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Consideration of Global Climatology and Loading Characteristics in Fatigue Damage Assessment of Ship Structures

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Abstract

Although the methodology for fatigue damage evaluation employed by other engineering disciplines is largely applicable to ship structures, there are some special considerations that are more relevant to ship structures than the land based or site specific offshore structures. The foremost among these considerations is the significance of wave climatology, or the global variability of such since most ship structures are designed for global, unrestricted services. The second factor prominent in a fatigue assessment is the loading and structural characteristics of the local details which requires refined consideration of the loading statistics beyond the traditional consideration of hull girder loading.

In this paper, the notions of various measures of climate severity are introduced. The significance of such parameters in the realm of different structural limit states, the fatigue limit state in particular, is explored by examining the results parametrically. Rationale of developing the strategy and criteria for screening in an overall fatigue strength assessment for ocean going vessels are presented.

1. Introduction

Up until the recent past, ship design based on a semi-empirical approach sufficed an overwhelming majority of designers. From global and detail configurations to local scantlings, answers are usually readily available from design handbooks and/or classification Rules. In general, semi-empirical approaches evolve from, and often are spoken of synonymously with successful operating experience; so in fairness, a semi-empirical approach is not without merit. In fact, in terms of the first yield limit state and a number of serviceability requirements such as minimum thickness and minimum stiffness, the approach has had a surprisingly excellent track record despite its simplicity.

Other failure modes such as fatigue and buckling have not been considered in a conventional design process with equal emphasis as first yield failure, if at all. Then the world maritime market became increasingly more competitive, partly owing to a series of energy crises, which compelled designers to reduce steel weight in their design. A clear path to achieve that goal is to reduce scantling or increase the percentage usage of high tensile steel (HTS), or both. As a result, structures are operating at a higher level of stresses. While this in itself does not cause direct problem in the consideration of the first yield limit state, problems in fatigue and buckling have been intensified. This is so because the fatigue resistance capacities of higher strength steel and weldment are known to be *not* superior to mild steels while the demand increases. Meanwhile, structural detail designs for HTS application were simply transported from the mild steel technology. Nowadays, it is safe to conclude that proponents and opponents of the semi-empirical design approach are in general agreement that designs should increasingly rely on approaches based on engineering fundamentals or first principles. Classification societies' Rule changes appear to confirm this trend with the objective of avoiding such problems in the future.

It would be grossly over-simplified to pin all the emerging problems in ship structures performance to the use of HTS. These problems, either individually or in combination with the use of HTS, compound and magnify the problems stemming from the use of HTS. These include the overall local detail design, workmanship, maintenance and repair, corrosion, and vessel operation, just to name a few. In depth probing of these issues is out of the scope of this paper. What will be focused on in this paper includes issues directly affecting the design process such as the wave environment and its associated loading, and loading combination.

For example, when examining the structural integrity of the deck and bottom structures, the hull girder loading can be expected to be primary. Grillage bending effect, at least for the bottom structure, should be considered secondary and the local bending between stiffeners subjected to hydrostatic and hydrodynamic pressure is tertiary. For the analysis of side shell structures, especially in the vicinity of the still water line, hull girder bending would be far less significant. The pressure loading and shear must then be promoted to primary while local bending would become secondary. How these loading components combine pose an interesting task, conceptually and in practice as the superposition of the individual extremes can be overly conservative. Another potential pitfall that can be easily overlooked is to assume that the statistical properties of the hull girder stresses can be blindly transported to characterize other load components. A case in point is containership forward hatch corner edge stress which differs from the hull girder stress in both their probability distribution and their dominant period because of torsional effects. All these points are important lessons learned from recent ship design analyses.

Another topic described in this paper is how to look at the wave environment's degree of severity. It will be shown later in this paper that a specific environment can excite very severe load effects in the realm of the ultimate limit state (or, in its place, the first yield limit state) while it may not cause as much fatigue damage as a "milder" environment, and vice versa. Rational criteria are proposed for a base line screening of the global wave statistics. Some interesting insights can be derived from such evaluations that may serve as background in the process of developing rational classification requirements to alleviate excessive fatigue damage in ship structures.

2. The U.S. Coast Guard's TAPS damage statistics

The preceding discussion stressing the importance of fatigue considerations in the ship design process may run the risk of being accused of academic evangelism rather than true lessons learned. One should also examine available damage statistics the inference to which may lead to valuable experience. By mid 1989, the U.S. Coast Guard had compiled and analyzed a set of damage statistics collected for the U.S. flag tanker fleet over 10,000 gross tons involved in world trade; and in particular, those engaged in a trade known as Trans-Alaska Pipeline Service (TAPS). Recognizing that fatigue induced fracture is a prevailing problem in some of the TAPS tanker vessels, the USCG requested the American Bureau of Shipping (ABS) to convene a meeting with TAPS operators and the USCG. Subsequent to that meeting, the data was re-analyzed and the USCG's report discussing the failure experience of these vessels was recently issued [1] †.

It is not the authors' intention to give an in-depth analysis and evaluation of the USCG report, which is in open literature. (A detailed analysis and inference can be found in Reference [2].) Rather, some striking inference can be deduced and conclusions cited. These key points are highlighted as follows.

† Numbers in brackets designate Reference at end of paper.

1. The TAPS tanker vessel population included in the USCG study totals 69 vessels. These accounted for 13 percent of the U.S. flag ships over 10,000 gross tons. However, these ships sustained about 59 percent of the reported structural failure.

2. Of the 26 classes (individual designs) of vessels in the sample ship population, 6 specific classes (24 vessels) were found most prone to structural damages. These top 35 percent accounted for 2/3 of the reported failures.

3. Among the 6 worst classes, the worst class consisting of six ships sustained twice as many reported failures than the 2 next worst classes combined. The 6 ships in the worst class were built with HTS (36 kg/cm²) material throughout their cargo block.

4. Two third of the 6 worst classes ships were built either partially or totally of HTS.

In light of these inferences, it is clear that the use of HTS at least contributes partially, but significantly to such a disproportionately high rate of local structural failure. Specifically, the facts clearly points, in the words of the Coast Guard report, to "poorly designed details, poor workmanship, and *fatigue* ...".

Another subtle point cited in the report was the time of occurrence of the reported damages which showed a high concentration in the months between October and March. This fact was further translated to heavy weather. Since the remainder of the U.S. flag ships also sailed during this period and were subjected to heavy weather, the glaring high rate of damage sustained by the TAPS vessels can be attributed to the severity of the wave environment around the Gulf of Alaska.

3. Fatigue assessment in the realm of a simplified method

Within the framework of the Palmgren-Miner linear, cumulative damage formulation, it appears that the most reliable method of analysis is full fledged spectral analysis. Most design codes, however, choose to adopt a simplified fatigue evaluation formula. Strictly speaking, the most commonly employed simplified fatigue evaluation formulas share a common basis with spectral fatigue analysis. Long term distribution of the stress range can be obtained from spectral analysis; and a simple mathematical distribution is fitted. Normally, a Weibull distribution is assumed.

Without loss of generality, the Weibull/spectral based formulation is referred to in this paper. The fatigue damage evaluation formula can be cast in the form (e.g., see Ref. [7])

$$D = (fTS_T{}^m/K)\,\mu\Gamma(m/h + 1)/[\ln(fT)]^{m/h} \qquad (1)$$

in which

$$\mu = 1 + \{\nu^{-\Delta m/h}\gamma([m+\Delta m]/h+1,\nu) - \gamma(m/h+1,\nu)\}/\Gamma(m/h+1) \quad (2)$$

and

- D = cumulative fatigue damage
- f = life time average of the response zero crossing period [hz]
- T = base line duration (usually taken as the design life) [sec]
- S_T = long term stress range as the most probable extreme value in time T
- m,K = parameters of the upper branch of the S-N curve
- h = Weibull shape parameter of the stress range distribution
- ν = $(S_q/S_T)^h \ln(fT)$
- S_q = stress range at kink of S-N curve
- $\gamma(a,x)$ = incomplete gamma function, Legendre form
- $\Gamma(a)$ = gamma function of argument a

With the exception of the factor μ, the damage formula is well-known. The factor μ, referred to here as the endurance factor, stems from the existence of the lower branch of the S-N curve which intersects the upper branch at point Q, at which the stress range is denoted by S_q. If the lower branch is absent, μ is equal to unity.

It can be readily observed that, on the premise of Eq.(1) for a given S-N curve, the relation contains three parameters, viz., the damage, D, the long term most probable extreme stress range, S_T, consistent with the base time period, T, and the Weibull shape parameter, h. Evidently, if two of these parameters are known, the third can be obtained. For instance, if h and S_T are known, the damage and thus the fatigue life (equal to T/D), can be easily computed. This is the primary purpose of the formula. On the other hand, if S_T and the damage are known (say, obtained from spectral analysis), the shape parameter can be backward calibrated applying the equal damage criterion. It is the authors' contention that this is the most reliable fashion to obtain the Weibull shape parameter if it is to be used subsequently for the fatigue assessment process in the context of the Weibull based simplified fatigue calculation.

The backward calibration of the Weibull shape parameter has been carried out within the framework of Eqs.(1-2) in a typical spectral fatigue analysis. First, the endurance factor, μ, is set equal to unity while the actual S-N curves employed in the spectral fatigue analysis have two branches. The resulting Weibull shape parameter is plotted in Figure 1 for two different wave environments as indicated in the figure. The calculation for h is then repeated using appropriate values of the endurance factor, μ, according to Eq.(2) and the resulting h values are shown in Figure 2. Evidently, when 2-segment S-N curves are used to obtain S_T and D, the use of Eq.(2) to compute μ is necessary and it provides a more rational representation.

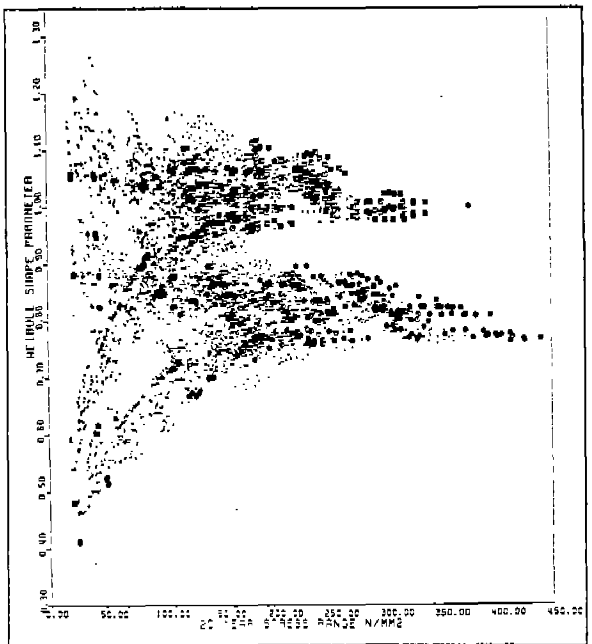

Figure 1 Weibull shape parameter in two typical wave environments, μ = 1

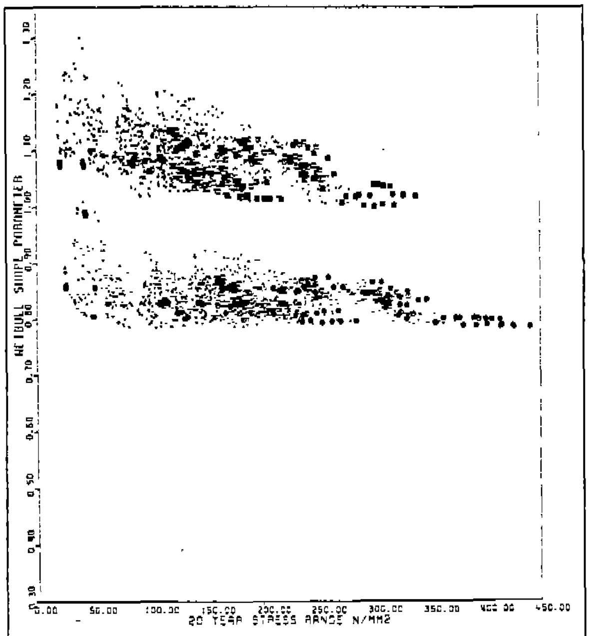

Figure 2 Weibull shape parameter in two typical wave environments, μ < 1

Referring to Figure 2, some interesting features can be observed. First, the Weibull shape parameter exhibits a fairly strong dependency upon the wave environment. As it will be demonstrated in a later part of this paper, a higher shape parameter would result in an even more dramatically higher fatigue damage. Thus, the shape parameters in a simplified fatigue analysis need to be a function of the wave environment to which the structure is exposed. Secondly, on the basis of the first observation, the wave environment that gives rise to generally higher values for the Weibull shape parameter (referred to as JS-01 here) can be said to be more hazardous than the one corresponding to lower shape parameter (referred to as JS-02 here) as far as fatigue damage is concerned. However, the JS-02 environment would result in greater most probable extreme stress range than JS-01 as the data points belonging to the JS-02 environment extend further to the right. It can thus be inferred that the severity of the wave environment should be measured with different criteria for various consequences (e.g., maximum stress versus fatigue damage).

It would be beneficial at this juncture to take inventory of several key points relevant to the Weibull based simplified fatigue calculation. First and foremost is the long term stress range shape parameter. It should be appreciated that, in the context of fatigue, this parameter depends strongly on the wave environment to which the structure is exposed. Secondly, the response characteristics such as the dominant frequency (or period) in the response stress range transfer function also play an important role. Figure 3 is a manifestation of this point. In this figure, a number of vessels for unlimited global service fall into a wide range of stress range shape parameter. Such a wide spread can be attributed to the various dominant response periods. Thirdly, the scatter of the Weibull shape parameter must be recognized and properly dealt with. Finally, a special form of the damage formula featuring the endurance factor, μ, is necessary for the formula to be applicable to classes of S-N curves having two segments.

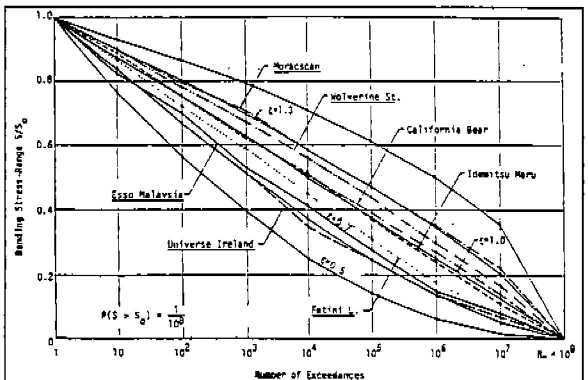

Figure 3 Weibull shape parameter for long term distribution of response for various vessels

While these key points were drawn from the framework of a Weibull based simplified fatigue analysis, it should be noted that the physics associated with the first two points, viz., referring to the characterization of wave severity and its dependence on the wave environment and the significance of the structural characteristics, are equally relevant to other formulations for fatigue analysis.

4. Wave intensity and response severity measures

When speaking of intensity of the wave environment, one should also refer to the response severity in order to place the term in a proper context. On the one hand, the severity of various wave environments can be measured by, for example, the maximum wave height associated with these environments. On the other hand, when a given marine structure (e.g., a ship), is exposed to these wave environments, the consequence of the wave severity is to be quantified in terms of some other parameters such as the most probable extreme value of a certain limit state (e.g., the stress range) , or the fatigue damage incurred by the structure at some specific locations. In other words, when the same marine structure is exposed to a more severe wave environment compared with a "milder" environment, ranked according to the maximum wave height, the corresponding most probable extreme and the fatigue damage need not reflect the same ranking of severity. This argument can be extended even further. These response variables, even when considered within the same wave environment, can reflect different degree of intensity depending upon the frequency (or period) contents of the environment with respect to those that dominate different structural responses.

In order to demonstrate the preceding notion, five wave environments identified as GP-128, GP-199, Alaska-California, Alaska-Yokohama, and Europe-New York are considered. The location of the grid-points are shown in Figures 4-a and 4-b. The Alaska-to-California region covers the route stretching from the Gulf of Alaska to Southern California which is represented by the collection of grid-points 145, 199, 168, and 156. The corresponding grid-points that constitute the Alaska-to-Yokohama route and the Europe-to-New York route are 199, 145, 016, 088, 295, and 181, 184, 187, 288, 275, respectively. In addition, a sixth wave environment known as the H-family [3,4] spectra, is also employed for this process. The H-family wave spectra are based on measured wave data and it has been used frequently as a data base at the American Bureau of Shipping for the purpose of calibrating the longitudinal strength requirement for ocean going vessels. Data for all the grid-points (other than the H-family) are represented by wave scatter diagrams derived from the U.S. Navy Fleet Numeric Weather Central hindcast data base using the Spectral Ocean Wave Model (SOWM) [5].

Short term extreme wave analysis can be carried out for the H-family wave spectra in conjunction with the probability of occurrence of the individual spectra. Similar short term analysis can be carried out for all the wave scatter diagrams identified by the wave characteristic period of a given region, weighted by the H_s-T_z joint probability. The results are shown in Figure 5.

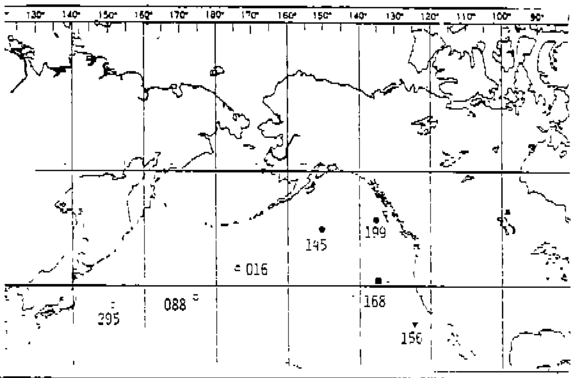

Figure 4-a Hindcast wave data grid point designation, Pacific Ocean

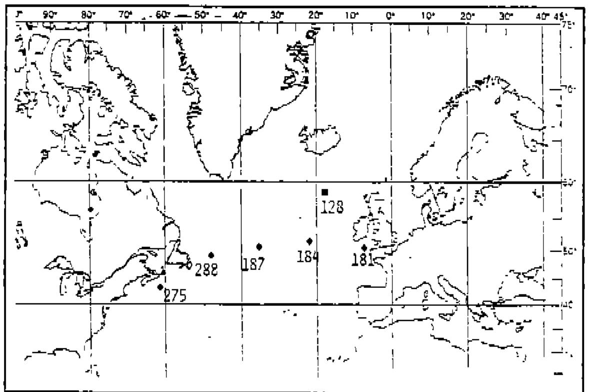

Figure 4-b Hindcast wave data grid point designation, Atlantic Ocean

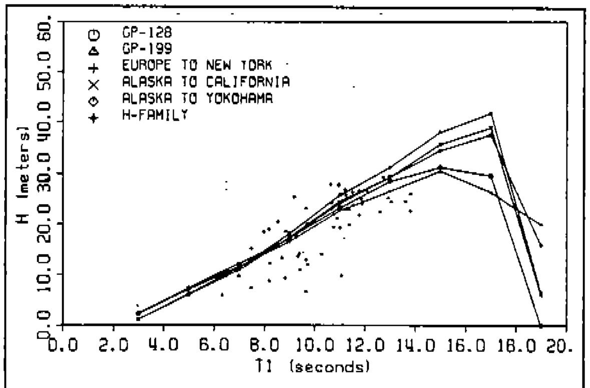

Figure 5 Extreme wave height versus mean wave period for various environments

Clearly, in terms of the maximum wave height, the regions can be ranked in terms of wave intensity in the order of GP-199, Alaska-California, Alaska-Yokohama, GP-128, and the H-family. On the other hand, if a vessel, whose dominant period (as reflected by the peaks of the wave induced bending moment RAO) is in the order, say, 10 seconds, is exposed to these wave environments, the long term most probable extreme bending moment is expected to be proportional to the wave intensity in the window around 10 seconds. On this basis, the H-family spectra would probably give rise to a highest bending moment while the ship's response to other environments would likely be roughly the same but somewhat lower than the response to the H-family wave environment. This expectation has been confirmed by results of actual ship motion analysis [6]. In any event, the response severity on this basis need not reflect the wave intensity ranking based on the "all time maximum" wave height. It can be anticipated that nor would it necessarily reflect the severity of the cumulative damage incurred. This point will be further examined after the necessary parameters are introduced.

Measuring Parameters of the Wave Environment and Response

For the purpose of this paper, the term "response severity" (hereafter simply the "severity") refers to the severity of the most probable extreme value (MPEV), normalized with respect to the MPEV obtained when the structure is exposed to the reference (or "NORM", N) wave environment. To this end, the region Europe-to-New York is chosen as the norm. Thus, a response severity parameter, RS, is defined as

$$\text{Response severity parameter (RS)} = \text{MPEV}/[\text{MPEV}]_N \quad (3)$$

Similarly, a fatigue severity parameter, FS, can be defined as

$$\text{Fatigue severity parameter (FS)} = D/D_N \quad (4)$$

A third parameter measuring how vulnerable a structure is to fatigue damage in a given wave environment can be introduced, separating the fatigue vulnerability parameter from the response severity parameter as follows:

$$\text{Fatigue vulnerability parameter (FV)} = FS/RS^m \quad (5)$$

For demonstration purposes, a set of stress range transfer functions corresponding to all wave headings (at 30 degrees apart) is selected. Spectral fatigue analysis can be pursued in a straight-forward fashion. Standard Bretschneider spectral form is assumed for this calculation. In the same process, the short term extreme stress range can be determined in conjunction with the known joint probability (for the given pair H_s and T_z) of the given wave scatter diagram. The results are summarized in Table 1 below.

It can be readily observed under the column "RS" that the most probable extreme stress range using the H-family wave spectra is the highest among the six "regions" while the others exhibit roughly the same values, which confirms the indication observed from Figure 5. The grid-point 199 (Gulf of Alaska) shows the highest fatigue vulnerability while having the second highest response severity and the highest fatigue severity. In any case, the tabulated values indicate that ranking based on RS and FV can be vastly different while neither follows the pattern of the "wave intensity" measured by the maximum wave height of the regions. In fact, the H-family data results in the smallest wave intensity while it is associated with the highest response severity.

Table 1 Variation of severity parameters with respect to wave environment

Region	RS	FS	FV	Wave Intensity
GP-128	1.030	1.587	1.454	1.008
GP-199	1.151	2.314	1.518	1.309
Alaska-California	1.087	1.329	1.035	1.236
Alaska-Yokohama	1.069	1.585	1.296	1.203
Europe-New York	1.0	1.0	1.0	1.0
H-family	1.341	2.031	0.842	0.952

The Role of Structural Characteristics

As mentioned previously, the fact that the RS ranking differs from that based on wave intensity notwithstanding, the RS notion and the wave intensity notion are really both imbedded in the information contained in Figure 5. The difference is that the RS measure depends upon the structural characteristics in terms of the "peak period" of dominant period of the response transfer function. In order to probe the influence of the dominant period of the structure, the set of "standard" transfer functions employed for the results of Table 1 can be used. The transfer functions, which are given in terms of the wave period, can be shifted uniformly so that the dominant periods are shifted uniformly for all wave headings. Standard spectral analysis similar to that used to obtain results in Table 1 can be repeated.

As mentioned in Section 3 in the foregoing, in the realm of a simplified fatigue analysis, the parameters entering the governing equation are the most probable extreme stress range, S_T, the cumulative damage, D, and the Weibull shape parameter, h, of the long term exceedance table of the stress range. For the purpose of the present work, S_T is determined through a short term extreme value calculation and the cumulative damage, D, is obtained through the spectral fatigue analysis. Once these two parameters are available, the equal damage criterion can be applied and the Weibull shape parameter can be obtained through backward calibration. It can be reasoned that the Weibull shape parameter is a convenient measure for the fatigue vulnerability. The influence of the structural characteristic period upon the Weibull shape parameter for the various wave environments is shown in Figure 6.

Evidently the Weibull shape parameter exhibits strong dependency upon the structural dominant period as well as upon the wave environment. In terms of the first three severity parameters shown in Table 1, i.e., RS, FS, and FV, their results are also dependent upon such a dominant period as shown in Figures 7 to 9. For the dominant period in the range of $8 \leq Tp \leq 17$ seconds, the average values of these parameters are shown in Table 2 below.

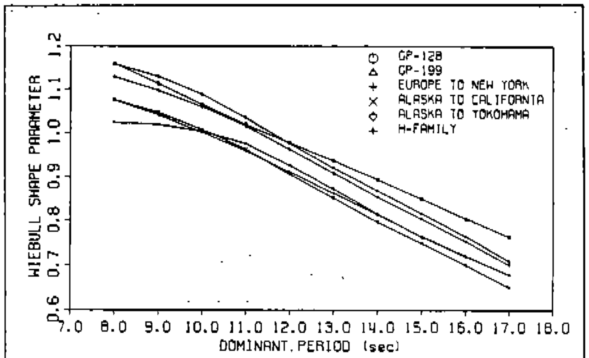

Figure 6 Weibull shape parameter versus structural dominant period

Table 2 Dependency of averaged severity parameters upon wave environment

Region	RS	FS	FV	Normalized Shape Para.
GP-128	1.069	1.977	1.623	1.085
GP-199	1.239	2.956	1.546	1.074
Alaska-California	1.145	1.474	0.985	0.991
Alaska-Yokohama	1.107	1.849	1.359	1.053
Europe-New York	1.0	1.0	1.0	1.0
H-family	1.096	1.351	0.969	0.998

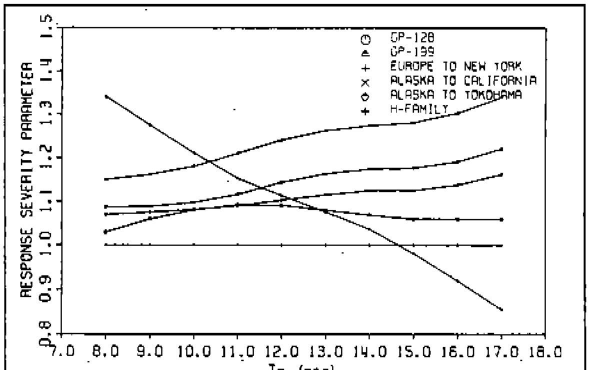

Figure 7 Response severity parameter, RS, versus structural dominant period

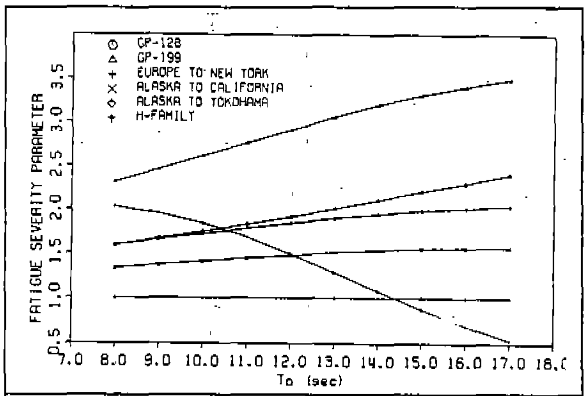

Figure 8 Fatigue severity parameter, FS, versus structural dominant period

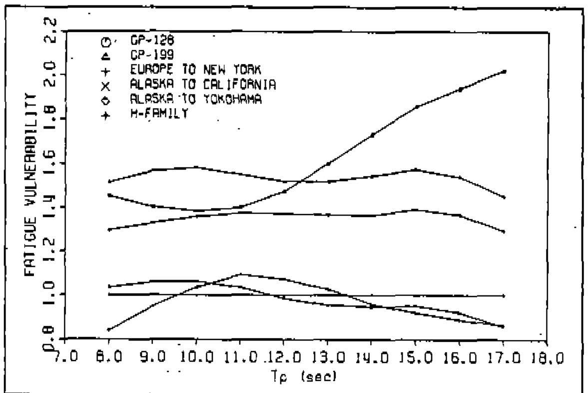

Figure 9 Fatigue vulnerability parameter, FV, versus structural dominant period

Here, the Weibull shape parameter shown is also normalized with respect to the norm (i.e., with respect to the average shape parameter of the Europe-to-NY route). It can be deduced that, for the wave environments considered here, the normalized shape parameter raised to the sixth power is approximately equal to the fatigue vulnerability parameter, FV. On this premise, the ordinate of Figure 5 offers a quick measure of the fatigue vulnerability of the regions. Moreover, once again, the three severity parameters (i.e., RS, FS, and FV) give different ranking of the severity of the wave environments considered.

Fatigue Vulnerability Based On Wave Data

In light of the notion of fatigue vulnerability factor, FV, introduced in the foregoing, the participating parameters are the fatigue damage and the most probable extreme stress range associated with the wave environment considered. Chen and Mavrakis [7] suggested a simple algorithm for the evaluation of the equivalent significant heights for fatigue damage estimate in conjunction with the commonly used format of the wave scatter diagram. Applicable to 1-segment S-N curves, the equivalent significant wave height representing all sea states having a characteristic period T_j is given by

$$H_j = [\Sigma\, p_{ij} H_{ij}^{m} / p_j]^{1/m} \tag{6}$$

in which p_{ij} is the joint probability of the pair (H_{ij}, T_j) and

$$p_j = \Sigma\, p_{ij} \tag{7}$$

is the marginal probability of all sea states associated with the characteristic period T_j. m is the negative slope of the 1-segment S-N curve and the range of summation covers all sea states in that group, i.e., with respect to the index i. The damage incurred from all sea states associated with T_j is proportional to $H_j^m p_j$. Since only the normalized damage is of interest in the fatigue vulnerability parameter, the constant of proportionality is not required. Hence, a damage factor, d, associated with the wave environment considered is given by

$$d = \Sigma\, H_j^{m} p_j \tag{8}$$

The summation operates on the index j.

Although this simple algorithm is limited to 1-segment S-N curves, it is approximately applicable to 2-segment curves provided that the negative slope of the S-N curve, m, is adjusted upward. In the example shown in Table 3, m is assumed to be adjusted to 3.8 for cases in which m = 3.

Table 3 Approximate damage vs. average damage

Region	Normalized D, approx.	Normalized D, spectral	Bias
GP-128	1.905	1.977	1.037
GP-199	3.000	2.956	0.986
Alaska-California	1.521	1.474	0.969
Alaska-Yokohama	1.858	1.849	0.995
Europe-New York	1.0	1.0	1.0
H-family	1.537	1.351	0.879

The equivalent significant wave height given in Eq.(6) is plotted in Figure 10. Notice the approximate damage measure given in Eq.(8) essentially represents the area under a curve in Figure 10 weighted by the

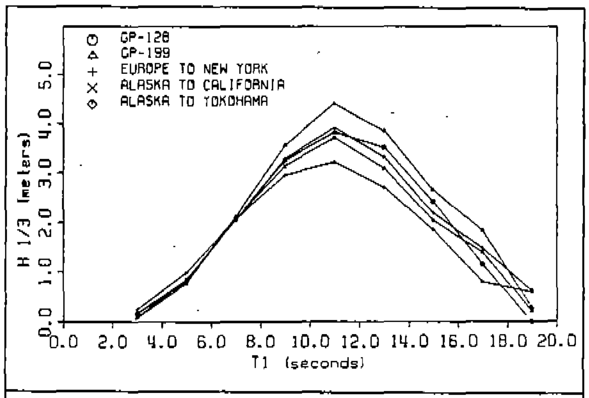

Figure 10 Equivalent significant wave height versus mean wave period

marginal probability of the characteristic period. In this sense, it is not strictly comparable to the average damage over the given range of the period. However, since the quantities tabulated here are normalized with respect to those of a reference region (viz., Europe-New York), the comparison is still meaningful; and they compare quite well as indicated by the closeness of the bias to unity.

Fatigue Vulnerability based on Munse's Approach

The Munse-Ang model [8] which leads to an estimate of the "allowable" stress range in fatigue can be applied to obtain a measure of the fatigue vulnerability. According to Munse's formulation, the "design stress range", S_D (or, when cast in the present notation, S_T), is given by

$$S_T = S_N \; \xi \; R_F \tag{9}$$

where R_F denotes the reliability factor and S_N is the stress range at cycle N on the S-N curve, and

$$\xi = [\ln(f\Gamma)]^{1/h} \,/\, [\Gamma(1+m/h)]^{1/m} \tag{10}$$

A second fatigue vulnerability factor can be defined as

$$FV_2 = [S_T/(S_T)_N]^m \tag{11}$$

It can be shown that, for a given S-N curve applied equally to all wave environments, this parameter depends on the Weibull shape parameter, h, only; and its dependency upon other parameters attached to the given S-N curve, such as the uncertainty measure, will drop out.

A comparison of the FV_2 versus the average FV obtained from Eq.(5) and tabulated in Table 2 are shown in Table 4. Once again, the Europe-New York route is used as a norm.

Table 4 Approximate fatigue vulnerability versus average FV shown in Table 2

Region	FV_2	Average FV	Bias
GP-128	1.620	1.623	1.002
GP-199	1.469	1.546	1.053
Alaska-California	0.938	0.985	1.050
Alaska-Yokohama	1.328	1.359	1.023
Europe-New York	1.0	1.0	1.0
H-family	1.002	0.969	0.968

The discrepancy is seen quite small. Except that of Alaska-California and H-family, the rankings based on AFV and the average FV are consistent.

5. Relative significance of various parameters upon fatigue

The wave environment and the structural characteristic period have been identified as very much influential to the fatigue behavior of marine structures in the preceding sections. There are other design factors which are judged significant in this regard and they are discussed below. Factors such as detail configuration (which undoubtedly affects the geometric stress concentration and is thus quite important), quality of materials, fabrication imperfection, and less than perfect weld profiles, etc. are less controllable in the design process and are thus excluded in the discussion.

Fatigue Strength — The character of the S-N data employed in the analysis is obviously the most significant. For example, if one employs the U.K. DEn S-N curves [9] for analysis and assumes that the Weibull shape parameter to be unity, the "allowable" stress which gives rise to a 20 year life for the class B curve and the class W curve differ by a factor of 3.6. However, error in the selection of the S-N class generally would not be so extreme. More likely, variability would only span two consecutive classes which, on the average, would result in an error of the "allowable" in the order of 20 percent. This is still very significant since error of that magnitude would be further magnified to a 75 percent error in the estimation of fatigue damage.

Design Life — The mathematical structure of the simplified fatigue damage formula indicates that, when all else being equal (i.e., the same S-N curve, Weibull shape parameter, and target damage), the allowable stress range depends upon the target design life, T_D, of the structure. For example, using the U.K. DEn S-N curves of classes D, E, F, F_2, G, and W, and a shape parameter h = 1, it can be deduced that the allowable stress range, normalized with respect to that for a 20 year design life, can be closely fitted by the power relation

$$S_T/S_{20} = (20/T_D)^{0.24} \tag{12}$$

As an example, the allowable stress range for a 5 year design life, S_5, by virtue of Eq.(12), is 1.41 times S_{20}. This relation thus provides a quick estimate of the allowable stress range for a given design life. It may be applied in ship design if a design life shorter than the nominal 20 years is justifiable.

Shape Parameter — Often in design codes built around the simplified fatigue evaluation formula, a value of 1.0 is assumed or recommended for the Weibull shape parameter in its application to ocean going vessels. From what is shown in Figure 6, the deviation of this parameter from unity in either direction can be quite significant. Translating such deviations to fatigue life, the deviation of life from that based on assuming h = 1 is even more dramatic. Figure 11 displays the trend of such deviations using the UK DEn E-curve. In the calculation that leads to this figure, the 20 year stress range is held constant at a value which tunes the fatigue life for h = 1 to be 20 years. It can be readily observed that, upon varying the Weibull shape parameter by ± 20 percent (from unity), the discrepancy in fatigue life can be as much as 870 percent. This observation underscores the importance of more precise knowledge regarding the Weibull shape parameter variability within a given wave environment and that from one region to another. Unless one can pin down the shape parameter within a reasonably narrow range for a given wave environment, the simplified fatigue analysis method would only be of very limited value even for the mere purpose of fatigue screening.

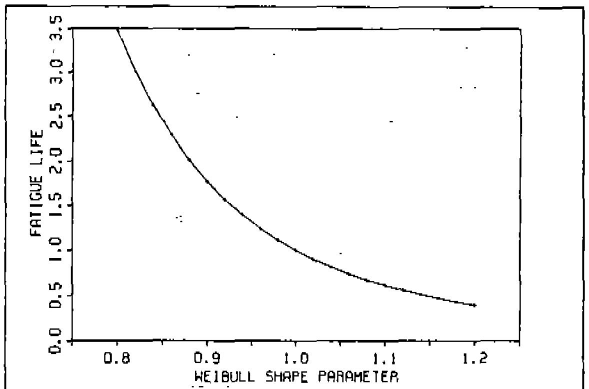

Figure 11 Variation of normalized fatigue life with respect to Weibull shape parameter

Ship Length — As illustrated previously in this paper, the Weibull shape parameter is heavily influenced by the structural characteristics in terms of the dominant period of the structure. When applied to ocean going vessels, it appears that such a period depends mostly on the length of the vessel. This contention is a direct consequence of the time-honored rule-of-thumb that the most significant wave induced bending is associated with an incident wave having a wave length equal to ship length. Examining known ship motion analysis results leads to an empirical relation:

$$T_p = 0.8\,L^{0.5} \tag{13}$$

This relation is readily applicable in conjunction with the information given in Figure 6, which shows that $h = h(T_p)$. Upon combining with Eq.(13) the shape parameter can be cast as a function of the vessel length.

It should be noted, however, that Eq.(13) is applicable to a stress field primarily attributed to wave induced bending. Perhaps it should be further restricted to wave induced bending under a head sea incident wave. The applicability of Eq.(13) is thus restricted to fatigue assessment of the deck and bottom structures the stress range of which is contributed mostly from wave induced bending moments. Calibration performed in the context of Eq.(13) for the hydrodynamic pressure exerted on the side shell near the still water line results in an expression similar to Eq.(13) except the constant of proportionality turns out to be 0.6 instead of 0.8. If this number is viewed from the vantage point of Figure 6, a smaller dominant period implies a higher shape parameter which implies increased fatigue vulnerability. Since 0.6 is 25 percent below 0.8, the increased shape parameter can be as high as 30 percent.

Wave Spectral Form — The results shown in this section were obtained using the Bretschneider spectral form. Repeating the calculation with the JONSWAP form spectra generally results in an increase of the shape parameter. While this observation is not conclusive, it is safe to say that the results would depend upon the spectral shape employed. It is believed that for fatigue assessment of ocean going vessels sailing in open water, the Bretschneider form may be more appropriate than the JONSWAP form, which was developed for fetch limited applications. However, there are proponents who advocate the use of Ochi's six-parameter spectra for North Atlantic applications. More detailed examination would be necessary to obtain greater insight into this issue. In any case, the spectral form clearly plays a significant role in fatigue assessment of ships; and it should be regarded as an important design consideration.

It is interesting to note that, although premature to conclude quantitatively the difference between the Bretschneider and JONSWAP forms, limited calculation indicates the qualitative ranking of the severity parameters (such as those shown in Tables 1 and 2) appears to be consistent.

6. Strategy for a fatigue assessment procedure for ship structures

Based on the discussions presented in the foregoing, a rational procedure for fatigue assessment can be developed (see for example, Reference [10]). It has been shown that it is possible to assess the severity of the wave environment employing the several parameters introduced heretofore. On this basis, if a ship is to be dedicated to operate in a clearly severe environment, a detailed, preferably a spectral based fatigue analysis should be pursued. On the other hand, if the dedicated route is known to be calm, a fatigue analysis may not be necessary. Of course, in the majority of cases, either the severity of the wave environment falls in a gray area or if the vessel is likely to be exposed to severe wave climates at least some of the time, such as the case of ships designed for unrestricted service, the course of action would not be as clear cut.

Global Wave Climate Evaluation

As a prerequisite for this strategy, the global wave environment can be ranked based on their severity, in terms of both the ship's response severity and fatigue vulnerability associated with a given wave environment. To this end, the global wave statistics data base compiled by BMT [11] is investigated.

The global wave climate atlas shown in Figure 12 gives a bird's eye view of the data available in the BMT data base. In all, the global waters are divided into 104 regions. On the basis of an annual average, accounting for all directions, each region is

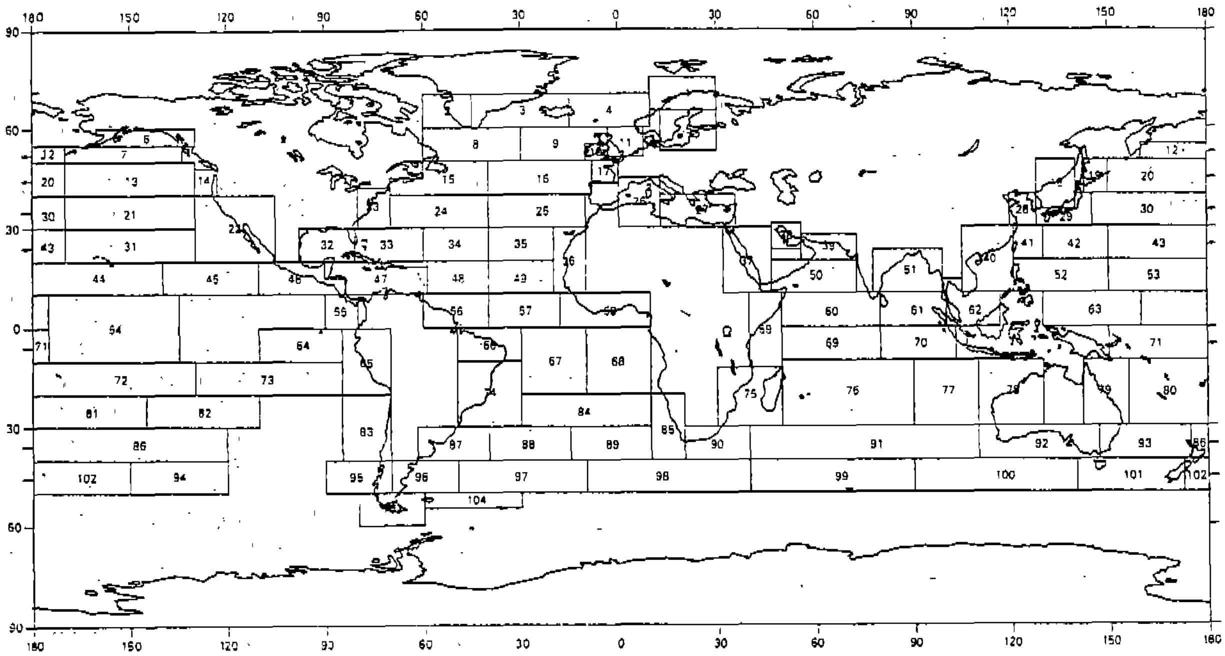

Figure 12 BMT global wave statistics zone designation

represented by one wave scatter diagram. The New York to Rotterdam route is once again selected as the norm, represented by the BMT designated zones 11, 15, 16, and 17. The standard set of transfer functions are once again employed and spectral fatigue analysis is carried out for all 104 regions plus the reference zone. On the relative basis, the results are not sensitive to the S-N curve selected. For the present purpose, the U.K. DEn D class curve is used.

An immediate question arising is "how does the BMT data compare with the hindcast data" on the basis of the severity parameters defined in the foregoing. The answer to this question is obviously "not very well". For example, using the hindcast data as a norm, the BMT reference zone's severity parameters are as follows:

Response severity, RS:	1.25
Fatigue severity, FS:	1.05
Fatigue vulnerability, FV:	0.60
Normalized shape parameter, ψ:	0.89

All these parameters for the hindcast based reference zone, of course, are equal to unity. These numbers show that, for the reference zone, the BMT data leads to higher responses, slightly higher fatigue damage, but distinctly lower fatigue vulnerability and shape parameter. However, making the same comparison for the other zones does not lead to the same picture. This indicates that the two sets of wave data are not quite consistent, as one might expect; so a little skepticism toward either (any) wave data base may be prudent. One of the reasons for the expected inconsistency is that the BMT data are "observed" data as against hindcast; the former includes rough weather avoidance on the part of the volunteer ships. It is noted that the New York to Rotterdam route consists of a data ensemble about two orders of magnitude larger than the population of the Gulf of Alaska regions (zones 6 and 7) in the BMT data base. This may or may not explain why the BMT zones 6 and 7 are very much milder than their hindcast counterpart (grid-point 199) in all severity parameters. Perhaps zones 6 and 7 cover a much wider area than grid-point 199 and averaging over a wider area may result in down-grading the severity.

It appears that inconsistency among available wave data base must be accepted as an unavoidable reality. While one may not justify to accord absolute faith toward any wave data base, it is necessary to assume that a given data base is at least self consistent.

On this basis, the 104 zones can be ranked according to the normalized fatigue damage (or fatigue severity, FS). If the threshold FS is taken to be 1.0, there are 25 zones (10 in the northern hemisphere and 15 in the southern hemisphere, almost exclusively located in the bands between 30 to 45 degrees latitude, north and south) that can be termed "severe" compared to the New York to Rotterdam route. On the other hand, there are 53 zones having an FS less than 0.33 that can be classed as "calm". It is interesting to observe that, among these "mild" regions, many have high response severity, RS, and others may have high fatigue vulnerability (and shape parameter); but not high on both. On the other hand, all 25 "severe" zones have high values for all severity parameters, i.e., RS > 0.97, FV > 0.93 and the normalized shape parameters exceeding 0.99. The normalized (with respect to the New York to Rotterdam route) parameters RS (response severity), FV (fatigue vulnerability), and FS (fatigue severity) based on the BMT data are shown in Figures 13 to 15.

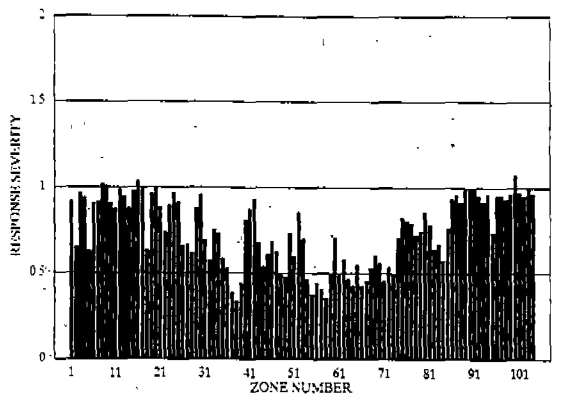

Figure 13 Normalized response severity based on BMT wave data

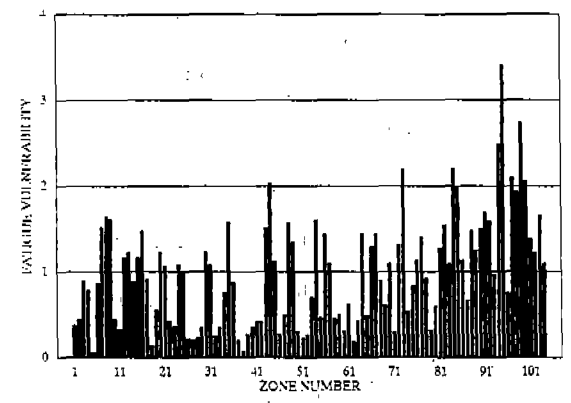

Figure 14 Normalized fatigue vulnerability based on BMT wave data

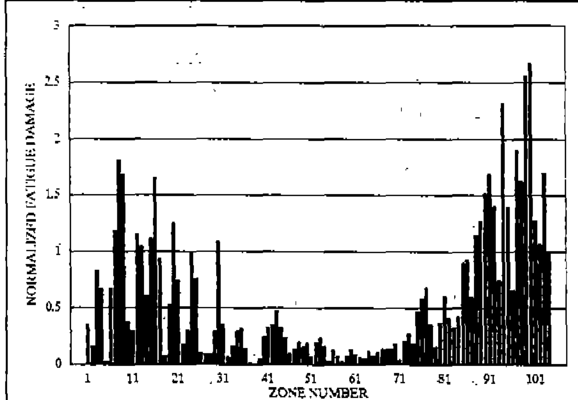

Figure 15 Normalized fatigue severity based on BMT wave data

Of course, the bottom line is the fatigue severity parameter, FS. How influential are the remaining severity parameters can be shown in the correlation matrix given in Table 5, in which the normalized shape parameter is denoted by ψ.

Table 5 Correlation of the severity parameters

	FS	RS	FV	ψ
FS	1.00	0.747	0.686	0.466
RS	0.747	1.00	0.240	0.022
FV	0.686	0.240	1.00	0.914
ψ	0.466	0.240	0.914	1.00

Evidently, the response severity parameter, RS, is correlated neither with the fatigue vulnerability nor the shape parameter. This has been pointed out earlier in this paper but the contention is now confirmed. The shape parameter is strongly correlated with fatigue vulnerability. Both RS and FV correlate with fatigue severity only moderately; but the respective correlation coefficients being in the order of 0.7 indicates that they both play an important role. What is not shown in Table 5 is that the product $RS^m FV$ virtually correlates with FS.

At this point, it is fair to raise the issue that since the FS factor measures the fatigue severity, why are RS and FV needed. In the first place, the notions of RS and FV (and ψ) provide better insight on why high responses (e.g., stress range) does not imply high fatigue damage; and vice versa. Furthermore, the purpose of fatigue screening is to circumvent detailed spectral fatigue analysis if the regions in question are known to be mild. Without a full fledged spectral analysis, the parameter FS is not know. Hence, although both RS and FV were derived from spectral fatigue analysis, if they can be replaced by some reasonable approximations, a meaningful fatigue screening scheme can be devised.

To this end, it is suggested that RS be replaced by the wave severity measured by the maximum wave height of the region in question. The fatigue vulnerability can be estimated through the notion of the "equivalent wave height" presented in section 4 (referring to Equations (5-8), Table 3 and Figure 10). This information is completely imbedded in the wave scatter diagram and the parameters involved can be computed with ease. These parameters (i.e., RS, FV, and the derived FS) for the 104 zones have been obtained and they can be shown completely correlated with their spectral based counterparts. On this basis, and a threshold value of 1.0 for FS, 19 of the 25 zones previously identified as "severe" again emerge as severe zones. If the threshold for FS is lowered to 0.86, all 25 "severe" zones are picked up plus 2 extra zones previously determined as very close to "severe". In short, the criterion based on approximate severity parameters derived from the wave scatter diagrams alone predicts the severe fatigue zones correctly (or consistently).

Similarly, the procedure for obtaining the fatigue vulnerability parameter, FV_2 based on Munse's approach can be recalled from previous discussions in this paper:

a) For a given stand-alone or composite wave scatter diagram, use the set of "standard response transfer functions" to perform a spectral fatigue analysis. With the resulting life time most probable extreme stress range, S_T and the fatigue damage, solve for the Weibull shape parameter, h, as a function of the dominant period for this wave environment.

b) Apply the function $h = h(T_p)$ to Eq.(11), compute the fatigue vulnerability parameter, FV_2.

Results derived from this process (i.e., FV_2) can be shown to be virtually correlated with FV obtained from spectral fatigue analysis as expected.

Allowable Stress Range

For ships operating in wave climates at par with the reference region, allowable stress ranges can be established based on the information of the Weibull shape parameter. Since the shape parameter is a function of the dominant period, a structural characteristics that can be estimated as a function of the ship length as shown in Eq.(13), a simple transformation leads to the shape parameter as a function of ship length. In this regard, the nature of the wave loading, whether it is dominated by the hull girder stress, pressure loading on the side shell, or inertia loading, such a transformation will result in different "formulae" as discussed in section 4.

This set of baseline allowable stress ranges is to be modified by both the RS and FV factors such that

$$F_a = (F_a)_N / [RS\,(FV)^{1/m}] \qquad (14)$$

On this premise, if the Weibull shape parameter is assumed to be 1.0 as is the case in many design codes, then FV = 1.0 and the allowable stress range is affected only by the response severity (or wave severity). This has been shown to be erroneous in this paper.

Since $(F_a)_N$, the baseline allowable stress range, is a function of the ship length and the loading type, F_a will also be a function of the ship length and the loading type. The modification factors, RS and FV, are in principle also functions of ship length. For the purpose of applying to Eq.(14), however, their respective average values will suffice.

Application to Ship Structures Fatigue Assessment

In principle, ship details suspected to be fatigue prone can be identified by way of the allowable stress screening. Once the critical locations in the structure are identified, their adequacy of fatigue resistance may be best evaluated by way of a spectral fatigue analysis. The allowable stress in question, of course, must contain the environmental modification factors used in Eq.(14). The criticality of the specific locations in the structure is not only relevant in fatigue analysis in the design stage, it may also serve as a guideline in subsequent inspection and monitoring programs for the vessel.

As mentioned previously, the simplified fatigue analysis does carry the spectral connotation if the shape parameter can be accurately evaluated. Since the shape parameters obtained and shown in section 4 were computed through spectral fatigue analyses and backward calibration, the simplified analysis results should be as accurate as the spectral fatigue analysis results. The only potential error which can be regarded as additional modelling uncertainty stems from the use of the "standard" response transfer functions. If the dominant period of the primary loading component can be accurately determined, the use of standard response transfer functions is not expected to lead to significant error.

7. Summary and concluding remarks

In a conventional ship design process, fatigue damage of ship structure typically has not been given as much attention as other considerations such as the global hull girder and local yielding strengths. The introduction of high tensile steels in ship design and construction signifies a new era in which the importance of fatigue considerations gradually gains acceptance in the ship design and construction industry. The lessons learned from the USCG structural casualty report simply helps to eliminate any lingering doubts as to whether fatigue considerations should be an integral part of the ship design process.

It should be recognized that the increasing use of HTS itself is not the only reason attributed to the frequency of fatigue induced fracture in specific trade routes such as the TAPS. This paper identifies the relevance of some factors which makes a specific wave climate particularly damaging to ship structures in terms of fatigue crack initiation. In particular, one should view the wave environment's severity from both the severity of the response's most probable extreme and the severity in terms of fatigue vulnerability. These two notions need not be correlated nor are they necessarily mutually excluded. For ships designed to operate in wave environments that have both high response severity and fatigue vulnerability, a thorough fatigue analysis for the ship structures would be prudent.

Classification societies such as ABS now are taking necessary steps to implement appropriate fatigue strength requirements in their Rules. This paper also presents a possible strategy toward that goal. These steps are built around the belief that the severity and fatigue vulnerability as well as the nature of fatigue loading are the most influential, in addition to other better known factors such as workmanship, weld profile and weld quality, corrosion, etc. It is also noted that the factors identified in this paper also depends upon the structures' characteristics, especially the dominant period of the response transfer functions. The latter is expected to be sensitive to the nature of the loading.

Some continued resistance within the ship building and maritime industry toward the full implementation of fatigue requirements may be anticipated and understandable. Fatigue analysis is often thought of as costly and time consuming. Nevertheless, the time-honored economic reality that paper is cheaper than steel should convince the skeptics that fatigue consideration makes economic sense. There are increasingly clear indications that this view is shared by many major shipbuilding organizations. Moreover, a rational approach and the enhanced safety benefit does not require analysis for every structural details. The insight gained from fatigue consideration in terms of identifying the critical fatigue sensitive locations in a given structure may also facilitate the long range planning of inspection, maintenance and monitoring of the ship structure during the ship's service life.

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