ESTIMATES
OF
EXTREME LONGITUDINAL
WAVE LOADS ACTING ON A SHIP

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CONTENTS

SYLLABUS

This work presents a brief description of the main methods pursued to derive more realistic estimates of extreme longitudinal wave loads acting on a ship during its life. Attempts to treat both loading and hull structural response probabilistically are critically assessed. Areas where further knowledge is required are pointed out.

1. INTRODUCTION

In the following description we are going to be concerned with one of the main factors in longitudinal strength design - longitudinal wave loads - - but keeping in mind that other factors, such as still water loads, slamming stresses, fatigue, temperature effects, combined loads and so on must not be neglated.

Between the dynamic effects due to the wave loading, one can refer bending moments, torsional moments, vertical and horizontal longitudinal and transverse shear forces. But in general we can say that longitudinal vertical bending moments due to waves are the most important and frequent effects.

Research on the problem of wave bending moments on hulls has made considerable progress. The traditional approach to wave loads assumed a deterministic solution. A wave of particular length and height is selected to evaluate the bending moment suitable for design.

However, due to random character of wave loads (they depend upon sea state, heading angle, frequency of encounter and so on) only statistical methods seem proper to be used.

A summarized description of the main methods to estimate the extreme longitudinal wave loads during a ship's life, will be presented.

2. LONGITUDINAL WAVE LOADS

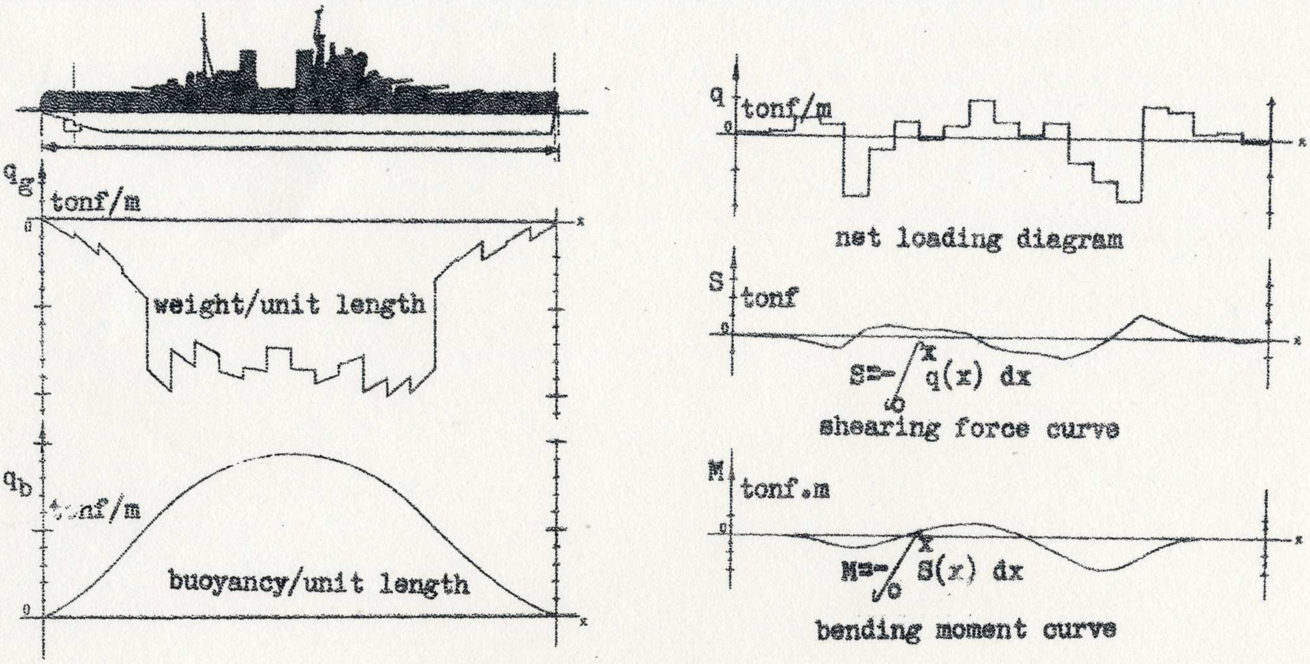
2.1. DETERMINISTIC APPROACH

The more severe loading will occur when a ship is running into or before relatively long waves. So, two "worst cases" are considered: the hogging condition and the sagging condition (fig. 1). The main assumptions are:

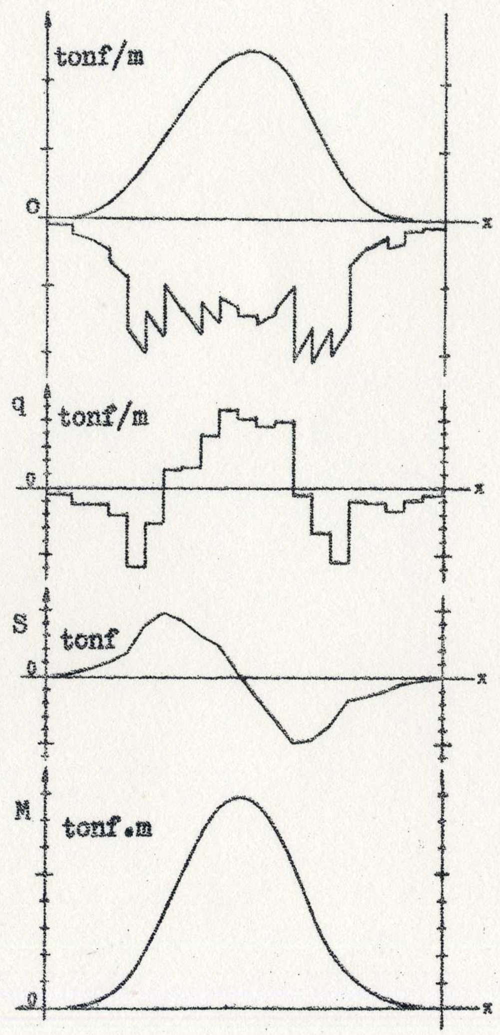
- all dynamic effects are negligible (this assumption is very unrealistic when very large ships are considered).
- static suspension of the ship on a single trochoidal wave with the following characteristics:

  λ (wave length) = L (ship length)

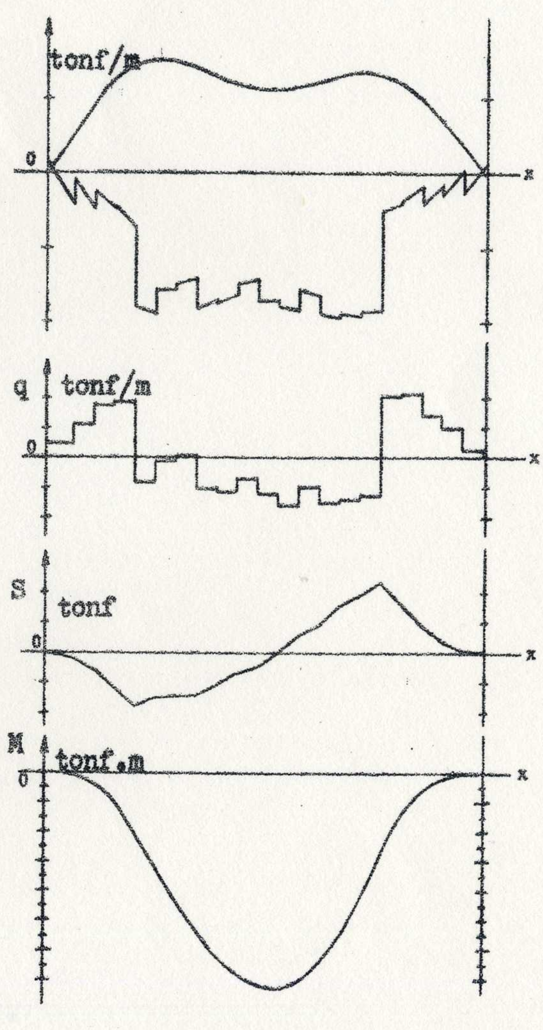
  common values of wave height are presented in table I. Fig. 2 presents a comparision of these different effective heights.
- water pressure on ship contributing to its buoyancy is proportional



STILL WATER CONDITION



HOGGING CONDITION



SAGGING CONDITION

Fig. 1

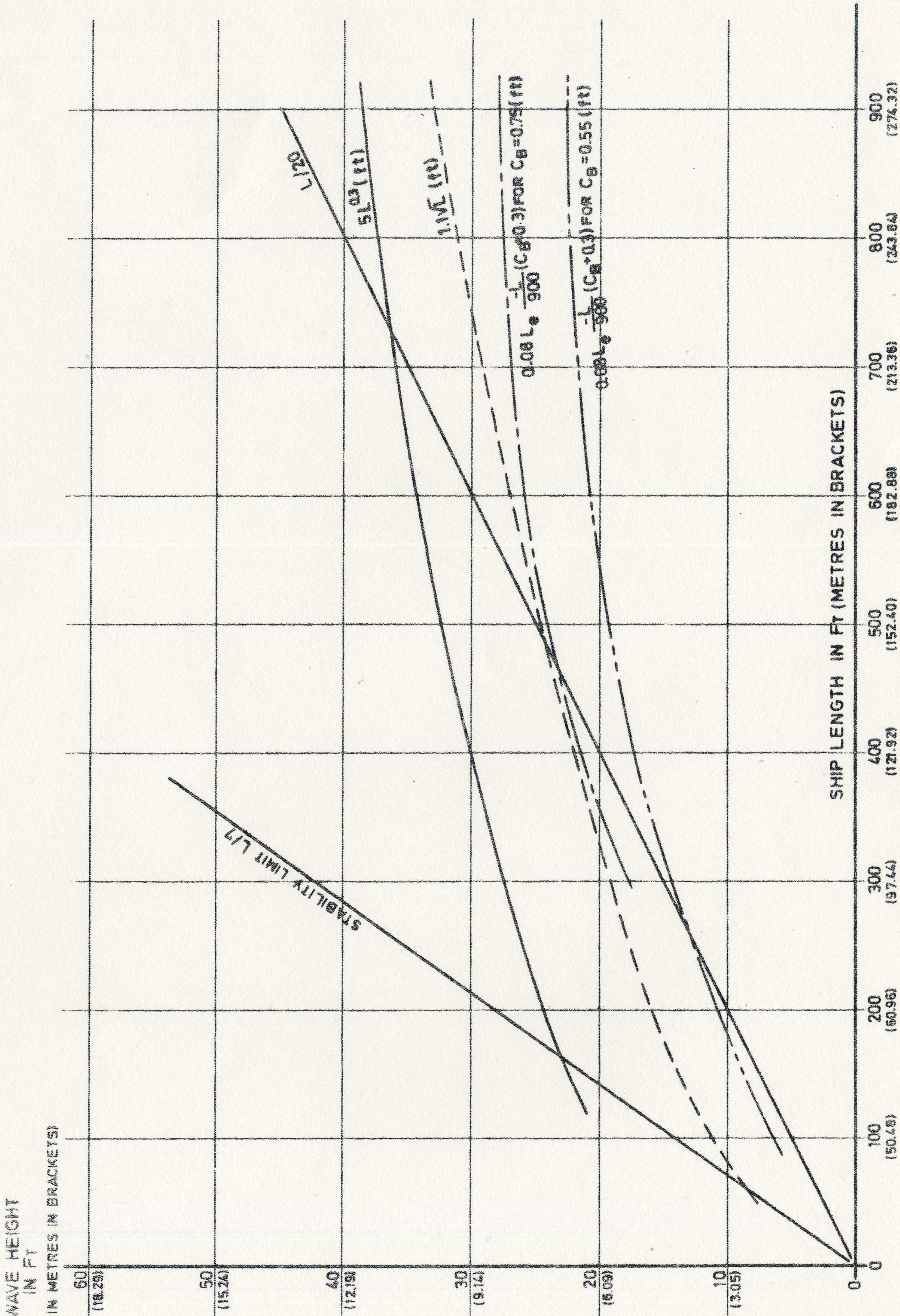

WAVE HEIGHT
IN FT
(IN METRES IN BRACKETS)
60
(18.29)
50
(15.24)
40
(12.19)
30
(9.14)
20
(6.09)
10
(3.05)
0
SHIP LENGTH IN FT (METRES IN BRACKETS)
100
200
(60.96)
300
(97.44)
400
(121.92)
500
(152.40)
600
(182.88)
700
(213.36)
800
(243.84)
900
(274.32)
STABILITY LIMIT L/7
L/20
5L^0.3 (ft)
1.1√L (ft)
0.08 L_e L/900 (C_B+0.3) FOR C_B=0.75 (ft)
0.08 L_e L/900 (C_B+0.3) FOR C_B=0.55 (ft)

Fig. 2

to depth below water surface. Centres of buoyancy and gravity lie at the same longitudinal position.

- when wave crest is considered amidship (hogging worst case) all disposableweights are removed from amidship. When wave trough is considered amidship (sagging worst case) all disposable weights are removed from the ends.

Stresses, strains and deflections are calculated using beam theory. These values are compared with similar past designs under standard methods of analysis. A standard factor of safety is retained covering all unquantifiable effects, such as:

- inaccuracies of loading estimate and analysis (assumptions, approximations).
- variations in material properties and dimensions.
- variations in workmanship (inadequate welding, handling, human errors.
- corrosion and accidental damage.

For longitudinal strength and by this approach, acceptable stress in deck or keel under hogging or sagging condition is generally $\simeq \frac{1}{2} \sigma y$

WAVE HEIGHT (ft)
(ship length L in feet)

$L/20$	—— WARSHIPS (U.K.)		
$1.1 \sqrt{L}$	—— U.S. NAVY DEPT.		
$.08 (C_B + .3) L_e^{-\frac{L}{900}}$	—— LLOYDS (U.K.)		
$K L^{.3}$	——	K = 5.00 for ships with	L = 300 - 400 ft
	——	K = 3.75 for ships with	L = 700 - 900 ft

TABLE I

OBJECTIONS TO THIS METHOD

- static nature of the method.
- effect of ship upon wave shape is ignored.
- wave length associated with greatest bending moments is not independent of ship form.
- due to water particle motion, the buoyancy is reduced at wave crest and increased at trough (Smith effect). So the peak bending moments are reduced (15 - 20%). More realistic calculations are very tedious.
- wave heights suggested are empirical.
- when we compare a new design with "satisfactory past designs" (no failures occurred) we can not get the efficiency of the new design. The structure may be stronger than necessary.
- little value for new ship types (very large ships, catamarans) where no past experience exists.

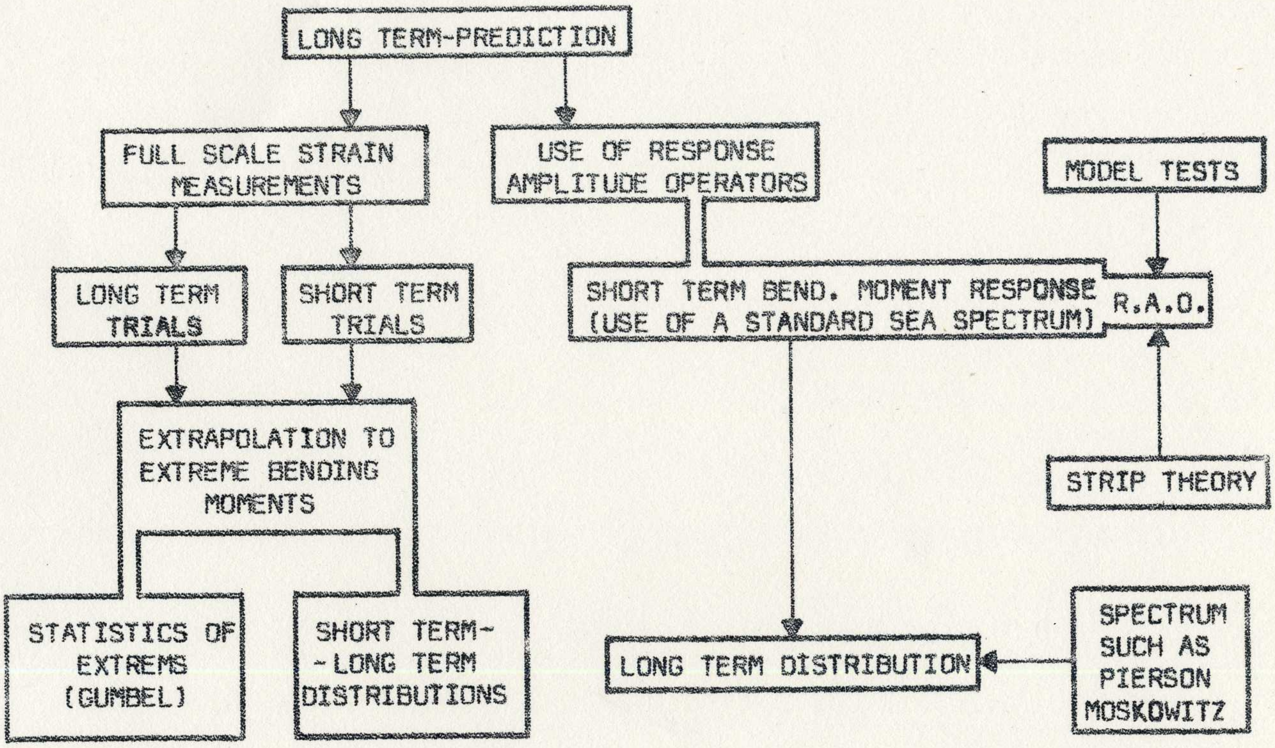
The deterministic approach still is widely used on comparative basis with past "successful" designs. However, particularly when no past experience exists, new "rational" methods are gaining ground.

2.2. PROBABILISTIC APPROACH

In a probabilistic approach the phenomena are treated as random events and "extreme values" of wave bending moments are defined statistically with a probability of ocurrence. Random analysis accepts and takes account uncertainties. It provides a more rational method than the precedent one.

Briefly we are going to describe the lines suggested in the next figure, which start from two basic methods used for long term predictions:

- full scale strain measurements.
- use of response amplitude operators.



2.2.1. FULL SCALE STRAIN MEASUREMENTS

Scientific equipment for the accurate measurement and recording of strain in ships is used. The strain history for a given ship can be converted to correspondent longitudinal bending moments, assuming a simple beam behaviour for the ship.

The long term trials involve statistical measurements on ships during significant periods of their service life. The equipment used on these trials can be of two kinds. The "extreme value gauge" only records the maximum readings in any given time interval. The "statistical strain gauge" records the number of times that a given value of strain is exceeded within a certain time interval. If visual observations of wind and sea state are made simultaneously one can have a crude correlation between sea state and bending moments. The data collected from one ship is not readily applicable to other ships.

During short term trials records of longitudinal strain are taken simultaneously with data relating to ship motion, general perfomance and sea state. This detailed information on the response characteristics of ships in a certain sea state is taken during relatively short periods of time.

The main objective of these trials is to obtain data which may be used for comparision with model tests and theoretical predictions, since they give a good correlation between strain and sea state. However, short term trials need special ships and trained personnel and they have little use for direct long-term predictions.

SHORT TERM/LONG TERM DISTRIBUTIONS

Experience has shown that individual data samples from relatively short periods of time (say 30 minutes; sea condition, ship's speed and heading being constant) conform to the Rayleigh distribution, which probability density function is given by the equation

$$p\,(x) = \frac{2x}{E}\, e^{\frac{-x^2}{E}} \qquad (x \text{ - strain, stress, bending moment}).$$

The cumulative probability is given by $P_S\,(x) = 1 - e^{\frac{-x^2}{E}}$ where the parameter E is the mean square value of x. The root mean square value $\sqrt{E}$ is used to describe the Rayleigh distribution of each record and it depends not only on the sea state but also on the ship characteristics and its loading condition (this effect is usully small).

For any new ship it is desirable to be able to make predictions in statistical terms of long-term distribution of bending moments, which it will experience throughout its service life.

The long term distribution of x can be written as $p\,(x) = P_S\,(x)\,.\,g\,(\sqrt{E})$ and the long term cumulative distribution as

$P\,(x) = \int_0^\infty P_S\,(x)\,g\,(\sqrt{E})\,d\,(\sqrt{E})$ where $g\,(\sqrt{E})$ is the long term probability density function of $\sqrt{E}$.

Both normal and Weibull distributions are used for $g\,(\sqrt{E})$. The latter can be used directly for either short or long term analysis.

STATISTICS OF EXTREMES (GUMBEL)

This is another method, attributed to Gumbel, used for extrapolation from full scale measurements to extreme bending moments with low probability of ocurrence in a ship's life.

This method deals with the maximum values of each serie of measurements (extremes). It involves only the mean and standard deviation of observed extremes which depend on the sample size and are obtained directly from tables.

If the experimental data conform to Gumbel theory, the statistical distribution of stresses may be expressed as a straight line on specially pre pared probability charts.

2.2.2. USE OF RESPONSE AMPLITUDE OPERATORS

The method has two main steps:

a) SHORT TERM BENDING MOMENT RESPONSE

The bending moment response spectrum and the wave frequency spectrum (both for encounter frequency) are related by a linear bending moment respon- se amplitude operator (RAO, receptance or transfer function):

$$S_{BM}(w_e) = |H_{BM\xi}(w_e)|^2 S_{\xi}(w_e)$$

The standard sea spectrum can be the Pierson Moskowitz, which is re- ferred in step b).

The bending moment receptance (RAO) can be found either by experiments in a selected sea state or by theoretical calculations. It depends on wave length (hence wave frequency $w^2 = \frac{2\pi g}{\lambda}$) and wave direction relative to ship (θ). Nowadays model experiments are used essencially to check theoretical results.

Usually the calculations are based on a "strip method" of analysing the forces acting on individual transverse sections of a ship in a regular head sea and determining the resulting motions (the method is being extended to oblique seas). After the motions have been evaluated, the distribution of both the static and dynamic forces along the length of the ship (load curve) can be calculated. A double integration of the load curve determines the shear forces and bending moments.

b) LONG TERM DISTRIBUTION

Long term prediction of bending moment can be made using root mean square values of bending moment obtained for range of sea states and applying methods similar to those described in reference (1). It requires the use of extensive wind and wave data gathered in last 15 years in various oceans, in form of wave energy spectra.

The well known Pierson - Moskowitz spectrum was obtained semi-empiri cally by the analysis of extensive wave data relating to fully developed sea conditions in the North Atlantic. The spectrum is:

$$S_{\xi}(w) = \frac{8.1 \times 10^{-3}}{w^5} g^2 \exp \left| - 0.74 \left(\frac{g}{Uw}\right)^4 \right|$$

where

w = wave frequency

g = acceleration due to gravity

U = wind speed 20 m above sea surface

$S_{\xi}(w)$ = wave energy for wave height ξ, frequency w

It seems that correlation between strip theory, model tests and the few short-term full-scale tests appears to be reasonable (ref. (2)). However for fine forms and extreme wave conditions that correlation is not so good. The assumption of linear response with wave height can be the main reason to explain the disagreement.

3. ASYMMETRIC AND TRANSVERSE LOADS

As referred before, the most important and frequent effects on ships due to wave loads are longitudinal vertical bending moments.

Measurements of strains due to asymmetric and transverse loads are questionable due to interaction between different kinds of loads, practical difficulties and local effects.

It was found, by measurements, that torsional moments are about 1/10 and 1/20 of the maximum vertical longitudinal moment. For conventional ships torsional strength is no problem but torsional deflections can be of interest to warship design. Both torsional strength and stresses can be significant for open decks and multihull ships. There are no definitive answers for this problem, since results from empirical formulas, strip theory (six degrees of freedom), model tests and full scale tests have por correlation. But it seems that improvements can be made with the use of strip theory and model tests.

Also lateral moments have been evaluated using strip theory but this application is questionable.

In oblique seas, both vertical and lateral bending moments occur, but not in phase. Maximum vertical bending moment occurs in head seas when lateral bending moments are negligible.

Empirical criteria are used for design, for instance considering late ral bending moment as a fraction of vertical bending moment (such as 2/5).

4. SHIP HULL RESPONSE

Since the input load due to sea waves is random, the ship response (output) is also random. In the previous part, we have been concerned, in a probabilistic manner, with the longitudinal wave load on a ship. But a ship itself is not an "ideal structure". It is a real one with strength variations due to manufacturing imperfections, differences in material properties, time variations of those properties (due for instance to corrosion), variations of scantlings and so on. The strength can be considered a random variable.

Also the design of a ship is not a "perfect" one. It contains assumptions and errors. As few factors can be predicted accurately there are uncertainties associated with the design parameters.

From the above it seems more rational to combine statistically load and strength distributions to estimate "risks of failure". This philosophy is applied in aeronautical and civil engineering (mainly with concrete structures) and recently has been suggested for ship structural design (however it is common to treat the symmetric wave loads in a probabilistic way). This will bring advantages over the traditional approach because it provides a more rational and controlled basis for the understood and control of safety.

The conventional factor of safety, which does not explicit any risk of failure, is now replaced by "risks of failure" which combines the different modes of failure. Failure is weighted by the probability of its ocurrence.

The above is the basis of the approach expounded in references (3) and (4).

Rational approach for longitudinal strength needs the use of long-term prediction of bending moment distribution over ship's life to ensure:

1) acceptably low risk of failure (which needs to be discussed) due to:

- overall hull girder collapse under extreme longitudinal bending.

- overall failure of hull girder by fracture due to fatigue damage or brittle fracture from cumulative distribution of bending loads during ship's life.

2) acceptably low rate of minor failure cracking due to local cumulative fatigue damage.

Since the use of the "risk of failure" as a measurement of structural safety implies to overcome a lot of difficulties, we arrive to the problem of the practicality of the approach suggested.

With the present lack of knowledge in some areas, one solution can be the use of a semi-rational approach (statistical-deterministic) which admits some degree of ignorance through the use of a "judgement factor" based on past designs (if possible) and it should be used comparatively.

Also some assumptions can be made. For instance one can consider the strength resistance as a random variable normally distributed and invariant with time.

The consideration of real frequency distributions of each variate requires adequate histograms of the variates (which may be not available) and requires more complicate computer calculations.

The application to a typical frigate and to a large tanker, referred in reference (4), shows that the statistical approach is workable. However many assumptions were made and the interpretation of results is not easy. Results should be used comparatively and more applications are expected with interest.

Further knowledge of some aspects is required. Let's suggest some areas where this necessity is more relevant to provide information for design purposes:

- Improvements on load defenitions and data for sea spectra. Accurate estimates of parameters $\sqrt{E}$ and λ to define the extreme values of bending moment, since results are very sensitive to these parameters.
  (Characteristic values can be used in first instance).
- Information, data and statistical defenition of strength variability due to uncertainties in material properties and fabrication.

- Deeper studies on time-dependent factors mainly corrosion.
- Mechanism of failure and correspondent experimental data.
  Effects of local micro-stresses concentrations on failure and fatigue.
- Improvements to strip theory.

Also the use of better strain gauges, testing techniques (including full scale destruction tests), faster and bigger computers is required.

Further investigations and research have to be done before to explore the use of statistical approach could be adopted for design purposes. For instance:

- on the use of total bending moment (wave bending moment + still water bending moment). The magnitude of the still water bending moment is also a variable since it depends on cargo distribution, etc.
- on the combination of vertical and lateral bending moment with torsion, slamming and vibratory stresses.
- on the discussion of acceptable risks of failure and social acceptability of those risks.
- on the finite element techniques.

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