It was decided that the most suitable ship for detailed study was the S.S. Wolverine State. Not only are service wave bending stress data available, but information could be obtained on dynamic stresses and on still water loadings.

The load calculations followed the procedures described in the preceding chapters. Considering first the loads affecting ultimate bending failure, each step will be described in turn. Then the combined effect of all loads will be considered and interpreted in terms of a simple design bending moment for hogging and sagging conditions, outbound and inbound. This load criterion will then be compared with conventional design standards.

Finally, brief consideration will be given to the cyclic loading pattern as a criterion relative to possible fatigue damage, and to a criterion for brittle fracture. For this ship, with relatively heavy shell plating, small hatches, and low length/depth ratio it was felt that criteria of shear, torsion or elastic deflection need not be considered.

STILL WATER LOADS

Estimated Bending Moments

During most of the time that data were collected on the S.S. Wolverine State the ship was engaged in North Atlantic service. Available data on service drafts indicated that the ship usually operated at drafts considerably less than full load, both east and westbound. However, in order to provide a typical numerical example, it was felt to be desirable to assume a fully loaded cargo condition on the outbound voyage and typical light loadings inbound.

Unfortunately, it was impossible to obtain detailed distributions of cargo and liquids for a sufficient number of actual voyages to obtain a statistical picture of still water bending moments. Hence, calculations were made, using the owners' loading manual as a guide, to supplement actual loading data. A normal distribution of still water bending moment in the light cargo condition was constructed as shown in Fig. 24, based on the available loading data and on calculated highest and lowest expected values in a 25-year lifetime. To determine the extremes,

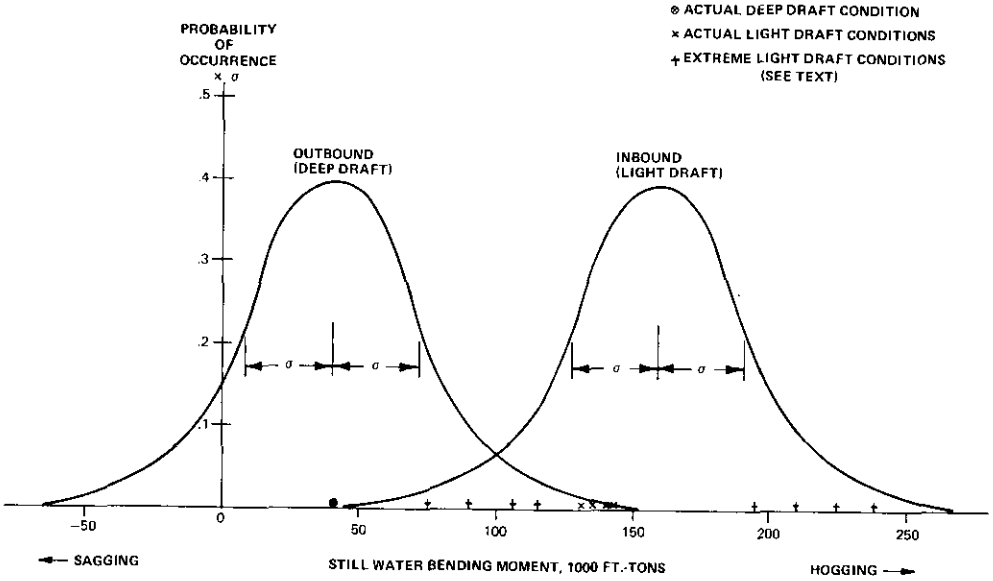

FIGURE 24 - Estimated Distributions of Still-Water Bending Moments, *S.S. WOLVERINE STATE*

the amount of cargo typically carried in the light load condition was imagined to be distributed more and more toward the ends of the ship until an estimated extreme condition was reached. We assigned to the resulting still water hogging bending moment (239,900 ton-ft.) a probability representing one occurrence in 25 years.

For 12 round trips per year, there are 300 crossings in each direction in 25 years. Thus the highest expected single occurrence would have a 1/300 = 0.00333 frequency, which corresponds to ±2.71 σ, where σ is the standard deviation. A similar approach was used to determine the minimum hogging condition in 25 years (75,100 ton-ft.), which corresponds to 2.71 σ below the mean. The mean value for the normal distribution is the average of the highest and lowest calculated values. Thus the mean and standard deviation, and from them the normal distribution, were determined as shown in Fig. 24, along with actual values determined from the loading data.

The mean still water bending moment for the full load condition was calculated from one actual voyage at nearly full load, and it was assumed that the standard deviation would be the same as for the light cargo condition. The results of the calculations are given in Table V. All bending moments are in ton-ft.

TABLE V

STILL-WATER BENDING MOMENTS
S.S. Wolverine State

	Bending Moments, Ton-Ft.	
	Full Load Outbound	Light Load Inbound
Mean	40,000 hog	157,500 hog
Standard deviation	30,400* hog	30,400 hog
10% are below	800 hog	118,300 hog
10% are above	79,200 hog	196,700 hog
Highest in 25 years	122,400 hog	239,900 hog
Lowest in 25 years	42,400 sag	75,100 hog

*Assumed the same as in Light Load Condition.

The above maximum values have been inserted in Table IX, along with extrapolated 1000-ship values and other results to be discussed below.

Classification Society Requirements

It should be noted that although classification societies do not in general base hull girder strength standards on a direct addition of still water and wave bending moments, still water moments are taken into account at the present time. (See Chapter III).

For the Wolverine State the maximum still water bending moment without penalty is calculated by ABS 1972 Rules to be 136,000 ton-ft. It may be seen that this value would be exceeded by the calculated value of 239,900 ton-ft in the hogging condition, inbound. If these conditions were included in the data submitted to the ABS at the time of the design of a similar ship today, some addition to the midship section modulus requirement might be made. At the time the ship was built (1945), however, there was no explicit still water section modulus requirement in the ABS rules.

FORWARD SPEED EFFECT

The bending moment (sagging) induced by the ship's own wave at forward speed in calm water was estimated on the basis of model test data on similar ships (36). At the design speed of 16 knots the result is a sagging bending moment of 2700 foot-tons in the heavy (outbound) condition and 5200 foot-tons in the light (inbound) condition. Thus the forward speed effect reduces the still water bending moments, which are hogging moments in both conditions. The model tests show that the maximum hogging moment due to forward speed occurs when the ship is at very low speed, and the reduction in still water bending moment at normal speed becomes zero.

The above figures have been entered in Table IX, in which a summary of all bending moments is given. Average values have been estimated for the table on the basis of service speed data.

THERMAL EFFECTS

Next an estimate was made of the thermal stresses to be expected under different symmetrical conditions of sea/air temperatures (sun overhead). Since calculations have shown that symmetrical heating of the deck results in compressive stresses in deck and bottom plating of nearly equal magnitude (119), only the changes in deck stress were computed.

The basis for calculating thermal stresses is described in Chapter VII. Calculations were made for five values of diurnal temperature change, representative of typical North Atlantic conditions. Average air temperature changes were determined from ships' logs covering a two-year period. The results were:

Season	Avg. Diurnal ΔT of Air
Winter	10°
Spring	9°
Summer	10°
Fall	7°

Because the seasonal variations were small, differences were ignored and a yearly average of 10° was assumed.

An additional ΔT of 40° was assumed for insolation with full sun, since the deck color is dark gray, as in the Esso Malaysia estimate (see Chapter VII). This figure represents full sun conditions; so adjustments were made for cloudy conditions. Available seasonal and annual cloud cover data for the North Atlantic route (82) are given in Table VI.

TABLE VI

DATA ON CLOUD COVER AND ESTIMATED TEMPERATURE DIFFERENTIALS, NORTH ATLANTIC

Season	Median Factor for Cloud Cover	% of time < 2/8 cover	% of time > 5/8 cover
Winter	6/8	10%	70%
Spring	6/8	20	60
Summer	5/8	20	60
Fall	6/8	20	60
Yearly avg.	6/8	20	60

Factor for Cloud cover	Diurnal ΔT			Estimated Frequency of Occurrence
	Insolation	Air	Total	
0/8	40°	10°	50°	10% } 20%
2/8	30°	10°	40°	10%
4/8	20°	10°	30°	20%
6/8	10°	10°	20°	30° } 60%
8/8	0°	10°	10°	30°

Again the seasonal differences were ignored in this table, and the yearly average figures for cloud cover were used. In order to relate the insolation temperature to the cloud cover information, we assumed that the insolation ΔT is directly proportional to the amount of cloud cover, while the air temperature change (10°) remained constant. The resulting diurnal ΔT's for different cloud conditions are also given in Table VI.

The calculated compressive stresses at deck edge for the Wolverine State are given in Table VII, and the calculated stress distribution is shown in Figure 25.

TABLE VII

CALCULATED CHANGES IN STRESS AND EQUIVALENT BENDING MOMENT, S.S. WOLVERINE STATE IN NORTH ATLANTIC SERVICE

Diurnal ΔT	Frequency of Occurrence, Table VI	Deck Compressive Stress, PSI	Corresponding Equiv. Sagging B.M., ton-ft.
50°	10%	2170	47,700
40°	10%	1740	38,250
30°	20%	1300	28,600
20°	30%	870	19,100
10°	30%	430	9,500
Weighted average		1040	22,900

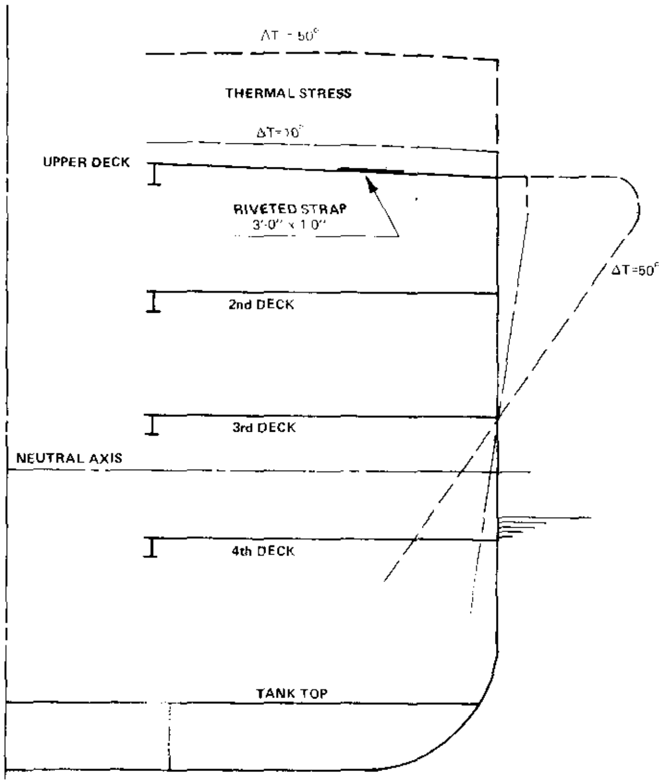

FIGURE 25 - Calculated Thermal Stresses,
S.S. WOLVERINE STATE

Next an "equivalent" sagging bending moment that would produce the same deck stress was computed for each value of diurnal ΔT, as listed in Table VII. The weighted average was then inserted in Table IX as the average sagging value. On the assumption that the bottom compressive stress in hogging would be approximately the same as the calculated deck stress in sagging, an effective hogging bending moment of 22,300 ton-ft. was calculated and entered in the table.

WAVE LOADS

Comprehensive computer calculations were carried out for the S.S. Wolverine State for two conditions:

(1) Full load.
(2) Light load.

The responses covered by these calculations included:

Vertical longitudinal bending moment.
Lateral " " "
Combined vertical and lateral longitudinal bending.
Torsional moments.

The calculations proceeded in the following steps, in accordance with the procedures described in Chapter IV:

Calculation of response amplitude operators at all headings to regular waves.

Comparison of above with model tests.

Prediction of response to irregular short-crested seas described by the H-family.

Estimating long-term cumulative distribution for North Atlantic service, based on the weather statistics given in Table VIII.

TABLE VIII

WEATHER DATA FOR NORTH ATLANTIC

Probability p	Average Significant Height $H\text{-}1/_3$ (ft.)	Range of $H\text{-}1/_3$ (ft.)
0.8454	10.0	5 - 15
0.1330	20.0	15 - 25
0.0201	30.0	25 - 35
0.0014	40.0	35 - 45
0.0001	48.2	45 and above

The effective vertical bending moment giving the combined effect of vertical and lateral bending was calculated by the method described in Chapter IV. The ratio Z_v/Z_L for the Wolverine State is 0.8446.

The program SCORES (49) was modified to suit the present purpose by appending a memory block to carry over the necessary information, so that it would still be possible to run SCORES in its original form for other purposes. The calculations necessary to give the long-term distribution were appended in the form of a subprogram.

Long-term calculated results are presented in Figs. 26 and 27, along with curves obtained from full-scale statistics for comparison. See also (10). Calculated bending moment results in regular waves are compared with model test results in (53). Values from Figs. 26 and 27 for combined vertical and lateral bending moments have been entered in Table IX.

DYNAMIC LOADS

We come now to the consideration of dynamic loads on the S.S. Wolverine State. For a ship of this type, springing would not be expected, nor is there sufficient flare to produce significant bow flare immersion effects. Stress records confirm that neither of the above effects were experienced significantly in actual service. Furthermore, a student thesis project at Webb with a jointed model of Wolverine State confirmed that only negligible springing stresses could be developed in the model tank.

However, slamming stresses resulting from bottom impact forward, followed by vibratory whipping response, were both expected and found in Teledyne records taken in the light load condition (103)(109).

As explained in a previous chapter, it is theoretically possible to predict the occurrence of slamming if one can specify the level of relative vertical velocity at

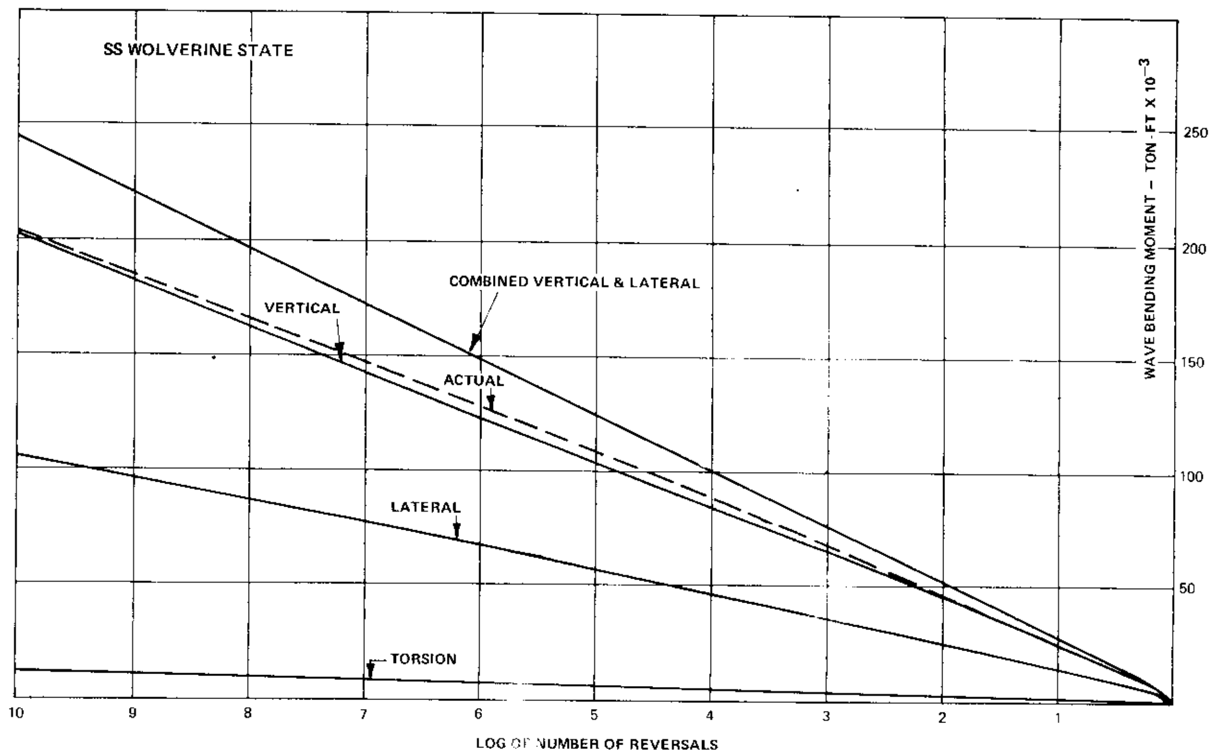

FIGURE 26 - Long-Term Distribution of Bending Moment, Light-Load Condition

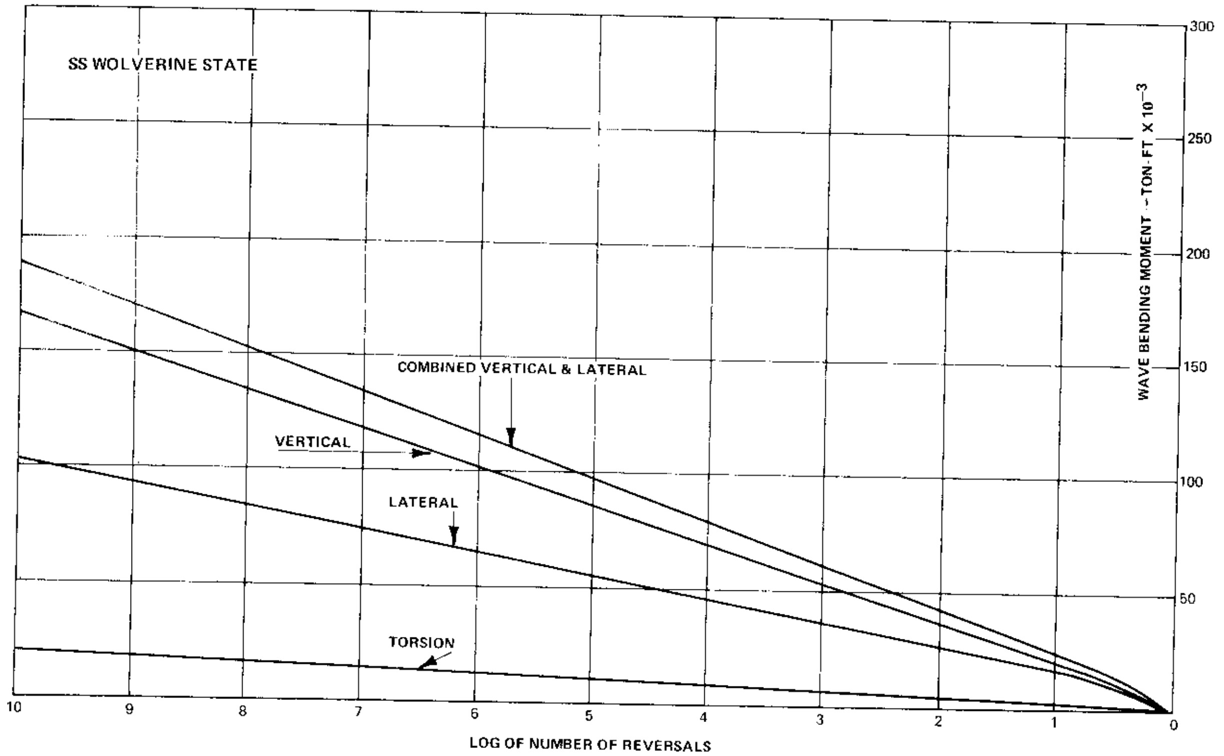

FIGURE 27 - Long-Term Distribution of Bending Moment, Full-Load Condition

which it will occur for the ship in question. Since there are still a number of doubtful questions about this procedure, reference was made in this case to the recorded data on the S.S. Wolverine State. The stress records showed that, over the entire period of data collection, slamming (with stresses exceeding 1.0 kpsi) occurred in 16% of the records. This can be considered to be an indication that in normal operation the probability that slamming will occur in any 20-minute period is 0.16 in the usual light load condition at which the ship operated. (Average draft forward was 16-20 ft.)

In the hypothetical full load condition (forward draft 29 ft.) the probability of slamming is greatly reduced, and for the present purpose was arbitrarily assumed to be 0.

Referring to Chapter VI, the following conclusions may be restated here:

1. the slam stress distribution σ_s is exponential:

$$p(\sigma_s) = a \exp\{-a(\sigma_s - c)\}$$

where $\sigma_s = \sigma_{so}/\text{RMS}$

$c = 0.36$

$a = 1$

2. the distribution of the phase angle ϕ is normal

$$p(\phi) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{\phi - \mu}{\sigma}\right)^2\right\}$$

where $\mu = 0.406$ radians,

$\sigma = 0.381$ radians.

The theoretical solution to the problem of calculating the distribution of the increase of the slam stress δ_s and the whipping stress δ_w over wave bending stress can be given briefly as follows:

$$p(\delta_s) = \frac{a}{2\sigma^2} \exp\left\{-\frac{a\delta_s}{2\sigma^2}\right\} A(a,\sigma,\mu)$$

where δ_s is the increase due to slamming, and the first two factors express the exponential distribution of additive δ_s, while the third factor A, deals with the truncation due to non-additive δ_s.

The expression obtained for whipping stresses leads to a Rayleigh distribution:

$$p(\delta_w) = 2b\, \delta_w \exp(-b\, \delta_w^2)$$

where δ_w is the whipping stress and b is a function of (a, μ, σ,c). All of the above relationships can also be interpreted in terms of the corresponding effective bending moments.

On the basis of these distributions, using available slam stress data for the Wolverine State, as previously discussed, we arrive at a maximum expected increase due to slamming over the lifetime of the Wolverine State of 6.81 KPSI, corresponding to an effective increase in the sagging bending moment of 133,000 ton-ft.

Similarly the maximum expected whipping stress was calculated at 6.95 KPSI, corresponding to an effective increase of hogging bending moment of 136,000 ton-ft. These figures have been entered in Table IX, along with figures calculated for 1000 ship lifetimes.

COMBINED LOADS

The results of all the load calculations for the Wolverine State can be tabulated in the manner shown in the accompanying Table IX. Results are given on the basis of both of the following long-term assumptions (where N is the number of wave bending cycles):

(a) One ship's lifetime: $N = 10^8$ for 25 years; approximately 300 round voyages in North Atlantic service.

(b) The combined lifetimes of 1000 ships ($N = 10^{11}$), i.e., bending moment expected to be exceeded with a probability of 0.001 in a ship's lifetime.

The latter has been suggested as a basis for a rational design criterion with respect to possible ultimate failure of the hull girder.

The dynamic loads associated with slamming have been entered only for the light load condition, under the assumption that slamming seldom if ever occurs when fully loaded.

If all the maximum stresses in Table IX are added directly, an unrealistically high value is obtained, because all of the maxima will probably not occur at the same time. Hence, a reduced total has been calculated, based on combining still water and wave bending by the method of Chapter VIII. The results of this calculation are shown in Fig. 28, using the normal distributions of still water bending moment previously given and the combined vertical and lateral wave bending moment data on which Figs. 26 and 27 are based. The reduced totals in Table X were then obtained by adding the forward speed effect (if any) and one-half the average thermal effect to the values read from the curves in Fig. 28. The dynamic effects of slamming or whipping have been added directly (light load condition), under the assumption that extreme wave bending and slamming are likely to occur at the same time. This assumption is obviously not correct, but it probably does not result in a large error because both effects require rough sea conditions. The expectation that at the same time that slamming gives an increased dynamic load (demand) on the structure the capability also increases is a favorable effect of unknown magnitude.

STRUCTURAL CAPABILITY

Having estimated the probable lifetime combined loading for the Wolverine State, separated into maximum hog and maximum sag, outbound (full load) and inbound (light load), it is of interest to see what these results signify in relation to conventiona design standards. This requires that we consider a "rational" evaluation of capability as well as of demand.

First, it should be noted that if the hull of the S.S. Wolverine State behaved like an ideal girder and tensile considerations governed, the bending moment

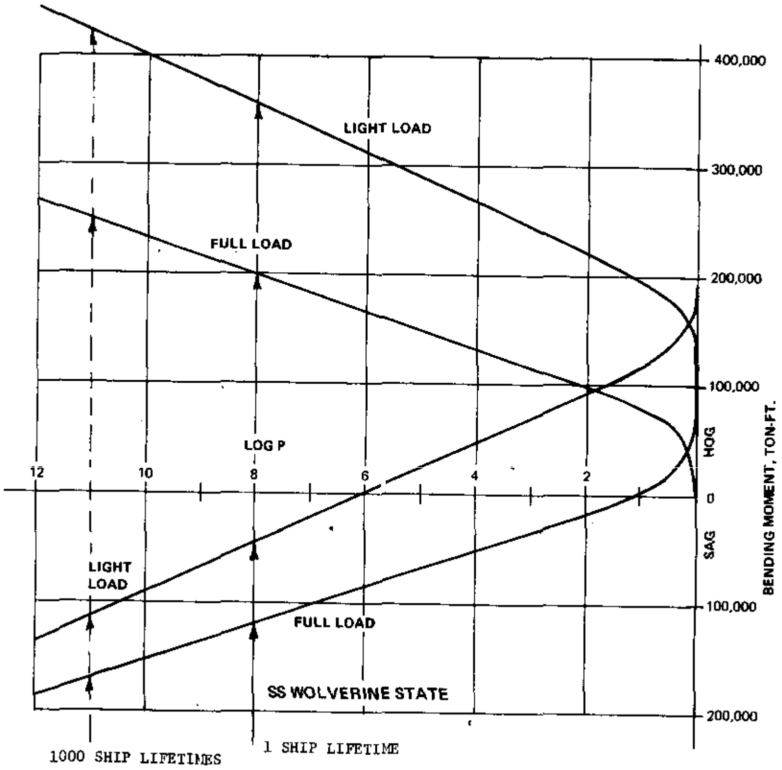

FIGURE 28 - Long-Term Distributions of Combined Bending Moments: Wave Bending (Vertical and Lateral) and Still-Water Bending

TABLE IX

SUMMARY OF LIFETIME HULL LOADS
S.S. WOLVERINE STATE

Showing individual maximum values	Average		Bending Moments in Ton-Ft. Max. Lifetime		Max. 1000 Ship Lifetimes	
	Hog	Sag	Hog	Sag	Hog	Sag
Full Load - Outbound						
Still water	40,000	-	122,400	42,400	176,800	96,800
Forward speed effect	-	1,000	0	2,700	0	2,700
Thermal effect*	22,300	22,900	46,400	47,700	46,400	47,700
Wave-induced	15,000	15,000	153,000	153,000	207,000	207,000
Dynamic	0	0	0	0	0	0
Light Load - Inbound						
Still water	157,500	-	239,900	-75,100	294,300	-20,700
Forward speed effect	-	2,200	0	5,200	0	5,200
Thermal effect*	22,300	22,900	46,400	47,700	46,400	47,700
Wave-induced			196,000	196,000	268,000	268,000
Dynamic { Slamming	-	63,650	-	133,000	-	170,000
Dynamic { Whipping	31,300	-	136,000	-	168,000	-

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*On compression flange only

TABLE X

COMBINED LIFETIME HULL LOADS
S.S. WOLVERINE STATE

Showing probable combined maximums	Bending Moments in Ton-Ft.			
	Max. Lifetime		Max. 1000 Ship Lifetimes	
	Hog	Sag	Hog	Sag
Full Load - Outbound				
Still water } Wave }[#]	200,000	118,000	252,000	170,000
Forward speed effect, average	0	1,000	0	1,000
Thermal effect, average	11,150	11,450	11,150	11,450
Dynamic	0	0	0	0
TOTALS	211,150	130,450	263,150	182,450
Light Load - Inbound				
Still water } Wave }[#]	360,000	43,000	423,000	112,000
Forward speed effect, average	0	2,200	0	2,200
Thermal effect, average	11,150	11,450	11,150	11,450
Dynamic { Slamming	-	133,000	-	170,000
Dynamic { Whipping	136,000	-	168,000	
TOTALS	507,150	189,650	602,150	295,650

[#] Combined probability.

capability at yield would be simply the product of section modulus by the yield stress of mild steel, 36 kpsi (16 tons/in^2):

Tensile yielding in deck (hogging):
Bending moment = 45,800 x 16 = 732,000 ton-ft.

Tensile yielding in bottom (sagging):
Bending moment = 47,200 x 16 = 753,000 ton-ft.

Of course, the tension flanges would be able to sustain considerably higher loads in conjunction with extensive plastic yielding.

However, it is the compression loading that usually governs the capability of a beam to sustain applied bending moments. An estimate has been made of the hull girder longitudinal bending moment capability of the S.S. Wolverine State, considering the compressive loading on this transversely framed vessel. Both hogging and sagging conditions have been considered and each will be discussed in turn.

It was assumed that the capability of a general cargo vessel's structure will be tested at sea with loading of cargo distributed more or less throughout its spaces. Thus, the 'tween deck plating would be constrained to buckle in a clamped-clamped mode by the cargo. Similarly, the lateral hydrostatic loading on bottom plating will strongly influence growth of plate deformation under in-plane loading. Weather (upper) deck plating, however, would normally not be subject to these constraints.

On the basis of the above, it was found that the plating of the 'tween decks would buckle at about two thirds of yield stress, while the heavier main deck plating would sustain in-plane loading to almost the yield stress. Schultz (129) found that due to plate unfairness the effectiveness of deck plating was about 83% and the unfairness patterns simply grew as loads increased. It was assumed that the capability could be assessed on this basis, no better information being available as to plate effectiveness in the unfair state.

The main deck plating has a nominal buckling stress in excess of 34 ksi, and because of the additional strap installed, it can be expected to sustain nearly yield stresses prior to buckling.

On the basis of the above, it was decided that a fair assessment could be made of moment capability by assuming 83% effective 'tween deck (sagging) or bottom plating (hogging) under compressive post-yield conditions.

Hogging Moment

It was assumed that decks and side plating under tension were fully effective, while bottom plating under compression was 83% effective. On such a basis the neutral axis of the effective structure was computed. Assuming next that the effective material was at compressive or tensile yield stress, the resisting moment of the effective material was computed about the neutral axis of the effective structure.

By this process it was found that the neutral axis would be at a position 24 feet above the base line and that the internal resisting moment of the section would be 753,000 ton-feet in hogging.

Sagging Moment

The buckling stress of the main deck plating was found to be

$$\sigma_c = \frac{k_c \pi^2 E}{12(1 - \mu^2)} \left(\frac{h}{b}\right)^2 = 34.5 \text{ ksi}$$

where $E = 30 \times 10^6$, thickness $h = 1.06$ in., $b = 30$ in. and Poisson's ratio $\mu = 0.3$. Under such a condition the second deck would have a stress well below buckling conditions and significant structural deformation would therefore have to take place before increased load capability could be generated. Hence, it seems reasonable to assume that all decks are fully effective. The resisting moment for main deck buckling can then be calculated from $M = \sigma Z$, where Z is the section modulus. It seems reasonable to include continuous longitudinal deck girders in the section modulus here, even though it is not customary to do so. Hence, with

$$\sigma = 34.5 \text{ ksi and } Z = 49{,}100 \text{ in}^2\text{-ft.},$$

the resisting moment for main deck buckling is

$$\sigma Z = 755{,}000 \text{ ton-feet.}$$

While it is true that additional moment could be developed in the limit as additional structure is induced until the ultimate load is reached, it appears unsound to consider it a possibility in the same sense as for hogging. The reason for this is that in hogging the double bottom is a primary system of collapse, while in sagging all three decks would have to be involved. However, if the procedure used in evaluation of hogging were used for sagging, considering upper, 2nd and 3rd decks to be 83% effective and at yield stress of 36 ksi, it is found that a load of 826 x 10^3 ton-feet could be sustained. In such a case, the neutral axis of effective material would be 20.95 feet above base line, with the moment computed about it.

Hence, in summary the estimated capability of the hull girder in hogging and sagging can be tabulated below in comparison with the expected maximum values from Table X for the light load condition.

	Capability Max. bending Ton-Ft.	Lifetime Demand Max. bending Ton-Ft.	.001 Probability Demand Max. bending Ton-Ft.
Hogging	753,000	507,150	602,150
Sagging	755,000	189,650	295,650

It is concluded that the structural capability of the Wolverine State exceeds the criterion for ultimate bending moment (demand) by a comfortable margin. This suggests that if fatigue and brittle fracture considerations were ruled out, some scantling reduction would be permissible. However, such a simplification is not permissible -- as proved conclusively by the occurrence of cracks in the upper deck of the ship in service. (See section on Fatigue).

No attempt was made to estimate the capability of the structure to resist short duration dynamic loads, but there can be no doubt that it is considerably higher than the static figures derived above.

CONVENTIONAL STRENGTH STANDARDS

At the time of the design and construction of the S.S. Wolverine State, there was no explicit section modulus requirement in the Rules of the American Bureau of Shipping, although minimum shell scantlings and strength deck sectional area were specified. It was customary to check the midship section design against the Load Line Regulations promulgated by the U.S. Coast Guard, which specified a required deck section modulus to be met by all vessels subject to Load Line assignment.

In this case the required deck section modulus by Load Line Regulations was 37,536 in^2-ft., on the basis of the formula

$$SM = f\ d\ B$$

where f is a factor having a value of 16.03 at ship length of 496 ft., d is the design draft of 32.75 ft. and B is the beam of 71.5 ft. It was customary in the case of ships with machinery aft for the ABS to add 10% to the Load-line required value, which gave a figure of 41,290 in^2-ft. Actual design values for section modulus for the Wolverine State were:

Deck	41,297 in^2-ft.
Bottom	43,161.

In 1961 a riveted doubler was added to the strength (upper) deck at the Owner's option, port and starboard. It was 5.0 ft. wide and 1 inch thick, and since its length of 169 ft. was less than 50% of the ship length it did not officially add to the section modulus. (It was also less than 40%, as required by current Rules). Recent calculations of section modulus, including the deck straps and other continuous longitudinal members omitted from the original calculation (but not deck girders), gave a deck section modulus of 45,800 in^2-ft.

A calculation of required section modulus by the current (1972) ABS Rules gives the following:

Deck	32,100 in^2-ft.
Bottom	33,100

It is impossible to relate the above required section modulus values to bending moment because the implied allowable stress is unknown. However, Arnott in 1939 (131) gave the standard design bending moment M for cargo vessels with machinery amidships as

$$M = \frac{L\Delta}{35}$$

where L is length and Δ is load displacement. Taking a block coefficient of 0.68 (minimum allowed in the Load Line and ABS Rules), the value of Δ for Wolverine State is 22,600 tons, and

$$M = \frac{496 \times 22,600}{35} = 321,000 \text{ ton-ft.}$$

At the time the ship was built this design bending moment included an unspecified still water bending moment, in addition to the wave bending moment. In fact, the 10% addition to section modulus for machinery aft was a still water consideration. The corresponding bending moment would be 353,000 ton-ft., which is smaller than the highest combined value in Table X of 602,500 ton-ft.

Current (1972) ABS Rules are more specific about still water bending moment requirements (see Chapter III). The maximum still water moment without penalty now would be 136,000 ton-ft. for this ship. If one uses the maximum lifetime still water value of 239,900 given in Table IX, this would mean an increase in the required section modulus by ABS Rules (1972) to:

Deck	47,300 in^2-ft.
Bottom	48,700

Since, as indicated above, the calculated section modulus for the ship with deck straps is 45,800 in^2-ft., it may be concluded that the ship would not quite meet present-day ABS Rule standards (1972), if the still water bending moment of 239,900 ton-ft. were considered a possible maximum value.

MINIMUM TOTAL COST CALCULATION

A preliminary and very approximate calculation has been carried out to illustrate the principles discussed in Chapter VIII for a hypothetical cargo ship, similar to the Wolverine State designed to present-day standards. As in Chapter VIII, it is assumed that the structural capability of the hull is deterministic and therefore that the probability of damage or failure is the probability of exceeding specific values of bending moment.

It was estimated that adding (subtracting) 0.2 in. to deck and bottom plating thickness would increase (decrease) the section modulus by 10% and this change would add (decrease) approximately $100,000 to the initial cost of the ship. An increase in section modulus of 10% would be equivalent to a reduction of average stress levels by a factor of 1/1.1 = 0.91, which reference to the long-term bending moment probability curves shows to correspond to a reduction of failure probability by a factor of 1/10. Similarly, a reduction in section modulus would increase failure probability by a factor of 10.

In order to carry out the calculation of total cost, the following assumptions were made:

Initial cost of ship	$15,000,000.
Replacement value at mid-life	8,000,000.
Failure cost F (replacement value + value of cargo + cost of temporary replacement)	20,000,000.

Since the structural capability of the Wolverine State was found to far exceed the demand corresponding to a lifetime probability of failure and loss of 0.001, it will be assumed arbitrarily that after a 10% reduction the section modulus of our hypothetical cargo ship would still provide at least a 0.001 failure probability, and a 20% reduction would provide 0.01 failure probability.

The total cost calculations on the basis of the above are summarized in Table XI.

TABLE XI
CALCULATED TOTAL COST
OF FAILURE

Design	I	p	pF	Total Cost
Basic Ship - 20%	$14,800,000	.01	$200,000	$15,000,000
Basic Ship - 10%	14,900,000	.001	20,000	14,920,000
Basic Ship	15,000,000	.0001	2,000	15,002,000
Basic Ship + 10%	15,100,000	.00001	200	15,100,200

This indicates an optimum somewhere near the ship with 10% reduction in section modulus. Since these figures are very rough and approximate, a number of other assumptions regarding costs and probabilities were also tried. Naturally there were changes in the final Total Cost column, but the general picture did not change significantly. This supports the conclusion in Chapter VIII that an ultimate failure probability of 0.001 is a reasonable tentative figure for a rational design criterion.

On the basis of some crude assumptions then, it appears that if only ultimate strength considerations were involved, some reduction in scantlings would be economically justified. However, it will be shown subsequently that the picture changes when consideration is given to structural damage that requires repair but does not immediately threaten the life of the ship -- as fatigue cracking, for example.

FATIGUE

Cyclic Loading

The long-term probability data discussed and presented in this chapter for the Wolverine State can be used to provide the load spectra (or patterns) which are needed to determine design criteria relative to fatigue. Since the project is concerned primarily with loads, and not with structural response, it will suffice to derive such loading spectra covering:

(a) Wave bending moments.
(b) Dynamic loads.

Results are presented in Fig. 29 for the light load condition, which corresponded to the actual normal operating condition of the ship in service. The wave stress curves are derived from Fig. 26, using actual section modulus (top), in the manner described in Chapter VIII. The dynamic stress curves were obtained by first estimating the histogram of whipping stress cycles for the light load condition (inbound) on the basis of 12 voyages per year, 0.16 probability of slamming (per 20-min. record) and 15 slams per 20-min. period when it occurs. (It was assumed that no slamming occurs in the hypothetical full-load condition, outbound). As previously noted, the techniques for predicting this in advance for a new design are not yet available. The histogram was then integrated to obtain the cumulative curve shown in Fig. 29.

It should be noted that the variation of mean value for the cyclic loading due to simple wave bending is given approximately by the still water loading information previously presented. The variation in mean value for the superimposed dynamic loading is given approximately by the data on wave bending moment (Fig. 26).

Service Experience

The Wolverine State was one of a group of five C4-S-B5 cargo ships built in 1945. A check of damage and repair records started in 1964 revealed for these ships one case of hull girder damage related to heavy weather -- the S.S. Hoosier State in January 1971, enroute from Antwerp to Philadelphia in ballast condition. A typical case of damage is described as follows:

> "Stbd. side crack between frame No. 115 and No. 116, starting at inboard rivet of gunnel bar forward to outboard rivet of deck strap, in a length of approx. 6.5 feet. Outboard rivet at crack arrester. Starts at 8 in. after frame 116 and travels aft. Crossing 117 approx. 7 ft. inboard of the longitudinal girder and travels between frames 117 and 118, 11 in. aft of 9 in. pillar and continues hatch insert approx. 9 in. and then inboard approx. 3 ft. on plate No. UD73. Longitudinal girder broken."

Temporary repairs were effected in the Azores and permanent repairs in New York in February, 1971.

Study of correspondence and the complete files of the Wolverine State and Hoosier State showed that the above type of damage had been a problem with all three of the States Marine C4-S-B5 vessels. In fact, riveted deck straps were installed by the owners in 1961 for the dual purpose of increasing the section modulus and providing additional crack arresters. Since these were war-built ships (1945) it is reasonable to assume that the quality of the steel was below the standards subsequently established. Whether there were fatigue cracks or brittle fractures, the riveted seams appeared to have been successful in limiting fracture propagation.

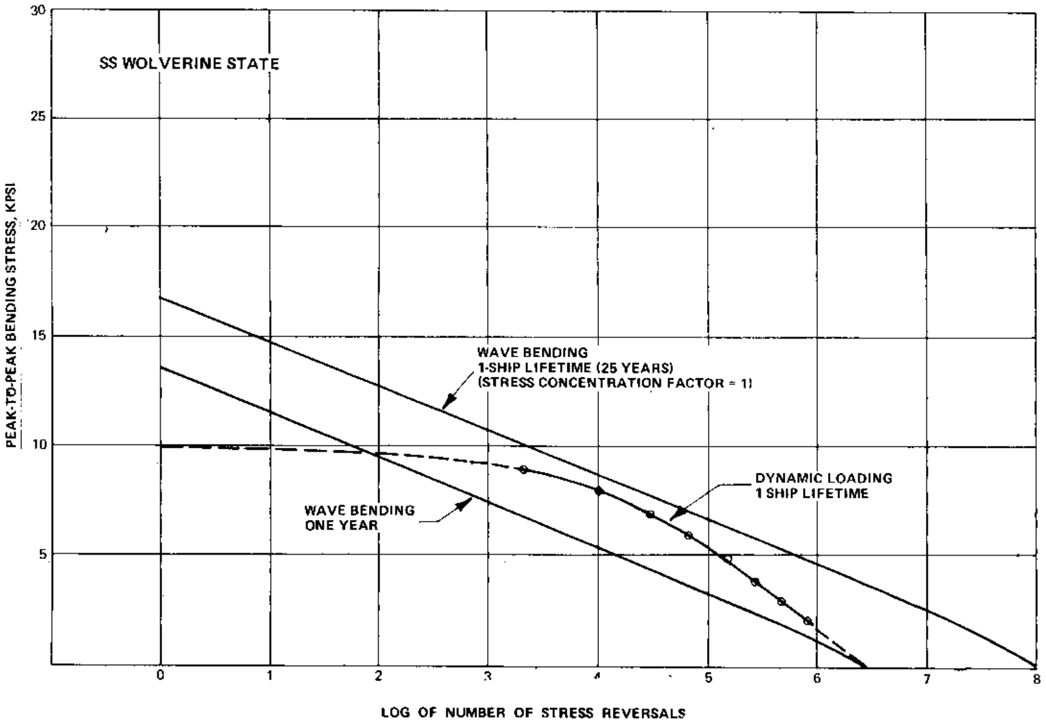

FIGURE 29 - Cyclic Loading "Spectra", *S.S. WOLVERINE STATE*

In a new ship being designed today and to be built with the present steel quality requirements, a lower probability of damage would be expected.

Total Cost with Fatigue Cracking

The total cost calculations previously presented will now be extended to include the effect of fatigue cracking, a type of damage that requires repair but rarely threatens the safety of the ship.

In addition to the previous cost and probability assumptions, it will be assumed that the lifetime expectation of structural damage, q, is 0.25 for the basic ship and that increasing (decreasing) the section medulus by 10% decreases (increases) this expectation by a factor of 1/2 (2). The cost of each damage, S (repair cost + cost of substitute ship + misc.), is assumed to be $1,000,000.

The new calculations are summarized in Table XII.

TABLE XII

CALCULATED TOTAL COST
OF FAILURE AND DAMAGE

Design	I	p	pF	q	(1-p) q S	Total Cost
Basic Ship - 10%	$14,900,000	.001	$20,000	0.5	$250,000	$15,170,000
Basic Ship	15,000,000	.0001	2,000	0.25	125,000	15,127,000
Basic Ship + 10%	15,100,000	.00001	200	0.125	62,500	15,162,500

The table indicates that when fatigue damage, as well as ultimate failure, is considered, the optimum design -- on the basis of some very crude assumptions -- is the basic ship.

It appears then that for a ship such as the Wolverine State, in which the capability far exceeds the demand associated with ultimate failure, attention must be shifted to the nuisance type damage associated with fatigue. The problem is to ascertain whether or not a reduction in scantlings on the basis of ultimate bending consideration would really increase the incidence of fatigue cracking to an uneconomical level.

BRITTLE FRACTURE

As indicated previously, no attempt has been made to establish a load criterion for brittle fracture. However, the loading picture for the Wolverine State should be the same as that obtained under Ultimate Loads, as summarized in Tables IX and X, except that we are concerned only with tensile loads. Hence, the compressive thermal effects need not be included.

Referring to Table X, it may be seen that in the light load condition, when slamming is likely, the largest bending moment would be 602,150 - 11,150 = 591,000 ton-ft. in hogging, which corresponds to a tensile load in the deck. Thus it appears that for this particular ship the principal danger of brittle fracture would be in the hogging condition as a result of large superimposed whipping following a slam. Since it has been shown that the ductile capability of the structure is above 753,000, the actual occurrence of brittle fracture would depend on stress concentrations, steel quality, temperature, and other factors.

X. CONCLUSIONS AND RECOMMENDATIONS

The following are the principal conclusions developed in the current project:

1. Basic techniques are now available for making rational calculations in probability terms of most of the loads acting on the main hull girder of modern merchant ships, including:

   Wave-induced loads.
   Still water loads.
   Thermal effects.

   Further development is needed for the calculation of dynamic loads.

2. Input data for the calculation of loads for ships on various ocean routes is incomplete. In particular, more actual wave records are needed -- even for the North Atlantic routes -- from which to obtain wave spectra for statistical treatment. Actual data on still water loads, particularly in ballast conditions, are also needed for different types of ship.

3. On the basis of the above, a rational load criterion can be set up for modern merchant ships in relation to ultimate failure by buckling or excessive permanent set, with some reservations in regard to dynamic loads.

4. A trial numerical calculation of ultimate bending loads for the S.S. Wolverine State shows that a large margin exists between the "rationally" determined loads and the capability of the hull structure to resist failure by buckling of one of the flanges. The proposed load criterion is less severe than current design standards (ABS), which presumably allow also for fatigue. When similar calculations have been made for a sufficient number of types of ship and checked against conventional empirical standards, it should be possible to adopt a new rational ultimate load criterion for use in the design of even the most unusual ships.

5. The loads affecting fatigue can be expressed as cyclic loading patterns derived from the above item 1, with separate data on the loads having different frequency of variation:

(a) Still water loads (shift of base line).
(b) Diurnal thermal effects.
(c) Low-frequency wave bending loads.
(d) High-frequency dynamic loads.

A fatigue loading criterion appears to be of great importance in design relative to keeping the frequency of occurrence of nuisance cracking at an acceptable level.

6. A load criterion relative to brittle fracture, including dynamic loads, is somewhat uncertain at the present time. However, the determination of the capability of the structure in advance of construction is also uncertain.

It is recommended that further research be carried out on subjects related to the problems of load criteria for ship design. In particular:

1. Obtain many more systematic wave records for important ocean routes that can be spectrum-analyzed and compiled systematically for reference. Of particular importance are the North Atlantic, North Pacific, and areas in the vicinity of the Cape of Good Hope.

2. Obtain systematic data from ship operators on still water loadings on several typical ships over a period of at least six months, from which actual still water bending moments can be calculated.

3. Check and refine available theories for calculating springing loads and stresses.

4. Investigate further slamming and whipping relative to midship bending stresses. Immediate emphasis in this big research area should be:

(a) Obtaining relatively short-term statistical data on the magnitudes of midship slamming stresses that are allowed to occur (by the shipmaster) on ships of different types under different conditions of loading, for guidance in preparing similar new designs.

(b) Obtaining relatively short-term statistical data on the magnitudes of the amount by which the above slamming, and whipping, increase the total combined stress (or bending moment) on ships of different types under different conditions of loading.

5. Investigate further both technical and economic aspects of fatigue damage.

6. Develop further the total cost approach to optimizing design, including failure and damage costs and making use of actual ship damage data.

7. Continue to investigate possible extreme load conditions arising from unusual circumstances, such as shallow water effects on wave spectra, unusually severe local sea conditions (Bay of Biscay), docking loads, wave impacts on side shell, loads due to shipping water on deck, etc.

8. Extend the work on wave loads beyond the determination of midship bending moments to include the determination of pressure distributions over the entire hull surface of a pitching, heaving and rolling ship. Such a detailed picture of hydrodynamic loads is believed to be essential for the application of modern finite element techniques of structural analysis.

9. Encourage parallel research on determining ship structural capability -- and probability of damage and failure -- on a probabilistic basis, considering both quasi-static and dynamic (rapidly applied) loads.

10. Investigate non-linear flare immersion effects on ships with large flare, including further study of dynamic structural response.

11. Continue research on methods for predicting slam loads and phase relations to wave bending.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of Teledyne Materials Research in furnishing additional data beyond that which has been published, of Oceanics, Inc., in connection with problems arising in the use of their computer program for wave loads, and of the American Bureau of Shipping for allowing certain results obtained at Webb under their sponsorship to be included in the report. Useful still water loading data were obtained from Mr. John Ritter of States Marine Lines and from Mr. John Boylston of Sea Land Services. Temperature data for a tanker were provided Mr. L. R. Breves of Esso International. Several part-time research assistants and students have been of assistance in various aspects of the project, including William Garzke, D. Finifter (MIT), Thomas Zielinski (Webb), and J. van Santen (Delft).

The helpful comments and suggestions on drafts of several chapters are greatly appreciated from the following individuals:

Prof. G. Aertssen, formerly University of Ghent, Belgium
Prof. J. Caldwell, University of Newcastle, England
John P. Dalzell, Davidson Laboratory
Mr. D. Faulkner, Ship Department, Ministry of Defence, Bath, England
Dr. R.A. Goodman, Lloyd's Register of Shipping, London
Prof. C.J. Jensen, Lloyd's Register of Shipping, London
M. Jourdain, Institut de Recherches de la Construction Navale, Paris
Prof. A. Mansour, Massachusetts Institute of Technology
Ir. J.J.W. Nibbering, University of Ghent, Belgium
Dr. N. Nordenstrøm, formerly Norske Veritas, Oslo
Dr. M.K. Ochi, Naval Ship Research and Development Center
Dr. Ing. Lorenzo Spinelli, Registro Italiano Navale, Genoa
Mr. K.V. Taylor, Lloyd's Register of Shipping, London

Figs. 1, 2 and 10, from a paper (3) published in the 1971 Transactions of the Society of Naval Architects and Marine Engineers, is included here by permission of that Society.

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