SSC-234

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EVALUATION OF METHODS FOR EXTRAPOLATION OF SHIP BENDING STRESS DATA

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SHIP STRUCTURE COMMITTEE

1972

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U.S. COAST GUARD HEADQUARTERS
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SR-171
1972

Dear Sir:

A major portion of the effort of the Ship Structure Committee has been devoted to improving the capability of predicting the loads which a ship's hull experiences. One of the most important parts of this effort has involved the measurement of structural response of actual vessels at sea and the analysis of the data obtained.

This report contains further information on the methods of analysis and the results obtained. Work in this all important area is continuing and will be reported as information becomes available.

Comments on this report would be welcomed.

Sincerely,

W. F. REA, III
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-234

Final Report

on

Project SR-171, "Ship Statistics Analysis"

to the

Ship Structure Committee

EVALUATION OF METHODS FOR EXTRAPOLATION OF SHIP BENDING STRESS DATA

by

D. Hoffman, R. van Hooff, and E. V. Lewis
Webb Institute of Naval Architecture

under

Department of the Navy
Naval Ship Engineering Center
Contract No. N00024-68-C-5282

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U. S. Coast Guard Headquarters
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1972

ABSTRACT

This report is a continuation of an earlier report*, giving results of the analysis of all available stress data from full-scale measurements on the following dry cargo ships:

S.S. WOLVERINE STATE
S.S. HOOSIER STATE
S.S. MORMACSCAN
S.S. CALIFORNIA BEAR

The results for the first two, which are sister ships of the C4-S-B5 type, cover a total of about 10 ship-years in the North Atlantic, and results are felt to be consistent and reliable. Results for the MORMACSCAN, covering brief periods in the runs from New York to Europe and New York to South America, appear to provide inadequate statistical samples. CALIFORNIA BEAR results for the North Pacific appear to be reasonable for that service.

Further details are given on two techniques for the analysis and extrapolation of full-scale data to longer periods of time, in order to predict extreme bending stresses (or bending moments) in service. One of the techniques employs the integration of rms stress data from individual stress records; the other makes use of the highest stresses obtained in each record (extreme values). Both techniques involve the classification of data by severity of weather in order to obtain greater generality of results. It is shown that extrapolated trends from the two methods are consistent.

Comparisons are made of non-dimensional bending moment coefficients for all of the ships on the basis of the same "standard" weather distribution.

*"Analysis and Interpretation of Full-Scale Data on Midship Bending Stresses of Dry Cargo Ships", Report SSC-196, June 1969.

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INTRODUCTION

The purpose of the Ship Structure Committee project SR-171 has been stated to be (1)* "to analyze the data on bending moment versus sea state obtained on both full-scale ships in service and on ship models, with the objective of predicting the type and level of bending-moment history that a ship will undergo throughout its life. This can then serve as an important guide for ship design."

As indicated in an earlier report (2), there has been a remarkable trend in recent years toward larger tankers and bulk cargo carriers, as well as a steady increase in the speed of general cargo ships. Questions have arisen as to the applicability of the old empirical standards of longitudinal strength to these new ships, and a need has arisen for a more fundamental approach to the design of ships for adequate longitudinal strength.

As before, we shall consider only one of the many factors involved in longitudinal strength -- wave-induced bending moment -- with the recognition that other factors, such as still water loads, slamming stresses, temperature effects, and combined loads must not be neglected. The wave bending moment is not a static quantity, and it depends on the response of the ship to particular seas. Since the seaway is constantly changing in a completely random and unpredictable way, and since it has been shown by previous investigators that response is affected by ship speed, heading, weight distribution, etc., it is obvious that a simple deterministic solution is not possible.

In the previous report, results of the analysis of stress data from full-scale measurements on two C4-S-B5 type cargo vessels, the S.S. Wolverine State and S.S. Hoosier State, were presented in the form of histograms and cumulative distributions, which together with previously analyzed full-scale data covered a total of five years of normal ship operation in the North Atlantic. In addition, results of analysis of full-scale data were given for two additional ships, the Mormacscan and the California Bear. The latter two ships represent higher speed types than the first two, and results covered several different trade routes.

All of the above-mentioned data are not of equal quality, and in some cases certain corrections or adjustments were found to be necessary in the analysis. Accordingly, one object of the present report is to put all data onto the same basis and to draw general conclusions from all the data. In all cases high-frequency slamming and whipping stresses were filtered out by Teledyne in the data reduction phase.

The earlier report (2) gave two rational techniques for the extrapolation of full-scale data to longer periods of time, in order to predict extreme bending stresses (or bending moments) in service. One of the tech-

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*Numbers in parentheses refer to References listed at the end of this report.

niques employed the integration of rms stress data from individual stress records; the other made use of the highest stresses obtained in each record (extreme values). Both techniques involved the classification of data by severity of weather in order to obtain greater generality of results. It was shown that extrapolated trends from the two methods were similar but revealed differences that warranted further investigation.

It is the two-fold purpose of the present report to present the results of further study of the two techniques of data analysis mentioned above and to provide a complete summary of the results of analyses of all statistical data obtained in the project for the Wolverine State, Hoosier State, Mormacscan, and California Bear, including data previously published (2).

Accordingly, a more rigorous description and comparison will first be given of the two mathematical models suitable for ship stress data analysis and extrapolation, as applied to a representative sample of Wolverine State data within one weather group. Complete results will next be given for all four ships by the rms method and results from different ships compared. The method of extremes will then be applied to data from 10 voyages of the Wolverine State and results compared with the rms method. Finally, conclusions and recommendations will be given for the entire project.

A companion report (3) deals with the use of model test results and ocean wave data to predict long-term distributions for any ship design and hence to obtain more general results than those presented here.

A tabulation of particulars of the ships (2) and a list of stress records taken on each ship are given in the Appendix.

PROBABILITY MODELS

Introduction

A previous report (4) has shown that a reasonable extrapolation of ship stress (or bending moment) statistics can be made by a method originally presented by Bennet (5). From time to time it has been proposed to apply extreme value theory to the problem (6), and recent results have appeared promising (7). However, preliminary Wolverine State results presented in (2) did not appear to be consistent with those obtained by the earlier rms method.

As stated in (2), page 39, "Figure 17 also shows a tendency for the extreme value extrapolation to level off at very large values of n, while the rms extrapolation continues to rise. Further investigation is required to determine whether this difference in trends is real, and if so, which method is a more valid basis of extrapolating the observed data." The relative merits of the two approaches are discussed and finally (p. 41), "It is expected that the results obtained from this further study will shed more light on the problem of extrapolating statistical data."

Accordingly, it appeared desirable to carry out a more rigorous theoretical development of the two methods, using the same basic assumptions in each case. The two probability models could then be tested by application to a limited sample of Wolverine State data within one weather group. These two steps have been carried out and are reported in this section.

Assumptions

The purpose of setting up a probability model is two-fold. If it fits the available data obtained over a reasonable period of time (say two to three years), then first it can be used with some confidence to extrapolate statistical trends to much longer periods -- as to the lifetime of a ship or of many ships. Second, it can be used as a basis for predicting long-term trends from model tests and ocean wave data (8).

In attempting to construct a reasonable mathematical probability model for describing full-scale stress statistics, the most suitable basis seems to be first to divide and classify all data by severity of weather. The following basic assumptions have been made, as in previous work:

1. All peak-to-trough stresses within individual 20-minute records are Rayleigh-distributed.

2. All rms stress values within any one weather group are normally distributed.

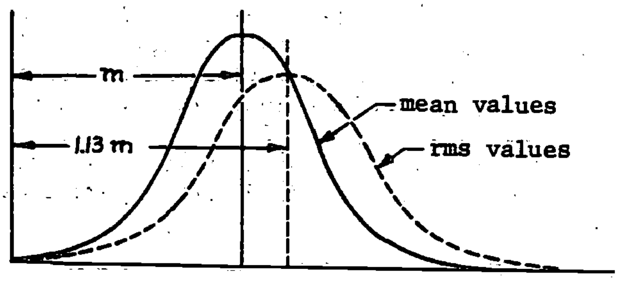
The first basic assumption regarding the applicability of the Rayleigh distribution to individual samples has been frequently made and justified (4)(8)(9). It is the direct consequence of considering the bending stress over a short period of time to be a stationary random process described by a relatively narrow spectrum (10).

The second assumption has been found by previous work (2) to be reasonable on an empirical basis. From a theoretical point of view, Dr. M. K. Ochi points out that the Central Limit Theorem has a direct bearing on our problem. This theorem says (in part) that if a large number of independent random samples are drawn from the same population, the distribution of the means of the constituent samples approaches a normal distribution, no matter what the distribution within the samples may be.

We are concerned with the question of how rms values of stress samples are distributed within one weather group. The Central Limit Theorem tells us only that the means (m) of all records should be normally distributed, provided that a large enough number of samples is taken. However, if the second of the above assumptions is valid, the relationship between the means and rms values of the samples is known. When the peak-to-trough stress data are Rayleigh-distributed, the ratio of mean to rms is:

$$\frac{m}{\sqrt{E}} = \frac{\sqrt{\pi}}{2} = 0.886, \text{ or } \frac{\sqrt{E}}{m} \approx 1.13$$

This means, as shown on the sketch,



that the abscissa of each point on the normal curve of mean values must be multiplied by 1.13, and the ordinate divided by 1.13 (to maintain unit area), to obtain the distribution of rms values. It is evident that the latter curve is another normal curve. Therefore, it seems reasonable to assume that when a sufficiently large number of samples (in a particular weather group) is available, the rms values should be normally distributed. Hence, our two basic assumptions appear to be consistent.

It is important to note, however, that in practice we are always dealing with finite samples of data. As will be shown later, histograms of rms values never exactly fit a normal curve, and peak-to-trough stresses in any record never exactly fit a Rayleigh curve. Nevertheless, there is theoretical justification for applying the above relationships to finite samples. In particular, it has been demonstrated by Dr. M. K. Ochi that the Central Limit Theorem is also applicable to this practical case. He shows that if the sample stresses are drawn from Rayleigh distributions, the relation

$$m/\sqrt{E} = 0.886$$

will hold exactly when E/n' approaches zero, where n' is the average number of peak-to-trough stresses per record. In the present case, where $E<10$ and $n' \approx 300$, the ratio E/n' is small enough so that the above relation should hold true. Hence, theoretically -- by virtue of the Central Limit Theorem-- the rms stress values should follow a normal distribution.

Nevertheless, it is obviously impossible to prove that our two basic assumptions apply exactly to all ship stress data collected. In the end the best test of applicability of these assumptions is how the theoretical long-term predictions compare with actual data. The following sections will provide definite evidence along these lines, within a single weather group.

Cumulative Distributions

Cumulative distributions are of interest because, as explained in (2), they predict the level of bending moment (or stress) that is expected to be exceeded once during a definite period of time. To know by how much the value will be exceeded, however, one must apply extreme value theory, as discussed later on.

It should be noted that on the basis of the above two assumptions there are at least two ways to proceed, each yielding a different type of cumulative distribution. After describing these two approaches, it will be shown that the two methods lead to consistent results in principle. It remains to be seen, however, whether the actual data follow one pattern better than the other.

The two approaches will now be described in relation to the situation within a single weather group. The combined effect of different weather conditions can readily be determined, no matter which method is used. The rms method developed by Bennet and Band leads to a cumulative distribution of all peak-to-trough stress reversals. This distribution is obtained simply by integrating all the Rayleigh distributions defined by a normal distribution of rms values (which are the Rayleigh parameters), as previously described (2).

The other approach makes use of extreme values data, i.e., the highest value in each record, instead of the rms value. A simple assumption previously used (2)(7) is that the extremes are normally distributed, but this may be shown to be inconsistent with the two assumptions stated at the beginning. For although the Rayleigh distribution gives us a prediction of the highest stress in each sample, depending on the number of stresses n' in the sample, the extreme values from many records -- even with the same n' and the same Rayleigh distribution -- will show some scatter. For n' = 300, the ratio of the highest expected stress in n' = 300, X_{300}, to the rms value, $\sqrt{E}$, is given by

$$\sqrt{\ln n'}^{*} + \frac{\gamma}{2\sqrt{\ln n'}} = 2.51$$

where γ is the Euler constant ($\gamma = 0.5772$). But since there will be more than one record having the same rms value, and hence the same Rayleigh distribution, we must determine the scatter of these extreme values. This can be done, as described below, assuming a constant number of stress reversals per record, $\bar{n}'$.

Once the distribution of extremes for a given rms value is determined, one can compute the overall distribution of extremes. This distribution can be compared with that obtained by the rms method, although the meanings are different and they have a different probability scale.

The accompanying graph, Fig. 1, shows the results of comparing the following ideal curves (probability models):

1. Cumulative distribution of all peak-to-trough stresses, X, obtained by Bennet and Band approach, assuming all data within one weather group have normally distributed rms values (mean = 1.297 KPSI and standard deviation = 0.485 KPSI), and individual records have Rayleigh-distributed stress reversals. Q is the probability per stress cycle; number of cycles, n= 1/Q.
2. Cumulative distribution of the predicted values of highest stresses in 300, X_{300}, assuming that there are 300 stress reversals in each individual record. As before, it is assumed that all data within one weather group have normally distributed rms values (mean = 1.297 KPSI and standard deviation = 0.485 KPSI), and individual records have Rayleigh-distributed stress reversals. Q is the probability per record; number of records, N = 1/Q.

The graph, Fig. 1, shows that at very low probability levels Curves 1 and 2 are separated by approximately log 300**. It can be proved that in the limit, as P approaches 0, the separation would be exactly 300. But at high probability levels, which are of minor interest here, there is no simple relationship in terms of record length or number of cycles.

Thus the two mathematical models are consistent at the low values of P (high values of N) which are of principal interest. For example, we can

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*ln = $\log_e$

**log = $\log_{10}$

say from Fig. 1 that one can expect a stress of 7.1 KPSI to be exceeded once in 10^5 cycles or once in $10^5/300 = 3.3 \times 10^2$ records. The highest stress in the entire population of stresses is the same as the highest extreme stress in all the records. Either curve can be constructed from a stated average rms value and standard deviation, using the two assumptions given at the beginning of this section.

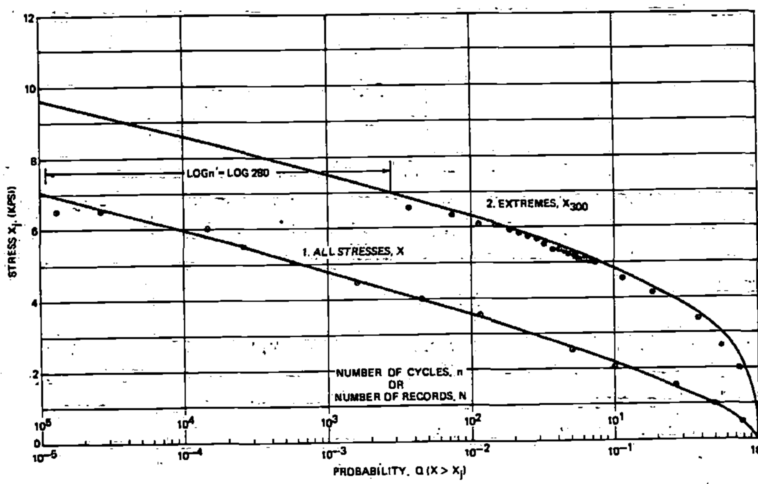


Fig. 1. Theoretical Cumulative Distributions of Peak-to-Trough Stress, and Actual Data Points from 270 Records. Weather Group II

Calculating the Cumulative Distribution of Extremes

The method of obtaining Curve 1 has been discussed in detail in earlier reports (2)(4). The method of obtaining Curve 2 has been developed by van Hooff on the basis of work by Longuet-Higgins (10) and will now be described. Within any weather group, instead of integrating the many Rayleigh distributions (as in the work of Bennet and Band), attention is focused on the predicted highest values in the individual records. If there are many records having the same rms value (i.e. the same Rayleigh distribution), there will be a scatter of predicted highest values. The cumulative distribution of such "highest values" is given approximately by this function from Longuet-Higgins (10):

$$P(X_{300} < X_j) = \exp\left[-\exp -\left(\frac{X_j^2 - E \ln n'}{E} \right) \right]$$

where E is the mean square value of peak-to-trough stress, and n' is the number of stress reversals in a record, here assumed to be 300. In this case we are more interested in the probability $X_{300} > X_j$ which is simply

$1 - P(X_{300} < X_j)$. For computational purposes it is necessary to know the corresponding probability density function, which is

$$p(x) = \frac{2X}{E} \exp -\left(\frac{X^2 - E \ln n'}{E}\right) \exp\left[-\exp -\left(\frac{X^2 - E \ln n'}{E}\right)\right]$$

In general, there will also be many records having other rms values and hence other Rayleigh distributions. For each Rayleigh distribution the corresponding distribution of predicted "highest values" is given above. The weighted summation of all these distributions yields a single cumulative distribution of probability per record of exceeding different levels of stress, i.e., Curve 2. The above summations were carried out by numerical integration (Gauss-Laguerre quadrature), using an electronic computer.

Comparison of Theory and Data

Actual data from the Wolverine State for voyages 219-241, weather group II, were available, having the stated mean rms-value and standard deviation. Accordingly, the highest values from all of the 270 records were plotted in the figure (Fig. 1), where they may be seen to fall below the theoretical Curve 2 (on the safe side) and to show approximately the same trend. (The highest value is plotted at $P = 1/N$, the next highest at $P = 2/N$, etc.).

Similarly, from the histograms of all stress reversals in the same 270 records, data points have been plotted in comparison with Curve 1. Again results are generally lower and similar in trend. Hence it can be concluded that the ideal curves show conservative trends in comparison with a limited sample of data.

Meanwhile, it is of interest to consider the possible reasons for the differences between the probability models and the data sample. First is the possibility that the rms values depart appreciably from the assumed normal distribution. The situation is shown graphically in Fig. 2, and the χ-square test shows $\chi^2 = 40$ for 9 degrees of freedom. This indicates a poor fit. Since the actual distribution is somewhat skewed toward low values of stress, the data should tend to be lower than the model -- as it is in Fig. 1.

A second source of discrepancy is the possible significant departure of stresses in individual records from the assumed Rayleigh distribution. This possibility is tested indirectly by plotting data in cumulative form on Weibull paper from four records selected at random (Fig. 3). It may be seen that the data follow the Rayleigh slope quite well in the region of interest.

Further indication of the applicability of the Rayleigh distribution for determining extremes is given by Fig. 4. Here the extreme values obtained by applying the Rayleigh factor for the highest value in 300 to the rms values are plotted against the corresponding actual highest values for each of the 270 records available. It may be seen that there is a fair amount of scatter, but on the average the correlation is good -- if a few questionable points for which n' is much less than 300 are ignored. The scatter may be described by means of an extremal distribution that will be discussed later on.

The departure of rms values from a normal distribution is surprising in view of the previous discussion of the Central Limit Theorem, coupled with the good agreement of the sample Rayleigh distributions. It may be that this particular sample is too small, since previous work (2)(4) has shown considerably better fit. If this is generally true, the ideal curves would in general fit the data even better than shown in Fig. 1, which is felt to be excellent agreement for engineering purposes.

A third source of discrepancy in case (2) is the variation in number of stress reversals from the assumed value of 300. Fig. 5 shows the result of calculating Curve 2 of Fig. 1 on the basis of n' = 500 in comparison with n' = 300. The difference between the curves is seen to be small. Actual values of n' varied in the range of 100 to 600, with an average of 304.

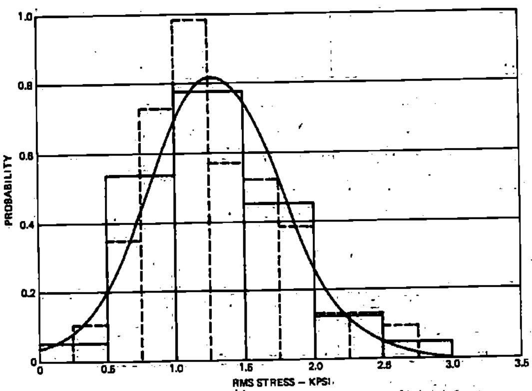


Fig. 2. Histogram of Peak-to-Trough RMS Stresses, with Two Class Intervals (Zeros Excluded), Compared with Normal Distribution. Weather Group II

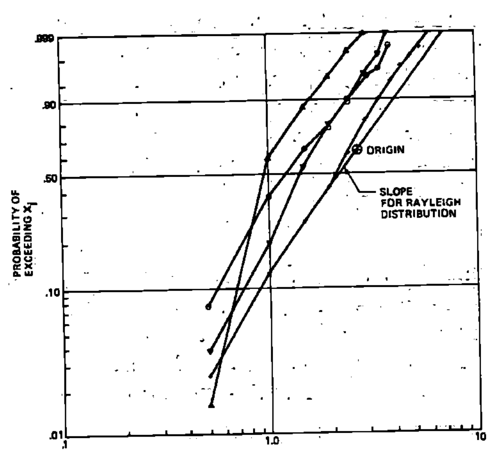


Fig. 3. Typical Peak-to-Trough Stress Records Compared to Rayleigh Distribution (on Weibull Paper). Weather Group II

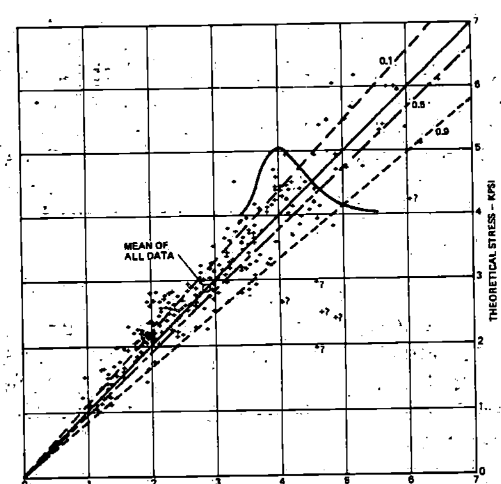


Fig. 4. Comparison of Actual Extremes with Those Calculated (300 cycles per record). Weather Group II

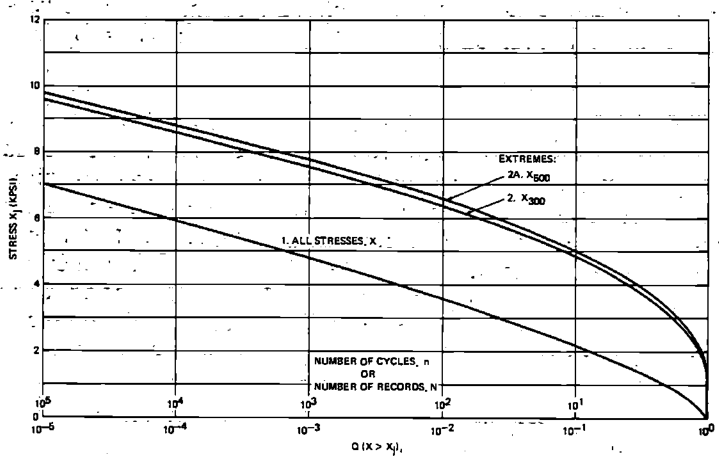


Fig. 5. Theoretical Cumulative Distributions of Peak-to-Trough Stress, Comparing Highest in 300 and 500. Weather Group II

Finally, a fourth source of discrepancy lies in the method of calculating the ideal curves. In both cases 1 and 2 a numerical integration is required, and the accuracy of the result is therefore dependent on the detail used in the calculation. In particular, the width of the stress increments into which the assumed data are divided is vital. For both cases the increment of 0.15 KPSI corresponded to 100 intervals in a total range of 15 KPSI, the upper limit of integration. For case 2 the truncation error of the computer was particularly troublesome, due to the double exponential form of the Longuet-Higgins distribution. It is believed that a satisfactory accuracy has been obtained between 0 KPSI and 11 KPSI.

Alternative Assumptions

Two other calculations have been made for comparison with Curve 2 of Fig. 1. In the two cases different assumptions were made regarding the distribution of highest stresses within the individual records:

3. The mode of the distribution of highest values in each record is the Rayleigh value of 2.385 x r.m.s.-value. Then the distribution of extremes is assumed to be normal, with a mean of 2.385 x 1.297 and a standard deviation of 2.385 x 0.485.

4. A normal distribution is again assumed for the actual highest values (extremes) in individual records, but the mean and standard deviation are obtained directly from the actual observed highest values. This is one of the methods used in (2).

The suitability of these alternate assumptions can be judged from Fig. 6, where it may be seen that the histogram of actual extremes differs from the theoretical. The normal curves appear at first glance to be reasonably good fits to the actual data, but closer inspection shows unsatisfactory fit at the high stress tail. In other words, the histograms are skewed rather than symmetrical. Nevertheless, it is of interest to see the consequence of making assumptions 3 and 4 on the calculation of the cumulative distribution of extremes. Fig. 7 shows, along with Curves 1 and 2 of Fig. 1, Curves 3 and 4 drawn on the basis of assumptions 3 and 4, respectively.

It is clear from Fig. 7 that assumptions 3 and 4 lead to similar results, but that both give values of stress lower than the actual data in the range of interest. This is to be expected on the basis of the poor fit shown in Fig. 6. On the other hand, the ideal Curve 2 somewhat overestimates the stresses. In order to account for this, Fig. 8 has been prepared comparing the sum of Longuet-Higgins distributions of extremes with the histogram. Although the fit may be seen to be much better than the normal distributions in Fig. 6, especially in the tail, it is generally somewhat higher than the histogram.

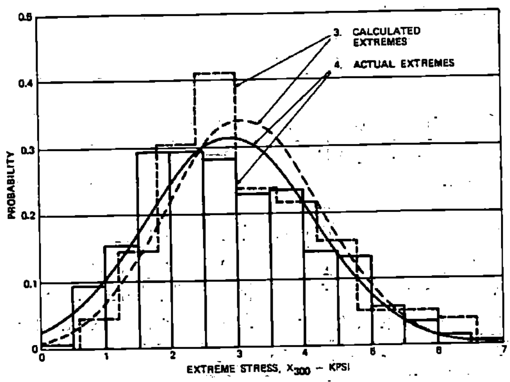


Fig. 6. Histograms and Corresponding Assumed Normal Distributions of Peak-to-Trough Extreme Stresses (300 cycles per record). Weather Group II

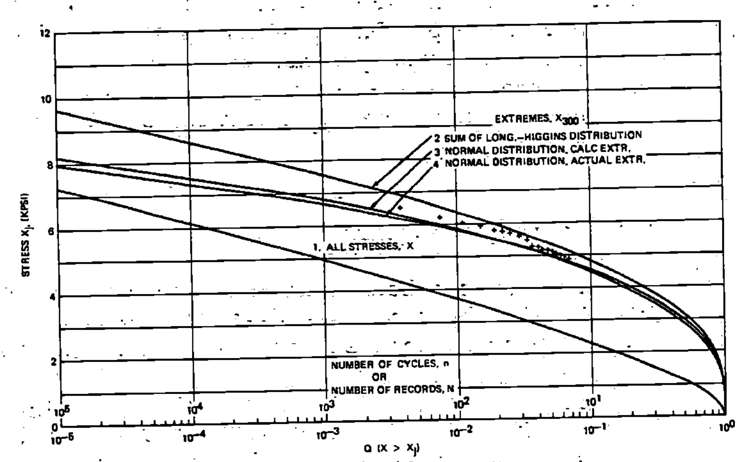


Fig. 7. Theoretical Cumulative Distributions of Peak-to-Trough Stress, with Various Assumptions. Weather Group II

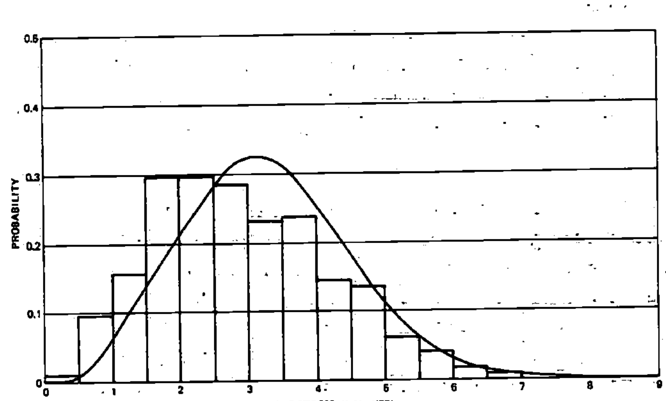


Fig. 8. Histogram of Peak-to-Trough Extreme Stresses and Sum of Longuet-Higgins Distributions. Weather Group II

The suggestion has been made that a so-called Weibull distribution is well suited to the treatment of long-term statistical data. Plotting of the stress data treated in this memorandum showed excellent agreement throughout the range of stresses. Likewise, the extremes (highest stresses in individual records) were found to fit a Weibull distribution very well, except at the very low stress range. However, this curve-fitting approach did not appear fruitful and was not pursued further because no functional relationship could be found between the parameters of the Weibull distribution and the mathematical model or the data itself.

The possible application of Gumbel's work on extreme values was also investigated. Even better agreement of the present sample of extremes was found with the limited form of Gumbel's third asymptotic distribution -- throughout the entire range of stresses -- than with Weibull. But again no way of determining the parameters could be found other than a curve-fitting technique.

Extremal Distributions

We may now consider the extension of the previous two methods to the prediction of highest values. Although the concept of extremes was used in the first stage of the second method above, the final answer was still expressed in terms of a cumulative distribution, i.e., neither method yielded an extremal distribution.

The reason for the extension into the realm of highest values is that although a cumulative distribution gives the probability of exceeding a certain stress level -- or the value that we would expect to be exceeded once -- it does not tell us by how much the stress will be exceeded. A distribution of highest values -- or extremal distribution -- has the valuable property of giving an estimate of the highest value in a sample, no matter how large it may be. It also provides a measure of the reliability of this estimate, or a form of confidence limit.

The determination of extremal distributions brings us to modern developments in mathematical statistics, particularly the principles of order statistics and the asymptotic expansions developed by Gumbel (11). The general relationships can be developed as follows, first for the case of a short period of time while conditions remain stationary.

Let

X = a value of peak-to-trough stress

$f(X)$ = probability density function of X

$F(X)$ = cumulative distribution function of X (as Curve 1 of Fig. 1)

$$F(X_j) = Pr(X \leq X_j) = \int_0^{X_j} f(X)dX$$

Then we have,

$$Pr(X \geq X_j) = 1 - F(X_j)$$

Now, in order to solve the extreme value problem, we have to use order statistics. That is, let

$$Y_1 < Y_2 < Y_3 \; . \; . \; . \; < Y_N$$

be ordered random selection from a sample of n stresses having the probability density function f(X). Note that $X_1 \; X_2 \; X_3 \; . \; . \; . \; .$ are n random samples from the population f(X). On the other hand, $Y_1 \; Y_2 \; Y_3 \; . \; . \; . Y_N$ are random samples from f(X) but are arranged in sequential order.

If we now assume that many samples (each having n stress values) are obtained, i.e., the whole process of 2 or 3 years' data collection were repeated several times, under the same stationary conditions, i.e., having the same probability density f(X), then the Y's from all records have their individual probability density functions. For example, Y_N (largest stress in n stresses) has a probability density function,

$$\phi\,(Y_N) = n[F\,(Y_n)]^{n-1} \; f(Y_n)$$

which can be evaluated in our case.

Then, the cumulative distribution function of Y_N is

$$\Phi\,(Y_N) = [F(Y_n)]^n$$

Thus, the probability that the largest stress exceeds X_j over a long period of time (n stress values) is

$$\begin{aligned} &Pr\,(Y_n \geq X_j) \\ &= 1 - \Phi\,(X_j) \\ &= 1 - [F\,(X_j)]^n \end{aligned}$$

It may be noted here that Curve 2 of Fig. 1 was obtained by using the above theory for the case n = n' = 300, with a simplifying approximation given by Longuet-Higgins.

Referring again to Fig. 4 comparing calculated and actual extreme values, this theory enables one to predict the distribution of actual values corresponding to any particular theoretical value. When this is done lines can be drawn on the figure representing the 0.10, 0.50, and 0.90 probability levels, as shown. Roughly 80% (0.90 - 0.10) of the points should fall within the 0.10 and 0.90 lines, and this is found to be approximately true -- except for a few questionable points. This result is very satisfactory, considering the possible errors involved in the numerical calculations.

Extremal Distribution of All Stresses

It is of interest to apply the above extreme value theory now to determine the mathematical model for the distribution of all the stresses in the sample under study, which are given in ideal form by Curve 1 of Fig. 1. In order to obtain the ideal extremal distribution of stresses, the cumulative distribution F(X) is obtained numerically from the assumed normal distribution of $\sqrt{E}$ values combined with the corresponding Rayleigh distributions. It is easier then to solve for the cumulative distribution of highest values of $\Phi(Y_n)$ than the density function $\phi(Y_n)$. Specific values of the latter can be obtained by differentiation.

Of particular interest are the 0.50 and 0.90 probability values. See Fig. 9. As would be expected, the 0.50 values -- which represent the expected highest value in an experiment having n cycles -- are slightly higher than Curve 1 (which gives the value expected to be exceeded once). The significance of the 0.90 probability values, which are also plotted in Fig. 9, can be grasped by assuming that the collection of data (n' stresses in each) is repeated many times, say N. For any specific value of N the 0.90 probability value tells us the stress that we do not expect to be exceeded in 90% of the N samples. Or, alternatively, it tells us the stress that we expect to be exceeded in not over 10% of the N samples. Hence, it is a form of confidence limit. Again it is not surprising to find that a point on the 0.90 curve at n corresponds exactly with a point on Curve 1 at 10n. In other words, the predicted value to be exceeded once in 10 samples of n' stresses is the same as the value that is predicted to be exceeded once in 10n stresses.

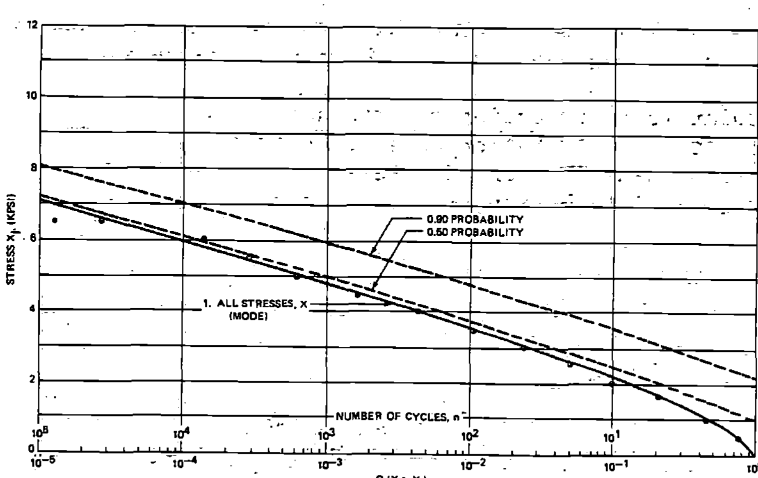


Fig. 9. 0.90 and 0.50 Probabilities from Peak-to-Trough Extremal Stress Distributions Compared with Cumulative Distribution. Weather Group II

The Extremal Distribution for the Second Curve

As was already mentioned, order statistics have been applied in arriving at Curve 2 of Fig. 1 but this was applied only to each of the Rayleigh samples. As the probabilities of these extremes are first weighted according to the normal distribution, and then summed, the ultimate result is still a cumulative probability, F(X') that the stress (X' or X_{300}) exceeds a given stress level X_j -- but by an unknown amount. The application of order statistics in this case yields the highest of the extremes $Y'_{N'}$ as follows. Thus, the probability that the largest stress exceeds X_j over a period of time (N' records) is,

$$Pr(Y'_{N'} \geq X_j) = 1 - F(Y'_{N'})^{N'} \text{ at } Y'_{N'} = X_j$$
$$= 1 - F(X_j)^{N'}$$

where: $1 - F(X_j)$ = cumulative probability as given by Curve 2

N' = number of records in the sample.

Since $F(Y'_{N'})$ cannot be expressed exactly, it is impossible to give an asymptotic expression, and even the numerical computation must be specially suited to the formula. The result is plotted in Fig. 10.

Again it may be seen that the 0.90 probability curve is displaced by log 10 from the basic curve (2). Hence, for design purposes we can read the extremal curve at any desired number of ship-years. It may be concluded that the two approaches are consistent, and that the difference between the cumulative curves and the extremal curves is relatively small.

No attempt will be made at this time to recommend any one particular mathematical model among the four that have been discussed:

(1) Cumulative distribution of stresses
(2) Cumulative distribution of extreme stresses
(3) Extremal distribution of stresses
(4) Extremal distribution of extreme stresses

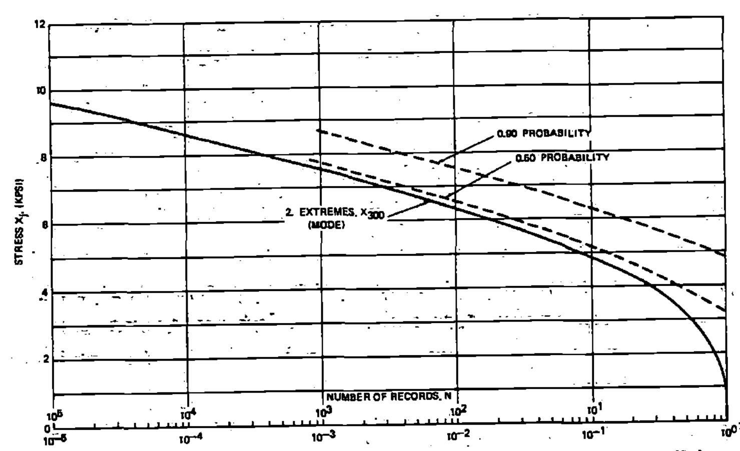


Fig. 10. 0.90 and 0.50 Probabilities from Peak-to-Trough Extremal Stress Distributions Compared with Cumulative Distribution. Weather Group II

Effect of Weather

All of the development so far has assumed roughly constant weather conditions, i.e., a fixed Beaufort No. -- or group of Beaufort Numbers. Variations of wave height within a weather group are in part responsible for the assumed normal distribution of rms values.

However, it is a comparatively simple matter to extend our mathematical models to include the effect of the entire range of Beaufort Numbers or weather groups. It is necessary first to know, or to assume, the percentage of time that each Beaufort No. or weather group is expected to occur. We can then make a summation of the curves for all weather conditions (each of which is like Curves 1 or 2) weighted in accordance with their percentages of occurrence. The result will be overall cumulative distribution curves showing probability of exceeding different stress levels in all weathers, either per cycle or per record. This work has been done for a sample of Wolverine State data in a later section.

Similarly, the extremal distributions can be summed up numerically to give the highest expected stresses for all weather conditions and the 0.50 and 0.90 probability curves determined.

Summary

The work described in this section has shown:

1. Two consistent mathematical probability models can be developed, one covering all observed stresses and the other the highest stresses in individual records, on the basis of two assumptions:

   (a) All rms stress values within any one weather group are normally distributed.

   (b) All peak-to-trough stresses within individual 20-minute records are Rayleigh-distributed.

2. Actual data in a limited sample for Weather Group II (270 records and 81,000 stress reversals) follow similar trends, but slightly lower in stress -- indicating that the predictions are on the safe side. Neither model shows a significantly better fit than the other.

3. Application of extreme value theory leads to the prediction of highest expected values per cycle or per record, which are slightly higher than the values to be exceeded once.

4. A form of confidence limit derived for the above is shown to be equivalent to a corresponding shift of the probability scale (i.e. 0.90 probability is obtained by reading the stress value at 10n or 10N).

5. The mathematical models can be extended to cover all weather conditions experienced over a period of time. This extension will be discussed in a later section.

EXTRAPOLATION BASED ON RMS VALUES

General

The principal method of analysis and extrapolation of ship stress data adopted here was that previously documented in (2). The purpose of this presentation is to summarize the total data accumulated over the eight-year period of data collection on board the four ships. During the above period several reports were published covering data available at the time. Band (4) summarized the first 20 voyages of the Wolverine State, designated 170-217, covering the period December 19, 1961 to January 10, 1964. He also published all the data accumulated on board the Hoosier State in 14 voyages (123-177) collected over the period of November 18, 1960 to June 16, 1963. The above results have since been superseded by (2), where ten additional voyages (219-241) were added to the Wolverine State data, and a correction factor was applied to account for the effect of irregularities in the plating which resulted in different results from the port and starboard gages (2). The previous report also includes the combined data for the two above sister ships as summarized for 44 voyages, representing 8.04×10^5 stress reversals. Since the publication of (2), additional data were collected on board the Wolverine State between May 12, 1965 and May 9, 1969, covering a total of 22 additional voyages, eight of which were between the U.S. and Viet Nam.

The S.S. Mormacscan was instrumented during the period of April 17, 1964 to February 25, 1967. Over this period 17 voyages were made, five in the North Atlantic and 12 from the U.S. east coast to South America. The overall long-term trend of stress obtained is presented in Fig. 3 of (2). However, allowance should be made for the fact that data from two different routes, as indicated above, are grouped together. The S.S. California Bear was instrumented throughout February 3, 1966 to October 14, 1968 while in service in the North Pacific between the U.S. west coast and Japan. A total of 13 instrumented voyages representing 2.38×10^5 stress reversals were analyzed. Preliminary results based on the first five instrumented voyages of the California Bear were previously published in (2).

The list of all voyages for all ships designated by dates and the number of tape reels recorded is given in the Appendix. All of the above information was gathered by Teledyne Materials Research Company through the eight-year program.

Because of the length of time associated with the collection of the above data, various improvements in reduction and analysis were introduced through the years. Care should therefore be taken when referring to previous publications such as (12)(13)(14) and (15). The data in Ref. (12) were hand analyzed while in (13)(14) and (15) the probability analyzer was available. Though the two methods of data reduction were cross checked, it was later revealed that the probability analyzer terminates the analysis of the record before twenty minutes have elapsed if one of its sixteen stress level counters has exceeded 255 reversals. This phenomenon is common in records of low stress level when analyzed at high sensitivity where stress levels of 0-0.5 and 0.5-1.0 KPSI constitute the majority of the stress reversals. In order not to bias the sample by excluding low rms stress records, all the records subjected to the above were later analyzed separately along with the so-called "zero" stress records reported previously.

References (4)(12)(13)(14) and (15) include a series of "dot plots" of rms stress vs Beaufort number which illustrate the distribution of the rms value within each Beaufort Number. Also shown are the mean values of stress at each Beaufort No. As originally calculated, these mean values included all of the zero stresses recorded. However, the majority of the zeroes should have been excluded because they were recorded in port or in protected waters. As a result, the mean curves were somewhat underestimated in the lower Beaufort range. Efforts were made to correct for the above in the present study by including only the appropriate zero and low stress records.

This section deals successively with the different ships studied, beginning in each case with the analysis of new data -- such as the last 22 voyages of the Wolverine State and last 12 voyages of the California Bear. All results for each ship type are then summarized and long-term trends of bending moment for each are presented. Finally, a comparison is given of results obtained from all four ships operating in various ocean areas.

WOLVERINE STATE

Newly Acquired Data

The data collection on board the Wolverine State constitutes the major port of the total data accumulated. Due to the long period over which it was recorded, some inconsistencies in the method of recording and reduction occurred. The first twenty voyages (170-217) (4) were recorded as an averaged single signal combined from the port and starboard gages. This was done in order to eliminate the effect of lateral bending, which would cause a difference between the two gages. The ten voyages (219-241) reported in (2) and seven additional (245-265) reported below were recorded on two separate channels -- port and starboard -- and were later electrically combined in the laboratory in correct phase to give the equivalent of the averaged signal. Thus the data available for these voyages consists of single channel output for port and starboard as well as a combined signal. The two methods were proved to yield identical results (2), with the latter facilitating further reduction of data by providing separate records for the port and starboard transducers. As discussed in (2), the electrical combined values are expected to represent the stress due to vertical bending only, while the mathematical average of separate port and starboard records would probably contain some additional stress due to lateral bending, since it does not account for the phase relationship between vertical and lateral bending.

Reference to a calibration correction factor that should be applied to all the above stresses was previously made in (2). This correction can be applied either to the combined signal or to the separate port and starboard signals before the averaging process.

The last fifteen voyages cannot be represented in such a consistent manner as the previous data. In eleven of the voyages data were recorded on one side only; in five of the voyages new gages were utilized whose calibration was not exactly known. Hence, there are certain doubts regarding data for the last 15 voyages, and they will be dealt with separately.

Considering first the voyages for which reliable data are available in the North Atlantic, Fig. 11 illustrates the variation of stress with Beaufort No. for the recent voyages 245-265. Due to the fact that records were obtained from more summer than winter voyages, two separate curves were prepared for the two seasons, and an averaged curve is given for the whole year, based on equal probability of winter and summer. This was necessary in order to combine these results with previously obtained data that were collected over equal periods of summer and winter. Also shown in Fig. 11 is a comparison between mathematically averaged and electrically combined results, indicating the apparent effect of lateral bending. It should be noted that a mean curve drawn between winter and summer curves approximately adjusts for the difference in the number of winter and summer records. However, a complete average of all year-round data would be expected to lie somewhat lower at the low Beaufort No. end of the curve because of the large number of low stress values in summer, which would weight the low end of the average curve heavily.

Old and New Data Compared

Fig. 12 presents a comparison of mean rms stresses between the new valid data (P & S electrically combined) and the new data combined with the old data presented in (2). The comparison is quite satisfactory, and the consistency of the trends of stress with Beaufort No. for the same ship in the same route is encouraging.

A comparison of the long-term predictions for the old and new data is given in Fig. 13. Good agreement is illustrated, with the new data being slightly on the low side.

The total results for all voyages of the Wolverine State and Hoosier State in the North Atlantic are given in Fig. 14. It is evident that the variation of mean rms stress in this plot can be regarded as linear, and a simple expression for the stress as a function of the Beaufort number can be derived. However, care should be taken in using such an expression, as the Beaufort scale itself is non-linear in terms of wind velocity.

The long-term prediction based on the total data for the C4-S-B5 ships in the North Atlantic is given in Fig. 15 for the actual and "standard" North Atlantic weather distributions. The difference between the two

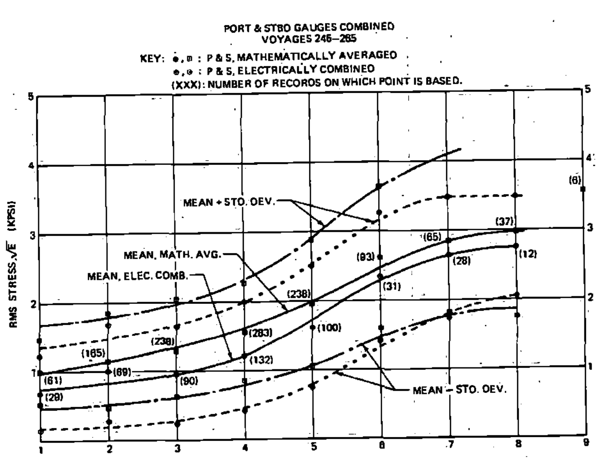


Fig. 11. Trends of Average RMS Peak-to-Trough Stress and Standard Deviation vs. Beaufort Wind Scale, Showing Difference between Mathematically Averaged and Electrically Combined Data, S.S. WOLVERINE STATE, Voyages 245-265

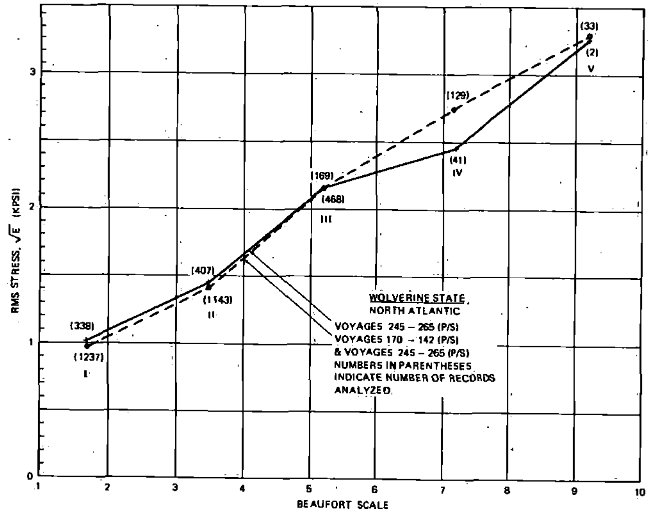


Fig. 12. Trends of Peak-to-Trough Stress from New and Old Data, S.S. WOLVERINE STATE

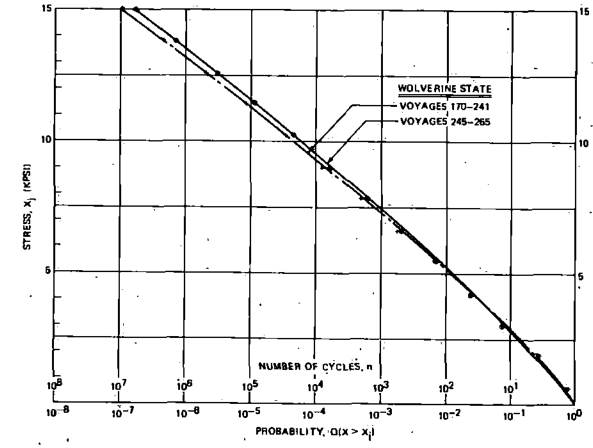


Fig. 13. Long-Term Trends of RMS Peak-to-Trough Stress, Showing Differences between New and Old Data, S.S. WOLVERINE STATE

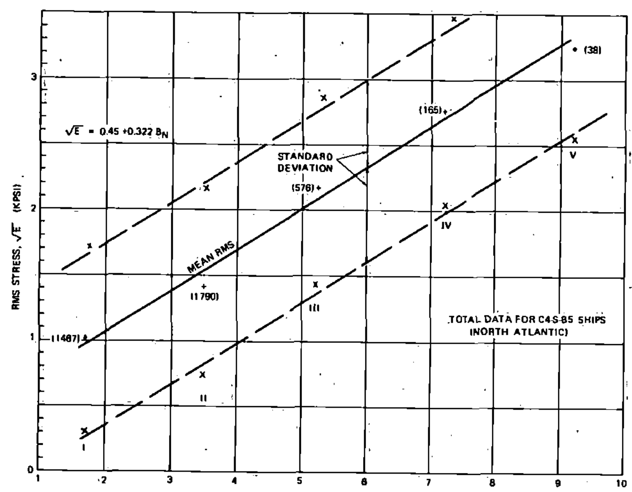


Fig. 14. Trends of Average Peak-to-Trough RMS Stress and Its Standard Deviation vs. Beaufort Wind Scale for the C4-S-B5 Class Ships in the North Atlantic

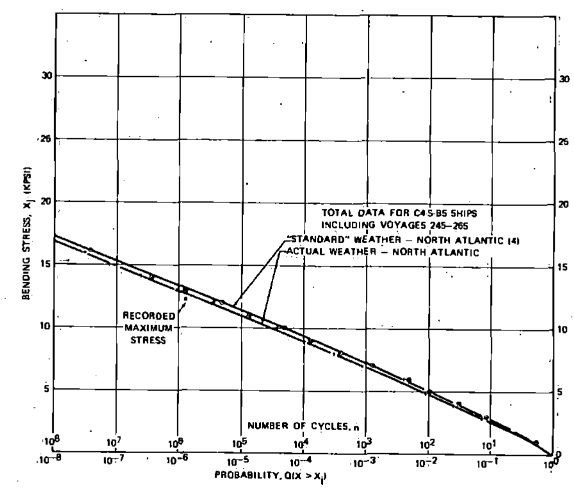


Fig. 15. Long-Term Trends of Bending Moment Coefficient for the C4-S-B5 Class in the North Atlantic, for Actual and for "Standard" Weather

curves is negligibly small, which indicates the reliability of the proposed standard North Atlantic weather distribution given in (4). Also shown is the maximum stress value recorded over the total period of data collection, which is slightly below the predicted line. The trends shown in Fig. 15 are based on a sample of roughly 1×10^6 stress reversals, which is considered to be an adequate sample for this purpose.

Last 15 Voyages

Considering the last 15 voyages (267-289), eleven voyages recorded data on the one side only, either port or starboard. This type of data is considered only partially valid and can only be utilized under certain assumptions, such as an allowance for the lateral bending component which is included in the raw data.

An additional inconsistency emerged as a result of the installation during 1965 of three more gages designated as New Port, New Temporary Port and New Starboard. Five of the above eleven voyages report data collected through the latter three gages, and correction factors were established by Teledyne for these gages (15). However, not enough data were accumulated to verify the accuracy of the proposed corrections. The records analyzed from the doubtful last 15 voyages are summarized in the following Tables I and II.

The information received from Teledyne for the above voyages was in the form of computer printouts listing data from all records for each voyage. The information given for each "interval," or record, included the Beaufort No. and the rms stress as obtained from the probability analyzer. The data were then rearranged into histograms for each voyages, or for each group of voyages recorded under identical conditions, giving for each Beaufort the number of occurrences of rms bending stress of magnitude within each stress range. The stress ranges started at 0 and went up in increments of 0.5 KPSI.

This information was processed at Webb through a computer program to give for each histogram the mean value and the standard deviation of the stress experienced at each Beaufort Number. The above output was corrected by applying a calibration factor depending on the particular gage used for recording. The voyages were then divided into two groups representing winter (November to April) and summer (May to October); for those voyages for which only records for one side (port or starboard) were available, the port or starboard data from the various voyages were combined and then averaged together. The average of the mean and standard deviation was obtained by somewhat different formulas than were used in previous reports, because of the necessity of combining record samples of different size.

Given a set of values m_i, s_i and N_i, where m is the mean, s, the standard deviation and N the number of occurrences, the two following basic formulas were used. They are derived in Appendix B of (3).

$$m_{AV} = \frac{m_1 N_1 + m_2 N_2 + \cdots \cdots m_n N_n}{N_1 + N_2 + \cdots \cdots N_n}$$

Table I. Summary of North Atlantic Recent Voyages Analyzed - S.S. WOLVERINE STATE

TABLE I SUMMARY OF NORTH ATLANTIC RECENT VOYAGES ANALYZED S.S. Wolverine State

Voy. No.	Gage Recorded	Season	No. of Records
267	New Starboard only	Summer	28
271	Port only	Winter	
273	" "	"	266
282	" "	"	
277	New Starboard only	Winter	94
288	Starboard only	Winter	
289	" "	"	133
TOTAL			521

Table II. Summary of U.S. - Viet Nam Voyages Analyzed - S. S. WOLVERINE STATE

TABLE II SUMMARY OF U.S. - VIET NAM VOYAGES ANALYZED S.S. Wolverine State

Voy. No.	Gage Recorded	No. of Records
279, 280, 281	Port, Starboard	
285, 286	P & S Combination	576
283 & 284	Port only	471
287	Starboard only	8
TOTAL		1055

$$s_{AV} = \sqrt{\left[\frac{\sum_{i=1}^{i=n}\left(m_i^2 + s_i^2\right)N_i}{\sum_{i=1}^{i=n} N_i}\right] - \left[\frac{\sum_{i=1}^{i=n} m_i N_i}{\sum_{i=1}^{i=n} (N_i)}\right]^2}$$

The above two expressions were programmed and were used for averaging the results obtained under different conditions, i.e., separate gages or seasons. The output was given for each Beaufort No. in terms of the average rms, standard deviation and the number of occurrences.

When combining port and starboard data the average curve of stress vs. Beaufort No. is known to be about 8-12% higher than the one obtained directly by one averaged signal (2). Such a correction could be applied to these curves in order to combine the total data. Since, in the case of the Wolverine State in the North Atlantic, 3142 records were previously analyzed and proved to be rather consistent, it was logical to treat the additional 521 separate port and starboard records discussed above with more caution. With regard to the Viet Nam-U.S. data, however, the sample is much smaller and omission of data collected on one side only leads to an insufficient statistical sample, which may have a more unfavorable effect on reliability of results than the use of a correction factor. (See next section.)

Once the curve of stress vs. Beaufort Number has been established and defined in terms of m_i, s_i, and N_i for each Beaufort, or for a group of Beauforts, as indicated in (2), the above information is used as direct input to the long-term calculations in a similar fashion to that described in Appendix D of (3).

For the remainder of the North Atlantic voyages, as given in Table I, it was decided to examine the effect on the long-term curve of including the data after making appropriate corrections as described above. Thus all winter voyages were combined to give one single curve of stress vs. Beaufort number. In order to increase the sample size, Voyage 259 from the previous 245-265 group, for which individual gage data were also available, was included in addition to the winter voyages listed in Table I. The results were calculated from port and starboard separately and averaged to give the mean line, as shown in Fig. 16.

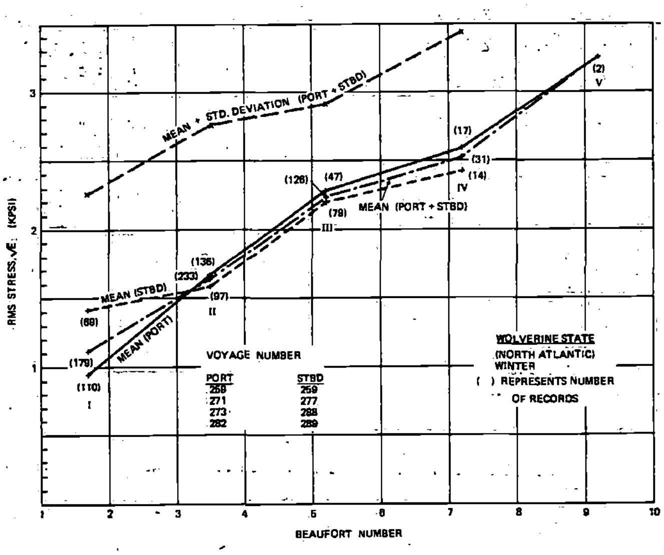


Fig. 16. Trends of Peak-to-Trough RMS Stress and Its Standard Deviation vs. Beaufort Wind Scale for the Last Voyages of the WOLVERINE STATE in the North Atlantic

It is interesting to note that, although each sample (port and starboard) was taken from different voyage groups, the results, after corrections for gage calibration factors, are reasonably close. The mean line representing a mathematical average of separate Port and Starboard data for the winter season (Voyage 259 and 271-289; from Fig. 16) is -- as expected -- substantially higher than the total data line for all seasons electrically combined (Voyages 170-265), as shown by Curve 1 in Fig. 17. Also shown in Fig. 17 are the electrically combined data for the recent summer voyages, Curve 2, as well as the mathematically averaged Port and Starboard line, Curve 3. Fig. 17 thus gives an indication of the magnitude of difference in stress due to season by comparison of Curves 1 and 2, while Curves 2 and 3 indicate the difference in stress due to the lateral bending moment component which is in the order of 0.25 KPSI, independently of sea severity.

Fig. 17 also shows the mathematical mean stress curve for all the new data from separate port and starboard gages (Voyages 245-289), for equal probability of winter and summer. In general, this curve is seen to be consistent but somewhat lower than the total data curve (Voyages 170-265), even though the former includes the effect of lateral bending. It seems likely that the reason for this result is the small size of the statistical sample.

The above results illustrate that data from one gage or from one season can be used if necessary. However, when enough data are available, as in the case of the <u>Wolverine State</u> and <u>Hoosier State</u> in the North Atlantic, it is felt that such doubtful data should be excluded.

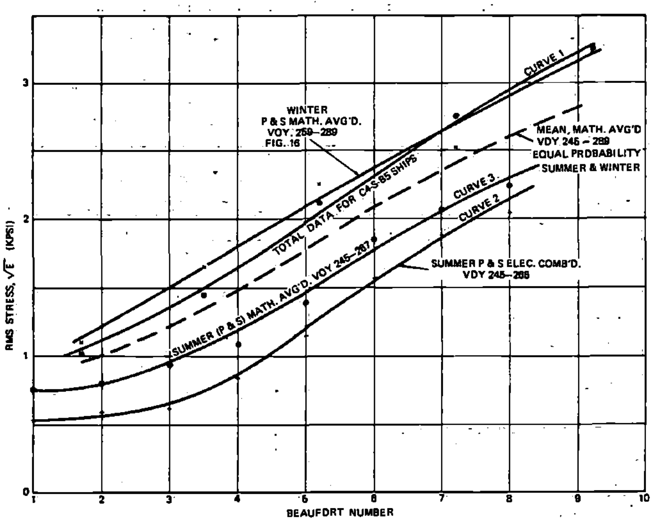


Fig. 17. Comparative Trend of Average RMS Stress Values vs. Beaufort Wind Scale for Various Combinations of Recent Voyages, S.S. WOLVERINE STATE

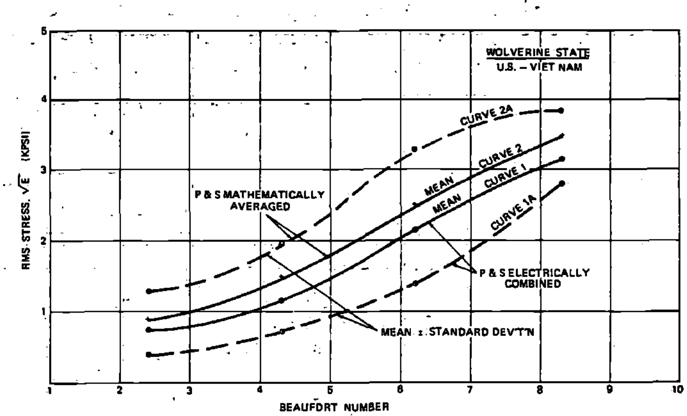
Viet Nam Voyages

As indicated previously, the data available from the Viet Nam voyages are rather limited. The ship was diverted to this service after Voyage 277, i.e., in the Spring of 1967. Eight voyages across the Pacific were recorded, each round voyage extending for about three months.

Five of the above voyages were properly documented by port and starboard simultaneous recording, thus yielding an electric average. The results are illustrated in Fig. 18, Curves 1 and 1A for the mean and standard deviation of the electrically combined results. Curve 2 and 2A indicate the mean and standard deviation from all eight voyages for port and starboard, separately.

The relation between the mathematically averaged and electrically combined curves is consistent with previously obtained data in the North Atlantic, and this indicates the relative reliability of Curve 1 for which only a limited number of records was available (576). No separation into winter and summer seasons was deemed necessary, because of the different character of the ocean zones covered under these voyages.

Fig. 18. Trend of Average RMS Stress and Standard Deviation vs. Beaufort Wind Scale for the WOLVERINE STATE on the Viet Nam Route



It should be noted that for Beauforts 8 and 9 the available number of records was limited to 10 only, and therefore the reliability of the standard deviation is questionable.

The information given in Fig. 18, Curves 1 and 1A, was used for long-term predictions and the results are summarized in Fig. 19. As no weather distribution other than the actual was available for this route, the long-term predictions were calculated on the basis of the actual distribution as well as for "tanker" and "general" routes (4). The actual recorded maximum stress is shown to be slightly below the predicted value.

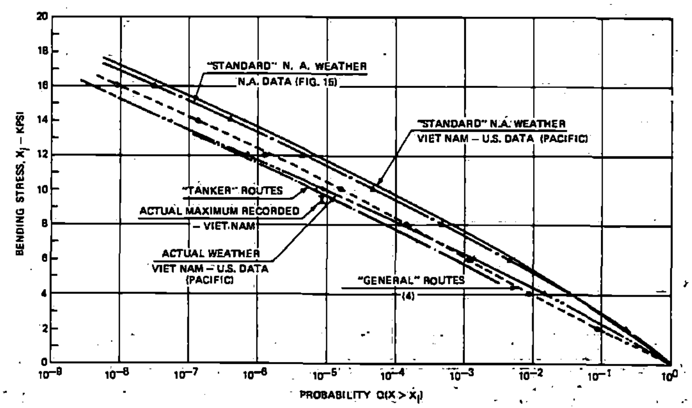


Fig. 19. Comparative Long-Term Trends of Peak-to-Trough Stress for the WOLVERINE STATE on North Atlantic and Viet Nam Routes

In order to compare the results with those previously obtained in the North Atlantic, long-term curves were also drawn in Fig. 19 for the standard North Atlantic weather distribution given in (4), one curve predicted from the Viet Nam data and the other from the north Atlantic data. The predictions based on the limited Pacific data are somewhat higher than those based on the extensive North Atlantic data, probably because of a single storm on the Viet Nam route for which high stress values were recorded.

Table III summarizes the records obtained and analyzed for the U.S.-Viet Nam voyages.

Finally Table IV gives a summary of stress data for all voyages of the S.S. Wolverine State in the North Atlantic and Viet Nam voyages, as plotted in Figs. 12 and 18, respectively.

Table III. Summary of Records for Viet Nam Voyages - S.S. WOLVERINE STATE

TABLE III SUMMARY OF RECORDS FOR VIET NAM VOYAGES
S.S. Wolverine State

Voy. No.	Recording Gage	No. of P. & S. Records	No. of Port Records	No. of Starboard Records
279	P. & S.	88	88	130
280	P. & S.	136	136	160
281	S.P. & N.S.	180	180	180
283	P.	-	258	-
284	P.	-	149	-
285	P. & S.	144	258	144
286	P. & S.	183	183	183
287	S.	-	-	7
Total Records		731	1252	804
TOTAL RECORDS USED		673	1165	772

Table IV. Summary of RMS Stress Data for S.S. WOLVERINE STATE - All Voyages (170-265)

TABLE IV SUMMARY OF RMS STRESS DATA FOR S.S. WOLVERINE STATE All Voyages (170-265)

North Atlantic	WEATHER GROUPS* I	II	III	IV	V	Total
m - mean, KPSI	.98	1.40	2.15	2.75	3.28	
s - Stand. Dev., KPSI	.704	.724	.721	.737	.720	
N_i - No. of Records	1237	1143	468	129	33	3010
$P_i = N_i / \sum_{i=I}^{V} N_i$	.4113	.3799	.1557	.0427	.0104	
U.S. - Viet Nam						
m	.76	1.18	2.17	3.15	-	
s	.356	.450	.764	.650	-	
N_i	351	270	42	10		673
P_i	.5218	.4012	.0623	.0147		

		B_N
*Weather Group I	-	1, 2, 3
" " II	-	4, 5
" " III	-	6, 7
" " IV	-	8, 9
" " V	-	≥ 10

CALIFORNIA BEAR

Data Analysis

Provisional results obtained from the California Bear were presented in (2). At that time no still water calibration was yet available and only five voyages were completed. By the end of 1968, when the instruments were removed from the ship, a total of 1224 records were accumulated from 13 voyages across the Pacific between the U.S. west coast and Japan. The data present a consistent sample with roughly an equal number of voyages in each season. The same two gages at port and starboard were used throughout the 13 voyages and only a small calibration correction was required, as determined from a still water calibration performed by Teledyne and reported in (15). As previously discussed in (3), it was found necessary to separate the data collected on the east- and westbound legs of the voyage because of substantially lower stress levels on the eastbound runs, perhaps in part because the draft was considerably lighter.

The reduced data were obtained from Teledyne in the form of histograms previously described in (2) and the r.m.s. stress values, both obtained from the probability analyzer. Extreme values per record as well as position, speed, wind data, etc., from logbooks were specified also.

The rms values were grouped by Beaufort No. to give the mean, m_i, and the standard deviation, s_i, for each of the four sub-totals, i.e. eastbound -- summer and winter -- and westbound -- summer and winter. The individual m_i and s_i for each Beaufort were then averaged into weather groups as defined in (4). Fig. 20 indicates the results for equal weighting of the seasons for both east and westbound voyages. It is clear that the difference between the west and eastbound voyages is increased as the Beaufort No. and stress level increase, but not necessarily in a linear fashion. Fig. 21 shows the total data for both east and west voyages, as well as the data combined on equal probability of east and westbound time at sea. Very little difference in stress is shown for the two cases, indicating again the adequacy of the sample collected.

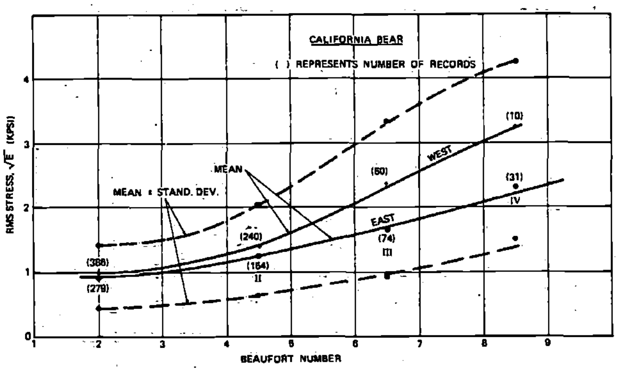


Fig. 20. Trends of RMS Stress Values and Standard Deviation vs. Beaufort Wind Scale for the S.S. CALIFORNIA BEAR, East and Westbound, in the Pacific

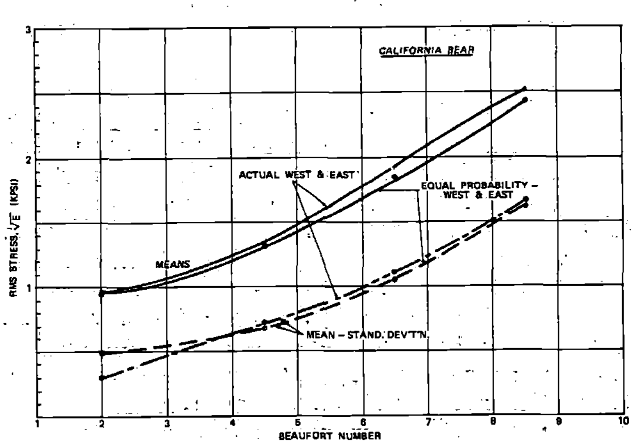


Fig. 21. Trends of RMS Stress Values and Standard Deviations vs. Beaufort Wind Scale for the S.S. CALIFORNIA BEAR in the Pacific

Three long-term predictions were performed for the above conditions, i.e., west, eastbound and average condition. The weather distributions were determined for the above conditions and are illustrated in Fig. 22. The results are given on normal probability paper. The probability of occurrence of a high Beaufort No. seems to be slightly lower for eastbound voyages.

The long-term trends of stress are given in Fig. 23 for equal probability of summer and winter. As expected, the highest stress not to be exceeded over a certain return period is greater for the westbound voyages. Similar curves to those shown in Figs. 20 and 23 were given in (3) in conjunction with the comparison between model and full-scale results.

The second type of analysis performed on the California Bear data was the summation of all the individual histograms supplied by Teledyne for each individual record. The histograms were given in terms of the number of zero crossings per stress bandwidth. A certain problem arises due to the different width of stress bands used by Teledyne for different records, which vary between 0.5, 0.75 and 1.0 KPSI. Certain assumptions had to be made when regrouping all records into standard bandwidths. Additional problems were encountered due to the fact that the probability analyzer can only handle up to 255 zero crossings in one bandwidth. This situation occurs primarily at low stress levels (i.e., low Beaufort No.) when most of the stress variations are within 0 to 1.5 KPSI and the first or second bandwidth 0 - 0.5 or 0.5 - 1.0 KPSI may be overloaded. Such records were rejected by the computer and listed separately. It was decided not to use these records due to the uncertainty involved in determining the length of the record analyzed. On the other hand, some records may also be rejected due to exceptionally high stress in the last counter i.e., 7.5 - 8.0 KPSI. Such rejected records were later rerun with wider bandwidths to avoid stress counts in the last bandwidth.

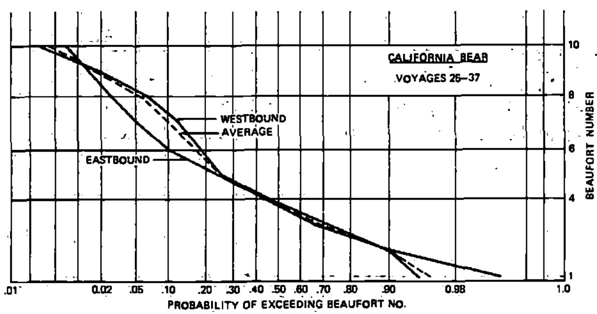


Fig. 22. Actual Weather Distribution for the CALIFORNIA BEAR, Voyages 25-37 in the Pacific

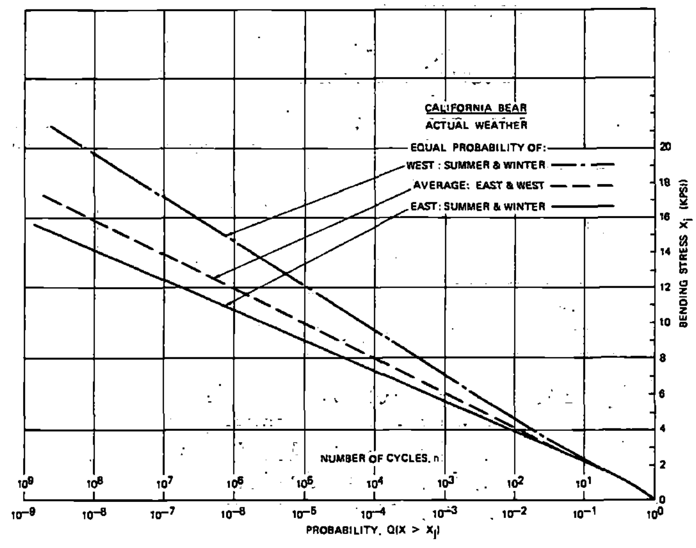


Fig. 23. Long-Term Trends for the CALIFORNIA BEAR in the Pacific

In summing up the individual histograms it was noticed that for one particular westbound voyage an exceptionally high stress (13 KPSI) was recorded. Such a single value may have a pronounced effect on the higher end of the stress distribution as a function of cycles encountered. It was therefore decided to show the distribution with and without the particular group of nine records, containing the high value, in order to illustrate the effect of such high values on the total distribution. While for the eastbound voyages the above extreme value was 62% above the next highest, for the westbound voyage where the same extreme stress occurred, it was only 15% above the next highest. The extreme value distribution for the westbound voyages is thus more consistent than eastbound.

Figs. 24 and 25 illustrate the cumulative distributions from the histograms and their comparison to the long-term predictions based on the rms values for east- and westbound voyages, respectively. The eastbound results are shown with and without the above discussed data. It is evident that neither of the two seem to agree absolutely with the predicted curve. It is felt that if the sample had been of more adequate size, the probability of encountering another severe storm on the eastbound leg would have been greater and the inclusion of all data would have yielded a more reliable answer. The agreement between the westbound curve and histogram points is acceptable and indicates somewhat higher predicted stresses, as expected from previous work.

Finally, Fig. 26 shows the comparison between the total average results from the California Bear, irrespective of voyage direction for both the rms predictions and the histogram distribution. The agreement is exceptionally good and further indicates that a large sample is required in order to get a meaningful result.

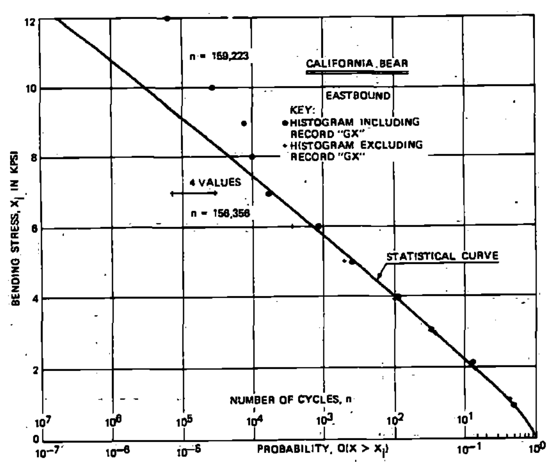


Fig. 24. Comparison of Long-Term Trends and Histogram Analysis for the CALIFORNIA BEAR in the Pacific, Eastbound

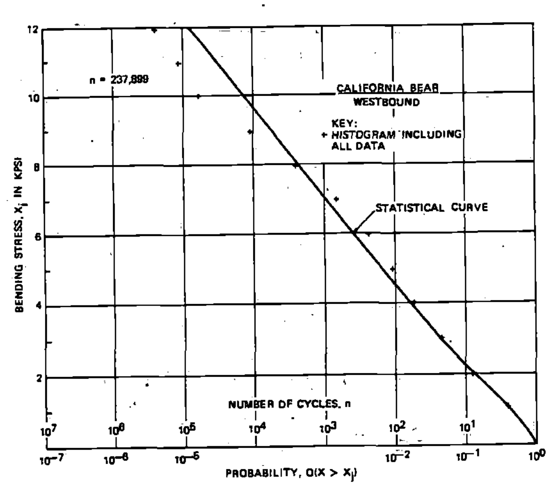


Fig. 25. Comparison of Long-Term Trends and Histogram Analysis for the CALIFORNIA BEAR in the Pacific, Westbound

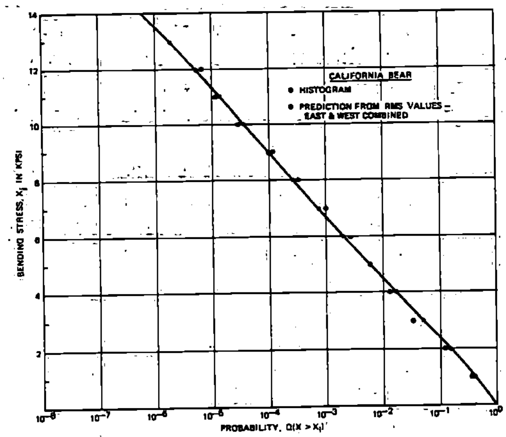


Fig. 26. Comparison of Long-Term Distribution with Histogram Data, S.S. CALIFORNIA BEAR

Table V gives a summary of California Bear results for equal probability of west- and eastbound voyages, as plotted in Fig. 21.

Table V. Summary of RMS Stress Data for S.S. CALIFORNIA BEAR in North Pacific

TABLE V SUMMARY OF RMS STRESS DATA FOR S.S. CALIFORNIA BEAR IN NORTH PACIFIC

	WEATHER GROUP*					
	I	II	III	IV	V	TOTAL
m - mean, KPSI	.96	1.32	1.85	2.44		
s - Stand. Dev., KPSI	.471	.607	.789	.800		
N_i - No. of Records	665	394	124	41		1224
$P_i = N_i / \sum_{i=I}^{V} N_i$	.5433	.3219	.1013	.0335		

*See note on Table IV.

MORMACSCAN

Data Analysis

The results given in (2) for the Mormacscan were considered provisional because of the lack of a still water calibration at that time. Furthermore, it was noted that there was a limited amount of data available for both the North Atlantic and South American runs. Fig. 27, which is Fig. 13 of (2), shows the trend of rms stress with weather and indicates some uncertainty regarding the trends of stress for Weather Groups IV and V. Furthermore, long-term trends were obtained from the data and plotted in Fig. 3 of (2) for both routes. It was concluded that results "appear to be unexpectedly low." (2).

It was hoped that additional data would be obtained later for the Mormacscan which would "lead to a plausible explanation of the differences shown." However, for this ship no further data were obtained. A still water bending calibration was carried out (15), but it indicated that no correction factor was required for the raw stress data. Hence, the Mormacscan results still appear questionable.

Further study of the data suggested that the important factor was the relatively small number of North Atlantic voyages -- five -- for which data were available. Furthermore, although these were all winter voyages (October - April) in two different years ('64-65 and '65-66), there were only 30 records in which the Beaufort No. was eight or above.

Our conclusion is that inadequate statistical samples were obtained for this ship. Nevertheless, a long-term prediction for the Mormacscan in standard North Atlantic weather has been made from Fig. 27 and plotted in Fig. 28 for comparison with the other ships.

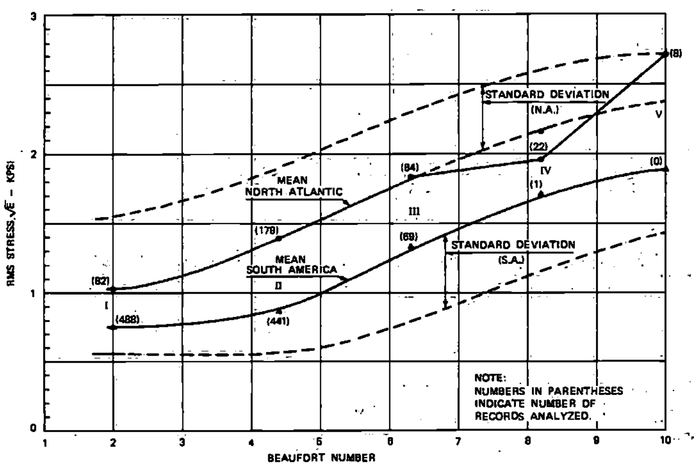


Fig. 27. Trends of Average Peak-to-Trough Stress and Standard Deviation vs. Beaufort Wind Scale for the MORMACSCAN on South American and North Atlantic Routes

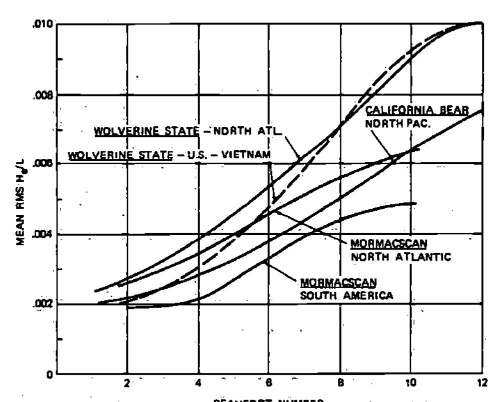


Fig. 28. Comparison of Bending Moment Coefficients vs. Beaufort No. for Several Ships in Actual Weather

Comparison of Results for the C4-S-B5, Mormacscan and California Bear

In order to compare results obtained for the three ship types in various ocean zones, a common basis should be established in terms of the bending moment coefficient, h_e/L, as defined in (2), and all three ships should be assumed subjected to identical weather conditions. A simple relationship between stress and bending moment is given in (2) for each of the three ships, i.e.:

Wolverine State & Hoosier State	$h_e/L = .0028X$
Mormacscan	$h_e/L = .0026X$
California Bear	$h_e/L = .0022X$

where X is the peak-to-trough bending stress. By applying the above to the stress trends previously derived for each ship the long-term bending moment distributions can be compared.

Fig. 28 illustrates the trends of bending moment coefficient vs. Beaufort number for all three ships. The data for the Mormacscan are given as separate curves for the two ocean zones, while separate curves are given for the Wolverine State in the North Atlantic and on the Viet Nam route.

In order to study the effect of weather severity of the various routes, the actual weather distributions are given for all four routes in question, i.e., North Atlantic, Pacific, U.S. - South America and Viet Nam. Fig. 29 illustrates the above using a logarithmic scale for the probability of exceeding a certain weather group severity. It should be noted that the actual weathers plotted are based on different sample size, as indicated. Nevertheless, it is clear that substantial differences in weather were encountered by these ships on different routes, and it would be expected that these differences would have a significant effect on long-term trends of bending moment.

Furthermore, previous experience has indicated that small samples taken over short periods may yield substantially different distributions, as shown in Fig. 30 for four different samples in the North Atlantic. From the 375 samples collected on board the Mormacscan, the 941 records sample collected on board the Wolverine State (Voyages 219-241), the 1026 records collected on board the Hoosier State and the total data collected on board the Wolverine State (Voyages 170-265), it is clearly demonstrated that the substantial scatter exists. However, the standard North Atlantic weather distribution as proposed by Bennet and given in (4) represent a good approximation for three of the curves, while the fourth from the Hoosier State seems to represent an unusual weather experience.

It is concluded that for comparison purposes it is important to standardize the weather distribution and eliminate such differences as illustrated in Figs. 29 and 30. The most meaningful comparison of the total data collected is achieved, therefore, through the long-term trends of the bending moment coefficients in standard weather. Figs. 31 and 32 illustrate the above, with data plotted on the basis of non-dimensional bending moment coefficient, h_e/L, first for actual weather in Fig. 31 and then for standard weather in Fig. 32.

Fig. 31 shows the trends for the Wolverine State in the North Atlantic and Viet Nam routes, for the California Bear in the Pacific and for the Mormacscan on the North Atlantic and South American routes. A large amount of scatter is shown, some of which must be due to the differences in weather encountered by the five ships.

Fig. 32, based on "standard" North Atlantic weather, shows much less scatter. However, considerable differences remain that are not readily accounted for. Although the ships are not very different in size, one would

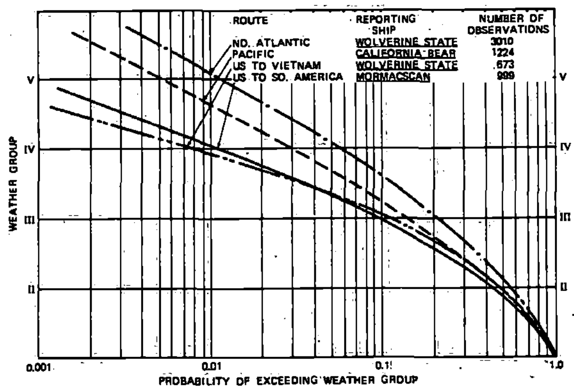


Fig. 29. Weather Distributions Obtained from Several Ships on Different Routes

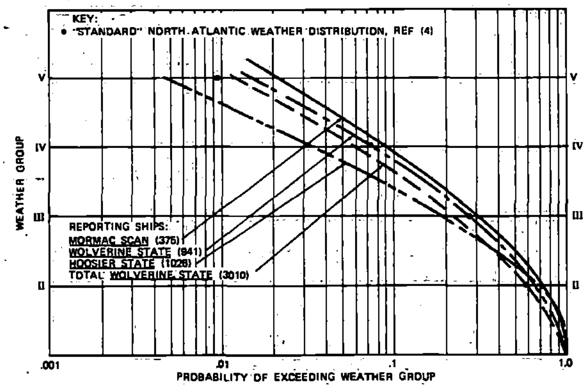


Fig. 30. Weather Distributions Obtained from Different Ships in the North Atlantic

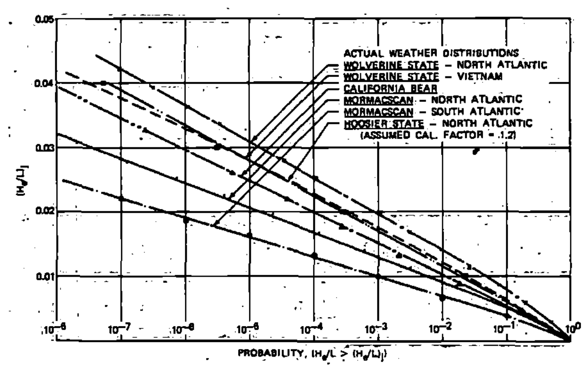


Fig. 31. Comparison of Long-Term Distributions of Bending Moment for Different Ships in Actual Weather

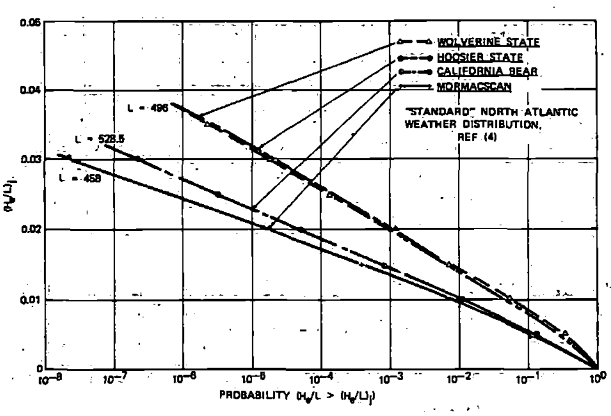


Fig. 32. Comparison of Long-Term Distributions of Bending Moment for Different Ships in "Standard North Atlantic Weather"

expect the largest -- the California Bear -- to have somewhat smaller bending moment coefficients than the Wolverine State. The actual difference is somewhat larger than would be expected. On the other hand, it would be expected that the smallest ship -- the Mormacscan -- would have the highest bending moments instead of the lowest.

A factor that may influence the comparison is the relationship between wind and wave height in the areas in which the ships operated. Since the Pacific waves may generally be less severe than those in the Atlantic, this may have been partly the reason for the fact that the California Bear is so much lower than the Wolverine State. However, the low relative position of the Mormacscan, even in the North Atlantic, is not easy to explain. The only explanation that can be offered is that an inadequate statistical sample was obtained for this ship (375 records compared with 1224 for the California Bear and 3010 for the Wolverine State).

EXTRAPOLATION BASED ON HIGHEST VALUES

In an earlier section a comparison has been made between two mathematical models for extrapolation of ship stresses (or bending moments) within one particular weather group. The second method, based on extreme values, was shown to be consistent with the more commonly used rms form of extrapolation. Accordingly, it appeared desirable to apply the second model to a larger sample of data, including many weather groups. This has been done for 10 of the 1964-65 voyages of the Wolverine State (219-241) that were previously analyzed by the rms method. These particular voyages were felt to be particularly suitable because they included stress data for Beaufort Nos. 1 to 10 inclusive.

The means and standard deviations of the rms stress values for Voyages 219-241 were previously calculated for each Beaufort No. and are plotted in Fig. 33. Data were also combined into weather groups, on a different basis than before, with results presented in Table VI.

Table VI. Stress Data for Voyages 219-291
With Calibration Correction
S.S. WOLVERINE STATE

TABLE VI STRESS DATA FOR VOYAGES 219-291 WITH CALIBRATION CORRECTION
S.S. Wolverine State

Modified Weather Group	Beaufort Numbers	RMS STRESS KPSI Mean	RMS STRESS KPSI Std. Dev.	No. of Records
I'	1 & 2	.952	.541	216
II'	3 & 4	1.274	.741	319
III'	5 & 6	2.014	.770	172
IV'	7 & 8	2.662	.791	97
V'	9 & 10	3.348	.572	41
				845

The cumulative probability curves for each weather group were calculated using the Bennet-Band method (4) based on rms values. Results are plotted in Fig. 34 for individual weather groups.

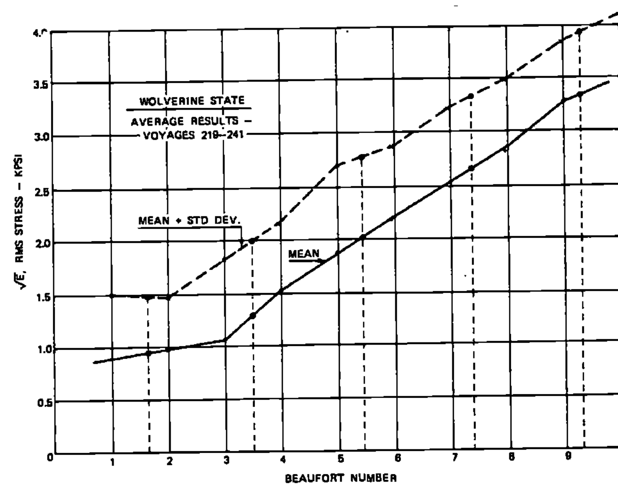


Fig. 33. Trends of Peak-to-Trough RMS Stress and Standard Deviations vs. Beaufort Wind Scale, S.S. WOLVERINE STATE, Voyages 219-241

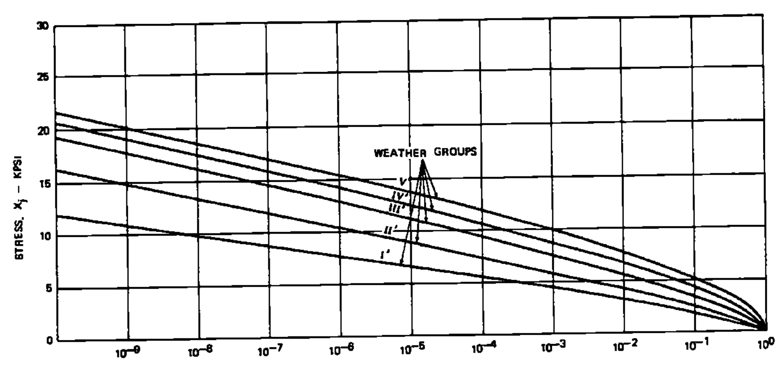


Fig. 34. Long-Term Distributions of Stress for Different Weather Groups, S.S. WOLVERINE STATE, by RMS Method (Voyages 219-241)

Fig. 35 shows the histograms of rms stress values for each weather group and compares them with the corresponding normal curves. The normal distributions were obtained by determining the mean and standard deviations for each group of data. At the lower Beaufort Nos. (Groups I' and II'), a correction was made for truncation at 0 KPSI. It may seem that the ideal curves fit the histograms quite well, in particular for the higher Beauforts.

It may be noted in Fig. 35 that the probability scales are adjusted so that the areas under the curves are proportional to the number of points (records) included in the calculations.

The method of extreme values, described in an earlier section, was then applied to the same data. Another family of curves was obtained, as plotted in Fig. 36. In this figure data from the histograms of extremes are compared with the curves for each weather group. It can be seen that the fit is satisfactory, considering the relatively small number of extremes available. The trend of the histogram is generally below the theoretically derived curve, except for a few points.

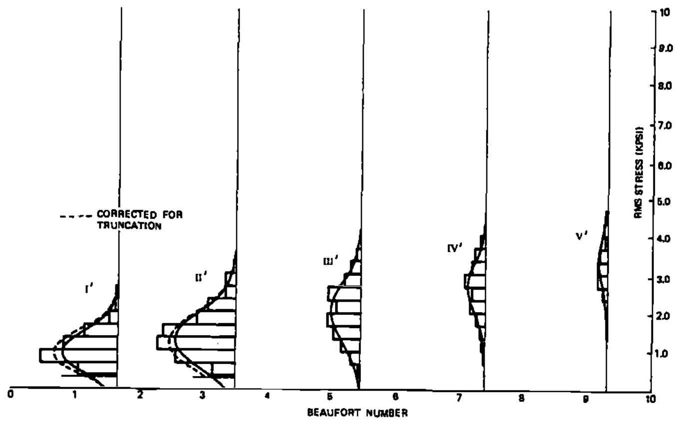


Fig. 35. Histograms of Peak-to-Trough RMS Stress, WOLVERINE STATE, (Voyages 219-241)

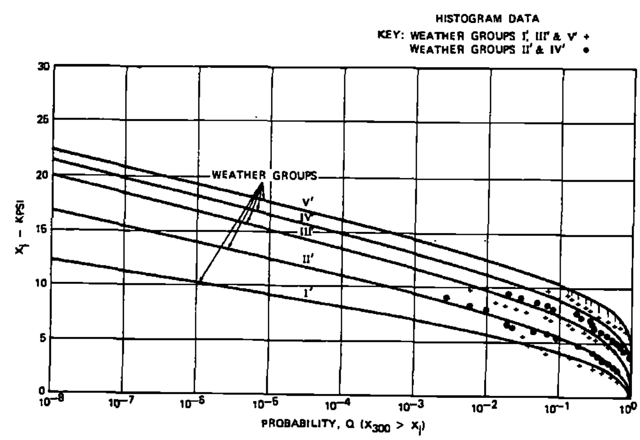


Fig. 36. Cumulative Distributions of Extreme Stress for Different Weather Groups, Compared with Data from Histograms, S.S. WOLVERINE STATE, Voyages 219-241

If each curve of Fig. 36 is compared with the corresponding curve in Fig. 34 it is found that each pair is separated horizontally by log n', except at large values of P, just as in the detailed study in the earlier section. The average value of n' for this larger sample is 310.

Finally, an integration was carried out of the curves in Figs. 34 and 36, on the basis of the actual distribution of weather groups experienced on the 10 voyages studied. The result is shown in Fig. 37. It can be seen that the combined points from the histograms of extremes again fall below the idealized curve, but the agreement is quite good.

As shown on the figure, the separation of the curves is exactly log n' = log 310 at small probability values. This gives further confirmation to the finding that the two methods of extrapolation are equivalent.

It is of interest to consider the possible reasons for the differences between the probability models and the data samples from the histograms.

First is the possibility that the rms values depart appreciably from the assumed normal distribution. This is shown graphically in Fig. 35, where the fit can be considered excellent, except perhaps in the lowest weather groups, as previously noted.

Second is the discrepancy due to the possibly significant departure of stresses in individual records from the assumed Rayleigh distribution. This possibility was tested by plotting data from four randomly selected records on probability paper. Fig. 3 shows in general a good agreement with the required slope of the Rayleigh distribution.

Further insight into the discrepancies may be obtained from Fig. 38, which shows the histograms of extreme stresses for each weather group, along with the theoretical curves calculated from the data plotted in Fig. 35. The fit can be seen to be excellent, particularly at the important high-stress tails. However, a slight overestimate by the curves may be clearly seen in Weather Groups II′ and III′, and even more in IV′ and V′. These slight differences can account for the fact that the data points in Figs. 36 and 37 fall a little below the cumulative curve.

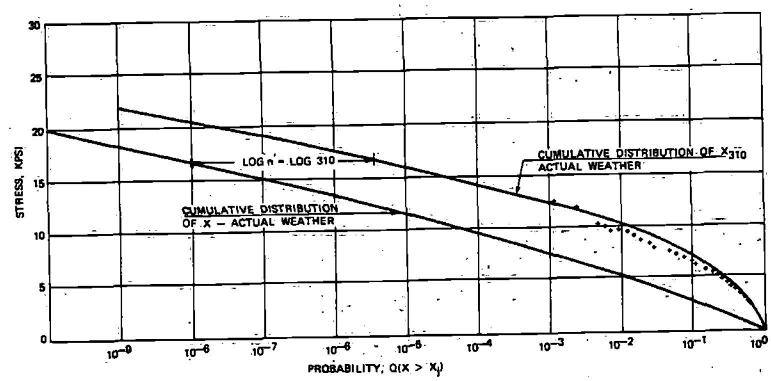


Fig. 37. Cumulative Distributions of Peak-to-Trough Stresses and of Extreme Stresses, S.S. WOLVERINE STATE, Voyages 219-241

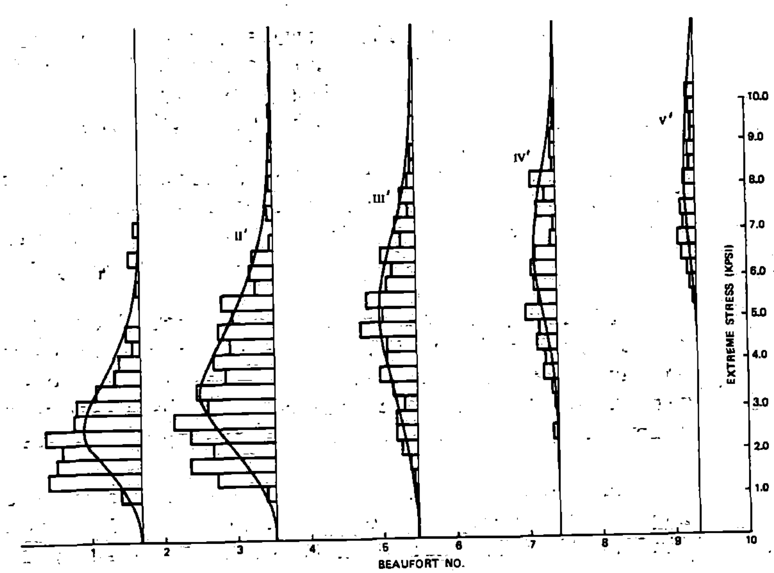


Fig. 38. Histograms of Extreme Peak-to-Trough Stress Compared with Longuet-Higgins Curves, S.S. WOLVERINE STATE, Voyages 219-241

It may be concluded that ship stress data can be analyzed and extrapolated to obtain long-term trends by either of two mathematical models, one using rms values and the other extreme values of regularly recorded stress records. In neither case is it necessary to assume any arbitrary form (Weibull, Gumbel, etc.) for the final long-term distributions. The advantage of the extreme value method was discussed in (2). It can be considered as a possible simplified data collection technique requiring only one extreme value per record rather than the distribution in the time domain of the actual stress variations as required for the other method. Of course, if one is concerned with fatigue problems, complete records are needed rather than just extreme values.

CONCLUSIONS

1. It has been shown that two different probability models give consistent results when used to analyze full-scale ship hull stress data for one ship and resulting long-term cumulative stress distributions agree very well with histogram data.

2. Both of the above models can be used to extrapolate stresses to much longer periods of time (lower probability), thus providing a sound basis for design of similar ships, provided that sufficient statistical data are available.

3. Accordingly, the conflicting trends obtained by the rms and extreme value methods in an earlier report (3) (Fig. 17) have been explained by the fact that the extreme value approach previously used was too crude for this purpose.

4. Only one of the above methods was used to compare the four dry cargo ships studied -- after converting from stress to non-dimensional wave bending moment coefficient and applying the same "standard" weather distribution:

(a) Results for the Wolverine State and Hoosier State, covering many years of data collection, appear consistent and reasonable except for recent results in which only port or starboard gages were operational.

(b) Results for the California Bear, a larger ship in North Pacific service, showed significant differences between west and eastbound voyages. Combined results showed somewhat lower bending moment coefficients than the above ships, probably because of more moderate sea conditions (for the same Beaufort Nos.) and a somewhat larger ship.

(c) Results for the Mormacscan in service from New York to Europe and to South America appeared quite low in comparison with the other ships, and it is felt that the statistical data sample -- particularly for the North Atlantic -- was inadequate for this ship.

5. The scope of the analytical techniques described in this report can be greatly increased by applying them to the prediction of long-term trends for new designs by model tests and calculations, as discussed in a companion report (3).

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APPENDIX

SHIP PARTICULARS

	SS Hoosier State & SS Wolverine State	SS Mormacscan	SS California Bear
Type	C4-S-B5 Dry Cargo	C3-S-33A Dry Cargo	C4-S-1a Mariner Dry Cargo
Machinery location	Aft	Amidships	Amidships
Builder	Sun Shipbuilding & Dry Dock Co.	Sun Shipbuilding & Dry Dock Co.	Bethlehem Steel Co., San Francisco Yard
Date	September, 1945	October, 1960	1954
Hull Number	359	622	
Length Overall	520' - 0"	483' - 3"	563' - 7 3/4"
Length between Perp.	496' - 0"	458' - 0"	528' - 6"
Beam, Molded	71' - 6"	68' - 0"	76' - 0"
Depth, Molded	54' - 0"	41' - 6"	44' - 6"
Load Draft, Keel	32' - 9 7/8"	31' - 5"	29' - 10 1/16"
Waterplane Coefficient	.752 (30' draft) .685 (18' draft)	.730	.724
Gross Tonnage	10,747	9,315	9,216
Net Tonnage	6,657	5,609	5,366
Midship Section Modulus (to Upper Deck)	45,631 in.^{2}-ft.	30,464 in.^{2}-ft.	43,900 in.^{2}-ft.
Dead Weight at Load Draft	15,348 L.T.	12,483 L.T.	13,418 L.T.
Shaft Horsepower, Normal	9,000	11,000	17,500
Shaft Horsepower, Maximum	9,900	12,100	19,250

L.T. = long tons

SUMMARY OF AVAILABLE RECORDS FOR ALL SHIPS

Summaries are given in the following lists of the voyages for which records were available for each ship. Dates are also given, along with Teledyne Tape Reel numbers for identification. The symbols (W) and (S) denote winter and summer voyages.

S.S. WOLVERINE STATE

Voy. No.	Date	Teledyne Tape Reel No.
170/1	Dec. '61 - Jan. '62 (W)	170W1,2
172/3	Jan. - Feb. 62 (W)	172W1,2,3
174/5	March 62 (W)	174W1,2,3,4
176/7	Apr. - May 62 (S)	176W1
178/9	May - June 62 (S)	178W1,2,3
182/3	July - Aug. 62 (S)	182W1,2
186/7	Sept. - Oct. 62 (S)	186W1,2,3
188/9	Oct. - Nov. 62 (W)	188W1,2,3
190/1	Nov. - Dec. 62 (W)	190W1,2,3
192/3	Dec. 62 - Jan. 63 (W)	192W1,2,3
196/7	Feb. - March 63 (W)	196W1,2
198/9	March - April 63 (W)	198W1,2
203/4	May - June 63 (S)	203W1,2
205/6	July 63 (S)	205W1,2
207/8	Aug. 63 (S)	207W1,2
209/10	Aug. - Sept. 63 (S)	209W1,2
211/12	Sept. - Oct. 63 (S)	211W1,2,3
213/14	Oct. - Nov. 63 (W)	213W1,2,3
215/16	Dec. 63 (W)	215W1
217/18	Dec. 63 - Jan. 64 (W)	217W1,2,3,4,5
219/20	Jan. 64 (W)	219W1
221/2	Feb. 64 (W)	221W1,2
223/4	May 64 (S)	223W1
229/30	Aug. 64 (S)	229W1
231/2	Sept. - Oct. 64 (S)	231W1
233/4	Oct. - Nov. 64 (W)	233W1
235/6	Nov. - Dec. 64 (W)	235W1
237/8	Dec. 64 - Jan. 65 (W)	237W1
239/40	Feb. - Mar. 65 (W)	239W1
241/2	April 65 (S)	241W1
245/6	June - July 65 (S)	245W1
247/8	Aug. 65 (S)	247W1
249/50	Sept. 65 (S)	249W1
259/60	Mar. - Apr. 66 (W)	259W2,3
261/2	May 66 (S)	261W1,2
263/4	June - July 66 (S)	263W1,2,3
265/6	Aug. 66 (S)	265W2
267/8	Sept. 66 (S)	267W1
271/2	Nov. - Dec. 66 (W)	271W1
273/4	Dec. 66 - Jan. 67 (W)	273W1,2
277/8	April 67 (W)	277W1,2
279*	June - July 67 (S)	279W1,2,4
280*	Oct. - Nov. 67 (W)	280W1,2,3,4
281*	Jan. - Feb. 68 (W)	281W1,3,4,5
282*	Feb. - March 68 (W)	282W1,2
283*	April - May 68 (S)	283W1,2,3,4
284*	June - July 68 (S)	284W1,2
285*	Aug. - Sept. 68 (S)	285W1,2,3,4.
286*	Oct. - Nov. 68 (W)	286W1,2,3
287	Dec. 68 - Jan. 69 (W)	288W1
288	March 69 (W)	288W1,2,3,4
289	April 69 (W)	289W1,2
52		112

A total of 61 instrumented voyages Nos. 170 to 289 of which 52 provided data suitable for analysis, 44 in the North Atlantic and 8 U.S. to Viet Nam (asterisks).

S.S. HOOSIER STATE

Voy. No.	Date	Tape Reel No.
123/4	Nov. - Dec. 1960 (W)	123H & 124H
137/8	Aug. - Sept. 1961 (S)	137H & 138H
139/40	Sept. - Oct. 1961 (S)	139H & 140H
143/4	Nov. - Dec. 1961 (W)	143H & 144H
147/8	Jan. - Feb. 1962 (W)	147H & 148H
149/50	Feb. - March 1962 (W)	149H & 150H
151/2	Mar. - Apr. 1962 (W)	151H & 152H
155/6	June 1962 (S)	155H & 156H
157/8	July 1962 (S)	157H & 158H
159/60	Aug. - Sept. 1962 (S)	159H & 160H
161/2	Sept. - Oct. 1962 (S)	161H & 162H
163/4	Oct. - Nov. 1962 (W)	163H & 164H
175/6	April - May 1963 (S)	175H & 176H
177/8	May - June 1963 (S)	177H & 178H
14		28

A total of 34 instrumented voyages Nos. 123 to 190 of which 14 provided data suitable for analysis, all in the North Atlantic.

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S.S. CALIFORNIA BEAR

Voy. No.	Date	Tape Reel No.
25	Jan. - Feb. 66 (W)	25CB1
26	Apr. - May 66 (S)	26CB1
27	July - Aug. 66 (S)	27CB1
28	Sept. 66 - (S)	28CB1
29	Jan. - Feb. 67 (W)	29CB1
30	Mar. - Apr. 67 (W)	30CB1
31	May - July 67 (S)	31CB1
32	Aug. - Sept. 67 (S)	32CB1
33	Oct. - Dec. 67 (W)	33CB1
34	Jan. - Feb. 68 (W)	34CB1
35	Apr. - May 68 (S)	35CB1
36	June - July 68 (S)	36CB1
37	Aug. - Oct. 68 (S)	37CB1
13		13

A total of 13 instrumented voyages Nos. 25 to 37, all in the North Pacific.

S.S. MORMACSCAN

Voy. No.	Date	Tape Reel No.
21	July 64 (S)	21 MMS1
22*	Sept. 64 (S)	22 MMS1
24*	Oct. - Nove. 64 (W)	24 MMS1
25	Jan. - Feb. 65 (W)	25 MMS1
26	April - May 65 (S)	26 MMS1
27	June - July 65 (S)	27 MMS1
28*	Sept. - Oct. 65 (S)	28 MMS1
29*	Nov. - Dec. 65 (W)	29 MMS1
30*	Jan. - Feb. 66 (W)	30 MMS1
31	Mar. - Apr. 66 (W)	31 MMS1
32	May 66 (S)	32 MMS1
33	June - July 66 (S)	33 MMS1
34	Aug. - Sept. 66 (S)	34 MMS1
35	Oct. - Nov. 66 (W)	35 MMS1
36	Dec. 66 (W)	36 MMS1
37	Jan. - Feb. 67 (W)	37 MMS1
38	March 67 (W)	38 MMS1
		17

A total of 18 instrumented voyages Nos. 21 to 38, of which 17 provided data suitable for analysis, 12 to South America and 5 North Atlantic (asterisks).

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13. ABSTRACT

This report is a continuation of an earlier report*, giving results of the analysis of all available stress data from full-scale measurements on the following dry cargo ships: S.S. WOLVERINE STATE, S.S. HOOSIER STATE, S.S. MORMACSCAN, and S.S. CALIFORNIA BEAR. The results for the first two, which are sister ships of the C4-S-B5 type cover a total of about 10 ship-years in the North Atlantic, and results are felt to be consistent and reliable. Results for the MORMACSCAN, covering brief periods in the runs from New York to Europe and New York to South America, appear to provide inadequate statistical samples. CALIFORNIA BEAR results for the North Pacific appear to be reasonable for that service.

Further details are given on two techniques for the analysis and extrapolation of full-scale data to longer periods of time, in order to predict extreme bending stresses (or bending moments) in service. One of the techniques employs the integration of rms stress data from individual stress records; the other makes use of the highest stresses obtained in each record (extreme values). Both techniques involve the classification of data by severity of weather in order to obtain greater generality of results. It is shown that extrapolated trends from the two methods are consistent.

Comparisons are made of non-dimensional bending moment coefficients for all of the ships on the basis of the same "standard" weather distribution.

*"Analysis and Interpretation of Full-Scale Data on Midship Bending Stresses of Dry Cargo Ships," Report SSC-196, June 1969.

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