rounded to 11,000 LTON.

The added displacement is assumed to be equally distributed along the length of the ship. A derivation of the previous equation is conducted in chapter 2. It is clear by comparing the as commissioned displacement to the present displacement that this class of ship is fast approaching its limiting displacement for strength. In fact, all NIMITZ class aircraft carriers are presently in stability status two, which means that neither an increase in weight nor center of gravity (KG) can be accepted without compensating for the increase by a reduction elsewhere. It is the goal of this analysis to show that present methods of determining the limiting displacement for strength are very conservative and that, indeed, a significant amount of weight may be added to the hull and still not exceed the bending moment capacity of this hull. It should be noted that numerous other limitations such as speed requirements, Side Protection System Immersion, nuclear propulsion, and trim requirements may limit the future growth displacement. The focus of this investigation is

squarely on hull girder bending moment limits. No other limitations are addressed in this study.

The total weight of the ship, or displacement, is comprised of the hull girder steel weight, the propulsion units, electrical, weapons, sensors, and anything else that has "weight." The structural weight of the ship accounts for approximately forty-nine percent of the displacement. The structure is composed of decks, bulkheads, and shell elements. These elements are made up of plates and stiffeners whose dimensions are often referred to as scantlings. The scantlings are a function of the ship length, operational profile, and the overall displacement of the ship. Hull girder bending moments subject the structure to hull girder primary bending stresses. These bending stresses are limited to a particular value in order to preclude structural failure, fatigue, and collapse. Traditionally, upon completion of the Contract Design Phase, the difference between the Calculated Primary Stress (σ_{1C}) and the Design Primary Stress (σ_{1D}), should be at least 1.0 tons per square inch (tsi) for combatant ships.[2] This difference is known as the Stress Factor for Primary Stress (M_S), and accounts for increases in hull girder stresses due to bending moment growth resulting from weight growth or weight redistribution. Design Primary Stress is not allowed to exceed the Limiting Primary Stress that normally varies from 8.0 tsi to 10.5 tsi depending upon the hull material. Therefore, the future weight, or displacement, is limited by the increase in the primary hull girder stress up to its limiting value. The value of this displacement is referred to as the "Limiting Displacement for Strength." Traditionally, the added weight is assumed to be distributed in the same proportion as the original full load weight

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[2] Naval Sea Systems Command Code 55Y1, "Design Standard for Hull Girder Primary Strength," Design Data Sheet 100-1, 28 June 1983.

distribution.[3] These results may be a conservative estimate of the future weight growth. In order to permit a larger limiting displacement for strength, an alternative method of determining limiting displacement for strength is required.

2 Past Practices

Numerous records indicate that it has long been Navy practice to allow a factor between the Calculated Primary Stress and the Design Primary Stress. Prior to World War II, this factor allowed for rivet holes, stress concentrations, and instability in compressive loadings, equaling approximately 15 percent.[4] After World War II, an extensive review of past practices and experiences was conducted by a committee formed by the Bureau of Ships. It was noted that "Wartime operations emphasized the necessity of ruggedness as a characteristic of combatant vessels, which because of tactical situations may be driven at high speed in heavy seas."[5] Ruggedness required, in the case of the DD 927 Class, an allowance of approximately 50 tons of steel (approximately 1% of displacement) and the increasing of the calculated bending moment by 10 percent. Gradually, the concept of utilizing a "ruggedness" factor was discarded to prevent confusion. By 1953, it had been replaced by the practice of requiring that the combination of primary and secondary stress not exceed 80 percent of the allowable strength of the material used. The Design Primary Stress Limit was established for HY-80 and HY-100 as 10.5 tons per square inch (tsi), for HTS as 9.5 tsi, and for OS as 8.5 tsi.

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[3] ibid.

[4] Naval Sea Systems Command Code 55Y1, "Design Standard for Hull Girder Primary Strength," Design Data Sheet 100-1, 28 June 1983.

[5] Ferris, L. W., BUSHIPS 440 Note, 27 January 1948.

In the mid 1960's, the practice of monitoring hull weight growth led to the introduction of the concept of "Limiting Displacement for Strength." This concept implied that there was an upper limit on displacement determined by hull girder strength.

The basic equations utilized for estimating the bending moment and stress were as follows:

(1) Bending Moment:

$$M = \Delta_C \, LBP \, / \, C$$

where M = Bending Moment

Δ_C = Displacement

LBP = Length Between Perpendiculars

C = Bending Moment Coefficient

(2) Stress:

$$\sigma_{1C} = M \, / \, Z$$

where σ_{1C} = Calculated Primary Stress

M = Bending Moment

Z = Section Modulus

The above equations may be combined to show that

$$\sigma_{1C} = M \, / \, Z = \Delta_C \, LBP \, / \, C \, Z$$

It should be noted that for a given ship, this practice assumes that LBP, Z, and C remain constant, such that a new constant C', may be used, where:

$$C' = LBP \, / \, C \, Z$$

therefore, $\sigma_{1C} = C' \, \Delta_C$

The prime (') is utilized to indicate a new or changed displacement. If this new

displacement is to be determined, then the equation becomes:

$$\sigma_{1C} / \Delta_C = C' = \sigma_{1L} / \Delta_L$$

thus,

$$\Delta_L = (\sigma_{1L} / \sigma_{1C}) * \Delta_C$$

$$\text{where } \sigma_{1C} = \text{Calculated Primary Stress}$$
$$\sigma_{1L} = \text{Limiting Primary Stress}$$
$$\Delta_C = \text{Contract Design Displacement, and}$$
$$\Delta_L = \text{Limiting Displacement for Strength}$$

While it is obvious that there is a definite limit as to how much weight or displacement

that a hull can resist, the published Limiting Displacement for Strength is not an absolute

value but needs to be reevaluated based on weight increases, weight redistribution, and

configuration changes.[6] When a ship approaches the limiting displacement, the stress

situation should be reevaluated based upon the best weight information available. The

lack of information detailing the exact location of weight addition and removal makes

establishing a realistic modified weight distribution an extremely difficult and time

consuming task.

An alternate, and more versatile, method for estimating the bending moment due

to small changes in weight is the Ferris Method[7]. This method is effective only for small

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[6] Ferris, L. W., BUSHIPS 440 Note, 27 January 1948.

[7] Ferris, L. W., "The Effect of an Added Weight on Longitudinal Strength," SNAME Transactions, 1940.

changes in weight relative to the ship's displacement. The change in longitudinal

bending moment for the hogging or sagging condition is:

$$\Delta M = P x / 2 - P K L / 4$$

where:

ΔM = change in bending moment in ft-tons

P = change in weight in tons

L = length between perpendiculars in feet

x = distance of point P from midship in feet

K = dimensionless hull shape coefficient.

P is positive for added weights and negative for removed weights, and x is always

positive whether forward or aft. The first term in the expression accounts for the change

in moment caused by the change in weight, while the second term accounts for the effects

of the opposing buoyancy wedge. Therefore, a positive answer indicates that the hogging

moment is increased or sagging moment is reduced; and a negative answer indicates that

the hogging moment is decreased or sagging moment is increased. For the hogging

condition, a weight added in the midsection of the ship reduces the longitudinal bending

stress, while a weight added near either end increases it.[8] This indicates that there is a

point in the forebody and one in the afterbody at which weight can be added without

changing the stress. For sagging, the effects are similar but opposite to those for hogging.

The ship's weight, consisting of fixed and variable weights, is divided into 22

ship segments to give a realistic representation of weight distribution along the length of

the ship. These 22 segments correspond to the standard 20 segments between the

perpendiculars plus one forward and one aft of the perpendiculars. The cross sections of

the ship, known as stations, are numbered from zero at the forward perpendicular to 20 at the after perpendicular. Light Ship (fixed weight) and Load (variable weight) components of the weight distribution must be readily separable in order to facilitate manipulation to simulate the various load conditions anticipated during the life of the ship. Fixed weights consist primarily of hull, hull engineering, machinery, fittings, equipment, and permanent ballast. Whereas variable weights consist of cargo, fuel, embarked aircraft, water, lubricants, water ballast, crew, provisions, and ship's stores.

Since the mid 1950's the following thirteen steps have been followed in calculating the longitudinal strength[9]:

1. Tabulate the longitudinal distribution of weights
2. Define the wave height, wave length, and wave center
3. Balance the ship on wave and still water
4. Tabulate the forces of buoyancy
5. Determine the loads from weights and buoyancy
6. Integrate the loads to give shearing forces
7. Integrate the shearing forces to give bending moments
8. Determine the effective structure
9. Calculate the moments of inertia and section moduli
10. Calculate the bending stresses
11. Calculate the shearing stresses
12. Calculate the deflections
13. Assemble work in suitable form for record in a longitudinal strength drawing.

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[8] Ferris, L. W., "The Effect of an Added Weight on Longitudinal Strength," SNAME Transactions, 1940.
[9] Naval Sea Systems Command Code 05P1, "Longitudinal Strength Calculation," Design Data Sheet 100-6, 29 May 1987.

3 Present Practices.

Present USN design criteria for longitudinal strength are specified in Naval Sea Systems Commands Design Data Sheet (DDS) 100-6 and utilizes a standard wave approach for determining primary stresses. This standard wave is of trochoidal form with wavelength equal to the ship length between perpendiculars (LBP) and height equal to $1.1\sqrt{LBP}$. The standard wave approach determines the design bending moment by statically balancing the ship on this trochoidal wave. The stresses derived from this bending moment are then compared with allowable values and adjusted on a trial and error basis, to reflect past experiences with ships already in operation. The standard wave approach does not, however, specifically account for the effects of transient loads such as whipping, green seas, wave slap, or fatigue or their effects on longitudinal distribution of bending moments other than by empirical "rules of thumb". Due to all of these uncertainties, large safety margins have been used to account for effects of slamming.

Since the current service life of Navy ships ranges from 30 to approximately 50 years, fatigue cracking is considered. The likelihood of fatigue cracks occurring is minimized by controlling hull girder seaway stress ranges based on the fatigue strength of the ship's structural details. Additionally, current practice requires that fatigue allowable stress range be tied to the ship's lifetime bending moments. The lifetime bending moments represent the magnitude (hog and sag) and number of vertical bending moment cycles expected during the ships service life. These bending moments include those due to changes in wave height and slam induced whipping. Ship speed and heading probabilities, wave height and whipping probabilities, ship characteristics, service life, operating time and geographic area have a great affect on lifetime bending moments.

Evolving practice has lifetime bending moments replace the traditional bending moments based on $1.1\sqrt{LBP}$ wave[10]. The fatigue allowable stress range is calculated using Miner's cumulative damage rule, the ship's lifetime bending moments, and the fatigue strength of the critical structural detail. Miner's rule is a widely accepted method for calculating damage resulting from cyclic stress.

4 Developments Supporting Determination of Longitudinal Strength.

Finite element methods have provided a capability to assess variations in design and materials. In finite element analysis, the standard loads are still used in conjunction with the standard design allowable stresses. The Navy, however, did not routinely use full ship finite element models until the design of the SAN ANTONIO (LPD 17) class and ZUMWALT (DD 21) class ships. Rather, hand calculations were used to determine the strength of the hull girder. Finite element models are used for determining local stresses as required.

Load and Resistance Factor Design is the newest approach utilized in designing Navy ships. The San Antonio (LPD 17) class amphibious ship is the first to be designed utilizing this approach. This method produces separate factors for loads and for strength of members so that computed maximum lifetime loads can be used in conjunction with strength computations in a reliability-based design. Reliability-based design requires

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[10] Ayyub, B. M., "Reliability-based Design of Ship Structures: Current Practice and Emerging Technologies," SNAME Technical Report for Contract DTCG23-97-P-MM1C76, July 1998.

consideration of three components: (1) structural strength, (2) loads, and (3) methods of reliability analysis.[11]

The computer program Ultimate Strength (ULTSTR) is used for the determination of the structural strength component. The original version of the Ultimate Strength (ULTSTR) program was envisioned to fill the need for an automated method of determining ultimate hull girder strength that was fast and easy enough to use such that it could be readily applied in the preliminary stages of structural design. This version was released approximately 20 years ago and has since undergone significant improvements. The original version of ULTSTR was unused for years after its initial development. However, due to increased interest in ultimate strength, the current version of ULTSTR has been brought back to the forefront.

An additional tool which is used is the Ship Hull Characteristics Program (SHCP). SHCP automates the calculation of typical naval architecture equations.

Neither Finite Element Analysis methods nor Load and Resistance Factor Design methods were considered viable for this study due to significant time and manpower constraints. The use of ULTSTR, with the assistance of NSWC Carderock Division, and SHCP provided the best opportunity for conducting a meaningful investigation into limiting displacement for strength. The procedure presented in chapter 6 is, relative to the two methods discussed above, a rudimentary way of determining if a detailed analysis of hull girder primary stress is required. In this procedure, bending moment capacity, determined by evaluating a section of a hull form utilizing the Ultimate Strength (ULTSTR) computer program, is utilized as a trigger limit. The bending moment of each

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[11] Ayyub, B. M., "Reliability-based Design of Ship Structures: Current Practice and Emerging Technologies," SNAME Technical Report for Contract DTCG23-97-P-MM1C76, July 1998.

section of the hull is determined utilizing the Ship Hull Characteristic Program (SHCP). One may modify section weights by manipulating input data files in SHCP. A graphical comparison is made between the two and if the bending moment capacity curve is exceeded by the section bending moment curve, then a detailed analysis should be performed. This method works very well as a indicator; however, it could be improved by knowing the exact location of weights added post construction.

5   Computer Analysis Tools.

To examine the accuracy of displacement being limited by increasing the bending moment associated with increased weight, this thesis examines the bending moment using new tools. Determining the hull girder displacement limit for strength requires the utilization of two computer programs, namely, the Ultimate Strength (ULTSTR) Program and the Ship Hull Characteristics Program (SHCP).

ULTSTR has undergone substantial change since its initial beginnings as the Gross Panel Synthesis Technique (GPST). GPST was presented by John C. Adamchak as part of his doctoral thesis in 1969.[12] ULTSTR is the logical progression of programming technology from GPST. The current version of ULTSTR was issued in 1997 and includes several improvements to the original version issued in 1982.

SHCP was developed by the Naval Sea Systems Command and was initially released in 1976. Since 1976, SHCP has undergone 14 revisions. Each revision either improved the functionality of the program or improved ease of use. John Rosborough of

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[12] Adamchak, J. M., "A Ship Structural Synthesis Capability Utilizing Gross Panel Elements," Massachusetts Institute of Technology, September 1969.

Naval Sea Systems Command, Code 05P5, has largely maintained SHCP for the past decade.

The major characteristics of each program are presented in the following sections.

`5.1 Ultimate Strength Program (ULTSTR).*

The Ultimate Strength Program was developed by Adamchak[13] and is used for estimating the collapse moment of a hull girder subjected to longitudinal bending. ULTSTR is designed to estimate the ductile collapse strength of conventional surface ship hulls under longitudinal bending. The program is based on a variety of empirical solutions for the most probable ductile failure modes for grillage structure. This procedure involves the incremental application of curvature (i.e. rotation) about the neutral axis of a section of the hull and computing the resulting equilibrium longitudinal moment. At each value of curvature, the program evaluates the equilibrium state of each gross panel and hard corner element relative to its state of stress and stability corresponding to its particular value of strain.[14]This leads to a moment-curvature relationship for the hull. The collapse (ultimate) moment at the section is defined as the point at which the value of moment reaches its peak and then drops off. Figure 1 provides a generic Moment-Rotation Curve.

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[13] Adamchak, J. C., "ULTSTR-A Program for Estimating the Collapse Moment of a Ship's Hull Under Longitudinal Bending," David W. Taylor Naval Ship Research and Development Center, Report No. 82/076, October, 1982.

[14] Adamchak, J.C., "ULTSTR (1997): The Revised Program for Estimating the Collapse of Ship Hulls or Hull Components under Longitudinal Bending or Axial Compression," Naval Surface Warfare Center, Carderock Division, NSWCCD-TR-65-97/21, July 1997.
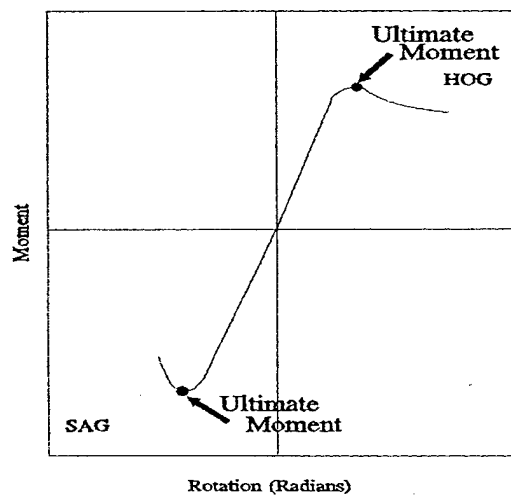
Figure 1. Generic Moment-Rotation Curve.

As Figure 1 indicates, the peak moment is usually defined as the hulls' "ultimate strength." It is possible for hulls with significant redundancy to have local moment peaks, that is, "a moment-curvature behavior that builds up to a peak moment value, drops off a bit, and then builds up to a greater peak value before dropping off in capacity again."[15] As curvature on an individual section is increased, the hogging or sagging bending moment increases until the ultimate moment is reached. This effect results in a change in slope of the moment-curvature diagram. The knuckle that is apparent on the curve just prior to the Ultimate Moment indicates the "first failure." The "first failure" could be a small element failure or it could be a component failure. In the interest of maintaining the unclassified nature of this thesis, ultimate strength values are not utilized.

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[15] Adamchak, J.C., "ULTSTR (1997): The Revised Program for Estimating the Collapse of Ship Hulls or Hull Components under Longitudinal Bending or Axial Compression," Naval Surface Warfare Center, Carderock Division, NSWCCD-TR-65-97/21, July 1997.

Rather, 1st Failure Moments and Maximum Allowable Moments, both of which are described later, are used in discussing the bending moment capacity of individual sections.

Several ductile and instability failure modes are considered in evaluating the equilibrium moment. Structural yielding is included as a ductile failure mode. Instability failure modes incorporate Euler beam-column buckling and stiffener lateral-torsional buckling (tripping).

In support of this study, Naval Surface Warfare Center (NSWC), Carderock Division performed an ultimate strength analysis of several hull cross sections of the CVNX class of aircraft carriers, specifically CVN-77. The results of this analysis were provided to the author NAVSEA. In this analysis, the ship cross section was represented by a series of "gross panel elements" and "hard corners." The cross section was modeled, and ULTSTR was executed to evaluate the ultimate moments of the cross-section. The collapse of the hull is addressed by the collapse behavior of the local components that make up the cross section, i.e., gross panel, stiffened or unstiffened, or hard corners. Figure 2 provides a graphical representation of the ULTSTR output data provided by NSWC, Carderock.

It should be noted that ULTSTR provides a bending moment capacity for the individual section under consideration. This bending moment capacity will be utilized in a comparison analysis that will be discussed in later sections.
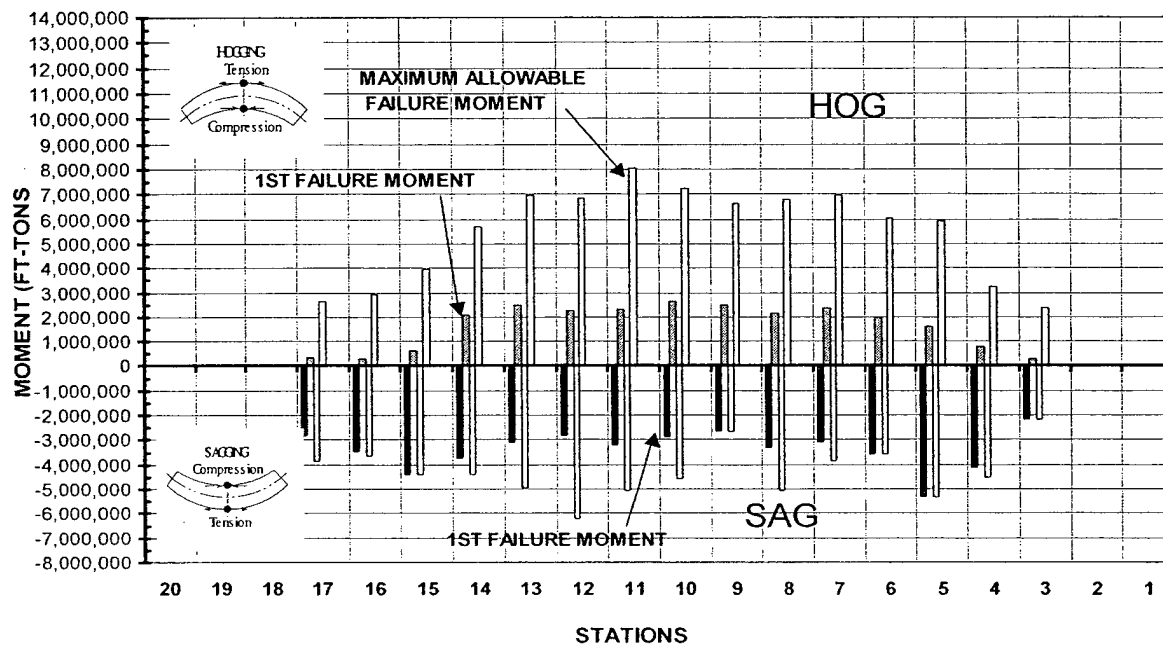
Figure 2. CVNX (CVN 77) Failure Bending Moments.

The collapse of the hull in ULTSTR is addressed by the collapse behavior of the

local components that make up the cross section. At each value of curvature, the

program evaluates the equilibrium state of each gross panel and hard corner relative to its

state of stress and stability corresponding to its value of strain.[16] ULTSTR then computes

the total moment on the cross section by summing the moment contributions of all the

elements that make up the section being evaluated. This moment contribution is

calculated by taking the product of stress, effective area, and lever arm. It is quite

impossible to determine at a glance what failure mode may be most critical for a

particular gross-panel element; therefore, it has been assumed that, once instability is

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[16] Adamchak, J.C., "ULTSTR (1997): The Revised Program for Estimating the Collapse of Ship Hulls or Hull Components under Longitudinal Bending or Axial Compression," Naval Surface Warfare Center, Carderock Division, NSWCCD-TR-65-97/21, July 1997.

detected in a given mode, the behavior follows through to failure in that same mode. [17]

Interaction among different modes of failure is an extremely complex problem and has not received much treatment.

The first failure moments, as reported in ULTSTR, result from onset of buckling for the plates, usually wide panels. Typically they do not have an adverse impact on the ultimate moment capacity of the section; however, it is proposed to be used as the lower bound for the moment capacity of a particular section (1st Failure Moment). For a stiffener, column buckling or tripping is the failure mode, which is equivalent to its ultimate failure. Consequently, the local failure is ultimate failure for a stiffener. However, it is proposed to be used as the upper bound for the moment capacity of a particular section (Maximum Allowable Failure Moment). The 1st Failure Bending Moment from the ULTSTR output represents the first failure of an element on a section and will occur at or below the Maximum Allowable Bending Moment. The Maximum Allowable Bending Moment Hog or Sag represents the point at which the value of moment in the section causes the first combined plate and stiffener element, or gross panel, to fail by column buckling or tripping. .

Note that ULTSTR does not report the ultimate failure mode of a plate, consequently it may be possible, but rather unlikely, that a plate may buckle before a stiffener fails. However, the formulas used for column failure use an effective width of plate for determining the strength or failure capacity, hence, it assumes that the plate has failed ultimately and no further reporting of plate failure is shown. Plate buckling is not

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[17] Adamchak, J.C., "ULTSTR (1997): The Revised Program for Estimating the Collapse of Ship Hulls or Hull Components under Longitudinal Bending or Axial Compression," Naval Surface Warfare Center, Carderock Division, NSWCCD-TR-65-97/21, July 1997.

included as an explicit separate failure mode because it influences collapse more indirectly by influencing plating effectiveness relationships, i.e. effective breadth, width, etc.[18]

Gross panel elements in the cross section can "fail" either through material yielding in tension or compression, or through structural instability. The structural instability failure modes are as follows:

1. Euler beam-column buckling, and
2. Stiffener lateral-torsional buckling, also known as "tripping."

The ULTSTR output file shows the following failure modes:

1. Gross panel unstiffened wide panel buckling.
2. Gross panel material yielding.
3. Gross panel Euler beam-column buckling occurring in the same direction.
4. Gross panel Euler beam-column buckling occurring by an alternating buckling pattern.
5. Gross panel stiffener lateral-torsional buckling or instability (tripping).
6. When the lower deck is in compression, and the tension side, usually the upper deck, reaches yield stress before any additional compression failure on the compression side and vice versa.

In the case of plate buckling, the wide panel buckling theory used by ULTSTR does not account for the plate aspect ratio. Consequently, the compressive capability of the panel may be too conservative for plates with an aspect ratio of a/b>1. The wide panel buckling theory assumes a unit width of 1. This may be seen by comparing the critical

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[18] Adamchak, J.C., "ULTSTR (1997): The Revised Program for Estimating the Collapse of Ship Hulls or Hull Components under Longitudinal Bending or Axial Compression," Naval Surface Warfare Center, Carderock Division, NSWCCD-TR-65-97/21, July 1997.

stress for simply supported plate buckling to the wide plate critical buckling stress as shown in Figure 3. The critical stress (σ_{cr}) for simply supported plate buckling can be calculated as follows:

$$\sigma_{cr} = k\,\pi^2 D\,/\,(b^2\,t)$$

where k = buckling coefficient
D = plate flexural rigidity
b = plate width, and
t = plate thickness

For simply supported plates, k is determined as follows:

$$k = ((mb)/a + a/(mb))^2$$

where m = the number of half-waves in the buckled shape
a/b = aspect ratio
b/a = inverse of the aspect ratio

When a/b << 1, m = 1, and k reduces to $k = b^2 / a^2$; therefore, for wide plate buckling the critical stress is:

$$\sigma_{cr} = \pi^2 D\,/\,(a^2\,t)$$

where a = plate length

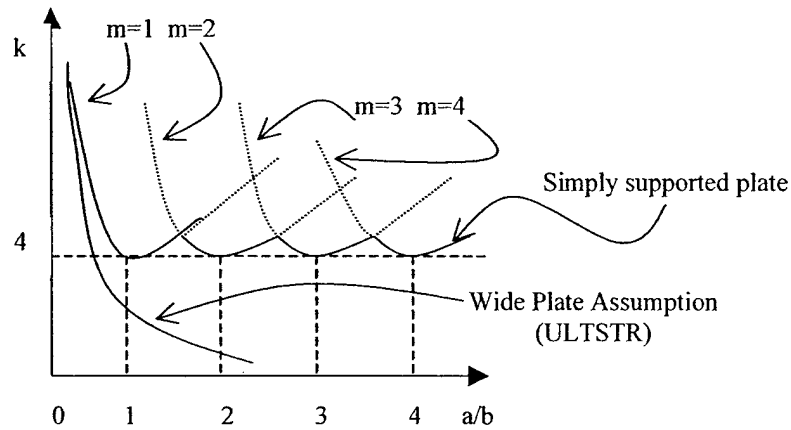The distance between the two curves in Figure 3 represents a measure of conservativeness between the two results.

Figure 3. Buckling Coefficient vs. Aspect Ratio.

Plates of [a/b >/= 1] are typically found in aircraft carrier structures.

5.2 Ship Hull Characteristic Program (SHCP)

The Ship Hull Characteristic Program is an extremely capable tool that consists of

a basic geometry interpreter used to load various volumetric and centroid properties into

a ship data table (SDT) and a set of modules which interrogate the SDT for information

required to perform basic naval architectural calculations.[19] The naval architectural

modules of SHCP provide a means of calculating or plotting the following :

> Hydrostatics
>
> Trim Lines
>
> Floodable Length
>
> Limiting Drafts
>
> Intact Stability
>
> Intact Statical Stability on Waves
>
> Damaged Stability Cross Curves
>
> Damaged Transverse Stability

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[19] Ship Hull Characteristic Program User's Manual, Version 4.20, March 2000.

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Damaged Longitudinal Stability

Damageable Length, and;

Tank Capacities and Free Surface

In addition, SHCP contains several modules that are utilized to input or modify ship data.

These modules include the following:

Ship Offsets Input

Design Condition

Sheer Deck Input

Compartmentation Input

Subdivision Input, and;

Liquid Loads Specifications

Of these numerous modules, only the following were required to be utilized for this

analysis. Those modules were:

Hull, Appendages and Referenced Offsets (HULL)

Design Condition (DESIGN)

Hydrostatics (HYDRO), and;

Longitudinal Strength (STRNGH)

Each of these four modules will be discussed in detail in following sections.

5.2.1 Hull, Appendages and Referenced Offsets (HULL).[20]

The HULL module calculates and stores the ship data table for the main hull, appendages and referenced offsets. It also checks offsets provided by the user for correctness. Any errors encountered are saved in the output file. Plots of the vessel's bodyplan and isometric may be

generated and checked by the user. Station Spacing, offset scaling, Length Between Perpendiculars (LBP), body plan scaling, and Main Hull geometry type data is entered into the program via this module. Two types of offset descriptions are utilized. Both types describe the ship as a series of station cuts where each station is modeled by offsets consisting of a series of heights and half-breadths (normal offsets) or a radius and optional vertical offset value (circular offsets) at a series of longitudinal locations. Three appendage types are provided: appendage by offset, point volumes, and line volumes. Each record indicates appendage type, whether buoyant, flooded, or null and a description.

5.2.2 Design Condition (DESIGN).[21]

The DESIGN module allows the user to specify one of three combinations of displacement, draft, trim, and longitudinal center of gravity (LCG). This file may specify draft and trim, displacement and

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[20] Ship Hull Characteristic Program User's Manual, Version 4.20, March 2,000.

[21] ibid.

trim, or displacement and LCG, only. The DESIGN module calculates the design displacement, draft, longitudinal center of buoyancy (LCB), station of maximum area, and other items for a particular vessel at an attitude specified by the user. The longitudinal position (X_{max}) of the station with the maximum sectional area A_{max} at the design waterline is found by determining the A and B coefficients of the curve segment which contains that specific station and then setting the slope of that curve [$(2*A*X_{max}) + B$] equal to zero and solving for X_{max}. Taylor's second order interpolation coefficients, found from X_{max} and the three stations describing the curve segment, are used to generate interpolated values of A_{max}, Y_{max} (the maximum half-breadth), and depth. The beam is computed as $2*Y_{max}$. SHCP calculates the form coefficients utilizing the following equations:

a. Midships section coefficient (also called the section area coefficient):

$$C_x = A_{max} / (beam * depth)$$

b. Prismatic coefficient:

$$C_p = Volume / (A_{max} * LBP)$$

c. Block Coefficient:

$$C_b = Volume / (LBP * beam * depth)$$

5.2.3   Hydrostatics (HYDRO). [22]

The HYDRO module allows the user to request standard hydrostatic properties for 1 to 100 waterlines or displacements for a

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[22] Ship Hull Characteristic Program User's Manual, Version 4.20, March 2000.

maximum of seven different trim conditions. If none of the requested waterlines or displacements is within 0.001 feet or meters of the Design Condition draft or displacement, the Design Condition draft or displacement is added to the list of waterlines or displacements for which calculations are performed. The calculated properties for the Curves of Form are presented in tabular form as a function of increasing waterline. A different set of hydrostatic properties is calculated and printed for each trim submitted. Ship specific information is interpolated at each waterline and trim to obtain cross section properties. This module utilizes the following formulas in determining ship specific information:

a. Displacement:

$$Displ = volume / Cfton$$

b. Prismatic coefficient:

$$C_p = volume / (A_{max} * LBP)$$

c. Waterplane coefficient:

$$C_{wp} = A_{wp} / (2 * LBP * Y_{max})$$

d. Transverse waterplane inertia coefficient:

$$C_{wpi} = W_{pit} * 1.5 / (LBP * (Y_{max})^3)$$

e. Longitudinal metacentric radius:

$$B_{ml} = W_{pil} / volume$$

f. Transverse metacentric radius:

$$B_{mt} = W_{pit} / volume$$

g. Height of longitudinal metacenter above baseline:

$$K_{ml} = KB + B_{ml}$$

h. Height of transverse metacenter above baseline:

$$K_{mt} = KB + B_{mt}$$

i. Tons per inch immersion:

$$TPI = A_{wp} / (12 * Cfton)$$

j. Change in displacement per foot of trim aft:

$$C_{idofts} = (-12) * TPI * LCF / LBP$$

k. Moment to trim one inch :

$$MTI = volume * B_{ml} / (12 * Cfton * LBP)$$

Where, A_{max} = cross sectional area at station of maximum area

A_{wp} = waterplane area

KB = height of center of buoyancy above baseline

LCB = longitudinal center of buoyancy

LCF = longitudinal center of flotation referenced from midships

Volume = volume of displacement

W_{pil} = longitudinal moment of inertia of waterplane

W_{pit} = Transverse moment of inertia of waterplane

Y_{max} = beam at the waterline at the station of maximum area

Cfton = volume in cubic feet displaced by a ton of water

LBP = length between perpendiculars in feet

5.2.4   Longitudinal Strength (STRNGH).[23]

The STRNGH module performs calculations of load, shear, bending moment, and stress along the length of a ship in still water and with the ship in both hogging and sagging conditions on a trochoidal wave. A weight distribution curve of the ship is described by locating up to 41 weight curve segments, and specifying the weights and their longitudinal centers of gravity between successive segment endpoints. For each wave condition trochoidal wave ordinates are generated for every ship and appendage station. The ship is balanced on this wave and draft

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[23] Ship Hull Characteristic Program User's Manual, Version 4.20, March 2000.

and sectional area at 100 points along the length of the ship are printed. After finding the balanced volume and it's LCB from the bow to each aft weight curve segment boundary, buoyancy, shear and bending moments for each weight curve segment are calculated. A standard wave length equal to LBP and height equal to 1.1 * √(LBP) were utilized.   In this analysis, the STRNGH module was the primary module utilized to manipulate section weights.

6 Estimated Effect of Bending Moment on Determination of Limiting Displacement.

Utilizing the traditional method of determining the Limiting Displacement for Strength, as demonstrated in the example in the Introduction, results in the difference between the limiting displacement for strength of the NIMITZ class aircraft carrier and its full load displacement of approximately 11,000 long tons (LTONS). This traditional approach indicates that the hull is capable of sustaining only 11,000 LTONS of additional weight when distributed equally at each station. The estimates reported in this section show that, in fact, the NIMITZ class hull is potentially capable of sustaining a significantly greater weight than the traditional approach suggests without exceeding the Maximum Allowable Failure Bending Moment.

The process consists of the use of the Ship Hull Characteristics Program (SHCP) and the Ultimate Strength (ULTSTR) Hull Girder Collapse Program. A brief outline of the steps involved follows:

1. The baseline longitudinal bending moment is determined utilizing SHCP. This moment is indicated on following figures as the Full Load Displacement

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Moment and is used as the basis for comparison with other derived bending moments. This moment is due solely to the weight-buoyancy distribution of the ship and no additional point loads are applied. A comparison between the ULTSTR Failure and SHCP bending moments is provided in Figures 4 and 5. One may note that in the hogging condition, it appears that the baseline CVN 77 bending moment exceeds the 1st Failure Bending Moment capacity. Since the 1st Failure Bending Moment and Maximum Allowable Bending Moment curves are derived from ULTSTR outputs which are preliminary results and are subject to the interpretation of an operator, this does not necessarily indicate an immediate failure with applied loads.

CVN 77 Sagging Bending Moment

Bending Moment (foot-tons)

1000000
0
-1000000
-2000000
-3000000
-4000000
-5000000
-6000000
-7000000

Station

■ CVN77 baseline
—×— 1st Failure Bending Moment
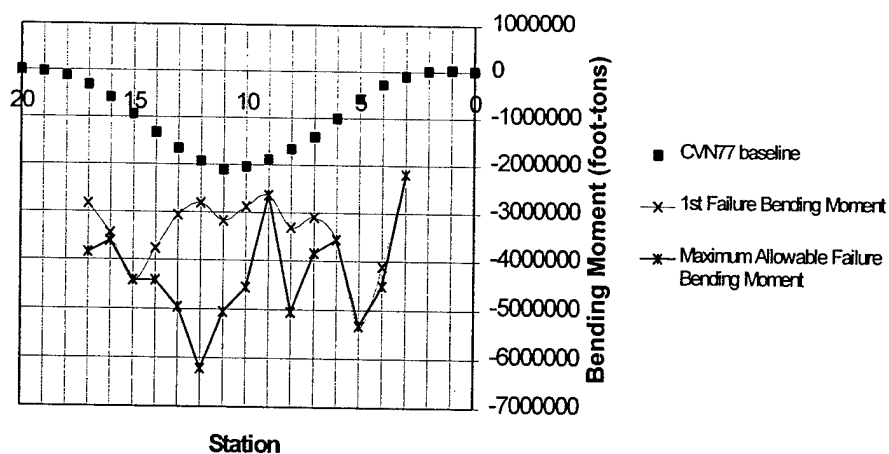—✳— Maximum Allowable Failure Bending Moment

Figure 4. CVN 77 Sagging Baseline Bending Moment Comparison.
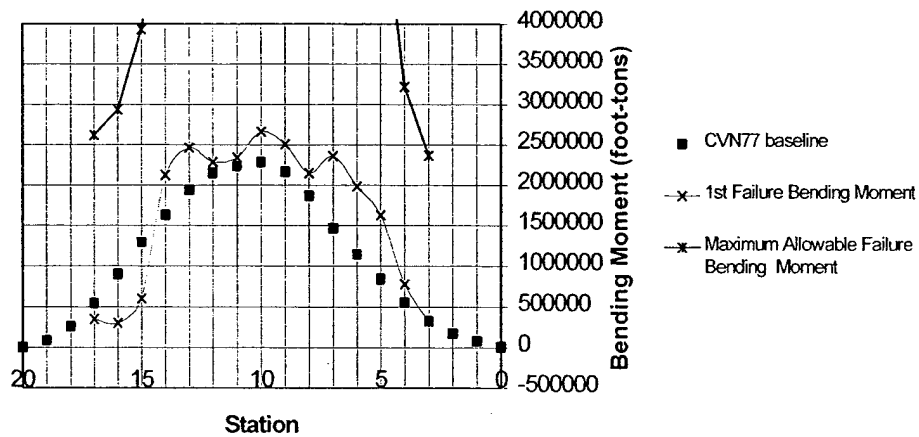
CVN 77 Hogging Bending Moment

Figure 5. CVN 77 Hogging Baseline Bending Moment Comparison.

2. The 1st Failure Bending Moment of the hull girder is calculated utilizing
   ULTSTR. This 1st Failure Bending Moment represents the first failure of an
   element on a specific section. It will occur at or below the Maximum
   Allowable Moment. In addition, the Maximum Allowable Bending Moment
   for hogging or sagging conditions is also calculated utilizing ULTSTR. This
   represents the point at which the value of the bending moment in the section
   causes the first combined plate and stiffener element, or gross panel, to fail by
   column buckling or tripping.

3. Weights, or loads, are added to various stations (iteratively) to determine
   revised maximum longitudinal bending moments for the hull due to the
   increased weight at a specific station. Weight additions are conducted by
   modifying the STRNGH module data input file utilized by SHCP.

4. A comparison is made between the first failure moments (from ULTSTR) and
   the revised maximum longitudinal bending moments (from SHCP).

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5. Finally, when these two moments are equal, the maximum weight capacity has been reached, and a revised limiting displacement can be determined.

Appendices A through H contain figures demonstrating the effect of various combinations of added weight. The process remains the same for all cases; therefore, only the case involving the addition of an 11,000 LTON point load will be discussed in this section. The 11,000 LTON weight has significance in that this weight determines the growth margin, from traditional methods, associated with the NIMITZ class aircraft carrier. A weight greater than this would make a ship of the NIMITZ class exceed it's limiting displacement for strength as calculated utilizing traditional methods. If this weight were distributed along the hull proportional to the design weight distribution curve, calculations show that there would essentially be no difference between the bending moment at limiting displacement and the bending moment at full load. Figures 6 and 7 show these results.
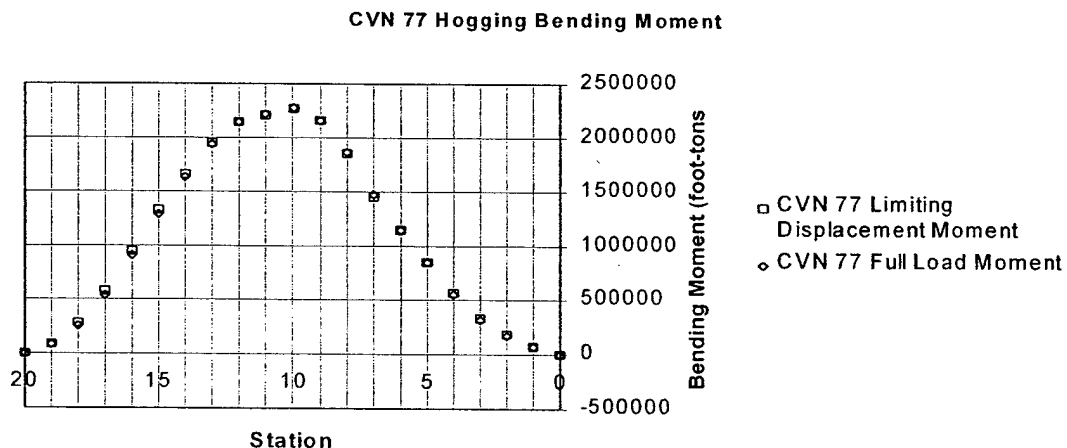
CVN 77 Hogging Bending Moment

Figure 6. CVN 77 Full Load and Limiting Displacement Hogging Bending Moment Comparison with 11,000 LTONS added proportional to full load weight distribution.
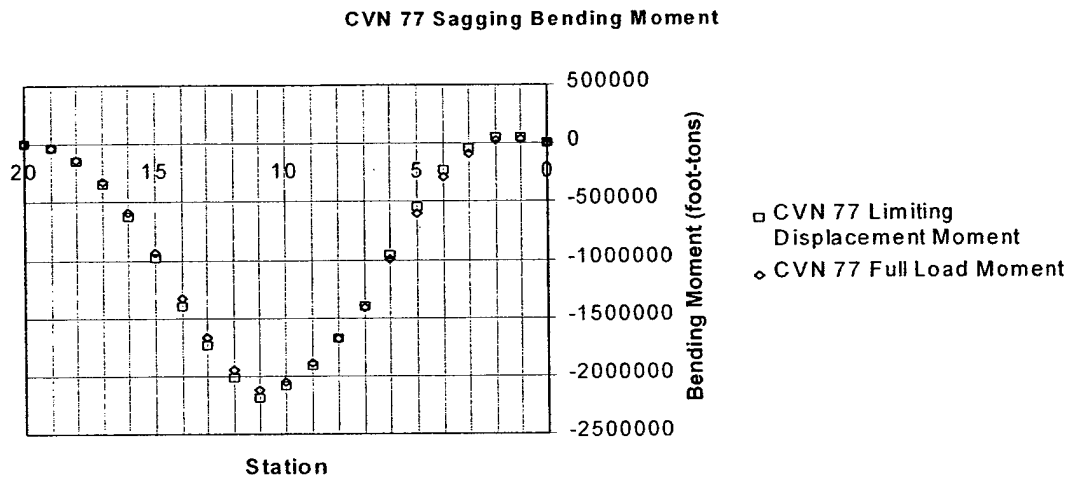
CVN 77 Sagging Bending Moment

Figure 7. CVN 77 Full Load and Limiting Displacement Sagging Bending Moment Comparison with 11,000 LTONS added proportional to full load weight distribution.

CVN 71 bending moment data is similar to the results presented in Figures 6 and 7. The CVN 77 hull includes a bulbous bow whereas the CVN 71 hull does not. The bulbous bow will have an impact on buoyancy; however, since added weight results in buoyancy change around the full load immersion, it is expected to have little impact on change in bending moment.

In this analysis, the weight is treated as a point load and is applied to each station from 0 to 20, sequentially. Refer to Figures 8 through 15 for a graphical representation of the effect on the hull girder bending moment of adding this point load.
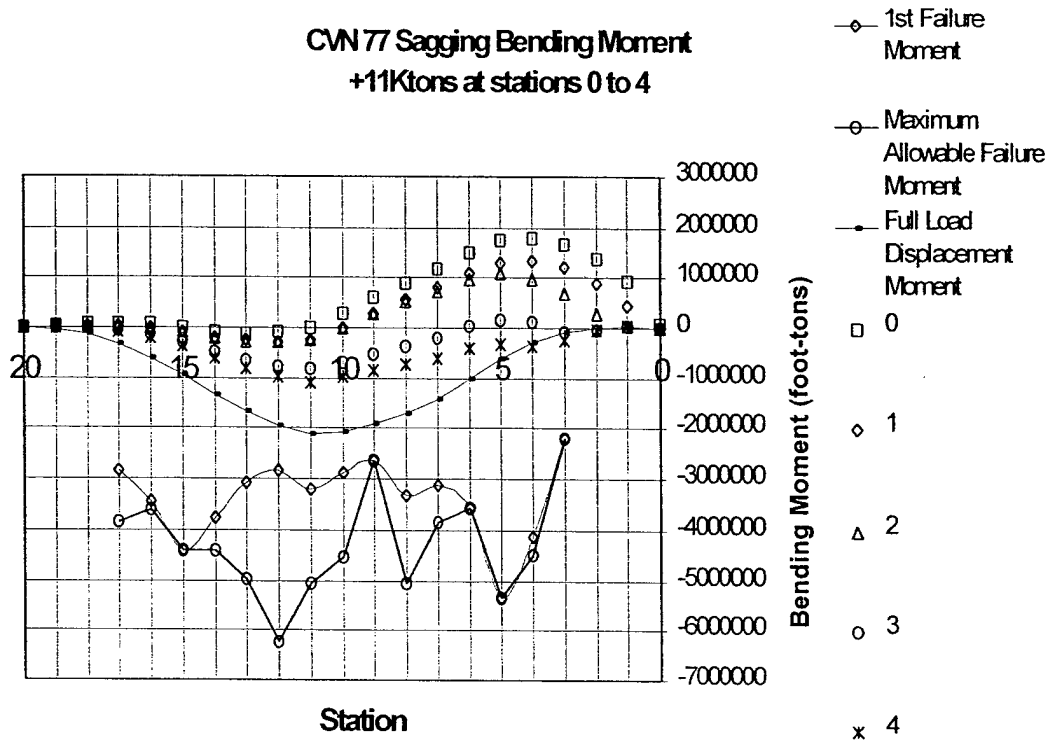
35

Figure 8. Sagging Bending Moment with 11,000 LTON point load applied at stations 0 to 4.

As can be noted in Figure 8, an addition of a point load of 11,000 tons at stations 0 through 4 can easily be accommodated by this hull form from the sagging perspective. Significant separation exists between the hull girder bending moments associated with the weight added at stations 0 through 4 and the 1st and Maximum Allowable Failure Moment curves in the sagging condition. This indicates that additional weight added to each station has minimal impact on the overall hull girder sagging bending moment. In fact, adding weight at certain stations can result in an improved bending moment curve, i.e. increasing the separation between the SHCP generated bending moment curve and the Maximum Allowable Failure Moment curve. Adding weight at the ends of the ship results in an increase of the hogging moments, and a decrease of the sagging moments.
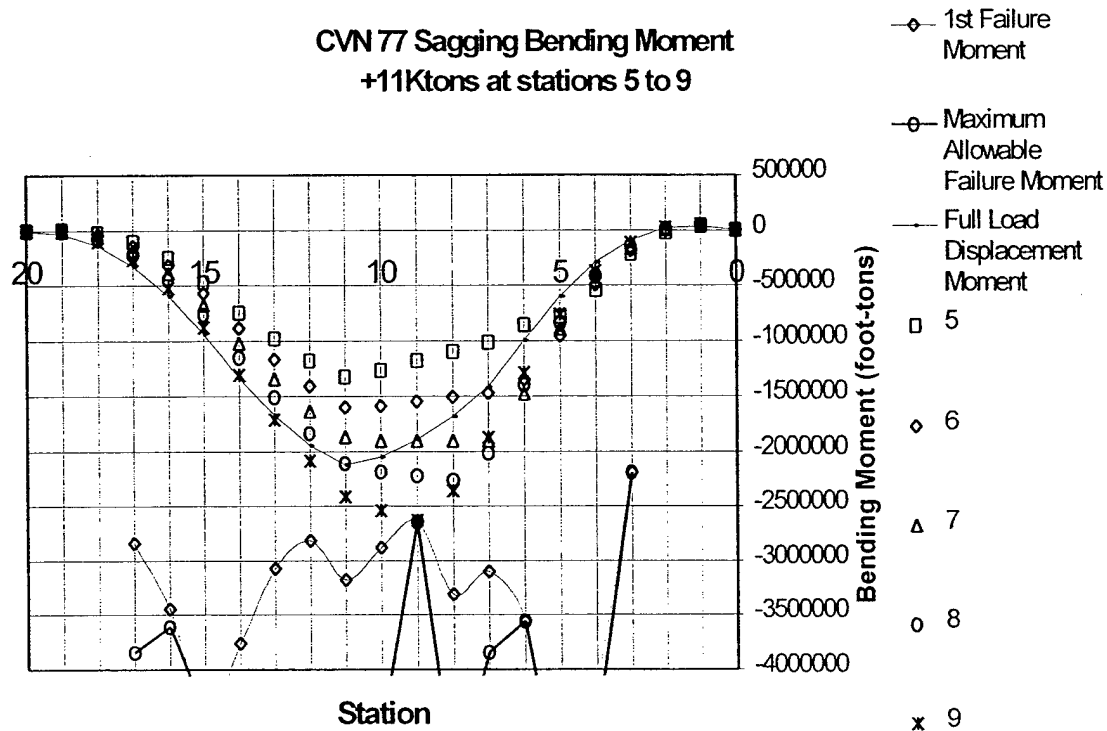
CVN 77 Sagging Bending Moment
+11Ktons at stations 5 to 9

Legend:
- —◇— 1st Failure Moment
- —○— Maximum Allowable Failure Moment
- —— Full Load Displacement Moment
- □ 5
- ◇ 6
- △ 7
- ○ 8
- × 9

Y-axis: Bending Moment (foot-tons)
X-axis: Station

Figure 9. Sagging Bending Moment with 11,000 LTON point load applied at stations 5 to 9.

As shown in Figure 9, a similar pattern is noted when adding an 11,000 LTON point load at stations 5 to 9. However, when the weight is added at station 9, the resulting bending moment at station 9 is equal to the 1st Failure Moment and Maximum Allowable Failure Moment. This indicates that some other form of failure has occurred at station 9. All other resulting bending moments fall within satisfactory limits. Again, this hull form demonstrates its capability to support an 11,000 LTON point load at all stations with the exception of station 9 being marginal.

**CVN 77 Sagging Bending Moment
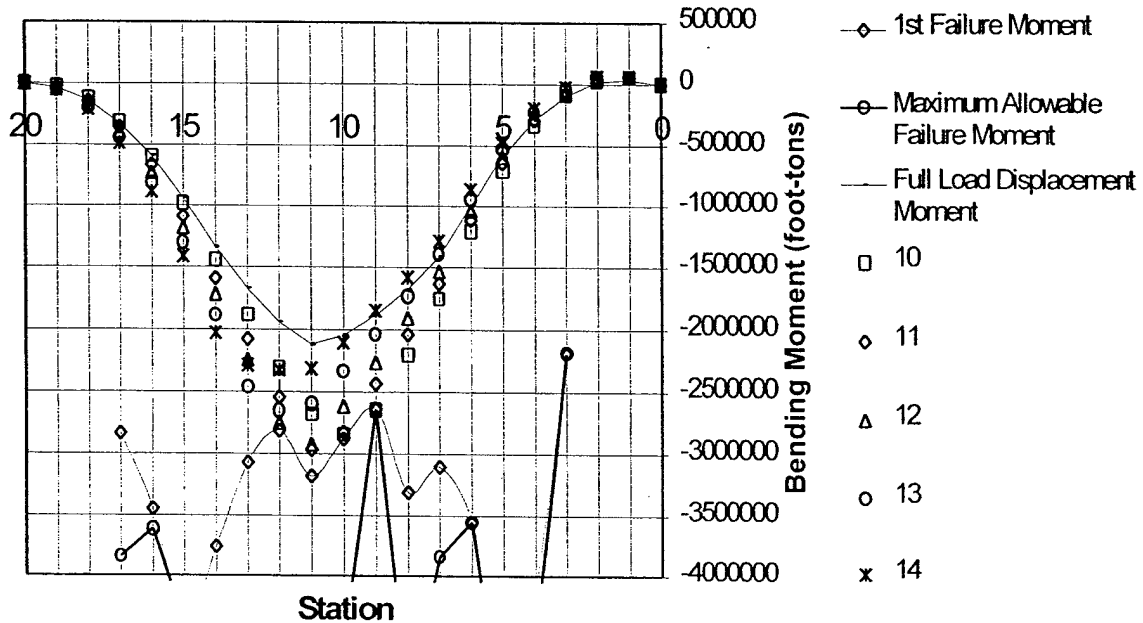+11Ktons at stations 10 to 14**

Legend:
- ─◇─ 1st Failure Moment
- ─○─ Maximum Allowable Failure Moment
- ──── Full Load Displacement Moment
- □ 10
- ◇ 11
- △ 12
- ○ 13
- × 14

Figure 10. Sagging Bending Moment with 11,000 LTON point load applied at stations 10 to 14.

Clearly, as shown in Figure 10, adding an 11,000 LTON point load at station 10 results in the hull girder bending moment matching the 1st Failure Moment at station 10. The 1st Failure Moment and Maximum Allowable Failure Moment are matched at station 9. Likewise, if the weight is added at station 12, then the bending moment at station 12 barely remains below the 1st Failure Moment for that station.

CVN 77 Sagging Bending Moment
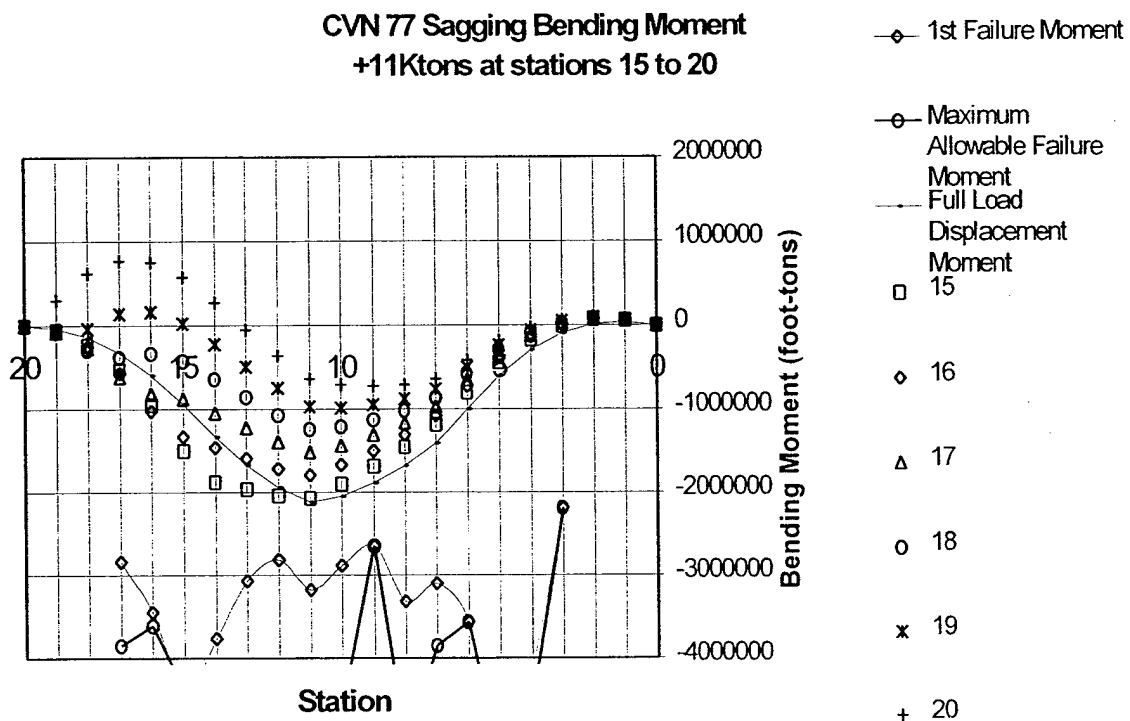## +11Ktons at stations 15 to 20

Figure 11. Sagging Bending Moment with an 11,000 LTON point load applied at stations 15 to 20.

Notably, in the sagging condition, the NIMITZ class hull can support adding this 11,000 LTON point weight at any station greater than station 10. At no sections do the revised bending moment curves approach the limits established by the 1st Failure and Maximum Allowable Failure Moment Curves. Refer to Figures 10 and 11.

Figures 12 through 15 show similar results for adding an 11,000 LTON point load to individual stations in the hogging condition. Figure 12 shows that if the point load is added at stations 0, 1, 2, or 3, it is possible that the hogging Maximum Allowable Failure Moment curve could be exceeded. Adding this point load to any other station results in a moment that is much less than the Maximum Allowable Failure Moment. One may note that the hogging 1st Failure Moment curve is almost immediately exceeded with any weight addition. Since this curve was derived from the preliminary ULTSTR results, it

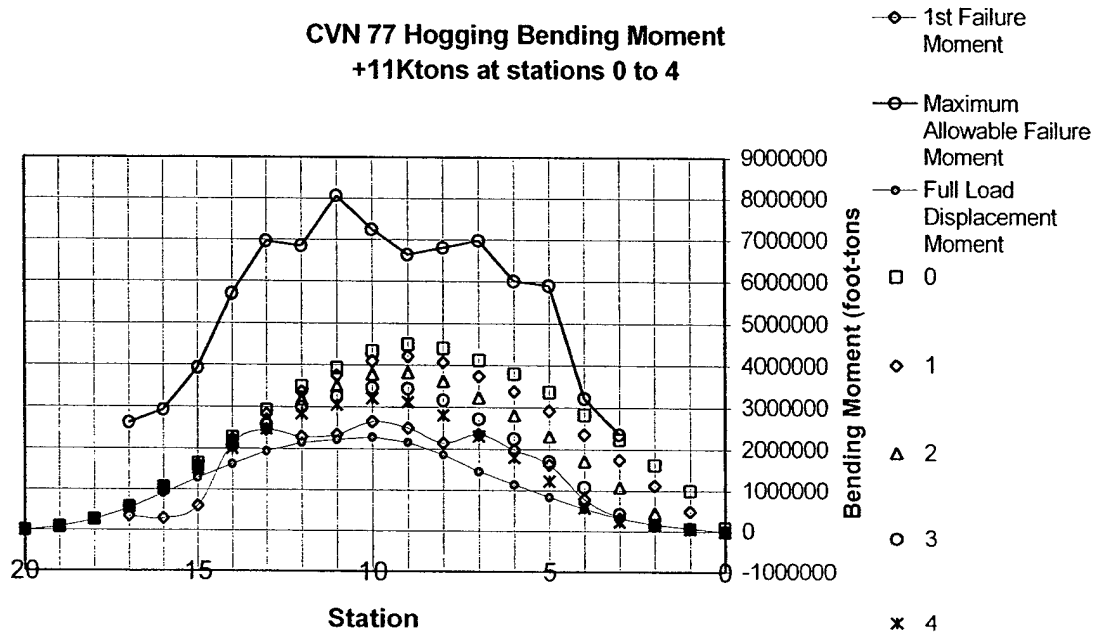could be refined and does not necessarily indicate an immediate failure with applied

loads.

Figure12. Hogging Bending Moment with 11,000 LTON point load applied at stations 0 to 4.
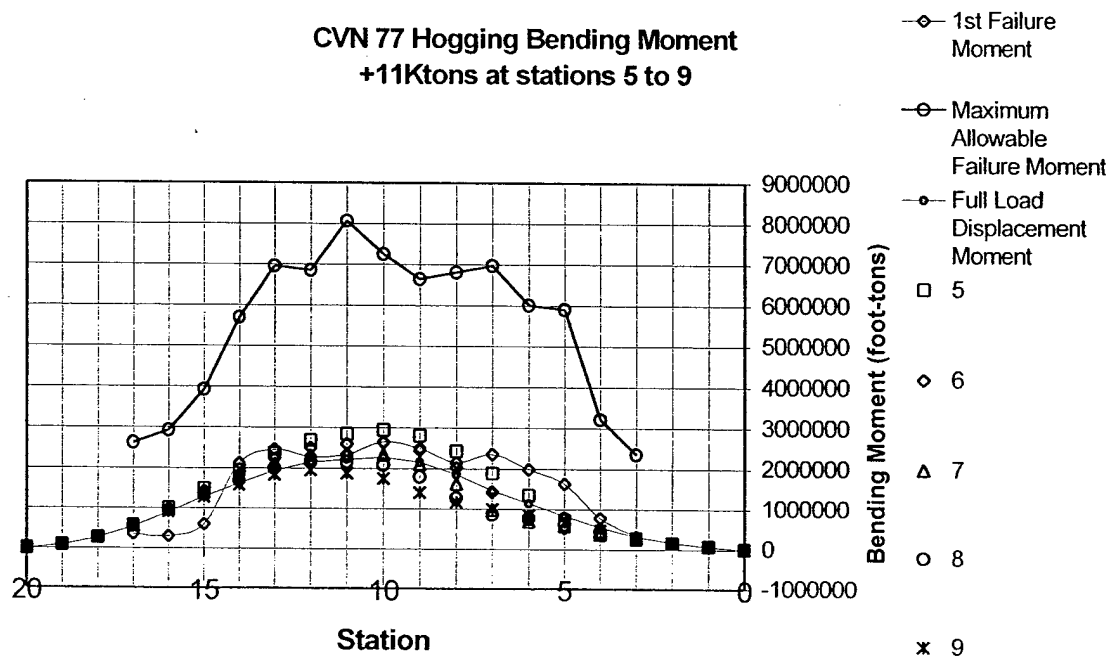
Figure 13. Hogging Bending Moment with 11,000 LTON point load applied at stations 5 to 9.

**CVN 77 Hogging Bending Moment
+11Ktons at stations 10 to 14**
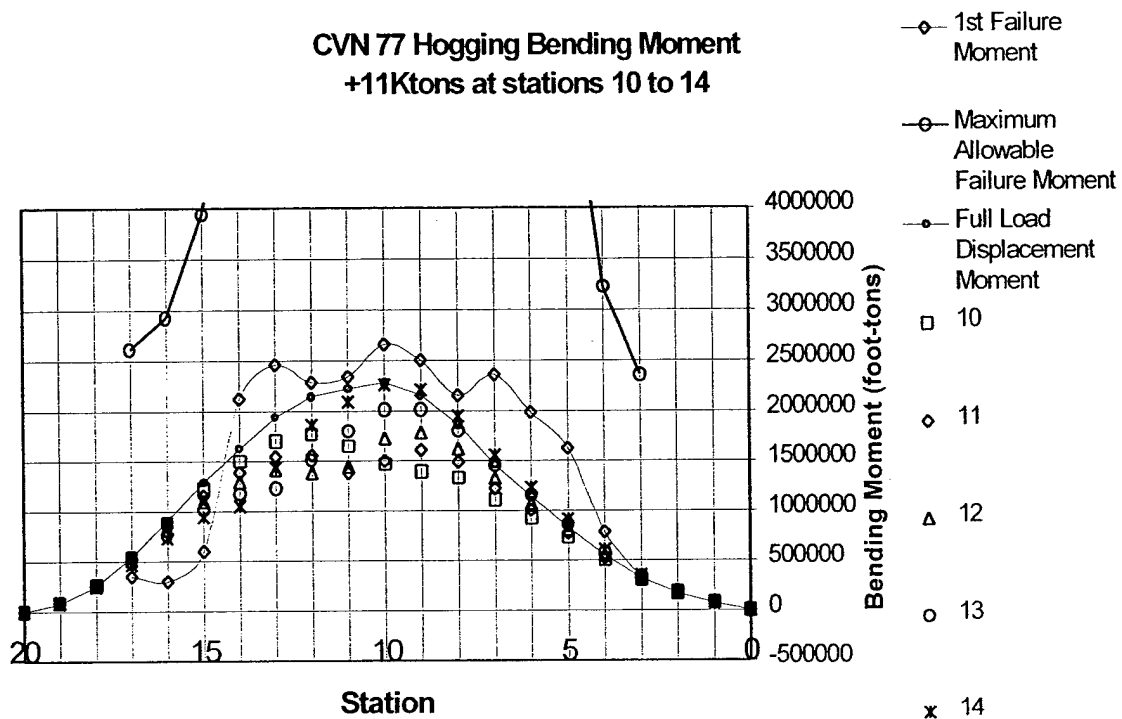
Figure 14. Hogging Bending Moment with 11,000 LTON point load applied at stations 10 to 14.

**CVN 77 Hogging Bending Moment
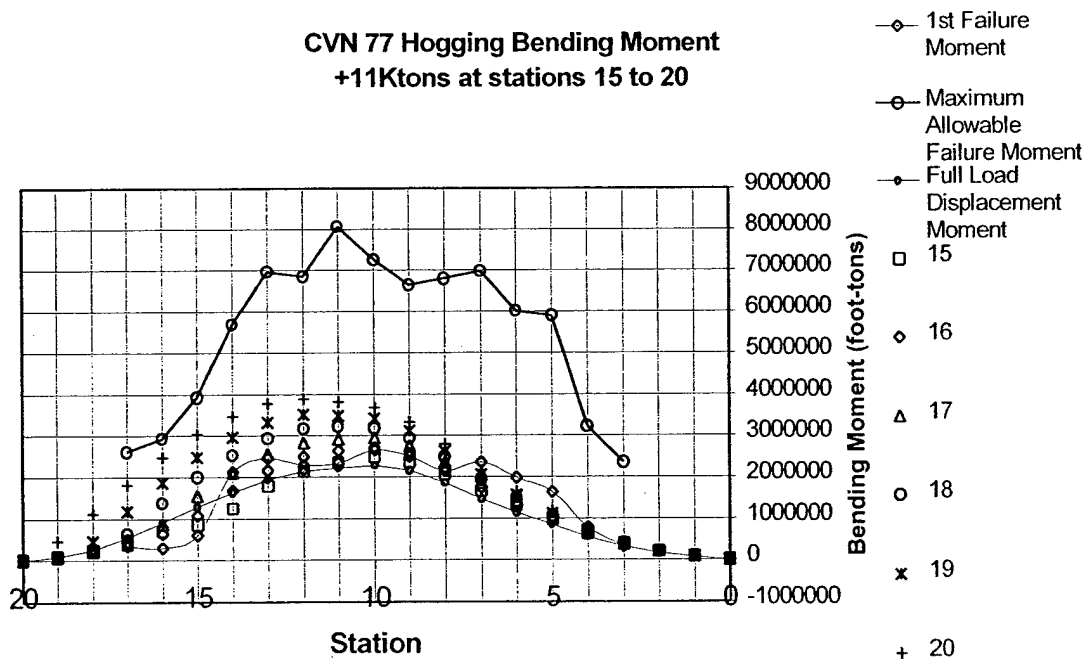+11Ktons at stations 15 to 20**

Figure 15. Hogging Bending Moment with 11,000 LTON point load applied at stations 15 to 20.

The analysis was conducted on two hull forms. The first analysis involved a bulbous bow hull form, CVN 77. The second analysis involved the traditional NIMITZ class non-bulbous bow, CVN 71. Section weights were similar for both hull forms; however, hull offsets were significantly different. Specific section weights and hull offsets were unique to each analyzed hull; therefore, the displayed hull girder bending moment curves are unique to each hull. The 1st Failure Moment and Maximum Allowable Bending Moment were derived from an analysis of the CVN 77 hull stations 3 through 17 using ULTSTR. The full load displacements of these two hulls are within 5 percent of each other. Since the degree of redundancy of the hull structures of CVN 77 and CVN71 is nearly exact, it is assumed that the results of the CVN 77 ULTSTR analysis also apply to CVN 71. Hence, the 1st Failure Moment and Maximum Allowable Bending Moment curves are also presented on the CVN 71 figures. The complete results of the analysis for CVN 77 are contained in Appendices A through D and for CVN 71 in Appendices E through H. One may note that no significant differences exist in the results of these analyses of the two hull forms under consideration. Each hull form was evaluated by adding point weights (i.e. 2,000; 10,000; 11,000; and 15,000 LTON) at each of 20 stations and obtaining a resulting bending moment for the hull after each weight addition. The results are provided in groups of 4 to 6 sections. Each curve represents the hull girder bending moment resulting from a point load applied at a single station. A synopsis of the analysis results for each applied point load is provided at the beginning of each Appendix.

7 Conclusions.

7.1 Specific Conclusions

All NIMITZ class aircraft carriers are quickly approaching their limiting displacement for strength (as calculated utilizing traditional methods). The traditional methods of calculating the limiting displacement results in a somewhat conservative value. A less conservative limiting displacement would provide a better measure of the estimated growth margin associated with the NIMITZ class aircraft carrier and could alleviate some of the concerns about aircraft carriers exceeding their limiting displacement. Several conclusions may be made:

1. The NIMITZ class aircraft carrier hull can accommodate more weight without exceeding maximum bending moment estimated by ULTSTR.

2. The ability to make a more detailed assessment using readily available tools exists.

3. The existence of the bulbous bow makes no difference in the analysis results.

7.1.1 Discussion of Conclusions

1. The process of determining limiting displacement for strength discussed herein shows that the NIMITZ class hull is potentially capable of sustaining additional weight which would exceed the currently established limiting displacement. When utilizing traditional means, the displacement growth allowed prior to exceeding limits is 11,000 LTON.

The current method assumes that the weight growth is distributed equally over the 20 stations. Under this premise, as shown in Figures 6 and 7, the hogging and sagging bending moments remain virtually unchanged. The effect of added weight on longitudinal strength is very dependent on the distribution and location of the added weight. Analysis results provided in the appendices indicate that as much as 15,000 LTON point loads could be applied at some locations without exceeding 1st Failure Bending Moment or Maximum Allowable Bending Moment curves while limits were exceeded at other locations. This indicates that the NIMITZ class hull has greater growth potential. Given that most new installations contribute on the order of hundreds to thousands of LTONS of additional weight and that the analysis results show that the NIMITZ class hull is capable of sustaining additions of a 15,000 LTON point load at most stations, it is unlikely that installations of individual systems will result in the Maximum Allowable Bending Moment being exceeded.

2. The process presented in this paper provides a means for determining whether a more detailed analysis must be conducted on a hull that is approaching its traditionally calculated limiting displacement. It is only as good as the weight data available for analysis. Section weights play an important role in determining whether established bending moment indicators will be exceeded or not. If the displacement of the ship is allowed to increase so that the resulting hull girder bending moment approaches the Maximum Allowable Bending Moment, then the resulting bending stresses will also increase. These increases in stress can have detrimental implications, particularly if the Ultimate Bending Moment of a section is exceeded. ULTSTR results are sensitive to the assumptions (load type, panel type, …) made in the preparation of the structural data, and the availability of pre- and post-processors is nonexistent. ULTSTR and SHCP are easily accessible and provide a

great capability in determining the longitudinal displacement for
strength.

3. The effect of added weight on the bending moment curves of the two
    hull forms discussed in the previous sections can be readily observed.
    The fact that the CVN 77 hull includes a bulbous bow has no effect on
    the results. If one compares the results of the analysis of the CVN 77
    and CVN 71 hulls (with and without the bulbous bow, respectively), it
    may be observed that the results are nearly exact.

In the past, ship classes such as CV-41, CV-66, and FFG's have approached their
limiting displacement for strength when analyzed using the traditional method.
Additional structural detail analysis corroborated the need for additional strengthening as
the displacement increased. The present method of determining limiting displacement for
strength has been useful as a flag to conduct further structural analysis. The method,
previously discussed, provides a viable means of determining a refined limiting
displacement for strength.

7.2 Recommendations.

Although the process of determining limiting displacement for strength presented
here is viable, there are several things that could be done to improve its accuracy. It is
recommended that:

1. A Weight Management Program be established as the single source for
    maintaining the location of weight additions and deletions. This
    analysis is based upon original (as commissioned) full load weight
    distribution. The accuracy of this method could be improved by

utilizing actual section weights which requires that the exact location of weight changes be known.

2. A standard procedure be devised in order to interpret the results of the ULTSTR analysis. Development of a Pre- and Post-Processor is essential to improving ease of use.

3. Additional studies be conducted to determine the exact effect on other limiting displacements of adding large weights. Although this analysis was primarily concerned with the limiting displacement for strength, there are in fact numerous other limiting displacements that require consideration. Over the years some of the limits have changed; however, the limiting displacement for strength has remained unchanged since the design of CVN 68. Limiting displacement and draft limits are also based upon requirements derived from:

> Intact or Damaged Stability
> Speed Requirements
> Side Protection System Immersion
> Nuclear Propulsion
> Hull Strength
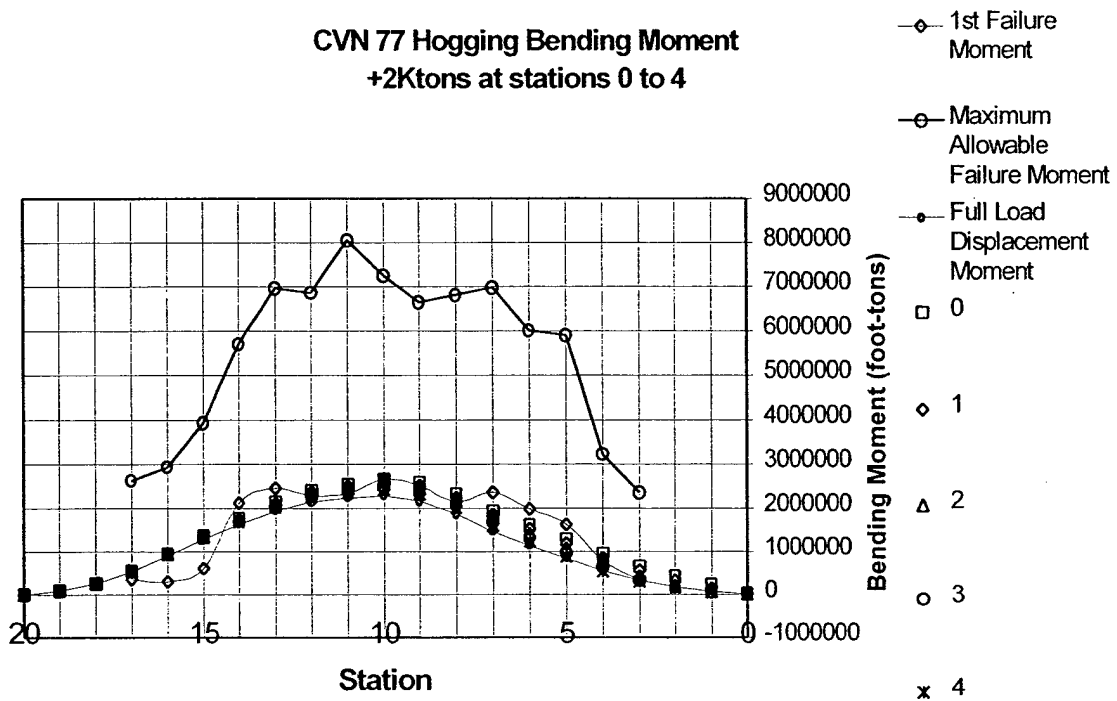> Reserve Buoyancy
> Propeller Immersion, and
> Trim Limits

Although this analysis demonstrates that the CVN 68 hull is capable of supporting an additional increase in weight, it does not consider the effects of these weight additions on the requirements associated with those factors listed above.
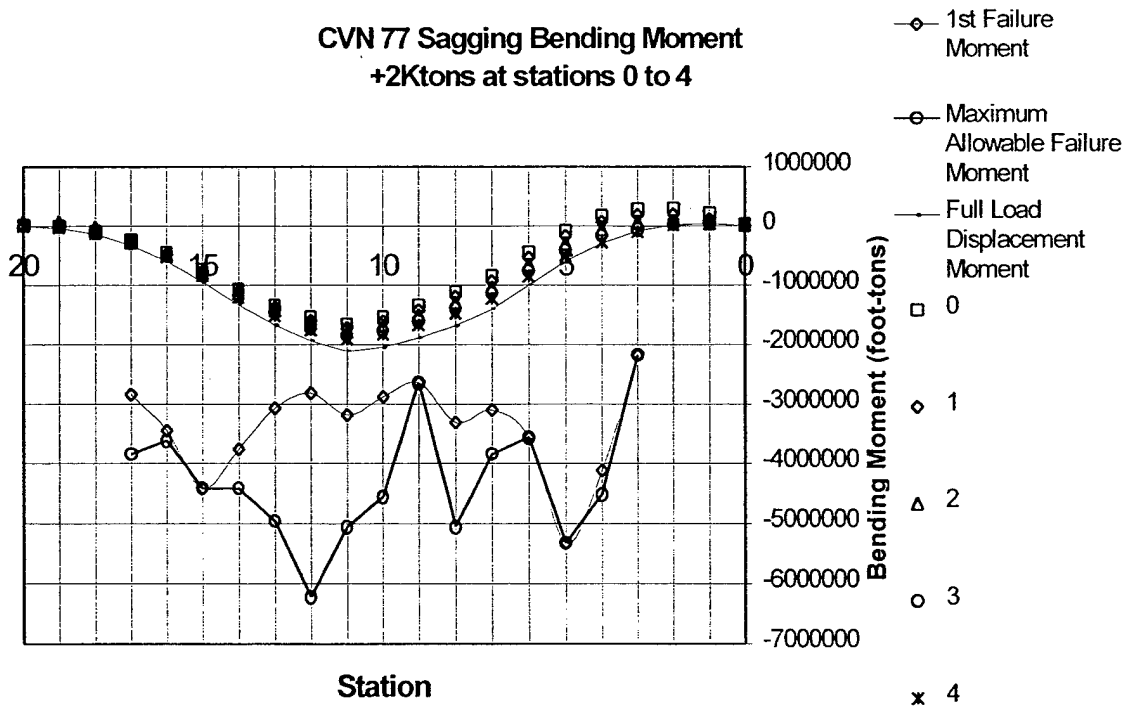
APPENDIX A:

CVN 77 HULL WITH 2,000 LONG TONS APPLIED AT EACH STATION

The figures in Appendix A show the resulting bending moments when a 2,000 LTON point load is applied at each station. Clearly, the bending moment capacity of the hull will not be exceeded when a 2,000 LTON point load is applied at any station.

CVN 77 Hogging Bending Moment
+2Ktons at stations 0 to 4

Bending Moment (foot-tons)

Station

Legend:
- —◇— 1st Failure Moment
- —○— Maximum Allowable Failure Moment
- —●— Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- ✕ 4

CVN 77 Sagging Bending Moment
+2Ktons at stations 0 to 4

Bending Moment (foot-tons)

Station

Legend:
- —◇— 1st Failure Moment
- —○— Maximum Allowable Failure Moment
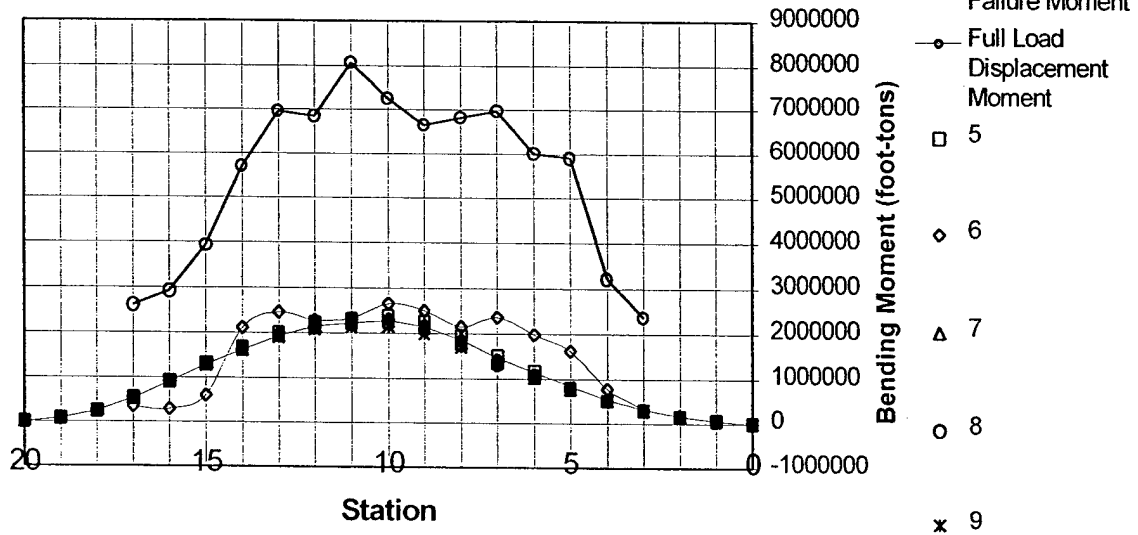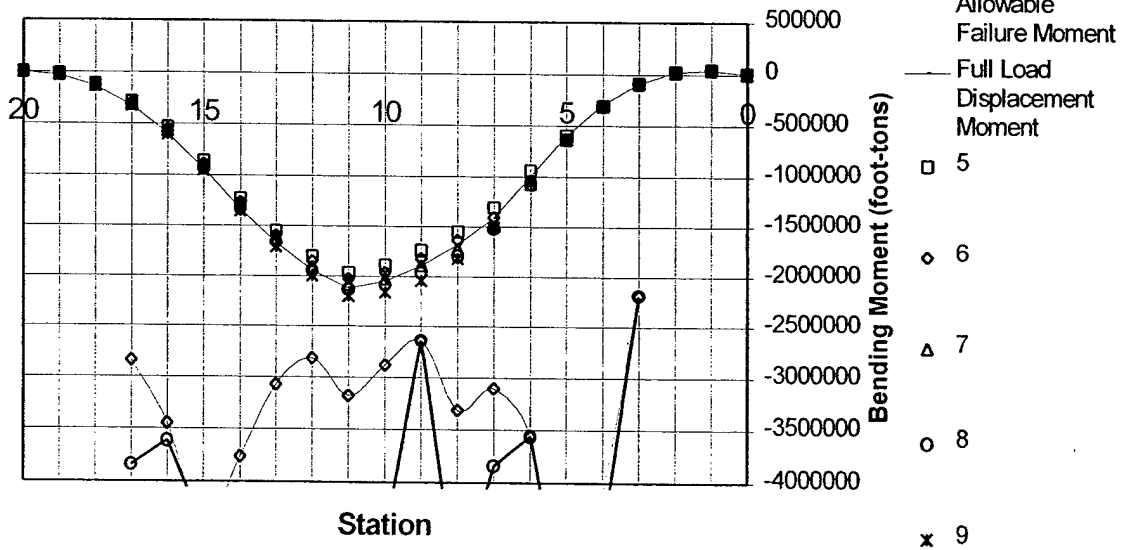- —●— Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- ✕ 4

CVN 77 Hogging Bending Moment
+2Ktons at stations 5 to 9

CVN 77 Sagging Bending Moment
+2Ktons at stations 5 to 9

CVN 77 Hogging Bending Moment
+2Ktons at stations 10 to 14

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 10
- ◇ 11
- △ 12
- ○ 13
- ✕ 14

Y-axis: Bending Moment (foot-tons)
X-axis: Station

CVN 77 Sagging Bending Moment
+2Ktons at stations 10 to 14

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 10
- ◇ 11
- △ 12
- ○ 13
- ✕ 14

Y-axis: Bending Moment (foot-tons)
X-axis: Station

CVN 77 Hogging Bending Moment
+2Ktons at stations 15 to 20

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 15
- ◇ 16
- △ 17
- ○ 18
- x 19
- + 20
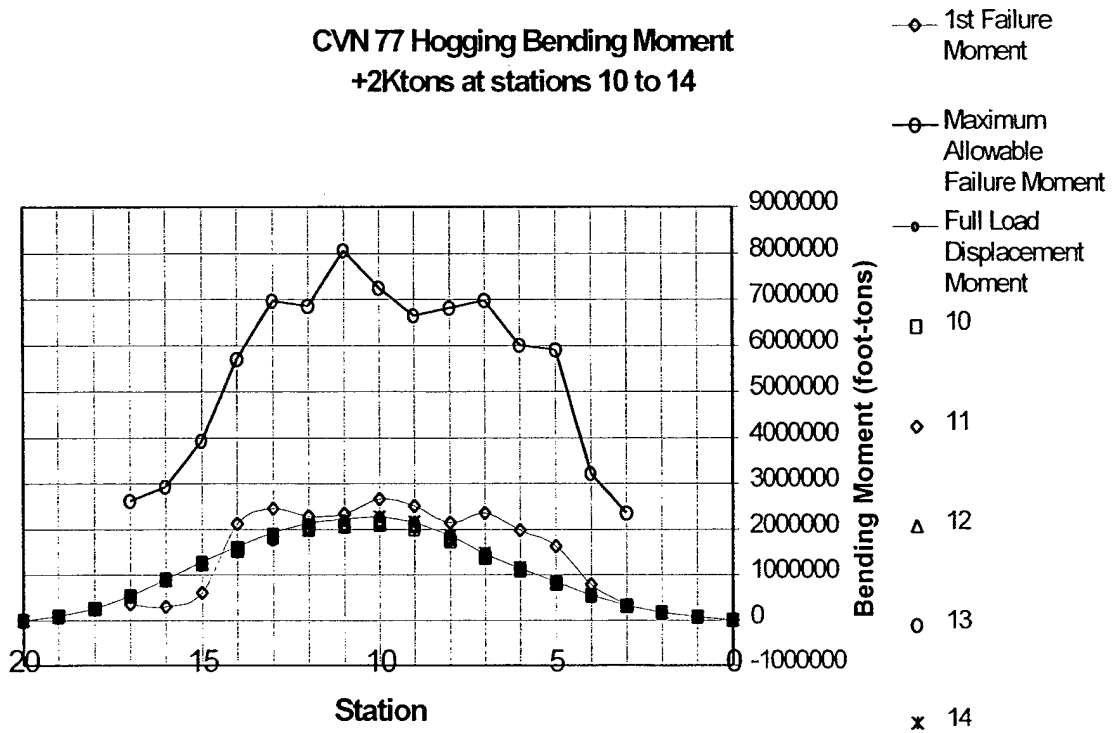
CVN 77 Sagging Bending Moment
+2Ktons at stations 15 to 20
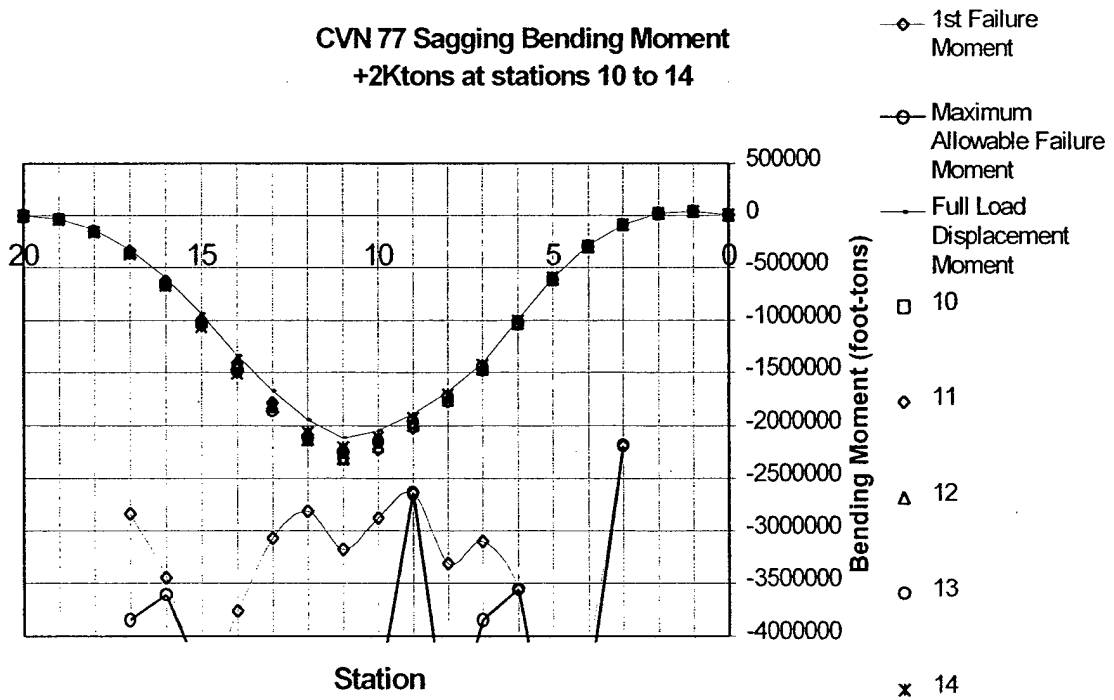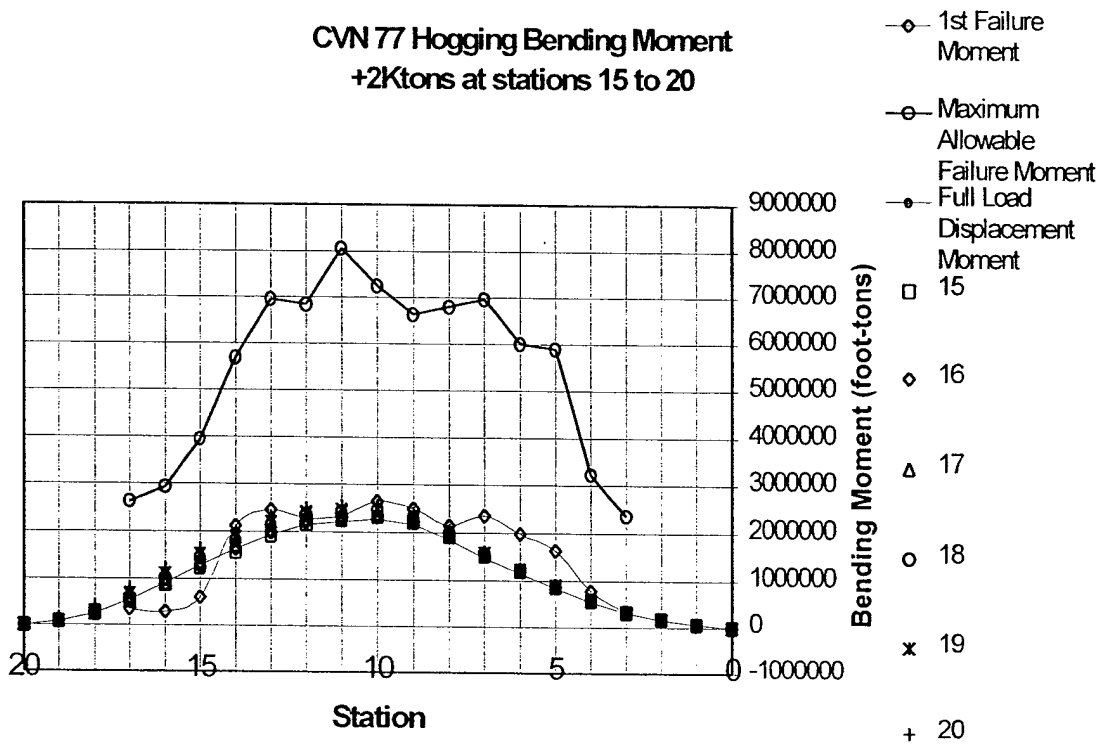
Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 15
- ◇ 16
- △ 17
- ○ 18
- x 19
- + 20
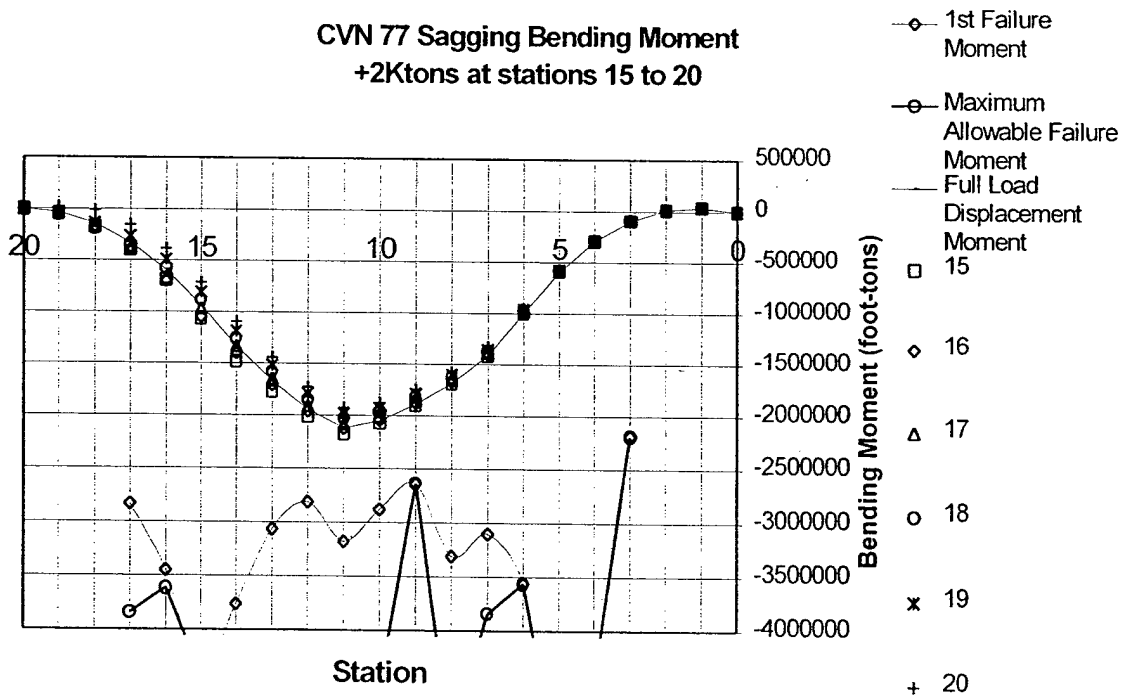
APPENDIX B:

CVN 77 HULL WITH 10,000 LONG TONS APPLIED AT EACH STATION

The figures in Appendix B show the resulting bending moments when a 10,000 LTON point load is applied at each station. Stations 0 through 4 are capable of sustaining a 10,000 LTON 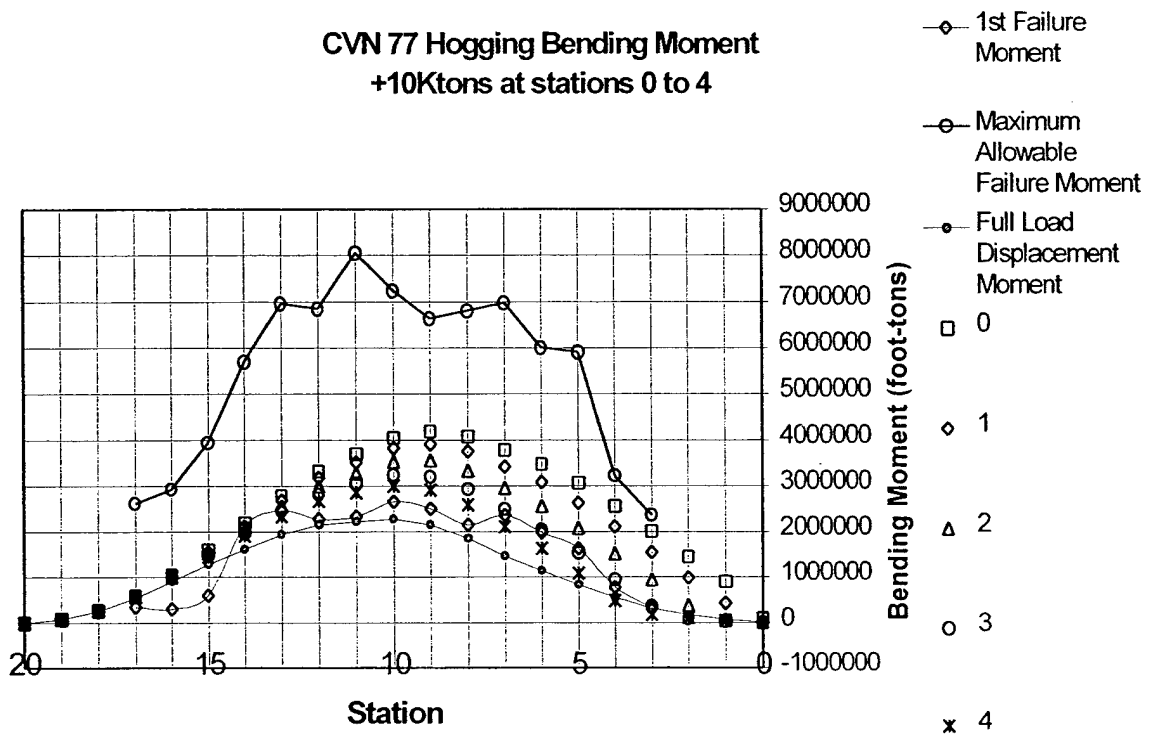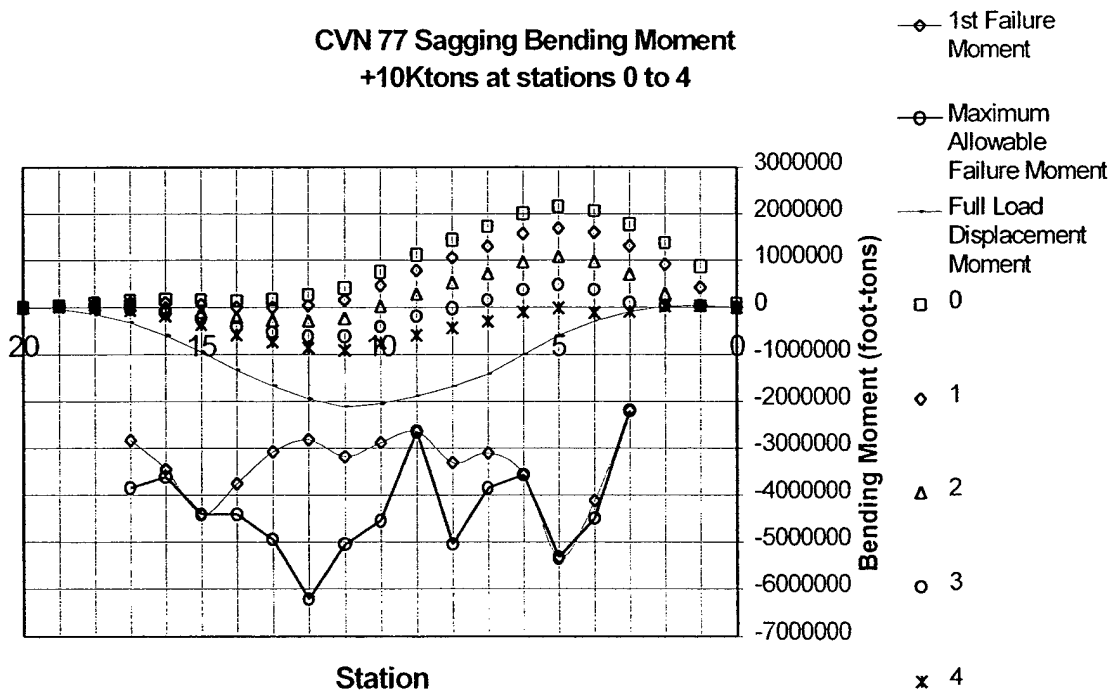point load in the sagging condition. Note that if the load is applied at station 1 or 2, the potential exists that the Maximum Allowable Failure Moment curve in the hogging condition may be exceeded. If the point load is applied at stations 9 or 10 in the sagging condition, then the ship bending moment will intersect the Maximum Allowable Failure Moment and 1st Failure Moment curve at station 9. This indicates the potential for failure at station 9 with this applied load. All other stations are capable of sustaining a 10,000 LTON point load without exceeding the Maximum Allowable Failure Moment curve.

CVN 77 Hogging Bending Moment
+10Ktons at stations 0 to 4

Legend:
- ——◇—— 1st Failure Moment
- ——⊖—— Maximum Allowable Failure Moment
- ——•—— Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- ✕ 4

Y-axis: Bending Moment (foot-tons)
X-axis: Station

CVN 77 Sagging Bending Moment
+10Ktons at stations 0 to 4

Legend:
- ——◇—— 1st Failure Moment
- ——⊖—— Maximum Allowable Failure Moment
- ——— Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- ✕ 4

Y-axis: Bending Moment (foot-tons)
X-axis: Station

CVN 77 Hogging Bending Moment
+10Ktons at stations 5 to 9

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 5
- ◇ 6
- △ 7
- ○ 8
- ✕ 9

Station

Bending Moment (foot-tons)

CVN 77 Sagging Bending Moment
+10Ktons at stations 5 to 9

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 5
- ◇ 6
- △ 7
- ○ 8
- ✕ 9

Station

Bending Moment (foot-tons)

CVN 77 Hogging Bending Moment
+10Ktons at stations 10 to 14

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 10
- ◇ 11
- △ 12
- ○ 13
- x 14

Y-axis: Bending Moment (foot-tons) — 9000000, 8000000, 7000000, 6000000, 5000000, 4000000, 3000000, 2000000, 1000000, 0, -1000000

X-axis: Station — 20, 15, 10, 5, 0

CVN 77 Sagging Bending Moment
+10Ktons at stations 10 to 14

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 10
- ◇ 11
- △ 12
- ○ 13
- x 14

Y-axis: Bending Moment (foot-tons) — 500000, 0, -500000, -1000000, -1500000, -2000000, -2500000, -3000000, -3500000, -4000000

X-axis: Station — 20, 15, 10, 5, 0

57

CVN 77 Hogging Bending Moment
+10Ktons at stations 15 to 20

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 15
- ◇ 16
- △ 17
- ○ 18
- x 19
- + 20

CVN 77 Sagging Bending Moment
+10Ktons at stations 15 to 20

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
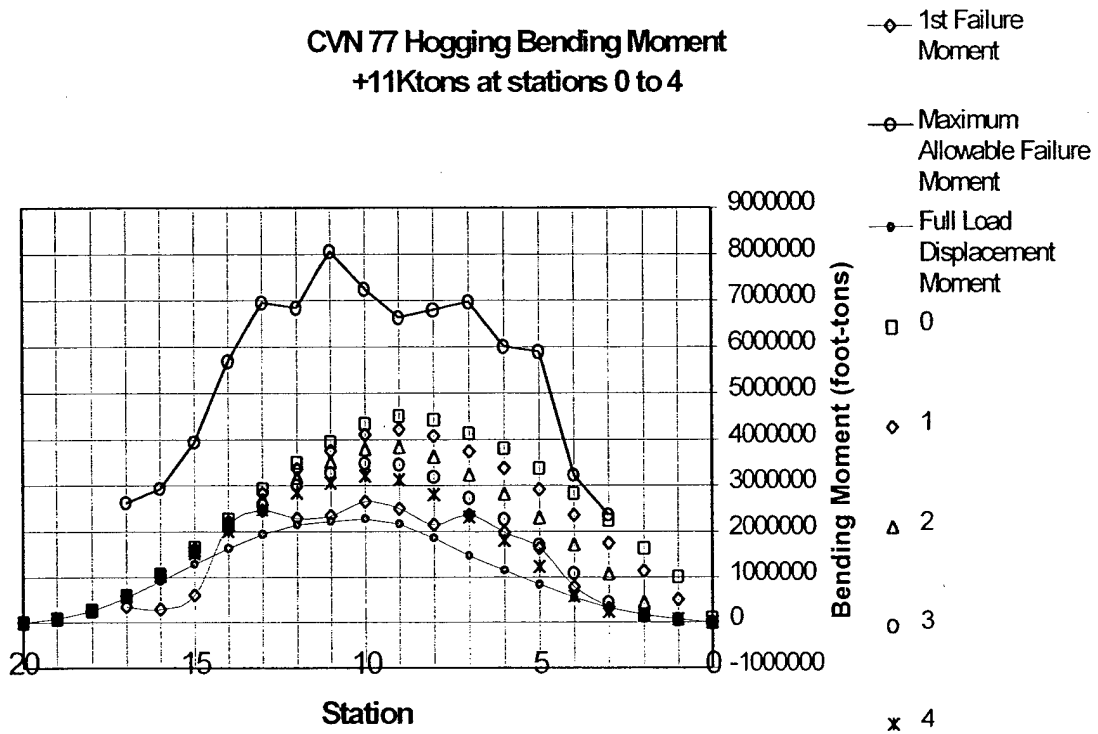- □ 15
- ◇ 16
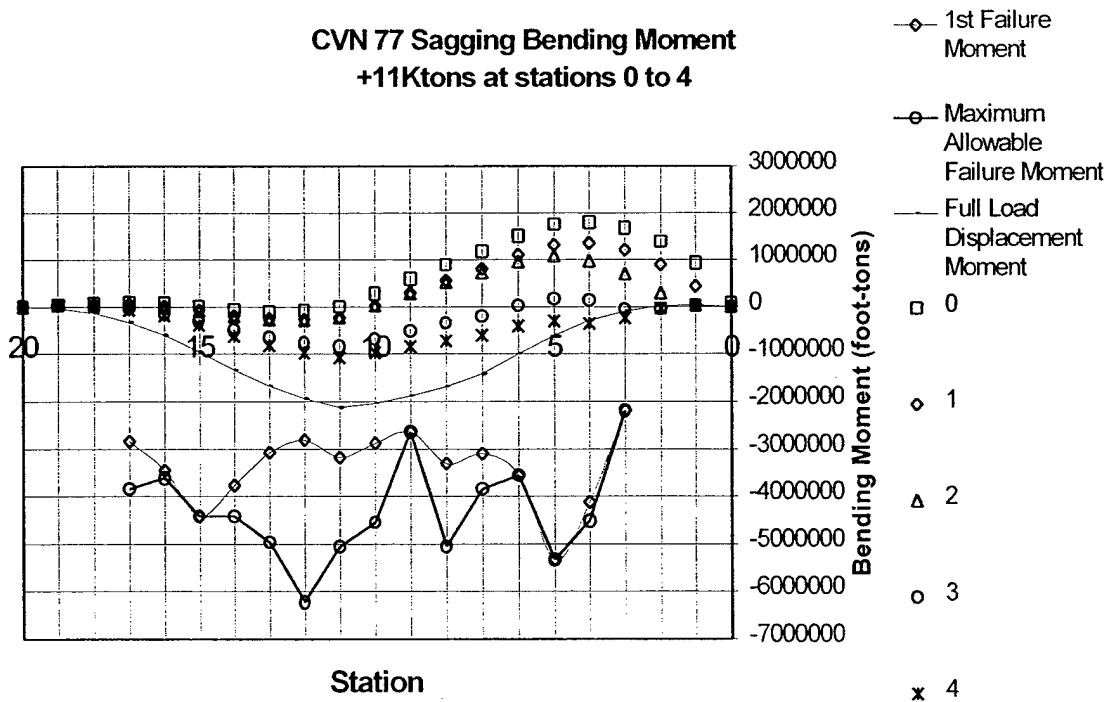- △ 17
- ○ 18
- x 19
- + 20

APPENDIX C:

CVN 77 HULL WITH 11,000 LONG TONS APPLIED AT EACH STATION

The figures in Appendix C show the resulting bending moments when a 11,000 LTON point load is applied at each station. The potential exists that the Maximum Allowable Failure Moment curve in the hogging condition may be exceeded if the point load is applied at stations 0 through 3. Additional comments are provided in Chapter 6.
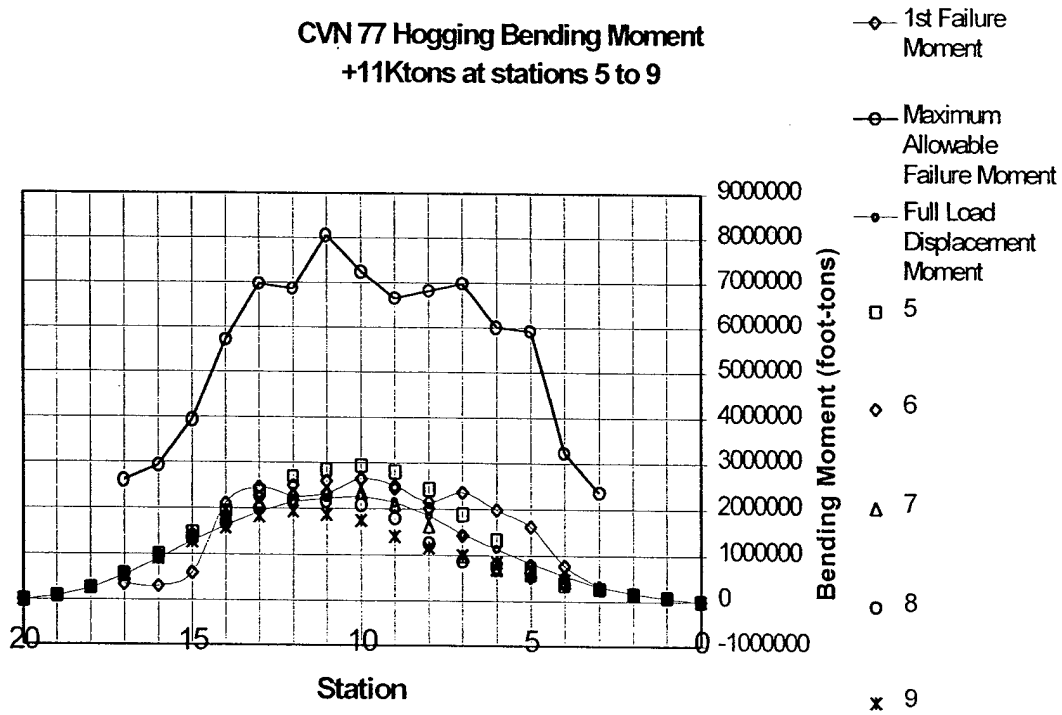
CVN 77 Hogging Bending Moment
+11Ktons at stations 0 to 4

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- ✕ 4

Station

CVN 77 Sagging Bending Moment
+11Ktons at stations 0 to 4

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- ✕ 4

Station

61

CVN 77 Hogging Bending Moment
+11Ktons at stations 5 to 9

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 5
- ◇ 6
- △ 7
- ○ 8
- ✕ 9

Y-axis: Bending Moment (foot-tons)
X-axis: Station

CVN 77 Sagging Bending Moment
+11Ktons at stations 5 to 9

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 5
- ◇ 6
- △ 7
- ○ 8
- ✕ 9

Y-axis: Bending Moment (foot-tons)
X-axis: Station

CVN 77 Hogging Bending Moment
+11Ktons at stations 10 to 14

Statio

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 10
- ◇ 11
- △ 12
- ○ 13
- ✕ 14

Y-axis: Bending Moment (foot-tons)

CVN 77 Sagging Bending Moment
+11Ktons at stations 10 to 14

Station

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 10
- ◇ 11
- △ 12
- ○ 13
- ✕ 14

Y-axis: Bending Moment (foot-tons)

CVN 77 Hogging Bending Moment
+11Ktons at stations 15 to 20

Bending Moment (foot-tons)

Station

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 15
- ◇ 16
- △ 17
- ○ 18
- ✕ 19
- + 20

CVN 77 Sagging Bending Moment
+11Ktons at stations 15 to 20

Bending Moment (foot-tons)

Station

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 15
- ◇ 16
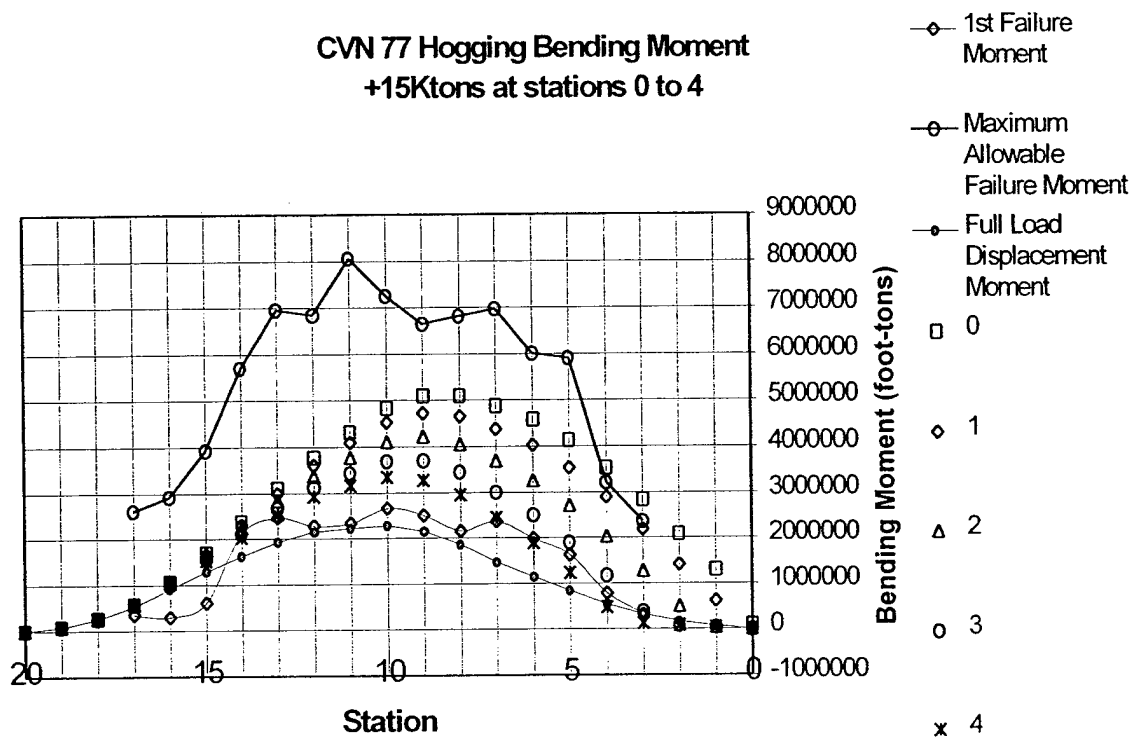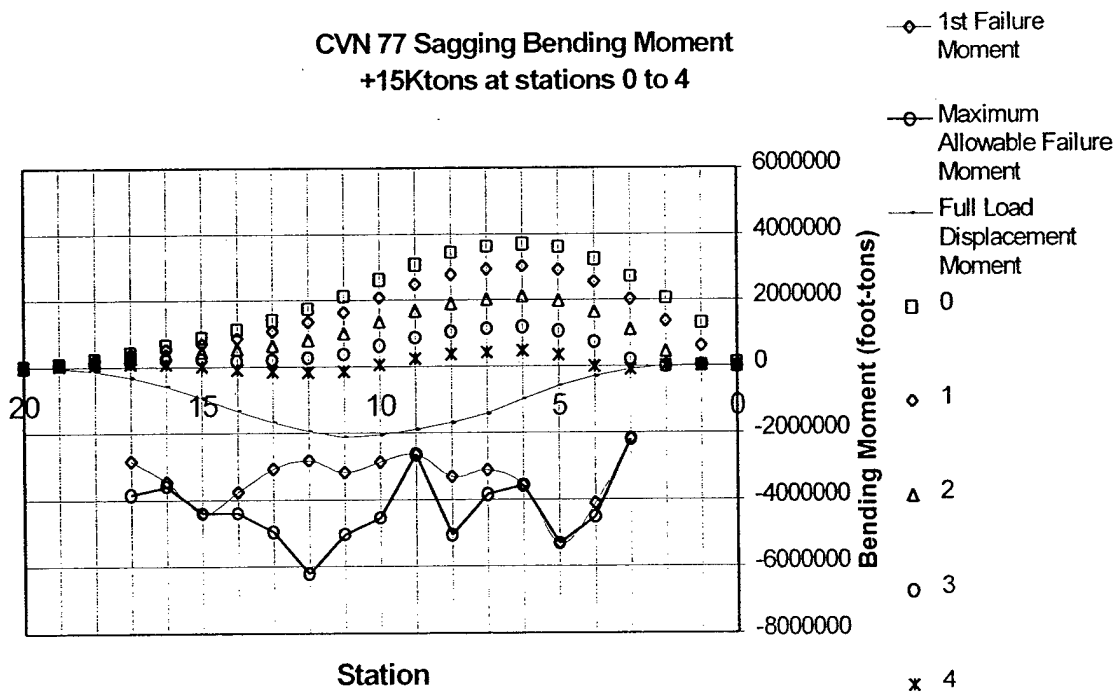- △ 17
- ○ 18
- ✕ 19
- + 20

APPENDIX D:

CVN 77 HULL WITH 15,000 LONG TONS APPLIED AT EACH STATION

The figures in Appendix D show the resulting bending moments when a 15,000 LTON point load is applied at each station. The first instance where the Maximum Allowable Failure Moment curve in the hogging condition was exceeded occurred with the application of a 15,000 LTON point load at stations 0 through 4. This is a clear indication that detailed analysis should be conducted when considering the addition of a weight of this size far forward in the ship. It is clearly indicated that adding this load at stations 10, 11, or 12 in the sagging condition requires additional analyses since the Maximum Allowable Failure Moment curve is clearly exceeded. If the load is applied at station 16 in the hogging condition, then there exists the potential that the Maximum Allowable Failure Moment curve could be exceeded indicating potential failure.
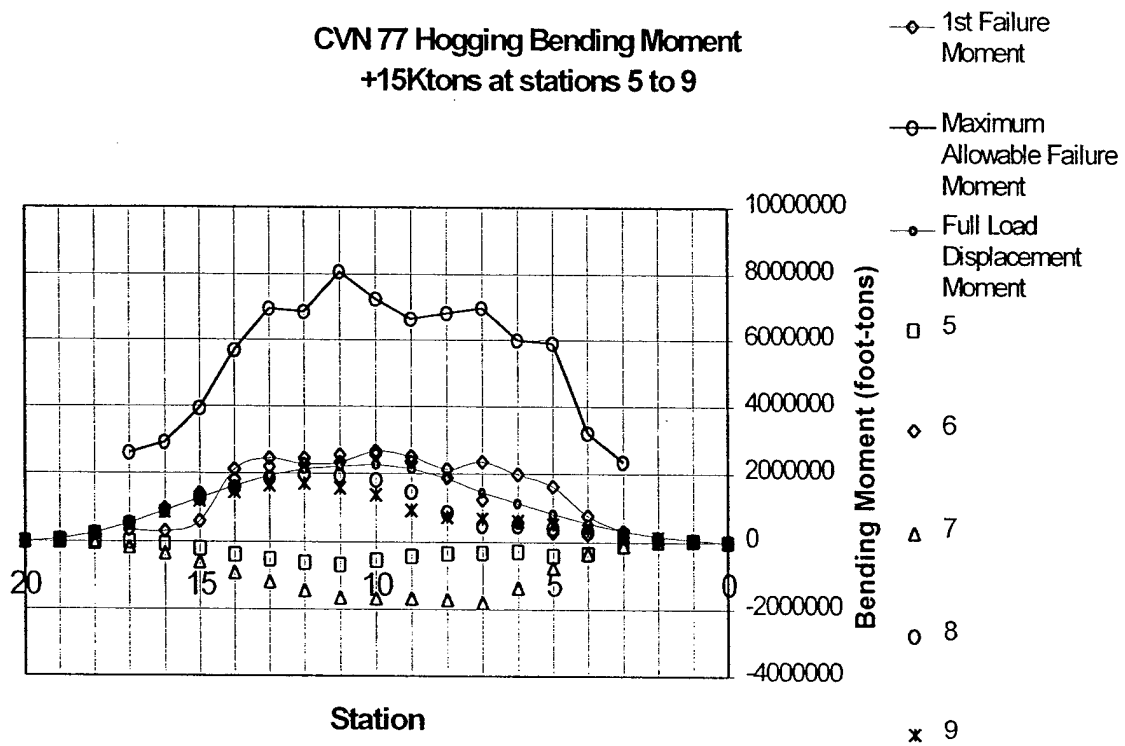
CVN 77 Hogging Bending Moment
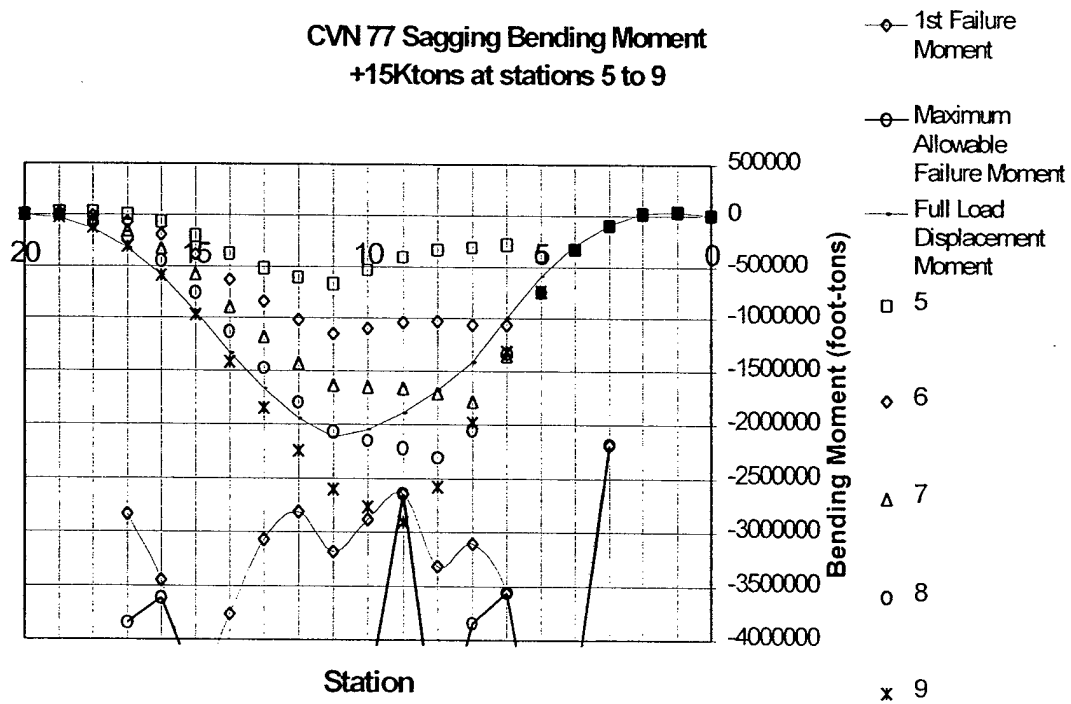+15Ktons at stations 0 to 4

Bending Moment (foot-tons)

Station

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- ✕ 4

CVN 77 Sagging Bending Moment
+15Ktons at stations 0 to 4

Bending Moment (foot-tons)

Station

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- ✕ 4

CVN 77 Hogging Bending Moment
+15Ktons at stations 5 to 9

1st Failure Moment

Maximum Allowable Failure Moment

Full Load Displacement Moment

□ 5

◇ 6

△ 7

○ 8

✕ 9

CVN 77 Sagging Bending Moment
+15Ktons at stations 5 to 9

1st Failure Moment

Maximum Allowable Failure Moment

Full Load Displacement Moment

□ 5

◇ 6

△ 7

○ 8

✕ 9

68

CVN 77 Hogging Bending Moment
+15Ktons at stations 10 to 14

Legend:
- ◇ 1st Failure Moment
- ⊖ Maximum Allowable Failure Moment
- ⊙ Full Load Displacement Moment
- ▫ 10
- ◇ 11
- △ 12
- ○ 13
- ✕ 14

CVN 77 Sagging Bending Moment
+15Ktons at stations 10 to 14

Legend:
- ◇ 1st Failure Moment
- ⊖ Maximum Allowable Failure Moment
- Full Load Displacement Moment
- ▫ 10
- ◇ 11
- △ 12
- ○ 13
- ✕ 14

69

CVN 77 Hogging Bending Moment
+15Ktons at stations 15 to 20

Statio

Bending Moment (foot-tons)

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 15
- ◇ 16
- △ 17
- ○ 18
- ✕ 19
- + 20

CVN 77 Sagging Bending Moment
+15Ktons at stations 15 to 20

Station

Bending Moment (foot-tons)

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
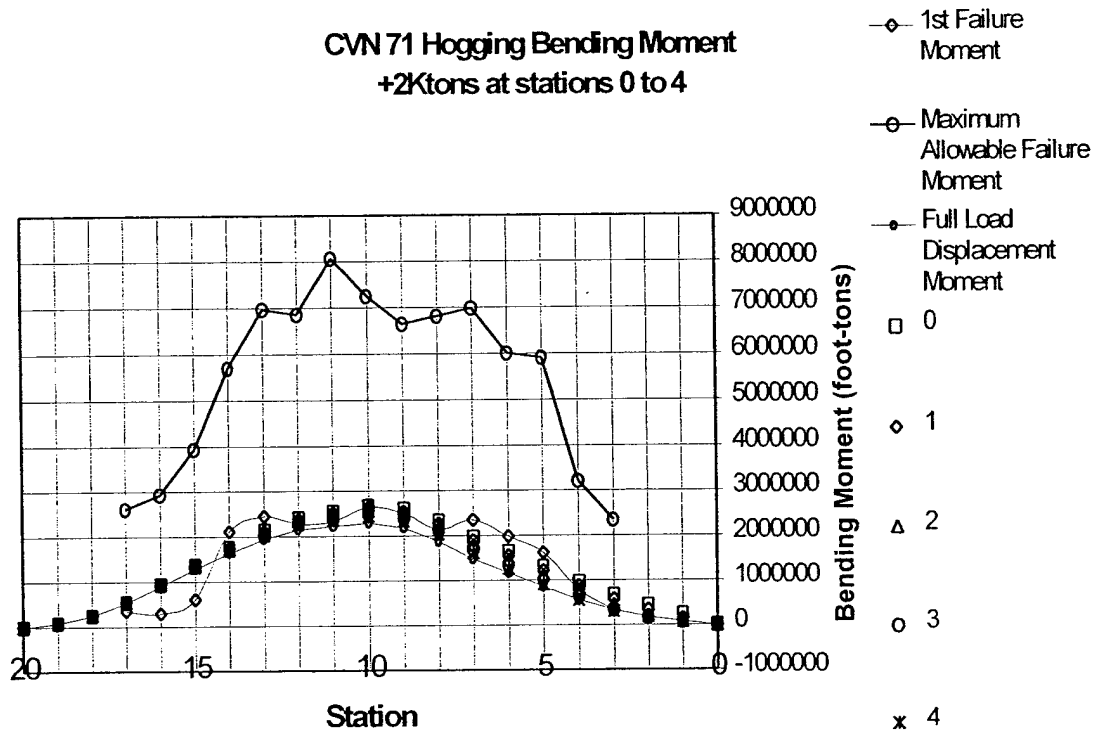- □ 15
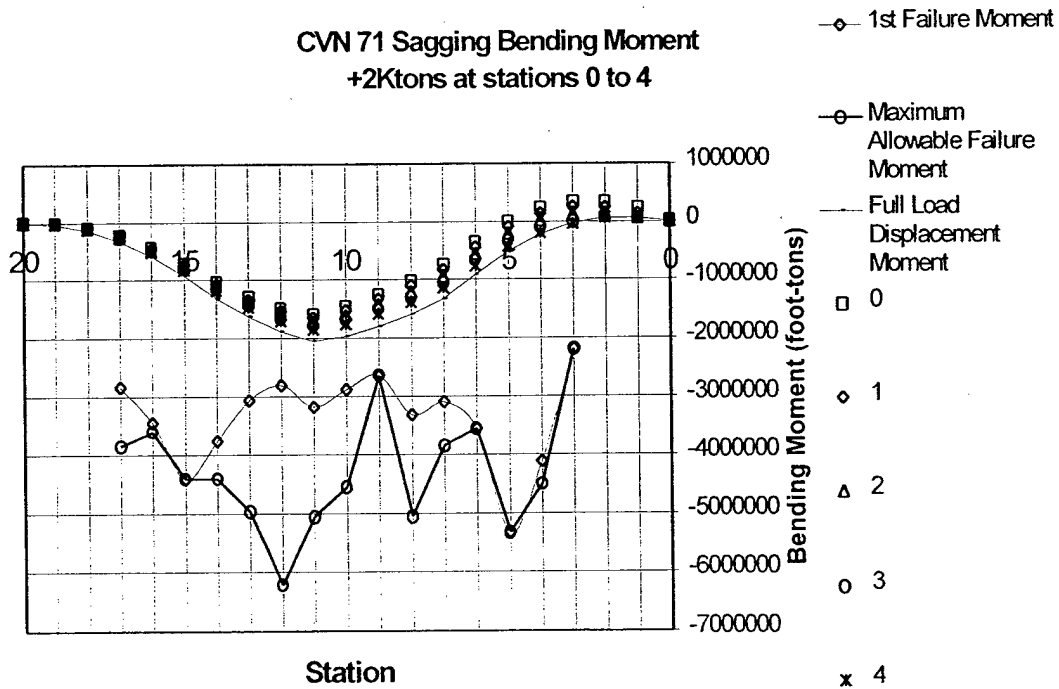- ◇ 16
- △ 17
- ○ 18
- ✕ 19
- + 20

APPENDIX E:

CVN 71 HULL WITH 2,000 LONG TONS APPLIED AT EACH STATION

The figures in Appendix E show the resulting bending moments when a 2,000 LTON point load is applied at each station. Clearly, the bending moment capacity of the hull will not be exceeded when this point load is applied at any station.
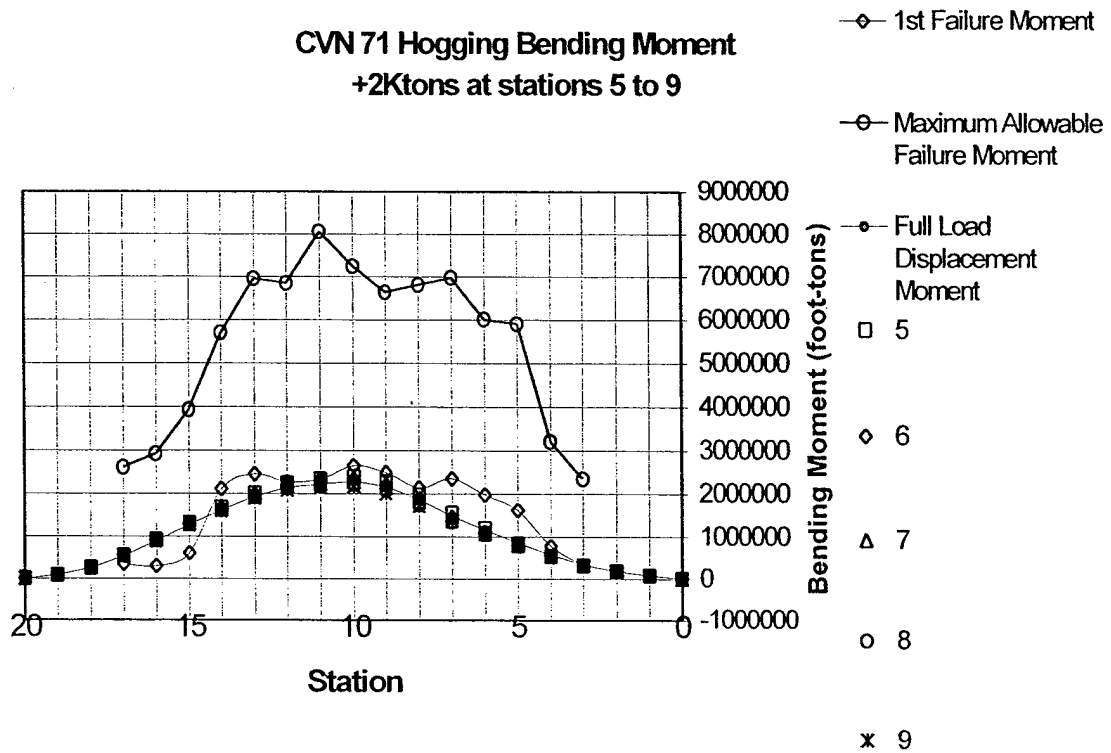
CVN 71 Hogging Bending Moment
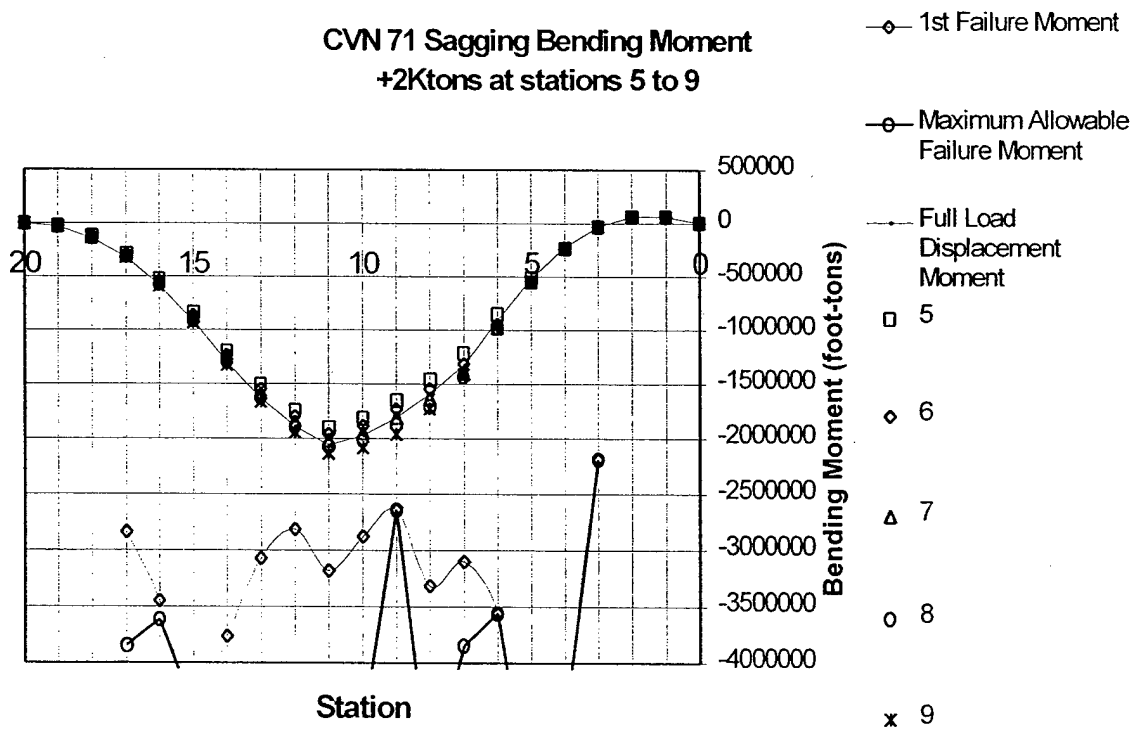## +2Ktons at stations 0 to 4

Legend:
- —◇— 1st Failure Moment
- —⊖— Maximum Allowable Failure Moment
- —■— Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- ✕ 4

CVN 71 Sagging Bending Moment
+2Ktons at stations 0 to 4

Legend:
- —◇— 1st Failure Moment
- —⊖— Maximum Allowable Failure Moment
- —— Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- ✕ 4

CVN 71 Hogging Bending Moment
+2Ktons at stations 5 to 9

Legend:
- —◇— 1st Failure Moment
- —⊖— Maximum Allowable Failure Moment
- —●— Full Load Displacement Moment
- □ 5
- ◇ 6
- △ 7
- ○ 8
- ✕ 9

CVN 71 Sagging Bending Moment
+2Ktons at stations 5 to 9

Legend:
- —◇— 1st Failure Moment
- —⊖— Maximum Allowable Failure Moment
- —·— Full Load Displacement Moment
- □ 5
- ◇ 6
- △ 7
- ○ 8
- ✕ 9

74

CVN 71 Hogging Bending Moment
+2Ktons at stations 10 to 14

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- 10
- 11
- 12
- 13
- 14

CVN 71 Sagging Bending Moment
+2Ktons at stations 10 to 14

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- 10
- 11
- 12
- 13
- 14

75

CVN 71 Hogging Bending Moment
+2Ktons at stations 15 to 20

Bending Moment (foot-tons)

Station

1st Failure Moment
Maximum Allowable Failure Moment
Full Load Displacement Moment
□ 15
◇ 16
△ 17
○ 18
x 19
+ 20

CVN 71 Sagging Bending Moment
+2Ktons at stations 15 to 20

Bending Moment (foot-tons)

Station

1st Failure Moment
Maximum Allowable Failure Moment
Full Load Displacement Moment
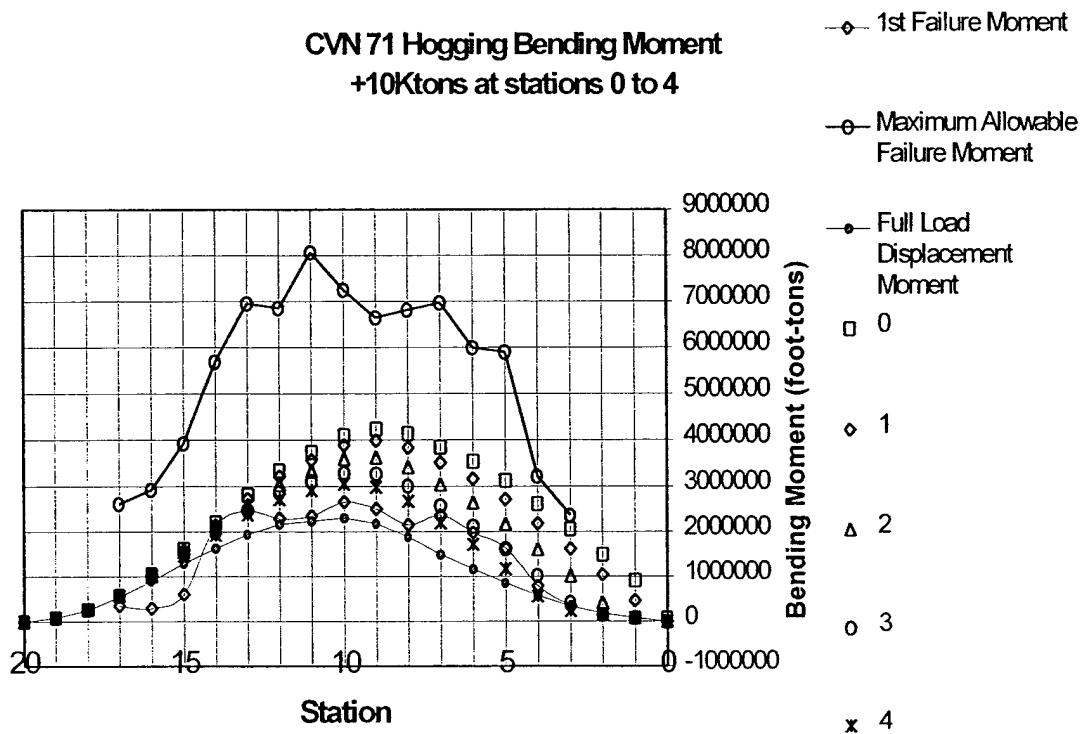□ 15
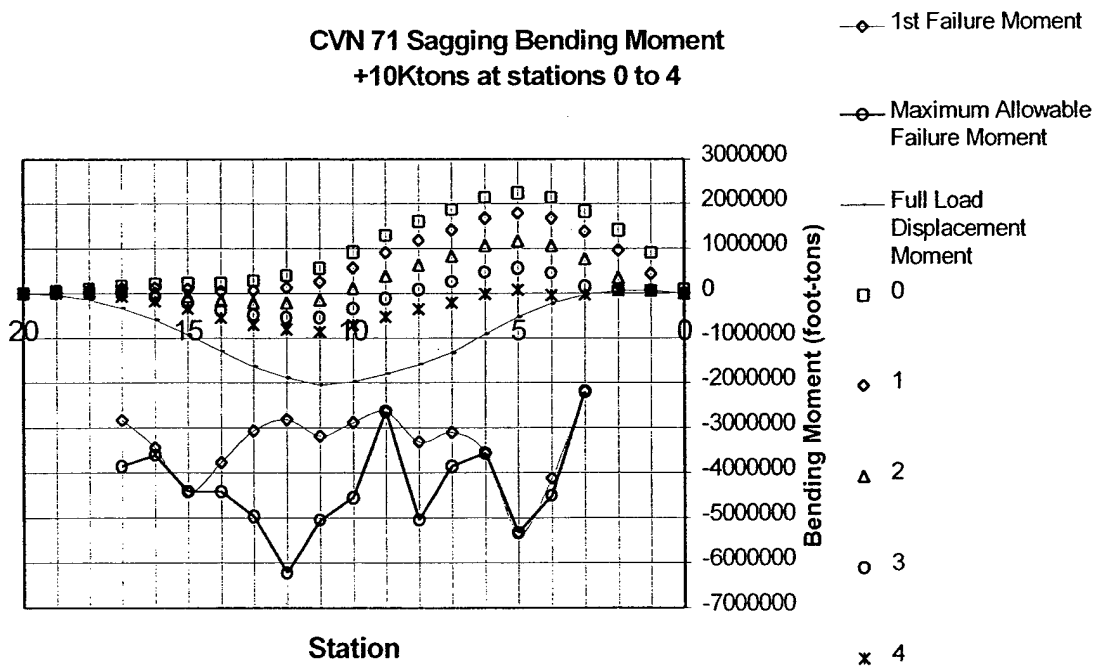◇ 16
△ 17
○ 18
x 19
+ 20

APPENDIX F:

CVN 71 HULL WITH 10,000 LONG TONS APPLIED AT EACH STATION

The figures in Appendix F show the resulting bending moments when a 10,000 LTON point load is applied at each station. Close attention should be paid when applying the point load in the hogging condition to stations 1 and 2. Although the resulting bending moment curve does not exceed the Maximum Allowable Failure Moment curve, it is very close to doing so. Likewise, if the point load is applied at station 10, then the potential exists that the Maximum Allowable Failure Moment curve may be exceeded at station 9. Application of the point load to any other station achieves satisfactory results.
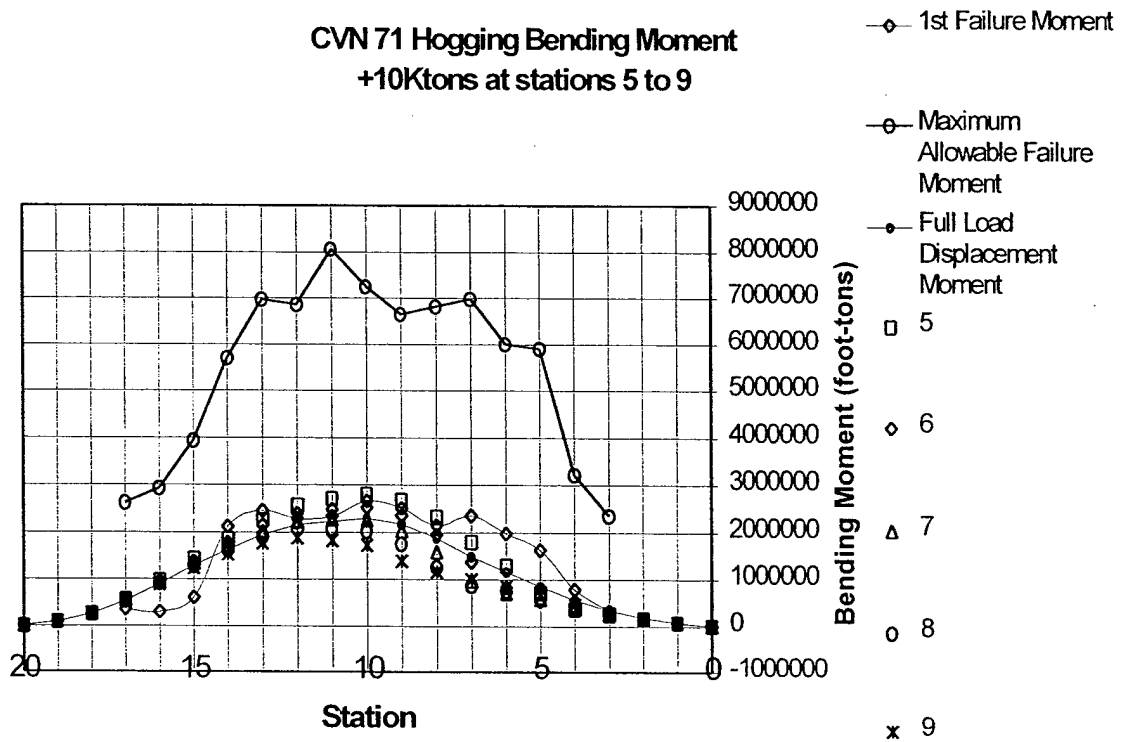
CVN 71 Hogging Bending Moment
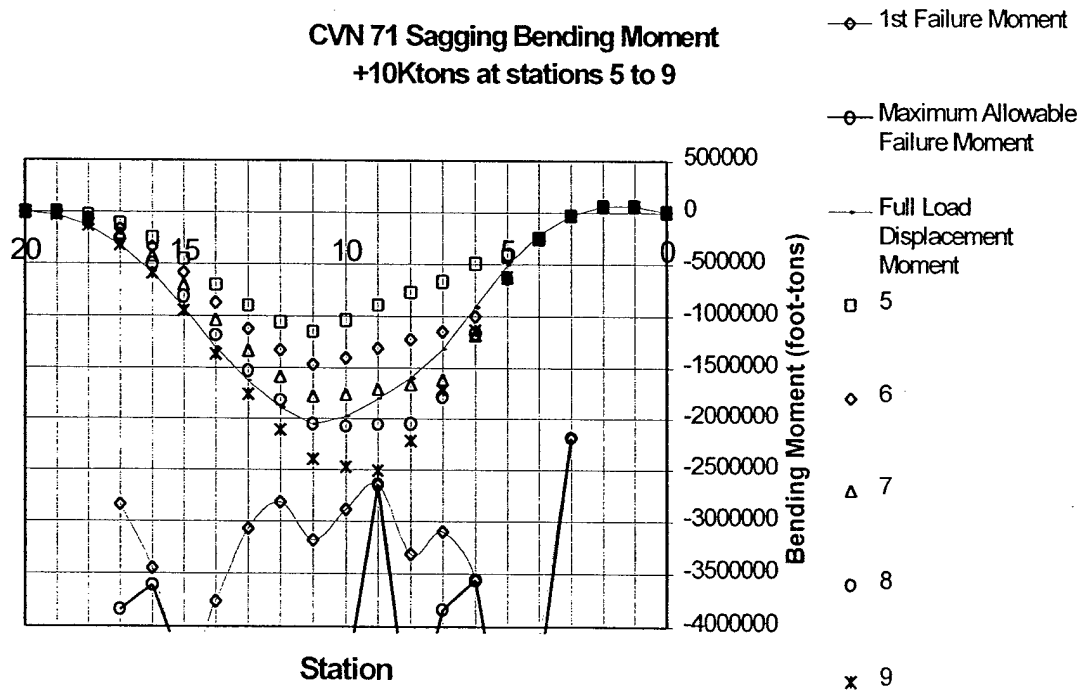## +10Ktons at stations 0 to 4

Legend:
- —◇— 1st Failure Moment
- —○— Maximum Allowable Failure Moment
- —●— Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- × 4

CVN 71 Sagging Bending Moment
+10Ktons at stations 0 to 4

Legend:
- —◇— 1st Failure Moment
- —○— Maximum Allowable Failure Moment
- —— Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- × 4

CVN 71 Hogging Bending Moment
+10Ktons at stations 5 to 9

1st Failure Moment

Maximum Allowable Failure Moment

Full Load Displacement Moment

□ 5

◇ 6

△ 7

○ 8

✗ 9

Bending Moment (foot-tons)

Station

CVN 71 Sagging Bending Moment
+10Ktons at stations 5 to 9

1st Failure Moment

Maximum Allowable Failure Moment

Full Load Displacement Moment

□ 5

◇ 6

△ 7

○ 8

✗ 9

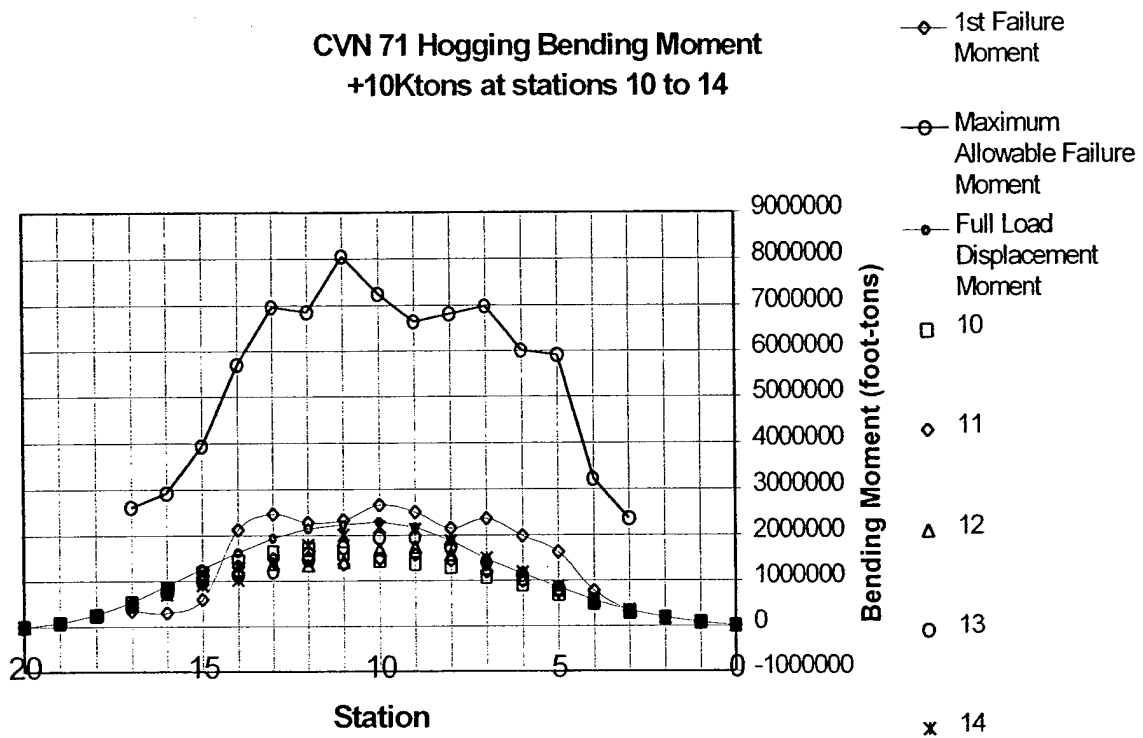Bending Moment (foot-tons)

Station

80

CVN 71 Hogging Bending Moment
+10Ktons at stations 10 to 14

CVN 71 Sagging Bending Moment
+10Ktons at stations 10 to 14
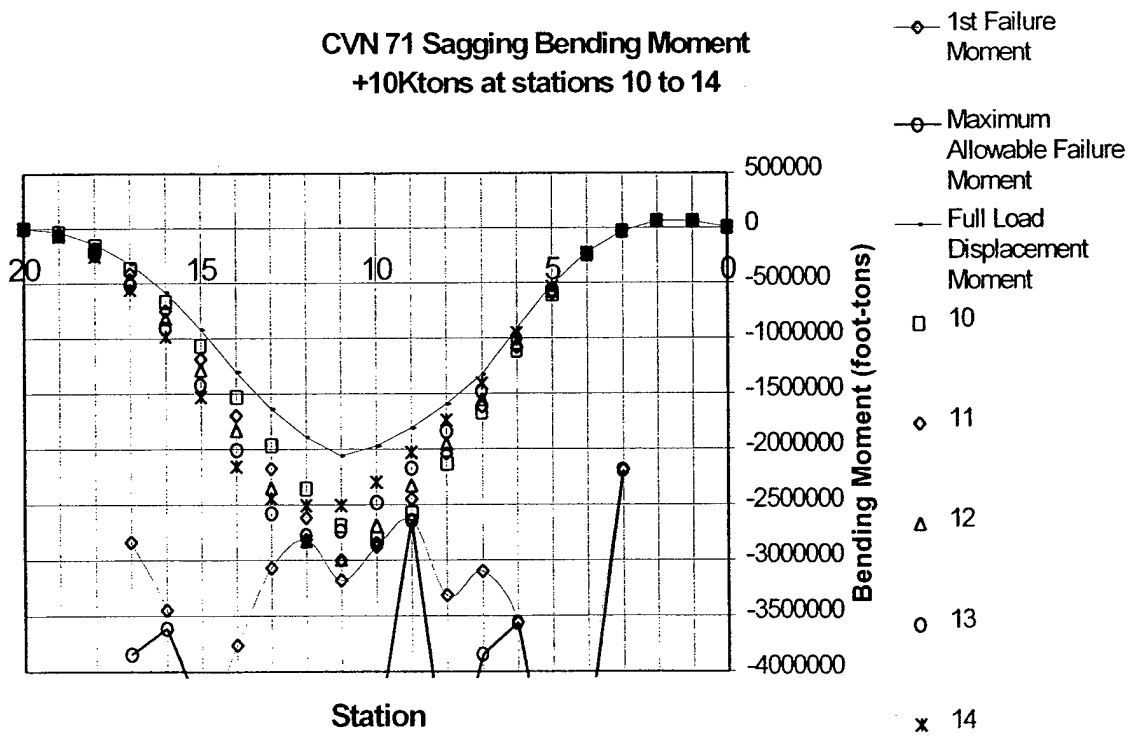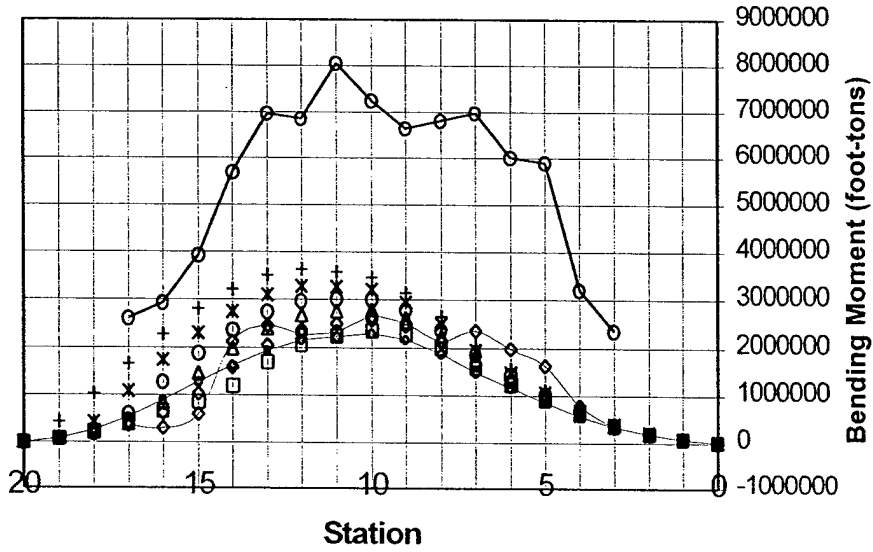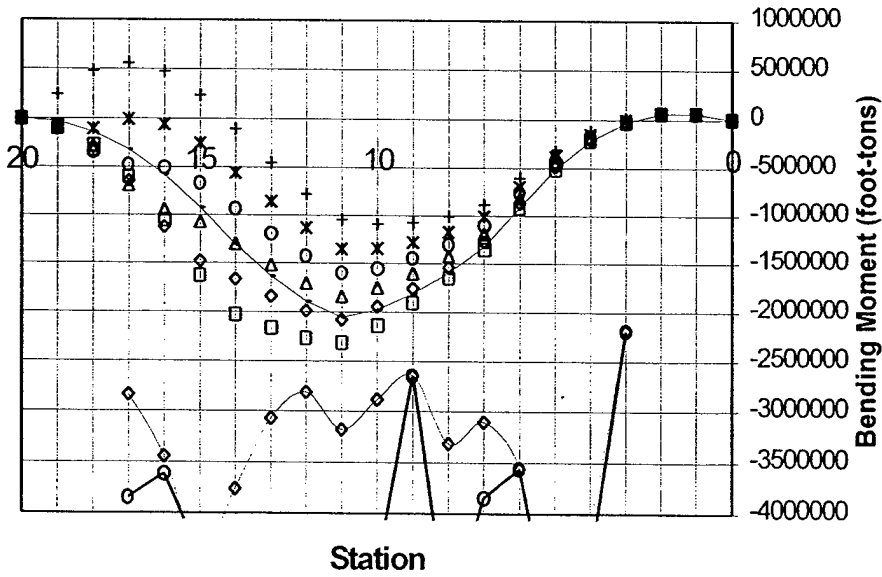
81

CVN 71 Hogging Bending Moment
+10Ktons at stations 15 to 20

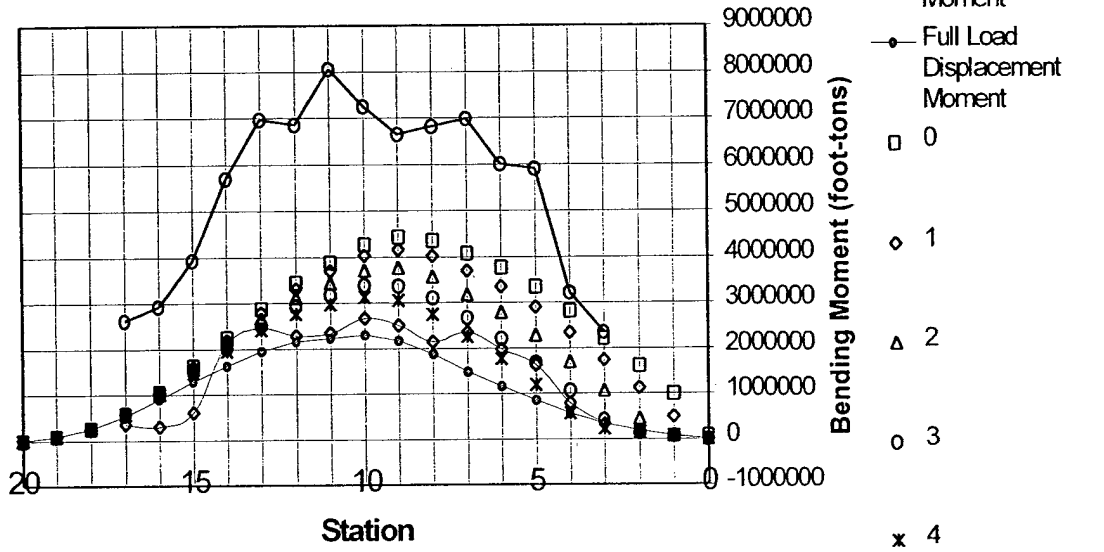## CVN 71 Sagging Bending Moment
+10Ktons at stations 15 to 20

APPENDIX G:

CVN 71 HULL WITH 11,000 LONG TONS APPLIED AT EACH STATION

The figures in Appendix G show the resulting bending moments when a 11,000 LTON point load is applied at each station. The 11,000 LTON point load may not be applied to station 0 without approaching the Maximum Allowable Failure Moment curve. A more detailed analysis is required. Applying the point load at stations 9 or 10 in the sagging condition results in the ship, 1st Failure, and Maximum Allowable Failure Moments being coincident. This condition also indicates a need for a more in depth analysis.

CVN 71 Hogging Bending Moment
+11Ktons at stations 0 to 4

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- × 4

Y-axis: Bending Moment (foot-tons)
Values: 9000000, 8000000, 7000000, 6000000, 5000000, 4000000, 3000000, 2000000, 1000000, 0, -1000000
X-axis: Station (20, 15, 10, 5, 0)

CVN 71 Sagging Bending Moment
+11Ktons at stations 0 to 4

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 0
- ◇ 1
- △ 2
- ○ 3
- × 4

Y-axis: Bending Moment (foot-tons)
Values: 3000000, 2000000, 1000000, 0, -1000000, -2000000, -3000000, -4000000, -5000000, -6000000, -7000000
X-axis: Station (20, 15, 10, 5, 0)

85

CVN 71 Hogging Bending Moment
+11Ktons at stations 5 to 9

Bending Moment (foot-tons)

Station

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 5
- ◇ 6
- △ 7
- ○ 8
- ✕ 9

CVN 71 Sagging Bending Moment
+11Ktons at stations 5 to 9

Bending Moment (foot-tons)

Station

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 5
- ◇ 6
- △ 7
- ○ 8
- ✕ 9

CVN 71 Hogging Bending Moment
+11Ktons at stations 10 to 14

Bending Moment (foot-tons)

9000000
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
-1000000

20   15   10   5   0

Station

—◇— 1st Failure Moment

—⊖— Maximum Allowable Failure Moment

—●— Full Load Displacement Moment

□ 10

◇ 11

△ 12

○ 13

✗ 14

CVN 71 Sagging Bending Moment
+11Ktons at stations 10 to 14

Bending Moment (foot-tons)

500000
0
-500000
-1000000
-1500000
-2000000
-2500000
-3000000
-3500000
-4000000

20   15   10   5   0

Statio

—◇— 1st Failure Moment

—⊖— Maximum Allowable Failure Moment

—— Full Load Displacement Moment

□ 10

◇ 11

△ 12

○ 13

✗ 14

87

CVN 71 Hogging Bending Moment
+11Ktons at stations 15 to 20

Legend:
- ◇ 1st Failure Moment
- ○ Maximum Allowable Failure Moment
- • Full Load Displacement Moment
- □ 15
- ◇ 16
- △ 17
- ○ 18
- × 19
- + 20

X-axis: Station
Y-axis: Bending Moment (foot-tons)

CVN 71 Sagging Bending Moment
+11Ktons at stations 15 to 20

Legend:
- ◇ 1st Failure Moment
- ○ Maximum Allowable Failure Moment
- • Full Load Displacement Moment
- □ 15
- ◇ 16
- △ 17
- ○ 18
- × 19
- + 20

X-axis: Station
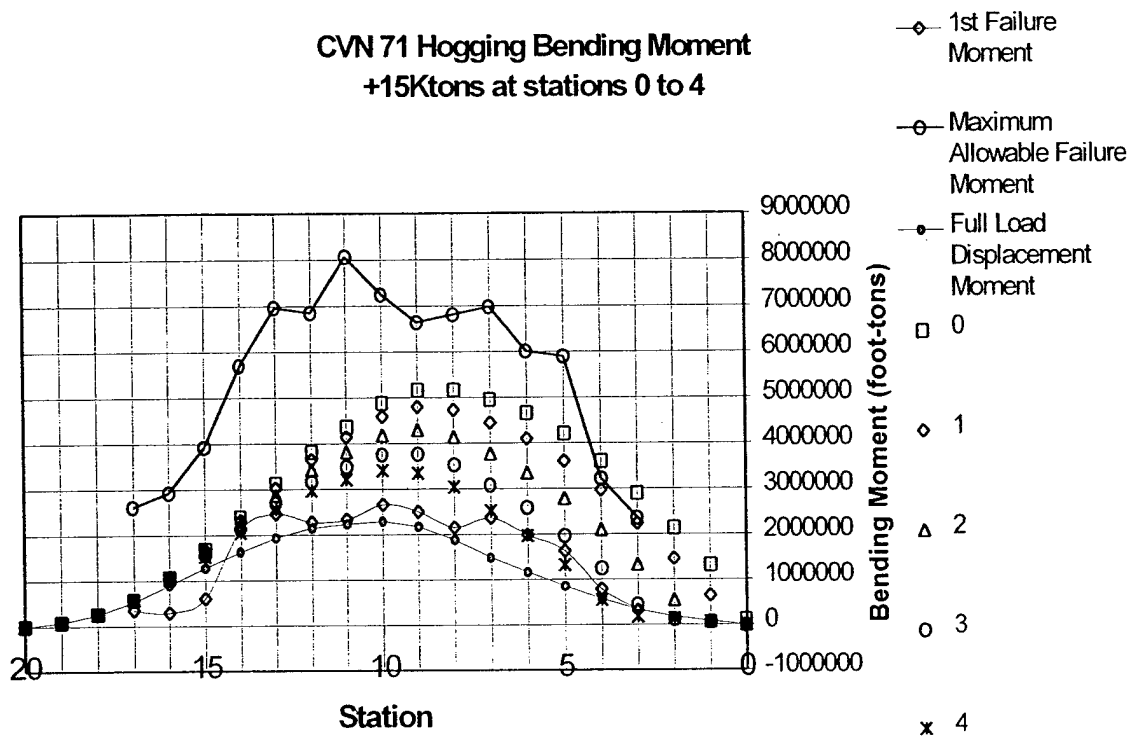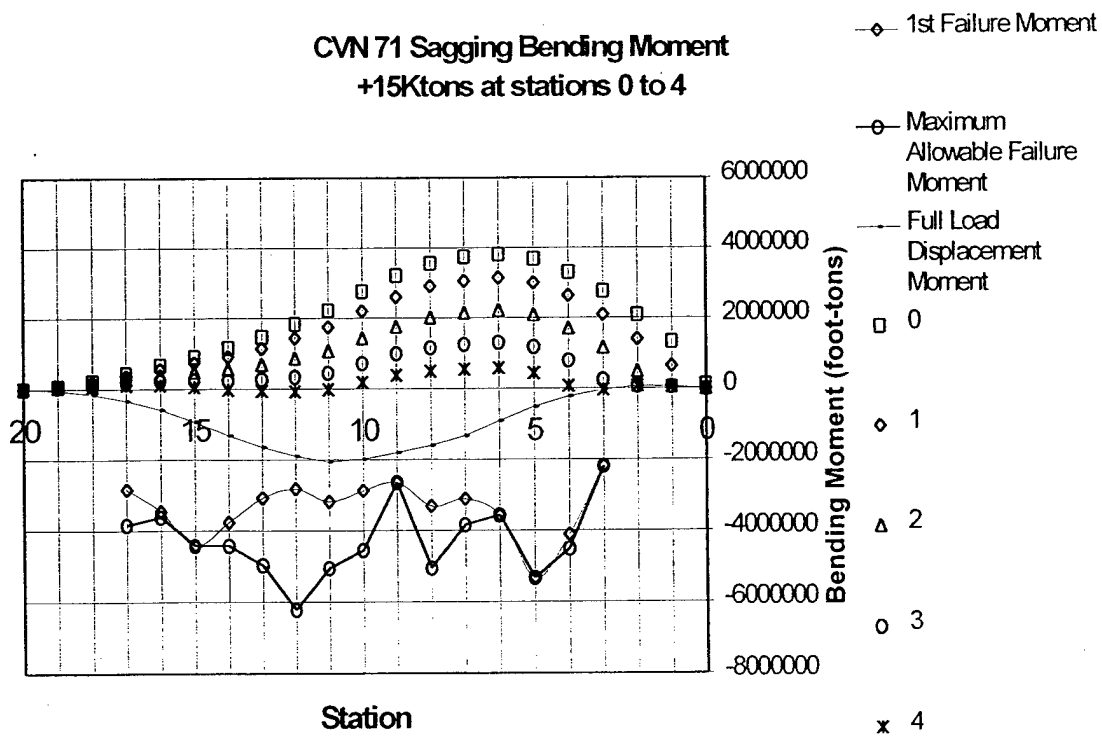Y-axis: Bending Moment (foot-tons)

APPENDIX H:

CVN 71 HULL WITH 15,000 LONG TONS APPLIED AT EACH STATION

The figures in Appendix H show the resulting bending moments when a 15,000 LTON point load is applied at each station. The 15,000 LTON point load may not be applied at station 0 or 1 in the hogging condition without exceeding the Maximum Allowable Failure Moment curve. Additionally, if the load is applied at stations 9, 10, or 11 in the sagging condition, then the Maximum Allowable Failure Moment curve will be exceeded at station 9 indicating a need for additional analysis. All other stations are capable of supporting the addition of this 15,000 LTON point load without exceeding the Maximum Allowable Failure Moment curve.
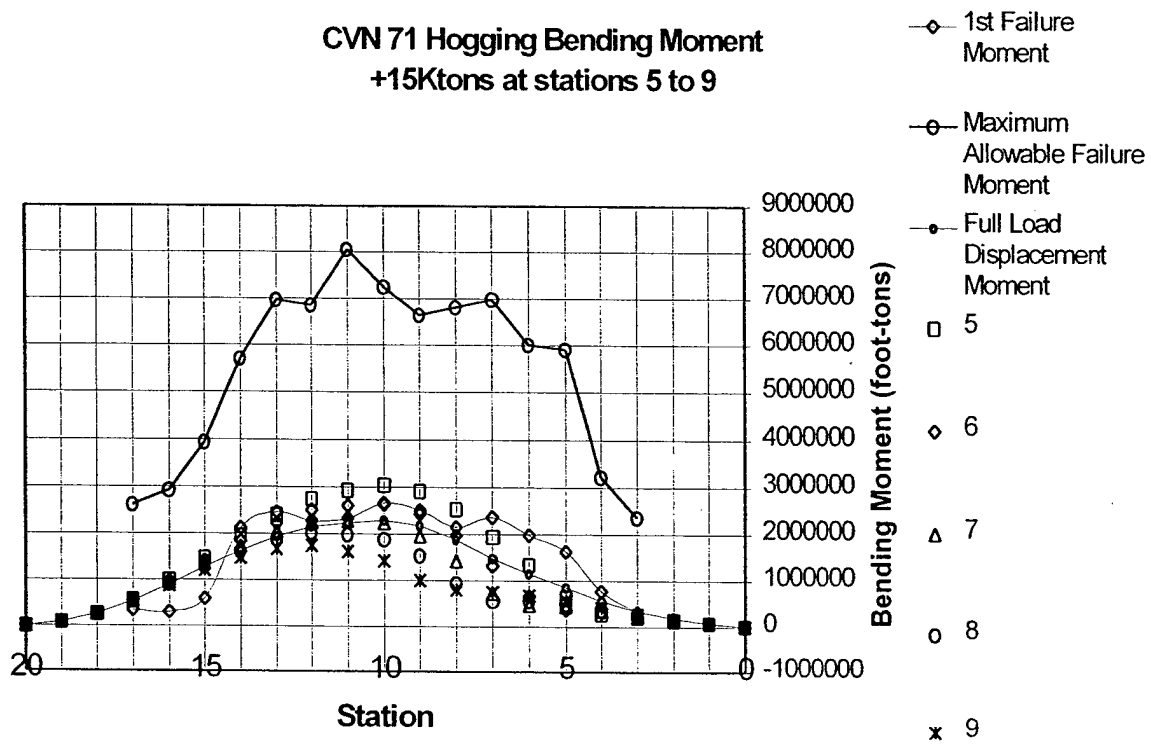
CVN 71 Hogging Bending Moment
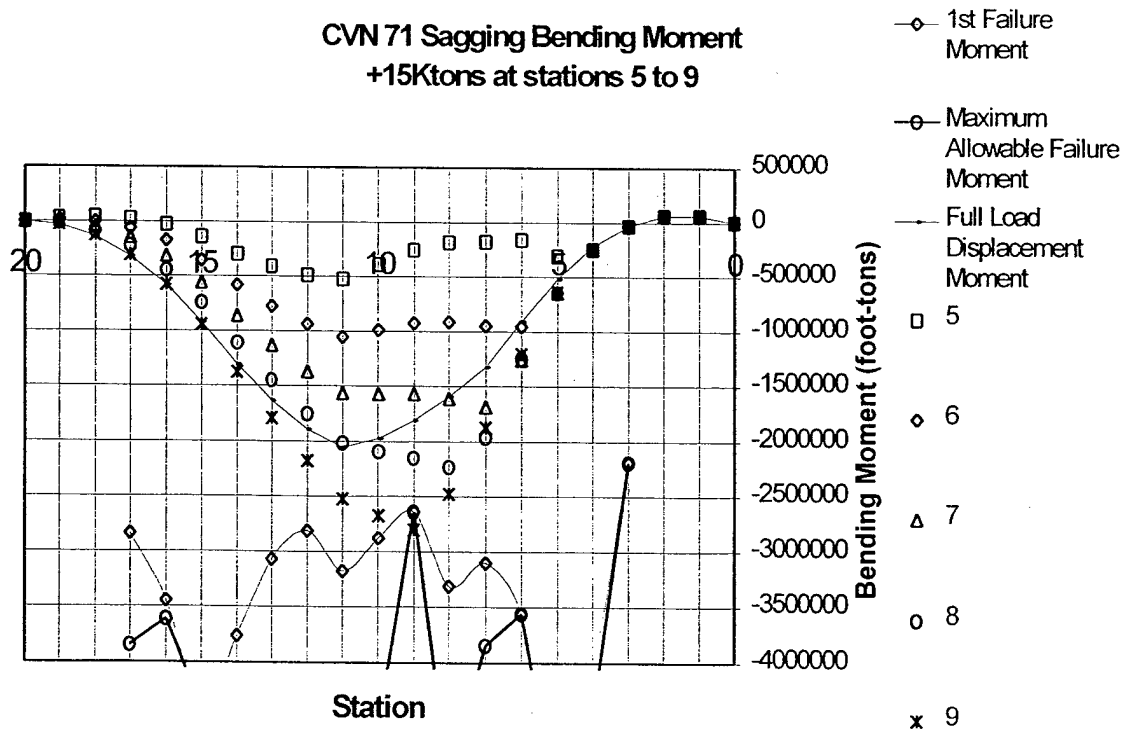+15Ktons at stations 0 to 4

CVN 71 Sagging Bending Moment
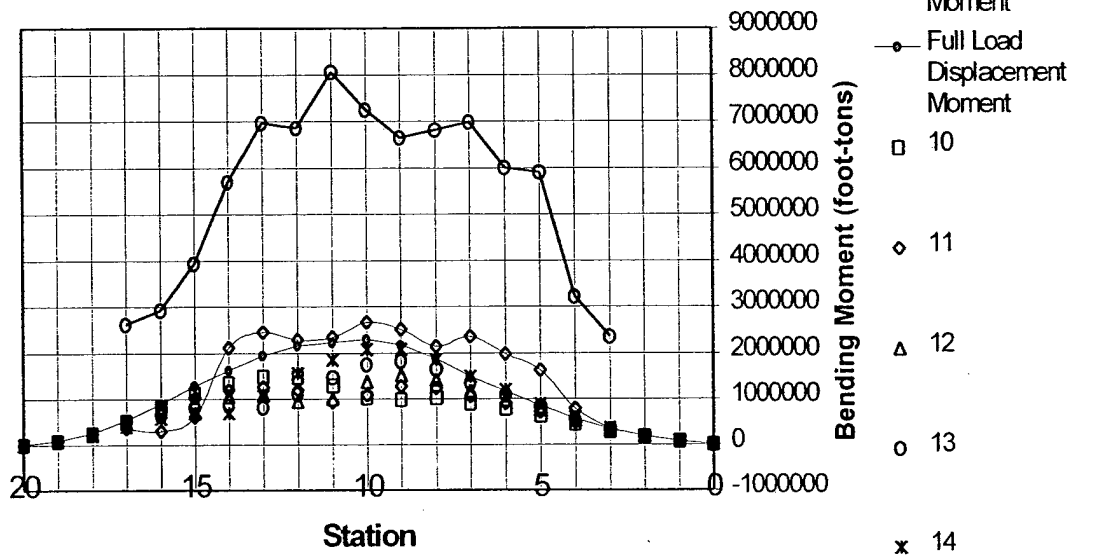+15Ktons at stations 0 to 4

91

CVN 71 Hogging Bending Moment
+15Ktons at stations 5 to 9

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 5
- ◇ 6
- △ 7
- ○ 8
- ✗ 9

CVN 71 Sagging Bending Moment
+15Ktons at stations 5 to 9

Legend:
- 1st Failure Moment
- Maximum Allowable Failure Moment
- Full Load Displacement Moment
- □ 5
- ◇ 6
- △ 7
- ○ 8
- ✗ 9

CVN 71 Hogging Bending Moment
+15Ktons at stations 10 to 14

1st Failure Moment
Maximum Allowable Failure Moment
Full Load Displacement Moment
□ 10
◇ 11
△ 12
○ 13
✗ 14

Bending Moment (foot-tons)

Station

CVN 71 Sagging Bending Moment
+15Ktons at stations 10 to 14

1st Failure Moment
Maximum Allowable Failure Moment
Full Load Displacement Moment
□ 10
◇ 11
△ 12
○ 13
✗ 14

Bending Moment (foot-tons)

Station

CVN 71 Hogging Bending Moment
+15Ktons at stations 15 to 20

—✕— 1st Failure Moment

—✳— Maximum Allowable Failure Moment

—●— Full Load Displacement Moment

▫ 15

◇ 16

△ 17

○ 18

✕ 19

+ 20

CVN 71 Sagging Bending Moment
+15Ktons at stations 15 to 20

—◇— 1st Failure Moment

—○— Maximum Allowable Failure Moment

—●— Full Load Displacement Moment

▫ 15

◇ 16

△ 17

○ 18

✕ 19
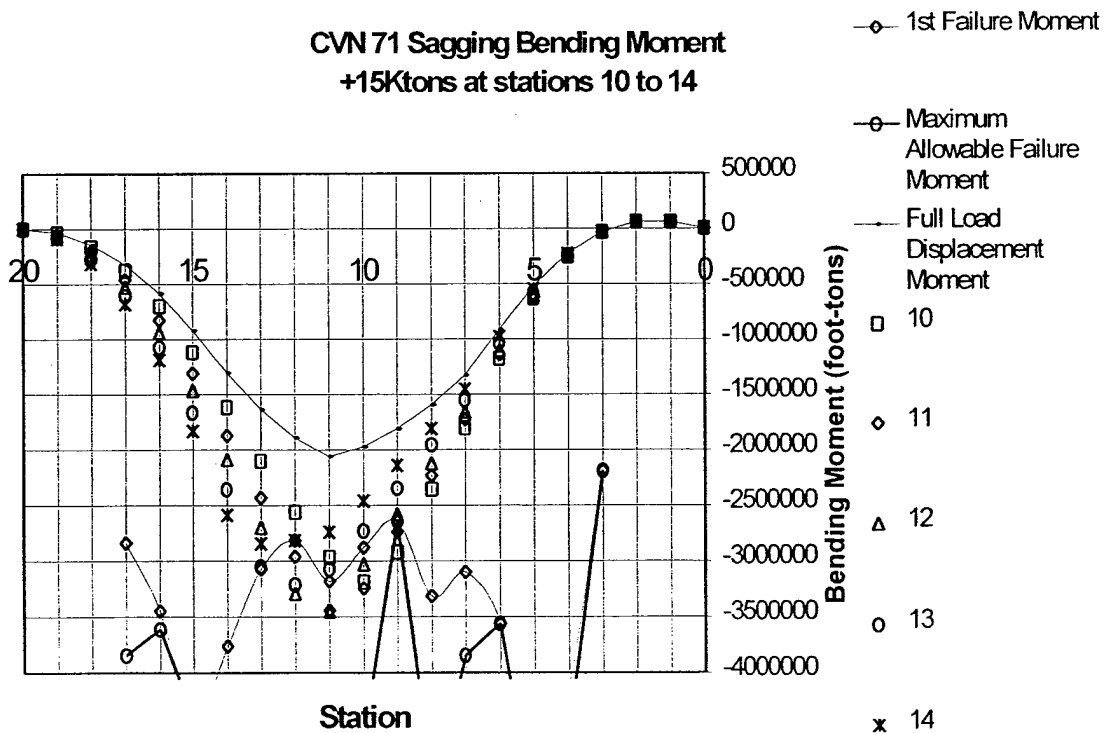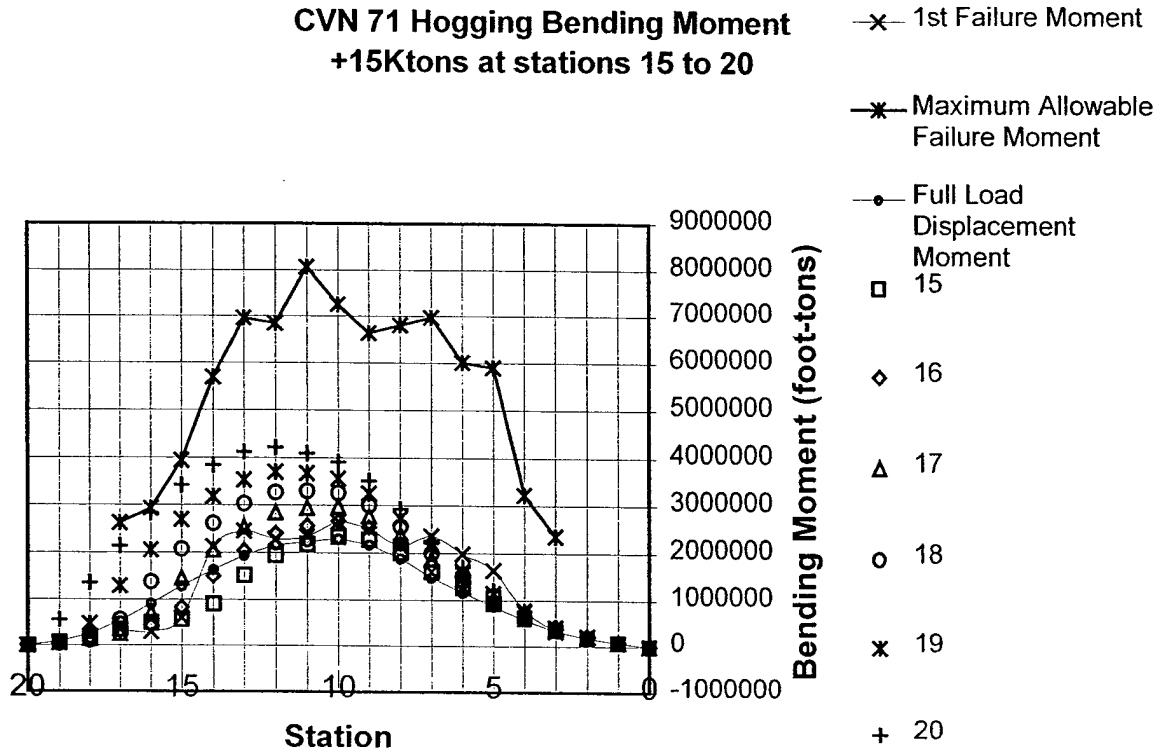
+ 20
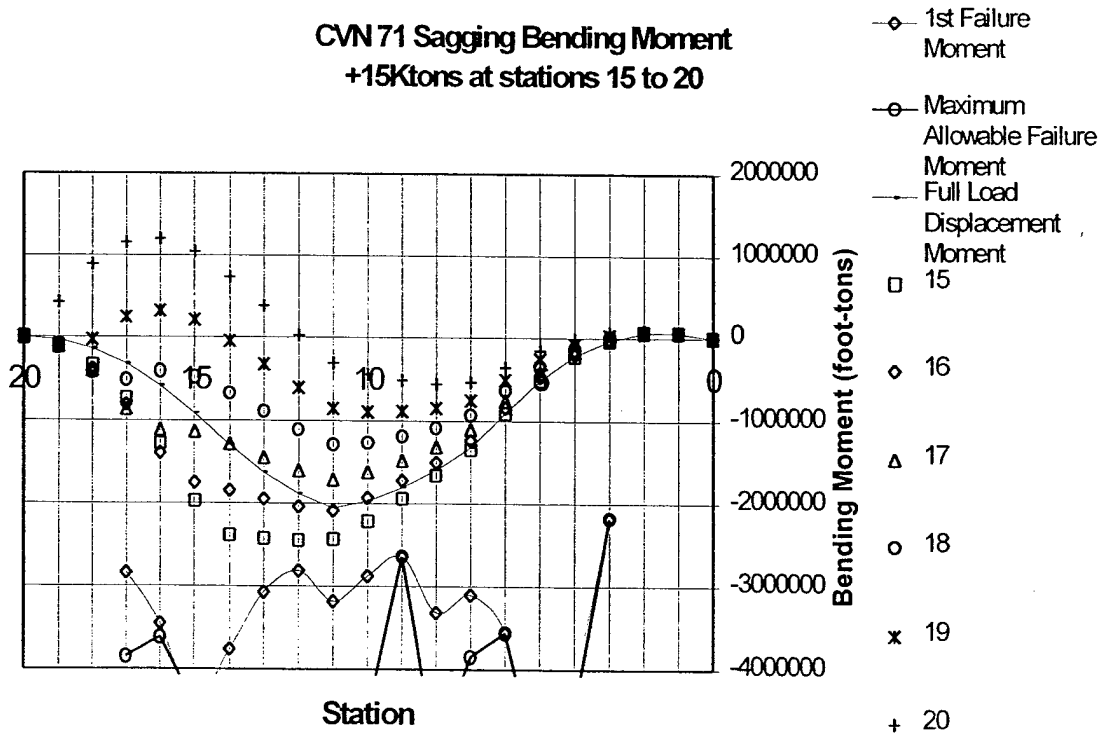
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