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Application of Loading Predictions to Ship Structure Design: A Comparative Analysis of Methods

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ABSTRACT

This paper reviews two statistical/probabilistic methods, the well-known long-term exceedance probability prediction and Ochi's extreme value approach, and compares results with the method embodied in the current ABS Rules for predicting a ship's dynamic vertical bending moment. Numerical calculations are performed for a sample tanker using the three different methods. Structural responses are also analyzed, applying different dynamic bending moments and the still-water bending moment to a finite element structural model.

Numerical results for the sample tanker indicate that Lewis' long-term exceedance prediction for 20-25 years of ship service time (probability level $10^{-7.6}$) is quite comparable to Ochi's probable extreme value. The two theoretical results are also shown to be in close agreement with the nominal dynamic bending moment specified in the ABS Rules requirements. The stress value obtained from the structural analysis based on Lewis' dynamic bending moment at $10^{-7.6}$ is comparable to the ABS required nominal permissible stress.

Ochi's design extreme value of vertical bending moment, incorporating a "risk parameter" of $0.01=10^{-2}$ for the sample ship closely agrees with corresponding exceedance prediction at a probability level of $10^{-7.6}x10^{-2}=10^{-9.6}$. The stress value for this case is higher than the nominal permissible stress required by the ABS Rules. This would indicate that if the design extreme vertical bending moment is used as the basis for the design of the ship girder structure, a higher permissible stress level should be established.

INTRODUCTION

Ever since St. Denis and Pierson published their well-known paper [1]* almost thirty years ago for handling the motions of ships in a confused sea, various theoretical procedures have been developed for predicting the ship's responses during its service time. In general, the theoretical methods fall into two categories: One is a long-term prediction of the probability of exceeding different response levels, where the Root-Mean-Square values of ship response are employed. Works by Jasper [2], Nordenstrom [3], Band [4] and Lewis [5] for example, are in this category. The other category consists of the work by Ochi [6, 7], where the extreme value theory is used. The longitudinal strength requirements of classification societies are generally developed on the basis of service experience, using a probabilistic approach to the determination of loads. For example, the theoretical procedure used by ABS in the development of its requirements employs the long-term exceedance approach developed by Band and Lewis.

The approach employed by the classification societies for establishing Rules requirements of ship longitudinal strength can be considered as semi-probabilistic since loads are predicted by a probabilistic method, but strength (permissible stress) is deterministic. Since various methods are often used in practice, a brief review of the long-term exceedance prediction of Lewis, Ochi's extreme value approach, and the method involved in the ABS Rules is given in the following.

Lewis [5] examined the 30-minute records of midship bending stress obtained every 4 hours from the C4-S-B5 cargo ships Wolverine State and Hoosier State in several years' service in the North Atlantic. He found that the individual data samples fitted closely to the Rayleigh distribution. Furthermore, dividing all the stress data into weather groups, the mean square values of available stress samples in each weather group were found to follow the normal distribution. Consequently, Band [4] suggested a probability model where the two aforementioned distributions were assumed to apply to a much larger "population" (or quantity of data). Hence,

* Number in brackets designates reference at end of paper.

an ideal cummulative distribution of stresses (or bending moments) could be constructed for each weather group by summing up all of the many Rayleigh distributions and integrating to different stress (or bending moment) levels. The total cummulative distribution could then be obtained by combining all of the individual cummulative distributions on the basis of the actual percentage of time each weather group would be encountered by ships in service, and on the basis of average weather on some particular route such as the North Atlantic. Little and Lewis [8] further evaluated the idealization of statistical data against the stress data collected from five ships with about 3-1/2 years' service. These five ships consisted of four tankers and one bulk carrier, and are 754.6 to 1076 feet in length. In addition, Lewis introduced the so-called H-family wave spectra which were selected in a random fashion from those given by Pierson, et.al [9]. The H-family wave data consists of five weather groups in accordance with significant wave heights 10, 20, 30, 40 and 48.2 feet. With the exception of the last group which contains 12 spectra, all other groups contain 10 spectra.

In contrast to Lewis' approach, Ochi [7] first analyzed wave data collected at Stations A, B, C, D, I, J and K in the North Atlantic, and then derived two families of wave spectra of two- and six- parameter, respectively, which can be considered to represent the "mean North Atlantic" sea conditions. Both the two- and six- parameter spectral family consists of 18 different sea severities (significant wave heights). But the numbers of wave spectra in each sea severity of the two families are different. In the two-parameter family, for each significant wave height there are nine spectra. The six-parameter family has eleven spectra for each significant wave height. For dynamic load prediction, Ochi introduced an approach based on extreme value theory. This predicts the highest response expected in a ship's lifetime by calculating the short-term extreme value for the most severe sea condition expected. Ochi also developed a long-term extreme value method where the frequency of various sea severities, as well as other factors including wave spectral shapes, ship speeds, and heading angles, are weighted according to their occurrence during the ship's service life time. This approach is similar but not identical with the Lewis method.

Prior to 1975, the basic concept of ABS Rules requirements for primary, longitudinal strength of the hull girder was to prescribe for each individual ship a basic section modulus based on its main geometric characteristics. The required section modulus amidships was then specified in terms of the basic section modulus and the maximum still-water bending moment in the governing loaded condition. With this section modulus the maximum primary bending stress in the hull girder, which can be produced when the maximum possible longitudinal bending moment is imposed on the ship could not exceed a nominal permissible stress level, which varied with ship length. The requirements for longitudinal strength in the above described form were successfully applied to ships for many years. Since 1975, ABS Rules strength requirements have been presented in a different format, in order to accommodate the recent findings obtained from the long-term dynamic or wave load studies. For the purpose of ship longitudinal strength evaluation, ABS now employs the long-term response prediction method suggested by Band and Lewis to generate a long-term response trend which is used as a basis for extending the existing ABS Rules to larger ships. The new requirements are specified in terms of the nominal still-water and wave-induced vertical bending moments. Stress limits are then specified in conjunction with the longitudinal strength requirements.

In view of the different assumptions and different approaches employed in the above two theoretical methods for determining extreme loads, it is of interest in this paper to investigate the ship structural response for the dynamic wave loads which are determined by each of the different methods, and to compare them with those given in the latest ABS Rules. Ship structural response subject to different loads at different probability/confidence levels will also be calculated, using a simplified finite-element structural model of a sample ship. No attempt is made to compare or correlate the theories pertaining to the different approaches. Mathematical derivations and proofs are avoided, with the exception of those necessary for presentation of the related topics. Evaluation and verification of the assumptions involved in developing the different methods can be found in other published literature. This paper begins with a summary of equations and formulas associated with the three different methods for determining loads under consideration. It is followed by a summary of the H-family and the six-parameter wave spectral data. Theoretically calculated dynamic loads based on these wave spectra, and the mathematical structural model of the sample ship are then presented. In the remainder of this paper, computed structural results of the sample ship, and concluding remarks are given. It is the authors' hope that through the numerical example, some light can be shed on the application of the different statistical/probabilistic methods for the evaluation of ship girder longitudinal strength.

PROCEDURES OF STATISTICAL/PROBABILISTIC METHODS FOR LOADS

Long-term Exceedance Probability (based on RMS values)

The basic assumption involved in this approach is that the short-term response of a ship in statistically unchanging seas is a narrow band process, and is distributed according to the Rayleigh distribution. That is, the probability density function, $f(x)$, of a random variable x takes the form:

$$f(x) = \frac{2x}{E}\exp(-x^2/E) \qquad (1)$$

where $E>0$ is the parameter of Rayleigh distribution for $0<x<\infty$. The parameter E is equal to twice the mean square value, m_o, if the peak value x is a single amplitude. If x is a double amplitude, E equals eight times m_o.

Defining by $g(\sqrt{E})$ the probability distribution of $\sqrt{E}$ to account for the variation of sea state (weather), ship speed, loading condition, and heading angle, then, by definition, a conditional distribution of x with respective to $\sqrt{E}$ is

$$f(x,\sqrt{E}) = f(x\,|\sqrt{E})g(\sqrt{E}), \qquad (2)$$

which leads to the probability of x exceeding x_o as

$$\Pr\{x\geq x_o\} = \int_0^\infty \exp(-x_o^2/E)g(\sqrt{E})d\sqrt{E}. \quad (3)$$

The probability given by the above equation is equal to the reciprocal of the number of cycles, $n(x_o)$, in which the random variable x is expected to exceed the value x_o once. The reciprocal of the number of cycles is also referred to as the probability level.

Most presently used long-term response prediction methods based on RMS values generally follow the format shown in equation (3). Differences, however, exist in the form of the probability distribution $g(\sqrt{E})$ suggested by different investigators, based on different data being employed in their analyses. In Lewis' approach, the probability is separated into two parts; one being the conditional probability that x exceeds x_o within each of a number of weather groups, the other being the probability with which the ship encounters each of these weather groups. Thus, equation (3) is expressed as

$$\Pr\{x\geq x_o\} = \sum_k \Pr(W_k)\Pr\{x\geq x_o|W_k\}, \qquad (4)$$

where $\Pr(W_k)$ is the probability of encountering the k-th weather group, $\Pr\{x\geq x_o|W_k\}$ is the conditional probability which, in turn, has similar expressions of the right-hand side of equation (3). Lewis further assumed that, for a specific condition of loading, the probability distribution of $\sqrt{E}$ was a function of ship speed and heading, and was a normal distribution in a particular weather group. Substituting this normal distribution into equation (4), it can be realized that the analytic integration is not possible. For numerical calculation, a value of five times the standard deviation has been adopted to replace the infinite upper limit of the integral like the one in equation (3). The finite upper limit of $\sqrt{E}$ has been shown by Band as the minimum value to insure sufficient accuracy in the final result. As a consequence, in Lewis' approach, the conditional probability that the variable x exceeds x_o in a particular weather group, W_k, can be evaluated numerically using the equation as follows:

$$\Pr\{x\geq x_o|W_k\} = \sum_{\sqrt{E}=0}^{\mu_k+5\sigma_k} \frac{1}{\sqrt{2\pi}\,\sigma_k} \times \exp\left\{\left[\frac{x_o}{\sqrt{E}}\right]^2 - \frac{(\sqrt{E}-\mu_k)^2}{2\sigma_k^2}\right\}(\delta\sqrt{E}) \qquad (5)$$

where

μ_k = mean value of $\sqrt{E}$ in k-th weather group, W_k

$$= \frac{1}{n_k}\sum_{i=1}^{n_k}\sqrt{E_i}\,,$$

σ_k^2 = variance of $\sqrt{E}$ about μ_k in k-th weather group, W_k

$$= \frac{1}{n_k}\sum_{i=1}^{n_k}(\sqrt{E_i}-\mu_k)^2$$

The total number of lifetime load cycles, $n(x_o)$, to be used for determining the load which is expected to exceed x_o, is given by Ochi, as in equation (11) of the next section.

Ochi's Extreme Value Approach

The extreme value is defined as the largest value of a random variable expected to occur in n observations. Denoting $\bar{y}_n$ as the modal value or the most probable largest value of the extreme probability distribution, it can be shown (see Hoffman and Karst [11], for example) that $\bar{y}_n$ has the asymptotic form for large n:

$$\frac{\bar{y}_n}{\sqrt{E}} = (\ell nn)^{1/2} + \frac{1}{2}\gamma(\ell nn)^{-1/2}+O(\ell nn)^{-3/2} \qquad (6)$$

where γ=0.5722....., the Euler's constant, and E is defined in equation (1). If the random process is narrow band, Ochi and Bolton [6] showed the number n in equation (6) can be expressed by

$$n = \frac{3,600T}{2\pi} (m_2/m_o)^{1/2} \qquad (7)$$

where

T = time in hours

m_o = area under the spectrum of random variable considered (mean square value of ship response in the present work)

m_2 = area under the second moment of random variable considered.

Considering the first term on the right hand side of equation (6), and using equation (7), Ochi's short-term probable extreme value approach is obtained as follows:

$$\bar{y}_n = \left[E\ell n \left\{ \frac{3600T}{2\pi} \sqrt{m_2/m_o} \right\} \right]^{1/2} \qquad (8)$$

Ochi and Bolton further showed that an extreme value higher than $\bar{y}_n$ given by equation (8) would occur with probability 0.632 for large n. This probability value is too high for prediction purpose in practice. Thus, a risk parameter α (usually taken to be 0.01) is introduced into equation (8). Denoting the recently obtained value by $\hat{y}_n$, then Ochi's short-term design extreme value, i.e., the expected highest value in a fleet of (1/α) similar ships, is

$$\hat{y}_n = \left[E\ell n \left\{ \frac{3600T}{2\pi(\alpha/k)} \sqrt{m_2/m_o} \right\} \right]^{1/2} \quad . \qquad (9)$$

In equations (8) and (9), m_o and m_2 are defined in equation (7). In addition,

T = longest duration of specified seas in hours

α = risk parameter

k = number of encounter with a specified sea in ship's service time

E = $2m_o$, if the peak value is a single amplitude; $8m_o$ for double amplitude.

Equations (8) and (9) are the basis for the subsequent sample calculation of the probable and design extreme values.

Ochi also developed his own version of the long-term response prediction methods for the most probable extreme value and the design extreme value. The probability density function of his long-term response is shown as follows:

$$f(x) = \frac{\sum\limits_{ijk\ell}\sum\sum\sum n_* p_i p_j p_k p_\ell f_*(x)}{\sum\limits_{ijk\ell}\sum\sum\sum n_* p_i p_j p_k p_\ell} \quad , \qquad (10)$$

where

$f_*(x)$ = probability density function for short-term response,

n_* = average number of response per unit time of short-term response,

$= \frac{1}{2\pi} \sqrt{(m_2)_*/(m_o)_*}$,

$(m_o)_*$ = mean square value of response spectrum,

$(m_2)_*$ = second moment of response spectrum,

p_i, p_j, p_k, p_ℓ = probabilities of sea condition, wave spectrum, heading angle and ship speed, respectively.

The total number, n, of responses expected in the lifetime of a ship is

$$n = (\sum\limits_{ijk\ell}\sum\sum\sum n_* p_i p_j p_k p_\ell) \times T \times (60)^2, \quad (11)$$

where T is the total exposure time of a ship to the sea.

The cumulative distribution of the probable extreme value, $F(\bar{y}_n)$, can be obtained by integrating equation (10). The function $F(\bar{y}_n)$, as shown by Ochi, has the following relationship with the total number, n, of response for a large n:

$$\left[1 - F(\bar{y}_n)\right]^{-1} = n \quad . \qquad (12)$$

For the design extreme value, $\hat{y}_n$, equation (12) is also applicable, except that the term on the right-hand side should be replaced by n/α, where α is the risk parameter.

Approach in ABS Rules

For the purpose of numerical comparison with other methods, only the vertical bending moment is considered. The required bending moment for ship girder longitudinal strength evaluation in the current ABS Rules [10] expresses the total bending moment amidships, M_t, as follows:

$$M_t = M_{SW} + M_W \quad , \qquad (13)$$

where M_{SW} and M_W are respectively the still-water bending moment and wave-induced bending moment. These bending moment components are given by

$$M_{sw} = C_{st} L^{2.5} B(C_b + 0.5) \qquad (14)$$

and

$$M_w = C_2 L^2 B H_e K_b \qquad (15)$$

where

$$C_{st} = \left[0.618 + \frac{110 - L}{462}\right]10^{-2}, \quad 61 \le L \le 110 \text{ m}$$

$$= \left[0.564 + \frac{160 - L}{925}\right]10^{-2}, \quad 110 < L \le 160 \text{ m}$$

$$= \left[0.544 + \frac{210 - L}{2500}\right]10^{-2}, \quad 160 < L \le 210 \text{ m}$$

$$= [0.544]10^{-2}, \quad 210 < L \le 250 \text{ m}$$

$$= \left[0.544 - \frac{L - 250}{1786}\right]10^{-2}, \quad 250 < L \le 427 \text{ m}$$

$$= \left[0.312 + \frac{360 - L}{2990}\right]10^{-3}, \quad 200 \le L \le 360 \text{ ft}$$

$$= \left[0.285 + \frac{525 - L}{6100}\right]10^{-3}, \quad 360 < L \le 525 \text{ ft}$$

$$= \left[0.275 + \frac{690 - L}{16400}\right]10^{-3}, \quad 525 < L \le 690 \text{ ft}$$

$$= [0.275]10^{-3}, \quad 690 < L \le 820 \text{ ft}$$

$$= \left[0.275 - \frac{L - 820}{11600}\right]10^{-3}, \quad 820 < L \le 1400 \text{ ft}$$

$$H_e,\text{Meter} = 0.0172L + 3.653, \quad 61 < L \le 150 \text{ m}$$

$$= 0.0181L + 3.516, \quad 150 < L \le 220 \text{ m}$$

$$= (4.5L - 0.0071L^2 + 103) \times 10^{-2}, \quad 220 < L \le 305 \text{ m}$$

$$= 8.151, \quad 305 < L \le 427 \text{ m}$$

$$H_e,\text{ Feet} = 0.0172L + 11.98, \quad 200 < L \le 490 \text{ ft}$$

$$= 0.0181L + 11.535, \quad 490 < L \le 720 \text{ ft}$$

$$= (4.5L - 0.00216L^2 + 335) \times 10^{2}, \quad 720 < L \le 1000 \text{ ft}$$

$$= 26.75, \quad 1000 < L \le 1400 \text{ ft}$$

$K_b = 1.0$ for $C_b \ge 0.80$
$= 1.4 - 0.5C_b$ for $0.64 \le C_b < 0.80$

C_b=block coefficient at summer load waterline. C_b is not to be taken less than 0.64. See [10] for the details.

$C_2 = (2.34C_b + 0.2) \times 10^{-2}$ for metric units
$= (6.53C_b + 0.57) \times 10^{-4}$ for inch/pound units

L,B=ship length and beam in meters or feet. (See [10] for the details).

The still-water and wave-induced bending moments given by equations (14) and (15) are in metric ton-meters or ton-feet. It should be noted that the term H_e in equation (15) does not represent a wave height. Rather, it is a parameter for calculating the required wave-induced bending moment by equation (15). The combination of the wave-induced bending moment and the still-water bending moment from equations (14) and (15), together with nominal permissible stress, would give rise to the section modulus required by ABS Rules. On the other hand, for $C_b > 0.8$ and the waterplane coefficient > 0.90, the value of the term H_e of equation (15) is approximately equal to the effective wave height used in the quasi-static calculation of bending moment. A more detailed discussion on this point can be found in the work by Stiansen and Chen [12].

The nominal permissible bending stress, in principle, should be a constant. However, to account for the different tolerated corrosion margins for different ships, and possible dynamic loading components, such as lateral bending and vibratory bending, might not be in the same proportion as the vertical bending, the nominal permissible stress suggested in the ABS Rules varies with ship's length, L, as follows:

$$f_p = 1.663 - \frac{240-L}{1620} \text{ tons/cm}^2, \quad 61 \le L \le 240 \text{ m}$$

$$= 1.663 + \frac{L-240}{4000} \text{ tons/cm}^2, \quad 240 < L \le 427 \text{ m}$$

$$= 10.56 - \frac{790-L}{845} \text{ tons/in}^2, \quad 200 < L \le 790 \text{ ft} \qquad (16)$$

$$= 10.56 + \frac{L-790}{2045} \text{ tons/in}^2, \quad 790 < L \le 1400 \text{ ft}$$

where f_p is the nominal permissible stress for <u>mild steel</u>.

WAVE SPECTRAL DATA

In the present work, two different wave spectral families are used in the dynamic response (vertical bending moment amidships) calculation for the sample ship; one is the H-family spectra introduced by Lewis, the other is Ochi's six-parameter wave spectra of the "mean North Atlantic."

The H-family of wave spectra was randomly selected from those prepared by Pierson [9]. The primary records used in Pierson's analysis were taken by the National Institute of Oceanography (U.K.) on British weather ships at Stations A, I, J and K in the North Atlantic. A total of 52 wave spectra in the H-family are grouped into 5 groups as shown in Table I. The characteristics of the average spectrum of each of the five groups in the H-family are shown in Table II. In Figure 1, the spectra of one group are displayed.

Nominal Significant Wave Height, Feet	Percentage of Occurrence	Number of Spectra
10	84.54	10
20	13.30	10
30	2.01	10
40	0.14	10
48.2	0.01	12

Table I - Percentage of occurrence and number of spectra of H-family wave data

Wave Group	1	2	3	4	5
H_s	3.362	6.071	8.839	11.810	14.378
m_{-1}	1.091	3.954	9.175	18.592	29.830
m_0	0.706	2.303	4.663	8.718	12.920
m_1	0.524	1.576	3.044	4.746	6.514
m_2	0.451	1.290	2.296	3.167	4.090
m_3	0.449	1.260	2.112	2.641	3.339
m_4	0.507	1.422	2.301	2.714	3.443
ω_p	0.550	0.500	0.450	0.400	0.400

Table II - Characteristics of the average spectra of the H-family wave data

Notes: H_S = significant wave height in meters

m_n = moments of wave spectrum in metric units, for n=-1,0,1,2,3 and 4

ω_p = peak frequency in rad/sec.

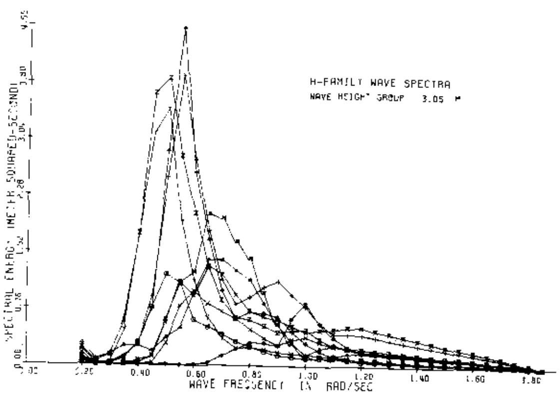

Fig. 1 - H-family wave spectra for significant wave height 3.05 meters

Ochi's six-parameter wave spectral family of the "mean North Atlantic" consists of 18 groups in accordance with the significant wave height. The suggested percentage of occurrence by Ochi [7], the significant wave heights and the durations of the sea states used in the present work are shown in Table III. The assumed duration of each particular sea state as shown in this table is approximately the same as that in Ochi and Motter [13], with the exception of the wave group of one meter significant wave height.

Significant Wave Height (meters)	Percentage of Occurrence	Duration Sea State (hours)
1.0	0.0503	50.0
1.5	0.2665	46.0
2.5	0.2603	46.0
3.5	0.1757	46.0
4.5	0.1014	46.0
5.5	0.0589	45.0
6.5	0.0346	39.8
7.5	0.0209	36.1
8.5	0.0120	30.1
9.5	0.0079	24.2
10.5	0.0054	17.0
11.5	0.0029	13.9
12.5	0.0016	9.3
13.5	0.00074	5.8
14.5	0.00045	4.1
15.5	0.00020	3.3
16.5	0.00012	3.3
17.0	0.00009	3.3

Table III - Wave group, percentage of occurrence, and duration of sea state of six-parameter wave family

Within each significant wave group of the six-parameter wave family, there are 11 members, of which the most probable spectrum is weighted by a factor of 0.50, and each of all other spectra is weighted by 0.05. For the significant wave height specified in the above table, spectra are generated using the following formula

$$S(\omega) = \frac{1}{4} \sum_j \left[\frac{(\lambda_j + 0.25)\,\omega_{mj}^4}{\Gamma(\lambda_j)} \right]^{\lambda_j} . \qquad (17)$$

$$\times \frac{H_{sj}}{\omega^{4\lambda_j+1}} \exp\left[-(\lambda_j + 0.25) \left(\frac{\omega_{mj}}{\omega} \right)^4 \right]$$

where $\Gamma(\lambda_j)$ is a gamma function, and j=1,2 stands for the lower and higher frequency components, respectively. In equation (17), the parameters H_{sj}, ω_{mj}, and λ_j are functions of significant wave height, and are given in Table IV of Ochi [7]. An example of the six-parameter family is shown in Figure 2.

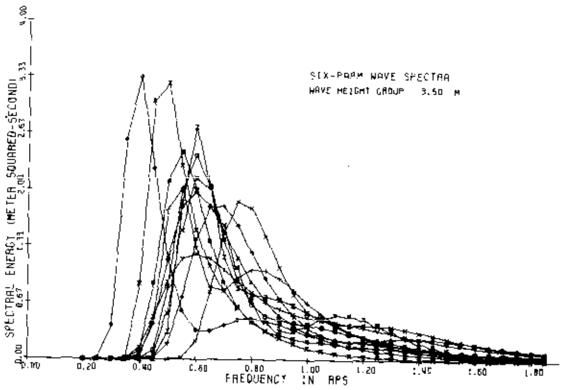

Fig. 2 - Family of six-parameter wave spectra for significant wave height 3.50 meters

NUMERICAL EXAMPLE OF RESPONSE CALCULATION

As a numerical example, the three different approaches discussed in the previous sections have been applied to an existing tanker for the dynamic vertical bending moment amidships calculation in the fully loaded condition of 105,700.00 metric tons. The hull girder scantling of this vessel was designed based on the wave-induced bending moment required by the ABS Rules, which is 345,800 meter-tons, and an allowable still-water bending moment of 207,800 meter-tons. The designed section modulus is 333,900 cm^2-meters for mild steel, leading to a bending stress at midship section of 1.658 tons/cm^2 which is the permissible stress specified in the current ABS Rules (see also equation (16) of this paper). Other information of the sample ship is shown in Table IV. In Figure 3, a sketch is presented showing the profile and cargo tank arrangement of the sample ship, where indication of the extent of the structural model used in the stress analysis is also given.

LBP, length between perpendiculars	234.00 m
B, breadth moulded	39.60 m
D, depth moulded	20.60 m
d, draft fully loaded	13.72 m
C_b, block coefficient for design draft	0.8165
V, ship speed designed	15 knots

Table IV - Principal particulars of the sample ship

Results of Long-term Exceedance Probability Prediction

When Lewis' long-term response prediction is used for computing the dynamic vertical bending moment, the H-family wave spectra discussed in the previous section are applied. The conditional probability for each wave group is evaluated according to equation (5) at 12 heading angles from the following sea to

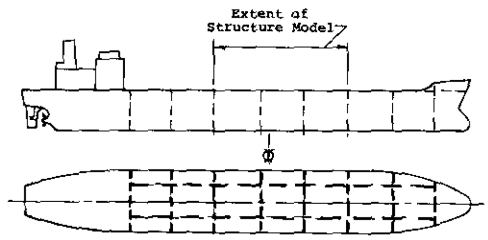

Fig. 3 - Profiles and tank arrangement of the sample ship

the head sea with an interval of 30 degrees, where the probability of encountering the different heading angle is assumed to be the same. The response spectra are calculated based on the H-family wave spectra and the transfer function of vertical bending moment by the program ABS/SHIPMOTION, wherein the ship speed is taken as 75 percent of design speed. ABS/SHIPMOTION program in computing the transfer function follows the strip method and the linearized ship motion theory. The mathematical derivation and the computational procedure of the program are discussed in the works of Raff [14], Kaplan [15], Kaplan, Sargent and Silbert [16], and Stiansen and Chen [12].

In the calculation of mean square response value for determining the conditional probability by equation (5), the cosine-square spreading function is employed to simulate the short-crestedness of the seaway. The spreading function used in the computation is given as

$$f(\mu_\omega)=\frac{2}{\pi}\cos^2(\mu_\omega) \qquad (18)$$

where μ_ω is the heading angle of the ship with respect to the wave. Furthermore, the ship's response in a seaway is considered as a random process which is not necessarily narrow band. For this case, the mean square value of the response spectrum is obtained by multiplying the mean square value of a narrow band process by a factor of $(1-\varepsilon^2/2)$ as Ochi and Bolton [6] suggested. Here ε stands for the broadness of response spectrum.

The conditional probability functions based on the H-family wave spectra are substituted into equation (4) for calculating the total probability, where the percentage of occurrence of each wave height group given in Table I is employed. Since the total probability is equal to the reciprocal of the number of response cycles, a curve can be obtained to represent the response of exceedance versus the number of response cycles (hence the probability level). Shown in Figure 4 is such a curve for the dynamic vertical bending moment amidships of the sample ship in the fully loaded condition.

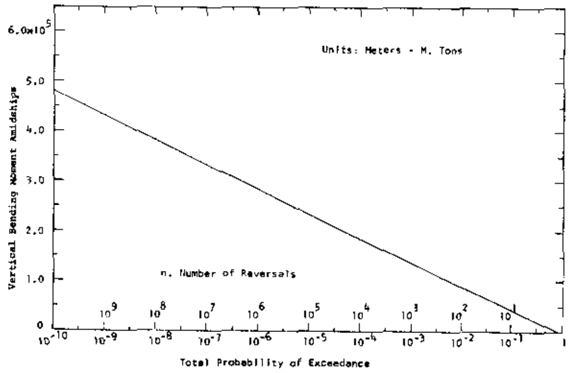

Fig. 4 - Long-term vertical dynamic bending moment at midship section of the sample ship in fully loaded condition, based on the H-family wave spectra

Assuming two-thirds of 20-year service time that the ship is exposed to the sea, the total number of vertical bending moment cycles of the sample ship, n, is calculated by equation (11). It should be noted that, for a non-narrow band response spectrum, the average number of response per unit time of short-term response, n_*, in equation (11), should be modified as suggested by Ochi and Bolton. The number of response cycles, n, calculated for the sample ship in this manner is $10^{-7.6}$. Consequently, as can be seen from Figure 4, the dynamic vertical bending moment of exceedance in 20-year service time is $3.61x10^5$ meter-tons at the probability level of $10^{-7.6}$.

The concept of applying a risk parameter, α, in Ochi's design extreme value can also be incorporated in the long-term exceedance probability prediction. Karst showed in Appendix A of Reference [17] that, with $(1-\alpha)$ percent assurance, the expected response to be exceeded should be read from the long-term response curve as the one in Figure 4 at a probability level of αn^{-1}, provided $\alpha \ll 1$ and $n \gg 1$. This is equivalent to the exceedance to be expected once in the service time of $(1/\alpha)$ similar ships. Taking $\alpha=0.01$, the expected vertical bending moment of the sample ship to be exceeded in the sea way represented by the H-family wave spectra, is given at the probability level of $10^{-9.6}$, which is $4.6x10^5$ meter-tons.

Similar to the H-family wave data, the six-parameter wave spectra generated by equation (17) based on the characteristics in Table III, are also employed in Lewis' long-term response prediction for the sample ship. The number of vertical bending moment cycles in 20-year service time is $10^{7.61}$. The expected vertical bending moment to be exceeded at probability levels of $10^{-7.61}$ and $10^{-9.61}$ are respectively $3.68x10^5$ and $4.54x10^5$ meter-tons. Comparing these results with those based on the H-family, it is interesting to notice that long-term prediction values of the two different families are very close.

Results of Ochi's Extreme Values

The short-term probable extreme value and the short-term design extreme value of vertical bending moment of the sample ship, are calculated by equations (8) and (9). In the calculation, only the six-parameter wave spectral family is employed. Assuming two-thirds of the 20-year service time that the ship is exposed to the sea, the total time of the most severe sea state of 17 meters significant wave height that the ship will encounter is 10.37 hours. If the average duration of this sea state is 3.3 hours, the number of encounters with this sea condition is about 3 times. For the sample ship, the calculations show that the vessel in head sea conditions give rise to the maximum vertical bending moment, which is $3.42x10^5$ meter-tons of the probable extreme value, and is $4.65x10^5$ meter-tons of the design extreme value with a risk parameter $\alpha=0.01$. Since Ochi's long-term extreme values should be the same as the short-term extreme values, as discussed by Ochi [7], the long-term extreme vertical bending moments for the sample ship in the present work are not presented. In order to compare the results of the two statistical/probabilistic approaches and that required by ABS Rules, Table V is prepared, from which it can be seen (a) There is practically no difference in the long-term exceedance predictions using the H-family wave data and the six-parameter spectra, (b) Comparing probable and design extreme values with long-term exceedance predictions at probabilistic levels of $10^{-7.6}$ and $10^{-9.6}$, respectively, calculation shows that the results of these two different statistical/probabilistic methods are comparable, and (c) The nominal vertical wave-induced bending moment required in ABS Rules is about 4 percent less than the exceedance prediction at a probability level of $10^{-7.6}$, and about the same with the short-term probable extreme value.

ABS Rules	Long-term Exceedance		Ochi's Extreme	
	$10^{-7.6}$	$10^{-9.6}$	Probable	Design
$3.458x10^5$	$3.61x10^5$	$4.6x10^5$	$3.42x10^5$	$4.65x10^5$

Table V - Comparison of vertical wave bending moments amidships of the sample ship

Note: Bending moment in meter-tons.

STRUCTURAL RESPONSE ANALYSIS

The structural response analysis is performed for the sample ship by using the program SHIPOPT developed by Hughes, Mistree and Zanic [18]. This program was developed for analyzing the structural response (stress, deflection, etc.), predicting the critical or failure values of the structural response, and optimizing the scantlings of all girders, frames and stiffened panels in segments of the hull girder. To achieve the functions just mentioned, the ship structure is represented by a finite-element structural model which consists of a number of compartments with the transverse bulkheads as the boundaries. The basic type of elements to represent the hull structure are:

(a) Multiribbed plane stress element for modeling the panels of stiffened plating. The element is nonconforming, and has constant shear stress and linearily varying direct stresses.

(b) Composite beam element for modeling of bracketed beams attached to plating.

(c) Strut element for modeling of pillars, screen bulkheads, passageways, and other portions of structure which are not primarily structural members but, because of their inplane rigidity, do contribute to the stiffness of the overall structure.

(d) Basic plane stress element (triangular and quadrilateral element).

In the present work, the midship portion containing three compartments as indicated in Figure 3 is modeled by finite elements. The midship portion of the ship is chosen, as it usually is subjected to the largest bending moment. Figure 5 illustrates a typical structural section where the strake number and node point number assigned in the finite-element structural model are also shown. Figure 6 shows one-half of the finite-element model with the centerline plane as the plane of structural symmetry. Figures 7 and 8 show the transverse bulkhead at model Frame 0 and the web frame at model Frame 9. For the analysis, the bending moments and shear forces are applied at the two end bulkheads of the structural model. The bending moments and shear forces on the boundaries of the structural model are computed by setting the ship on a simple wave with a length approximately the same as the ship's length. The wave height is chosen such that the total vertical bending moment is equal to the sum of the dynamic bending moment and the still-water bending moment of the ship in the loading condition under consideration. Bending moments and shear forces at the two end boundaries of the structural model are obtained from the quasi-static condition. Pressure exerted on the side and bottom shell structure is directly calculated based on the local draft of the ship in the simple wave.

In view of the long-term exceedance results, which are very close to those by Ochi's extreme value approach, as shown in Table V, structural analysis is performed for two cases where the dynamic vertical bending moment amidships are 3.61×10^5 and 4.6×10^5 meter-tons. These cases correspond to Lewis' results at $10^{-7.6}$ probability level (corresponding to Ochi's probable extreme value) and $10^{-9.6}$ (corresponding to Ochi's design extreme value), respectively. The longitudinal inplane plating stresses for these two cases are shown in Figure 9, which indicates that for the case of $10^{-7.6}$ probability level, the maximum stress is 2.10 tons/cm^2 in the deck and 2.16 tons/cm^2 in the bottom plating. For the case of $10^{-9.6}$ probability level the maximum stress is 2.43 tons/cm^2 in the deck and 2.32 tons/cm^2 in the bottom plating. It should be noted that the inplane stress consists of the primary stress and the secondary stress. It should also be noted that, as indicated in Figure 5, the bottom and deck plating, and other parts of the structure are of high-tensile steel. For these structural members the allowable stress value is higher than in mild steel by the ratio of

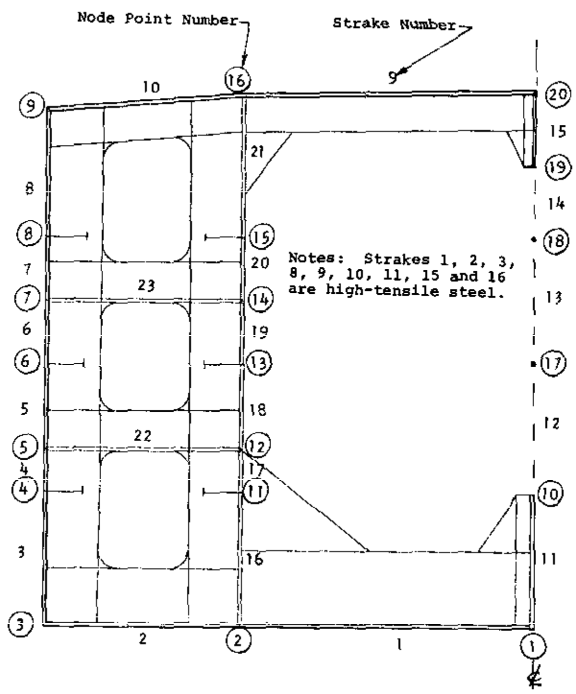

Fig. 5 - Typical section of structure, together with strake and node point number used in finite-element structural model

1/0.78 or 1.28. Applying this factor to the stresses obtained from the finite-element analysis, it can be seen that the stress level for the case of a $10^{-7.6}$ probability level is close to the ABS required nominal permissible stress of 1.658 tons/cm². In the case of a $10^{-9.6}$ probability level, the maximum inplane stress exceeds the nominal permissible stress by about 14 percent.

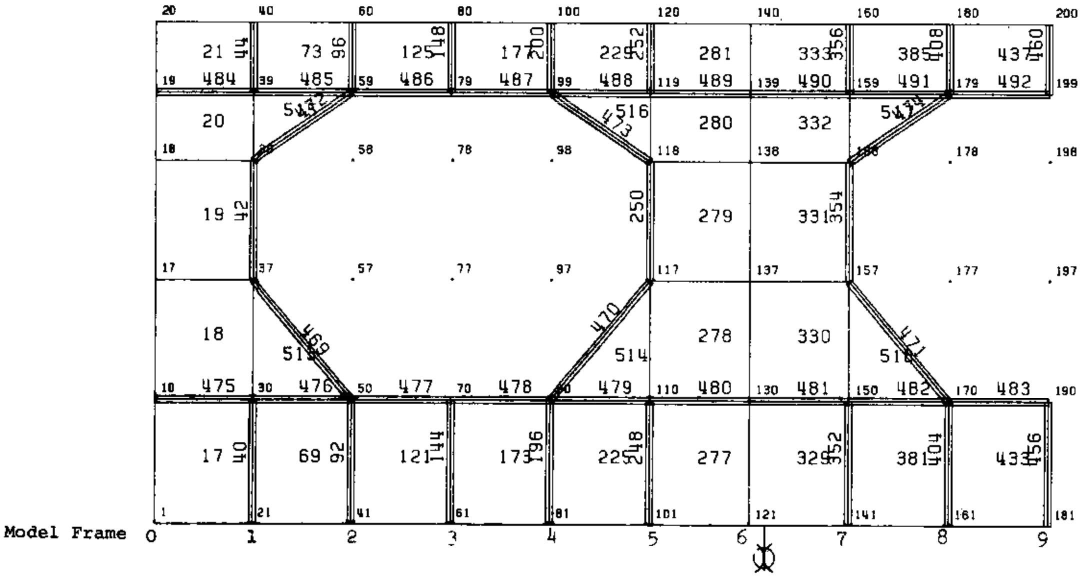

Fig. 6 - Finite-element structural model

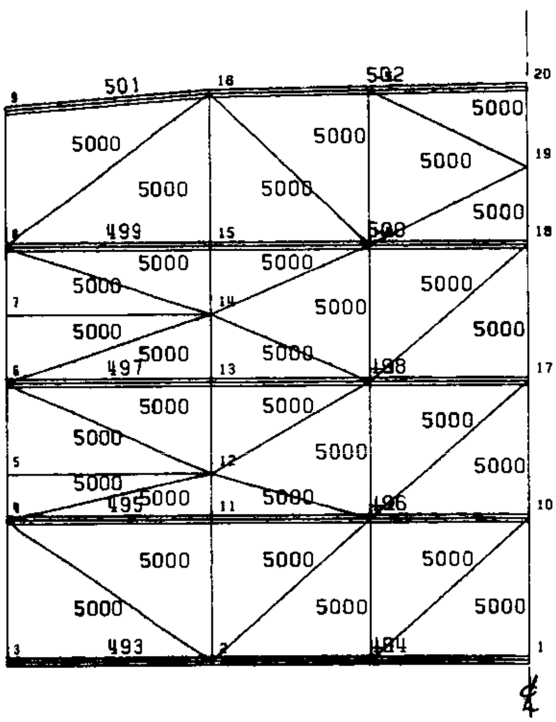

Fig. 7 - Finite-element structural model of transverse bulkhead at model Frame 0

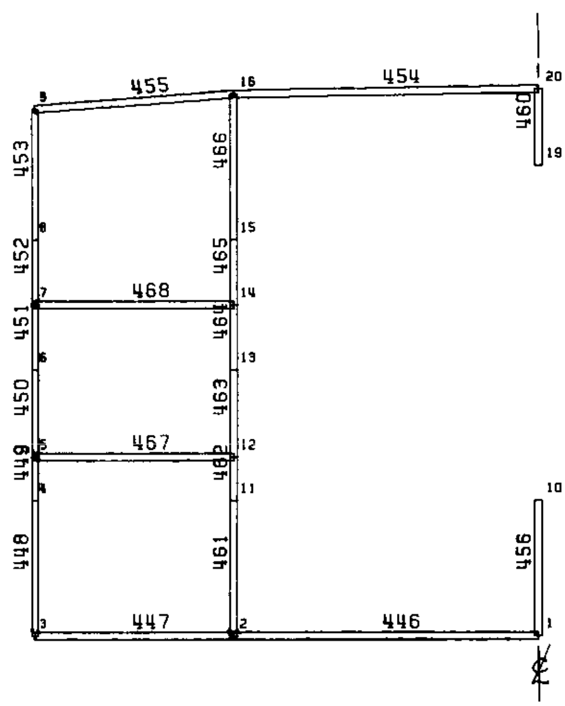

Fig. 8 - Finite-element structural model of web frame at model Frame 9

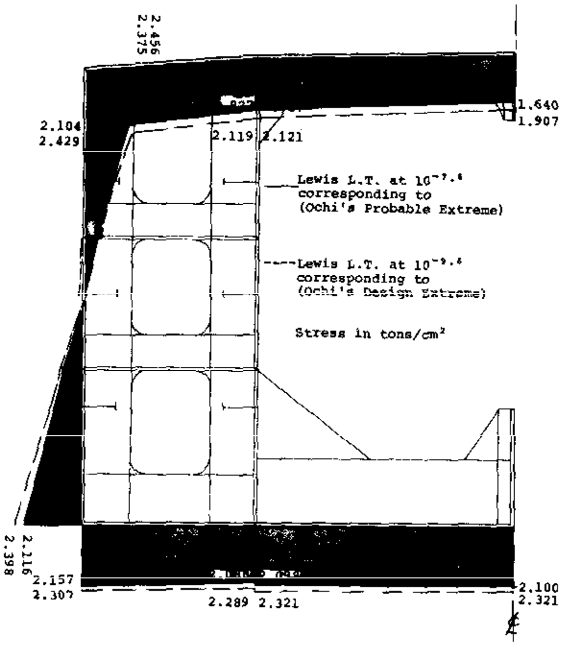

Fig. 9 - Stress values of midship section structure

CONCLUDING REMARKS

The dynamic bending moment of the sample ship has been computed using different methods. Corresponding structural analysis is performed by using a structural finite-element program. Based on the results of the present study on the sample ship, the following conclusions can be drawn:

1. The H-family wave data and Ochi's six-parameter wave spectral family of the mean North Atlantic are comparable in predicting the long-term response prediction. This may not be totally surprising, because of the fact that the two families of wave spectra are generated from similar wave data in the North Atlantic.

2. Numerical comparison shows that using Ochi's probable extreme value approach is equivalent to using the long-term exceedance approach, predicted at a probability level corresponding to 20-25 years service time. In the present study for the sample ship, the probability level is $10^{-7.6}$ for the vertical bending moment. The "design" extreme value with a risk parameter of 0.01 corresponds to the long-term exceedance prediction at a comparable probability level of $10^{-9.6}$.

3. The dynamic vertical wave bending moment required by ABS Rules agrees very well with the probable extreme value by Ochi's method and is about 4 percent less than the exceedance prediction at $10^{-7.6}$ probability level for the sample ship. This indicates that the nominal wave load predicted theoretically is in good agreement with ABS Rules.

4. For the case where the long-term dynamic bending moment at $10^{-7.6}$ probability level is considered, the maximum in-plane stress calculated for the sample ship is comparable to the nominal permissible stress specified by ABS Rules. This indicates that the long-term exceedance predictions for 20-25 years service time (similarly Ochi's probable extreme values) are in line with those specified by classification societies. On the other hand, if the dynamic bending moment at $10^{-9.6}$ probability level (also, Ochi's "design" extreme value) is used in evaluating ship girder strength, it is advisable to consider using a higher stress limit which is based on extreme load considerations.

5. The H-family and the six-parameter wave spectral data which represent the general sea conditions of the North Atlantic may not be adequate for the dynamic load calculation for ships in other areas or specific ship routes, such as coastal water regions, the North Pacific, etc.. For ships in a particular ocean area other than the North Atlantic, representative wave data of the particular location similar to the two spectral families are needed.

6. The dynamic load, in particular the vertical bending moment of the sample ship presented in this paper, is calculated based on linear theory of ship motion. For ships where the effects of nonlinear motion, such as slamming, flare impact, green water, etc., are significant, further study is needed in order to apply the probabilistic/statistical methods in the determination of hull girder strength.

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