SSC-240

LOAD CRITERIA FOR SHIP STRUCTURAL DESIGN

SHIP STRUCTURE COMMITTEE

1973

SHIP STRUCTURE COMMITTEE

AN INTERAGENCY ADVISORY
COMMITTEE DEDICATED TO IMPROVING
THE STRUCTURE OF SHIPS

MEMBER AGENCIES:

UNITED STATES COAST GUARD
NAVAL SHIP SYSTEMS COMMAND
MILITARY SEALIFT COMMAND
MARITIME ADMINISTRATION
AMERICAN BUREAU OF SHIPPING

ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U.S. COAST GUARD HEADQUARTERS
WASHINGTON, D.C. 20590

SR 198
18 JUL 1973

The development of a rational procedure for determining the loads which a ship's hull must withstand is a primary goal of the Ship Structure Committee program. In the last several years, considerable research activity has been devoted to theoretical studies on the prediction of hull loads and to measurement of response both on models and on ships at sea.

This report describes a first effort into the synthesis of the results of these diverse projects into a rational design procedure.

Comments on this report would be welcomed.

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

SSC-240

Final Technical Report

on

Project SR-198, "Load Criteria"

to the

Ship Structure Committee

LOAD CRITERIA FOR SHIP STRUCTURAL DESIGN

by

Edward V. Lewis
Dan Hoffman
Walter M. Maclean
Richard van Hooff, and
Robert B. Zubaly

Webb Institute of Naval Architecture

under

Department of the Navy
Naval Ship Engineering Center
Contract No. N00024-71-C-5372

U. S. Coast Guard Headquarters
Washington, D.C.
1973

ABSTRACT

Consideration is given to the critical loads on ships' hulls, as indicated by possible modes of structural damage and/or failure. It is recognized that of particular importance is the possibility of damage in the form of compression buckling or plastic flow in tension of one or both flanges which could lead to ultimate failure. Another mode of failure is by fatigue, which is important because cracks may occur which must be repaired before they propagate to a dangerous extent. A third mode of failure is brittle fracture, which is particularly difficult to deal with but can be minimized by control of material quality and use of the customary "fail-safe" approach by using crack arresters. Finally, the possibility of shear and/or torsional buckling requires consideration.

Hence, an ultimate load criterion is set up involving the following bending moments:

Quasi-static wave-induced, vertical and lateral combined.

Still water, including effect of ship's own wave.

Dynamic loads, including slamming, whipping, and springing

Thermal effects.

The determination of each of these loads is discussed in detail, and the need for further clarification of dynamic loads is brought out. Methods of combining these loads, all expressed in probability terms, are considered.

A criterion for cyclic loading is discussed, involving the prediction of the expected number of combined loads of different levels, as well as the expected shifts of mean value.

A criterion for brittle fracture is also discussed.

Attention is given to estimating an acceptable probability of failure for use in design. Finally, calculations of loads are carried out for a typical cargo ship, the *S. S. WOLVERINE STATE*. The loads are then combined in accordance with the proposed ultimate load criterion and compared with the standards under which the ship was designed.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

SHIP STRUCTURE COMMITTEE

The SHIP STRUCTURE COMMITTEE is constituted to prosecute a research program to improve the hull structures of ships by an extention of knowledge pertaining to design, materials and methods of fabrication.

RADM W. F. Rea, III, USCG, Chairman
Chief, Office of Merchant Marine Safety
U.S. Coast Guard Headquarters

CAPT J. E. Rasmussen, USN
Head, Ship Systems Engineering
and Design Department
Naval Ship Engineering Center
Naval Ship Systems Command

Mr. K. Morland
Vice President
American Bureau of Shipping

Mr. E. S. Dillon
Deputy Asst. Administrator
for Operations
Maritime Administration

CAPT L. L. Jackson, USN
Maintenance and Repair Officer
Military Sealift Command

SHIP STRUCTURE SUBCOMMITTEE

The SHIP STRUCTURE SUBCOMMITTEE acts for the Ship Structure Committee on technical matters by providing technical coordination for the determination of goals and objectives of the program, and by evaluating and interpreting the results in terms of ship structural design, construction and operation.

NAVAL SHIP ENGINEERING CENTER

Mr. P. M. Palermo - Chairman
Mr. J. B. O'Brien - Contract Administrator
Mr. G. Sorkin - Member
Mr. C. H. Pohler - Member

U. S. COAST GUARD

LCDR C. S. Loosmore - Secretary
CAPT H. H. BELL - Member
CDR J. L. Coburn - Member
CDR W. M. Devlin - Member

MARITIME ADMINISTRATION

Mr. J. J. Nachtsheim - Member
Mr. F. Dashnaw - Member
Mr. A. Maillar - Member
Mr. R. F. Coombs - Member
Mr. F. Seibold - Member

MILITARY SEALIFT COMMAND

Mr. R. R. Askren - Member
Mr. T. W. Chapman - Member
CDR A. McPherson, USN - Member
Mr. A. B. Stavovy - Member

AMERICAN BUREAU OF SHIPPING

Mr. S. Stiansen - Member
Mr. I. L. Stern - Member

NATIONAL ACADEMY OF SCIENCES
Ship Research Committee

Mr. R. W. Rumke - Liaison
Prof. R. A. Yagle - Liaison

SOCIETY OF NAVAL ARCHITECTS & MARINE ENGINEERS

Mr. T. M. Bueerman - Liaison

BRITISH NAVY STAFF

Dr. V. Flint - Liaison

WELDING RESEARCH COUNCIL

Mr. K. H. Koopman - Liaison

INTERNATIONAL SHIP STRUCTURE CONGRESS

Mr. J. Vasta - Liaison

I. INTRODUCTION

RATIONAL DESIGN

For many years the goal of truly rational design of ship structures has been discussed, and a great deal of research bearing on this objective has been carried out. The concept was described, for example, in an early planning document of the Ship Structure Committee (1)*, and since the establishment of the International Ship Structures Congress (I.S.S.C.) in 1961 it has been regularly discussed on a worldwide basis by Committee No. 10, Design Philosophy. Although this report is intended only to indicate progress to date, it is hoped that it will assist in the advance toward the ultimate achievement of rational design of the main hull girder.

The concept of rational design involves the complete determination of all loads on the basis of scientific rather than empirical procedures, in order that uncertainties may be reduced to a minimum. This approach carries with it the idea that the response of the structure can also be accurately determined and that arbitrary large factors of safety, or "factors of ignorance," can be avoided. The concept is consistent with the modern approach to structural design that considers the "demand" upon and "capability" of the structure. In short, instead of insuring that a simple calculated design stress is below the ultimate strength of the material by an arbitrary factor of safety, an attempt is made to determine the demand of all loads acting on the structure and then the capability in terms of load-carrying ability -- the load the structure can withstand without failure. Of course, this approach requires a definition of failure, which may be a serious buckle, a major crack, complete collapse, or a tensile failure (Chapter II). The concept of rational design of a ship hull is believed to be consistent with a probabilistic approach, which has already been found to be essential for dealing with random seaway loadings. Both demand and capability can be expressed in terms of probabilities, and a satisfactory design is then one in which the probability of failure is reduced to an acceptably low value. The problem of determining local loads or stresses for detailed structural design is much more complex and is not discussed here.

This particular report deals only with the demand -- or loading -- on the hull girder, but an attempt has been made to formulate it in a manner that is consistent with the above approach. In due course, with the cooperation of the ship structural designer, it is anticipated that a rational design procedure will evolve (2).

---

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

It is not intended to minimize the importance of the conventional empirical approach to ship structural design which has served the designer, builder and operator well through the years. But there is currently a substantial need for a fully rational approach because of such new maritime developments as larger ships, faster ships, unusual hull configurations (such as the catamaran), and new materials. Complete and comprehensive load criteria can facilitate the extrapolation of ship design into new configurations, using new concepts and materials.

LONG-RANGE PATTERN OF LOAD VARIATION

It may be useful at this point to describe the typical long-range pattern of load variations on typical merchant ships as background for the detailed discussion of the various types of loads in subsequent chapters.

For completeness, we should perhaps begin with the construction of the ship on the building berth. Strictly speaking the only loads present are those induced by the weight of the structure itself. However, there are residual stresses in the plating and locked-in stresses due to welding, often of considerable magnitude and sometimes sufficient to lift the bow and/or stern off the keel blocks. The locked-in stresses are of particular concern where they may exist in combination with other stresses at a weld defect or notch and under certain conditions could help to produce a brittle fracture. For other types of failure it seems reasonable to consider them to be of minor significance to longitudinal strength, since they tend to be eliminated by "shakedown" or adjustment in service. That is, an occasional high longitudinal wave bending load -- in combination with other loads -- may be expected to cause local yielding in any of the high residual stress region. Upon determination of this high wave load the structure will tend to return to a condition of reduced residual stress.

During launching a high longitudinal bending moment may occur, but this is usually calculated and allowed for by the shipyard. During outfitting a continual change of still water shear and bending moment can be expected as various items of machinery and outfit are added. The longitudinal still water bending moment on the ship can always be calculated, but the midship stress will probably not correspond exactly to this calculated value because of possible built-in hog or sag residual stresses, and departures of the hull behavior from simple homogeneous beam theory. In short, the ship is never in a simple no-load condition nor even in a condition where the absolute value of even the longitudinal bending moment is exactly known. Such a built-in bending moment will not be considered in this report since it is believed that changes in load while the ship is in service are of primary significance.

In general the still water hull loadings vary quite slowly. When a ship is in port there are gradual changes in the bending moments, shears, and perhaps the torsional moments as cargo is discharged and loaded, fuel oil and stores are taken aboard, etc. During the voyage there are even more gradual changes in mean loadings as fuel is consumed, and ballast is added or shifted. Typical changes of this kind are shown in Figs. 1 and 2(3). Finally, at the end of voyage changes resulting from cargo discharging and loading, plus possible fuel oil and ballast changes, will again modify the bending moments, shearing forces and torsional moments. The loading changes in port may be considerable and depend on the nature and quantities of cargo carried on various legs of the voyage. These changes do not show up in Figs. 1 and 2 because the recording equipment zero was customarily readjusted at every

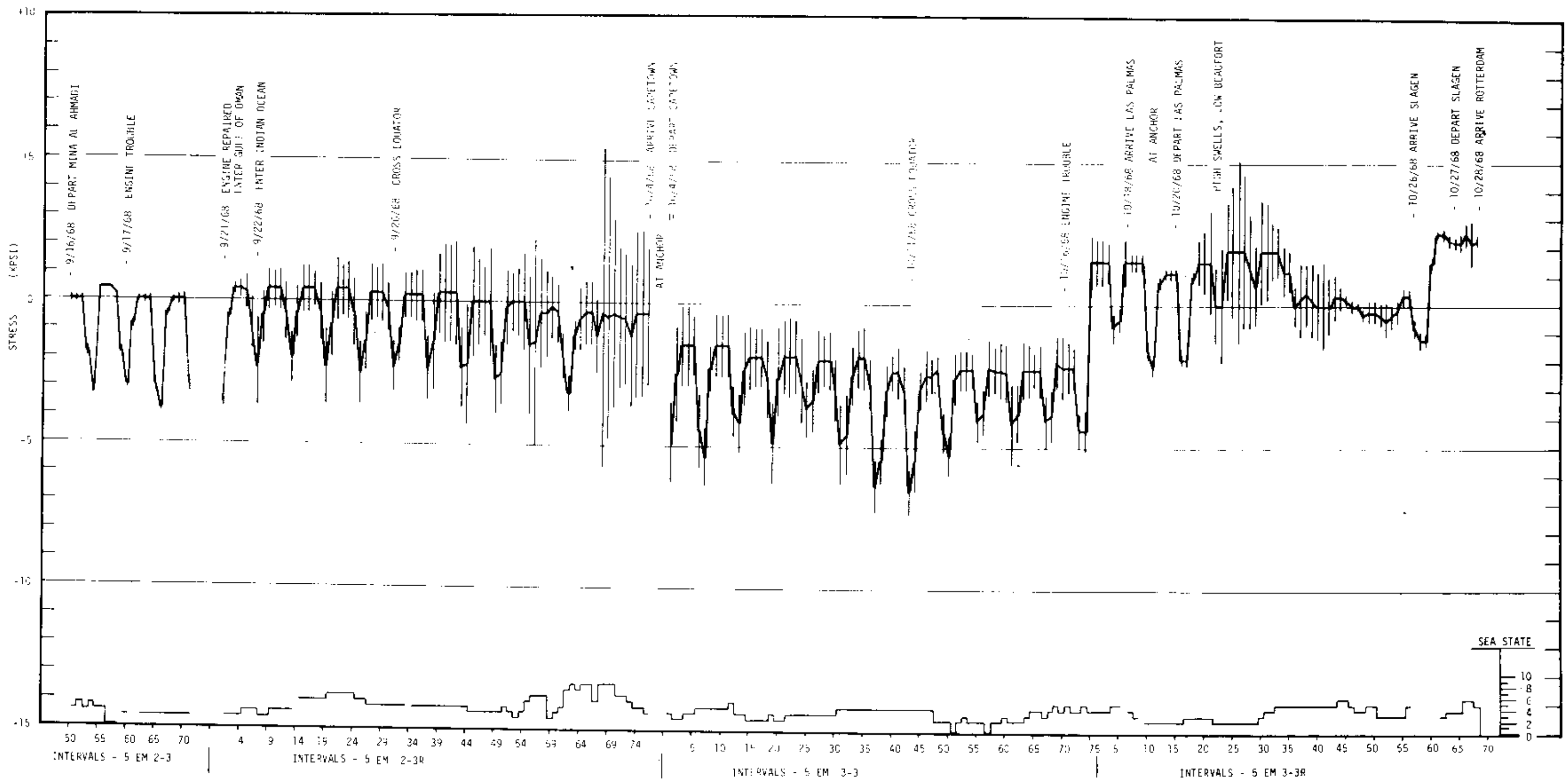

FIGURE 1 - Typical Voyage Variation of Midship Vertical Bending Stress, *S. S. ESSO MALAYSIA*, Loaded Condition (3)

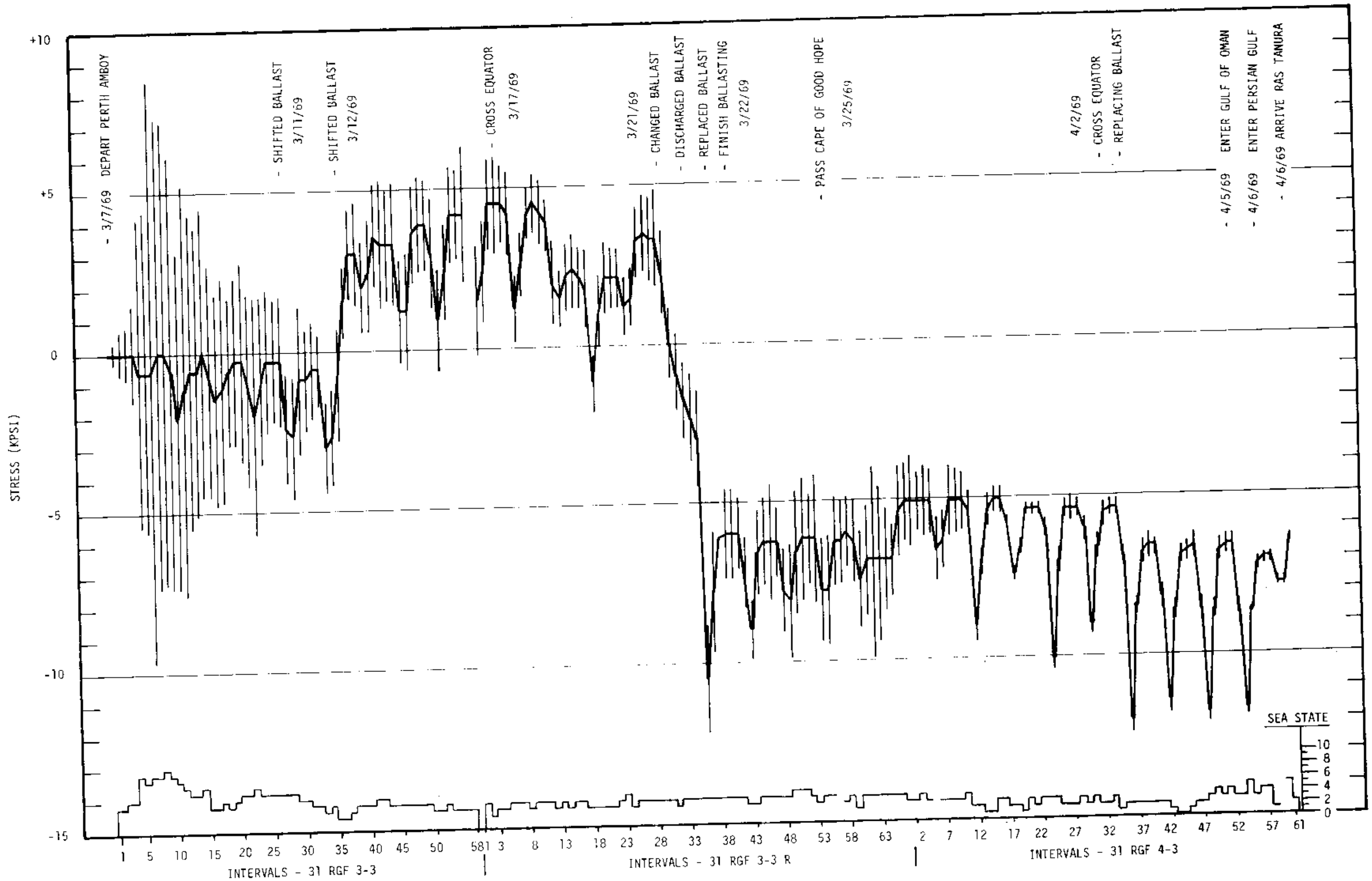

FIGURE 2 - Typical Voyage Variation of Midship Vertical Bending Stress, *S. S. R. G. FOLLIS* (3)

port visit. As explained in an SSC report, "This capability is necessary to prevent the dynamic stress range from exceeding the limits of the instrumentation system" (4).

When the ship gets under way to go to sea, the first new hull loading to be experienced -- especially if the ship is a high-speed vessel -- is the sagging bending moment induced by the ship's own wave train. This longitudinal bending moment is a function of ship speed, and will be superimposed with little change onto other bending moments (5).

Another load variation results from diurnal changes in air temperature* and in radiant heating from the sun. The effect is clearly shown in Figs. 1 and 2*. Such thermal stresses can be explained on the basis of irregular or uneven thermal gradients, which can perhaps be considered as the "loads." In general, if a beam is subject to heating that produces a uniform thermal gradient from top to bottom it will deflect and there will be no resulting stresses. But, if the gradient is not uniform, stresses will be induced. In the case of a floating ship, the temperature of all the steel in contact with the water will be at the nearly uniform water temperature, and there will be very little change from day to night. But the portion of the hull above water will usually be at a different temperature that changes continually and depends on both the air temperature and the amount of sun radiation (extent of cloudiness, duration of sunlight, altitude of sun at noon). In respect to the latter factor, the color of the deck is important also. There is usually a marked change in stress in the vicinity of the waterline, especially on the sunny side of the ship, but from the point of view of longitudinal strength the temperature change of the weather deck -- in relation to the underwater hull temperature -- is significant.

Another large load at sea is that induced by the encountered waves (Fig. 3). This load usually varies in an irregular fashion with an average period of 5-10 seconds, depending on the ship. Not only is there irregularity in wave-induced loads from one cycle to the next, but there is a pronounced variation in average level with ship heading and with weather changes during a voyage and from one season to another. The irregularity of these loads is, of course, due to the irregularity of the waves at sea. However, the baffling irregularity of ocean waves has yielded to modern analytical techniques. This was explained by Dr. Norbert Wiener, who developed the necessary statistical techniques for another purpose. "How could one bring to a mathematical regularity the study of the mass of ever shifting ripples and waves ....?," he wrote (6). "At one time the waves ran high, flecked with patches of foam, while at another, they were barely noticeable ripples ..... What descriptive language could I use that would portray these clearly visible facts without involving me in the inextricable complexity of a complete description of the water surface. This problem of the waves was clearly one for averaging and statistics .." In time Wiener evolved his mathematical tool, spectrum analysis -- a means of breaking down complex patterns into a large number of measurable components.

In recent years wave-induced bending moments have been extensively studied, so that a good statistical picture is beginning to emerge. Research over a number of years (4) (7) has provided a bank of statistical stress data on four cargo ships in several services. Using some of these data it has been found (8) that two different mathematical models can be used to extrapolate such results to much longer

---

*Gages were temperature compensated.

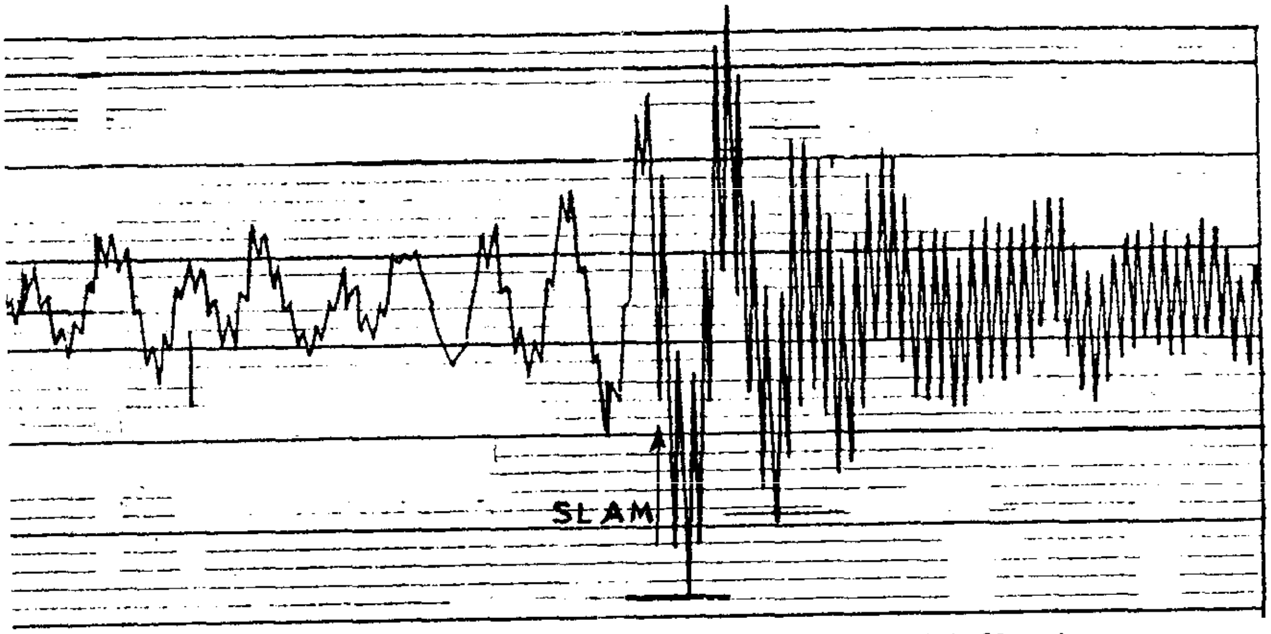

Figure 3 - Typical Record of Midship Vertical Bending Stress with Slamming, M.V. *FOTINI L.*

term probabilities. Furthermore, it has been shown that using the same mathematical models -- combined with model tests in regular waves and ocean wave spectra -- short-term (9) and long-term trends (10) can be predicted with a precision that depends only on the reliability of the data. At the same time, computer programs have been developed for applying ship motion theory to the calculation of loads in regular waves as a substitute for model tests.

Finally, oceangoing ships experience dynamic loads, the most troublesome of which result from impact (slamming) and the vibratory response (whipping) that follows it (Fig. 3). In general these loads are transient and therefore are difficult to deal with statistically. They are superimposed on the previously mentioned loads. Both full-scale measurements (11) and theoretical studies (12) (13) have been carried out on slamming and whipping, and these have clarified but not solved the problem. Shipping of water on deck and flare immersion are other sources of transient dynamic loading.

Recent attention has been focused on another dynamic phenomenon, springing, which under certain conditions seems to be excited more-or-less continuously in flexible-hulled ships, without the need for wave impact. Considerable progress has been made toward solution by means of theoretical and experimental studies (14).

All of the above loads will be discussed in detail in subsequent chapters.

HULL LOAD CRITERIA

In general treatises on structural design (15) two types of loading are usually distinguished: controllable and uncontrollable. In the first case one can specify design loads with instructions to insure that these are never exceeded. An example is a highway bridge designed on the basis of a posted load limit. In the second case, usually involving natural forces, one must make a statistical analysis and endeavor to design on the basis of the expected loads, with no limitation on the structure or its operation.

In the design of ships, still water loads are generally controllable and wave loads are not. If calculations of typical conditions of loading indicate that excessive still water bending moments might occur, specific operating instructions may be issued to make sure that certain limits are not exceeded. The possibility has been discussed of specifying limiting wave bending loads, as well -- somewhat in the same manner that wing loads on an aircraft are limited by requiring certain performance restrictions. Such a limit on wave loads for ships could only be applied if special instrumentation were available to advise the officer on watch when and if the limiting bending moment is reached, since there is no way for him to judge this loading unaided. Furthermore, he must have guidance information at hand that will enable him to take steps to reduce the bending moment if it should approach the safe limit.

Dynamic loads are partially controllable, since the vibratory response of the hull girder can be felt by the Master on the bridge. By a change in ship speed and/or course he can reduce the magnitude of the exciting forces and thus indirectly reduce the loads to levels that he has found by experience to be acceptable.

In this report a compromise approach has been adopted regarding statistical dynamic wave loads. An effort is made to determine all the loads acting on the ship's hull to provide load criteria from which a satisfactory but economical structural design can be developed. However, to guard against the possibility of some unforeseen extreme load condition, it is recommended that suitable stress instrumentation be provided as a warning device for added safety (16).

A great deal of research has been done in recent years on the ship hull loadings mentioned in the previous section, much of it in the Ship Structure Committee (SSC) program. Research under other sponsorship has also contributed to an understanding of hull loads, including particularly that supported directly by the U.S. Navy, the Society of Naval Architects and Marine Engineers and the American Bureau of Shipping in this country, and by various organizations in Great Britain, Norway, the Netherlands, and Japan, as reported to the International Ship Structures Congress (I.S.S.C.). A partial bibliography is given at the end of this report (Appendix A).

Some typical loads have received more attention than others, however, leaving gaps in the overall picture. It is the purpose of this report to present a comprehensive and reasonably complete picture of the hull loads and hence load criteria for ship design, with particular emphasis on dry cargo ships. Hence, consideration will be given in the next chapter to identifying the critical loads of interest to the ship structural designer. In succeeding chapters each of the various loads will be discussed in turn, and consideration of typical magnitudes and of procedures for detailed calculations will be included. Finally the problems of combining these loads for hull girder design purposes will be taken up. Where important gaps in our knowledge appear, they will be identified and recommendations made for further research. A numerical example for the S.S. Wolverine State will be presented.

A number of attempts have been made to consider how the available material on loads can be combined and applied to the rational design of ships. Of these, particular mention might be made of the work of Caldwell (17), Aertssen (18), Abrahamsen, Nordenstrøm, and Røren (19), and of Committee 10 of the I.S.S.C. (20).

II. CRITICAL LOADS

INTRODUCTION

Before discussing hull loads in detail it is necessary to consider the different ways that the structure can suffer damage or fail. The object is to investigate structural aspects of the problem only to the extent necessary to be sure that all of the necessary information on loading -- or demand -- will be made available to the structural designer. In short, we must ask, what are the critical loads and how do they combine? Meanwhile, it is hoped that work will continue toward developing a completely rational approach to ship structural analysis and determination of the capability of the structure.

Discussion of critical loads can be facilitated by defining structural failure. Caldwell (17) considers ultimate failure as the complete collapse by buckling of the compression flange and simultaneous tensile failure of the tension flange. However, it is clear that a considerably less severe damage would be a serious matter, as indicated by such factors as necessity for major repairs, interference with normal ship operation and non-watertightedness. As pointed out by C. S. Smith in discussion of (17), "In designing a midship section, the designer should consider the various levels of damage which a hull girder may experience between the limits of initial yield and final collapse, and should attempt to relate each level of damage to an applied bending moment."

Hence, for our purpose we may define damage as a structural occurrence that interferes with the operation of the ship to the extent that withdrawal from service for repair is required. Failure is then a severe damage that endangers the safety of the ship.*

Further study of the subject of critical loads during this project has resulted in no basic improvement in Gerard's analysis of specific ways in which the hull girder could fail, as given in "A Long-Range Research Program in Ship Structural Design" (1). He considered overall damage by compressive buckling, overall tensile yielding, low-cycle fatigue cracking and brittle fracture. To these should be added combined normal and shear stress buckling, and it is possible to elaborate somewhat on his scheme and in certain respects to obtain more definite statements.

The types of damage that should be considered then in connection with critical loads might consist of any of the following:

Damage

- Excessive hull deflection associated with buckling and/or permanent set.
- Fatigue cracking.
- Brittle fracture, minor or extensive.
- Shear or torsional buckling.

Failure

- Collapse and/or fracture of the hull girder.

---

*This is sometimes referred to as "collapse" (20), but we feel that this term connotes buckling failure to the exclusion of tensile failure or permanent set and therefore prefer "failure."

Although only the last is considered to be structural failure, all of these types of damage are important for a longitudinal strength criterion. Clarifying the nature of these potential damages will assist us in providing the necessary information on loads.

The magnitude of elastic hull deflection is usually considered in the design criteria of classification societies, and it will also be discussed in this chapter.

Finally, consideration should be given to other minor effects, such as the forces generated by rudders and anti-rolling fins. And other types of service loading, such as berthing, drydocking, and grounding, which may have direct effects on primary hull girder structure, cannot be overlooked. Local damage to structure that is not part of the main hull girder is excluded from consideration.

An important consideration in structural design is corrosion. However, since this is not a load it will not be considered in this report.

PERMANENT SET AND ULTIMATE FAILURE

We may first consider overall static damage to one of the "flanges" (deck or bottom) in either compression or tension, i.e., buckling or elasto-plastic yielding. The effect of lateral as well as vertical longitudinal bending and torsion must be included here. Consideration must be given to the combined effect of still water bending, wave bending and thermal loads. In addition, a basic question is whether or not the superimposed dynamic effects of high frequency "whipping" following a slam and/or flare entry should be considered, as well as the effect of wave impacts on the side of the ship and continuously excited springing. It is quite possible that the short duration of dynamic bending moments -- and stresses -- limits the amount of permanent set or buckling that they can produce. As noted by Spinelli, "It should be borne in mind that the short time in which the wave moments due to slamming develop their maximum values, and the entity of the total deflection that would be consequent on them, make the probability of its realization extremely scarce" (21).

And in referring to plastic deformation, Nibbering states, "In practice these deflections will not develop the very first time an extreme load of the required magnitude occurs. The time during which the load is maximum is too short, especially when a part of the load is due to slamming" (22). This is a problem in structural mechanics not within the scope of this project, and therefore we shall attempt merely to identify and evaluate dynamic as well as static loads.

Finally, local loads (not due to longitudinal bending) on which all of the above are superimposed must not be overlooked. These include deck loads, cargo loads on innerbottom, liquid pressures within tanks, and external water pressures.

Although there seems to be general agreement on the importance of ultimate strength, involving extensive plastic yielding and/or buckling, there seems to be some doubt as to how to deal with it in design. From the point of view of the present study, however, definite conclusions can be drawn regarding the load information needed for designing against potential damage of this type.

FATIGUE

Second is the possibility of fatigue cracking, which seldom constitutes failure but is important for two reasons: fatigue cracks can grow to the point that they must be repaired, and fatigue cracks are notches that under certain circumstances can trigger rapid propagation as brittle fracture. Nibbering notes, "It is a favorable circumstance that fatigue cracks propagate very slowly in ships' structures" (22).

The possibility of fatigue cracking is increased by the presence of stress concentrations -- as for example, at hatch corners (23)(24), and it involves consideration of the magnitude of still water bending -- i.e., the shift of mean value -- as well as the range of variation of wave bending moments. For example, a ship may operate with a large still water sagging moment (loaded) on its outward voyage and with a large still water hogging moment (ballast) on its return, and such a large variation in mean value needs to be considered in relation to fatigue. As before, consideration of lateral as well as vertical bending must also be given. Dynamic loads and vibratory stresses may be expected to contribute to the fatigue loading.

It appears that the fatigue loading histories of actual ships show considerable variety. Hence, the objective for this study is felt to be simply to obtain clear statistical or probabilistic pictures of each of the types of loading involved:

1) Probability density of mean still water bending moments, which tentatively and approximately appears to be two normal curves, one representing outbound and the other inbound conditions.

2) Long-term cumulative distribution of wave-induced bending moment, which together with 1) can be interpreted as a low-frequency loading "spectrum."

3) Probability density of high-frequency bending moments associated with dynamic loads (slamming, whipping and springing). The combination of these effects with low-frequency loads is a difficult problem, as discussed in later chapters.

4) Thermal stress conditions, which cause a diurnal change in stress level.

At first glance it appears to be a hopeless task to collect all the necessary statistical data on the various loads for ships of different types and to develop ways of combining them that are not only sound by probability theory standards, but are meaningful from the viewpoint of the mechanics of fatigue and of the properties of the materials used. A short-cut answer, as proposed by Gerard (1) would be simply to design to avoid overall combined loads as listed above that exceed the yield point of the material anywhere in the structure, including areas of stress concentration. Design of the structure on this basis would virtually insure the ship against low-cycle fatigue, but would possibly lead to heavier structure than in present designs. Since fatigue cracks can be detected and repaired, it is not felt that it is necessary to limit stresses to yield point level in this way, Attempts should be made to understand and evaluate all components of cyclic loading.

BRITTLE FRACTURE

Third, is the possibility of failure by brittle fracture. This mode of failure was common in early days of welded ship construction, but has been greatly reduced in recently built ships. It cannot be overlooked in a comprehensive scheme, however. All of the above-mentioned loads apply, including residual and thermal stresses and the notch effect of weld defects. It has been pointed out that a low-cycle fatigue crack can be the initiation point for brittle fracture (24).

It is generally recognized that the following factors are involved in brittle fracture:

(1) Ambient temperature.

(2) Steel characteristics (transition temperature).

(3) Notches or stress raisers, including weld defects.

(4) Stress (or load) level.

(5) Strain rate.

Secondary factors include strain as well as stress fields, corrosion effects, metallurgical effects of welding, structural details that introduce constraint, and residual stresses.

Because of improvements in design and materials, brittle fracture now seldom occurs in actual service. However, it is conceivable that if, as a result of more rational approaches to design, working stress levels are increased we may again have trouble with brittle fracture. Furthermore, it is important to recognize that brittle fracture has been brought under control by careful attention to material qualities, selection and control of fabrication techniques, and inspection at all stages of construction. Diligence cannot be relaxed, especially as new materials, new fabrication techniques, and more rational design procedures are introduced.

Nibbering maintains "that 90% of all ships in the world move regularly and undamaged in conditions where the temperature is lower than the crack-arrest temperature of their steels .... The nominal stresses mostly are so low that with present day quality of design and workmanship brittle fractures cannot initiate" (22).

For design purposes the load information needed is generally the same as for ultimate bending, as discussed in a preceding section, including all dynamic loads, except that only tensile loads need be considered. Rate of application of dynamic loads and ambient temperature conditions should also be specified.

Of the various dynamic loads, it is believed that consideration should be given particularly to the midship stress following a bottom impact slam. Since higher modes than the hull fundamental are involved, the strain rate may be quite high. See Chapter VI for further discussion.

SHEAR AND TORSION

Fourth is the possibility of shear failure in the hull girder "web." Although this is a problem in the design of light naval vessels, it has not been of much concern in more heavily built merchant vessels. This is not to say that shear loading on the side shell or longitudinal bulkheads is unimportant, but rather that other types of side shell loadings probably constitute more severe criteria of satisfactory design. Though there is a possibility that the side shell of merchant ships is excessively heavy, safe reductions in these scantlings can only be made by developing more precise ways of determining the hull girder torsion and shear loadings, as well as lateral loadings due to such aspects of operation as bumping into dock structures, being handled by powerful tugs, etc.

Another aspect of concern here arises from the recent development of large bulk carriers which are frequently loaded only in alternative holds with high density ores. The result of such loading is that large shear and moment variations are experienced along the vessel's length which must be allowed for in the design of hull girder structure. Further definition of this problem area is needed, since it can be expected that large shear and moment, coupled with reduced structural effectiveness of the hull girder material, can lead to combined loadings of critical magnitude.

Torsion is important in relation to both shear and deflection, especially in wide-hatch ships (25). Excessive hatch distortion has become the major area of concern as progressively larger hatch sizes have been employed. Hence, methods need to be established for determining the magnitude of torsional loading as a basis for rational design. In so doing, the influence of transverse shear on torsional deformation, resulting from the unsymmetric nature of the ship's structure, must be included. That is to say, the transverse shear loading must be defined not only as to magnitude but as to effective point of application as well, and it must also be directly related to the torsional loading, since both are developed simultaneously in any particular oblique wave condition.

To provide sufficient information on loads to carry out a satisfactory analysis of torsional stresses it is necessary to know more than simply the torsional moments, since this implies a knowledge of the torsional axis. Hence, for example, in model tests carried out in regular waves at the Davidson Laboratory for the SL-7 research program, the following measurements were made at the critical sections:

Vertical bending

Horizontal shear	About arbitrary but known axes
Vertical shear	
Torque	

Since both amplitudes and phase angles were recorded, this provided the complete information required for a general stress analysis -- provided, of course, that the number of sections for measurement was adequate. Such analysis would, in the case of cellular container ships, probably include the intersections of closed cell systems as well as hatch corners.

It is concluded that shear and torsion need to be considered both as separate load criteria and in combination with other criteria previously discussed.

DEFLECTION LIMITS

Overall hull girder design may be affected by elastic longitudinal deflection. Some of the pertinent factors are:

1. Possible damage to shafting piping systems, etc.
2. Effects of deflection on drafts entering and leaving port.
3. Effects of hull flexibility on natural vibration frequency and hence on springing and whipping stresses.

The question is whether some design criteria should be introduced to limit deflection in service, aside from the possibility of damage or failure of the structure.

Direct effects of abnormal deflections on shafting, piping, etc., could no doubt be provided for in design. Effects on drafts forward, aft and amidships -- hence on load line requirements, bottom clearances, etc. -- could be dealt with by special attention to loading condtions, perhaps with the help of additional arrangements for ballast. But the effect of hull flexibility on dynamic structural response requires further consideration. It has been established by the work of Kline (26) and others that the increase in natural period associated with greater hull flexibility is favorable from the viewpoint of slamming and the vibratory stress, or whipping, that follows a slam. However, such may not be the case for the more continuous vibratory response referred to as springing. Evidence to date suggests that the latter phenomenon is increased by increasing hull flexibility.

In the past deflection has been limited by restrictions on length/depth ratio. For example, the rules of the American Bureau of Shipping require that special consideration be given to any design for ocean service in which L/D is greater than 13. Whether or not such a severe limitation is necessary has never been clearly established, but there can be no doubt it has prevented difficulties from deflection in mild steel ships.

The question of deflection generally arises, therefore, only with consideration of unusual ship proportions or when a material other than ordinary mild steel is to be utilized. For example, a recent Ship Structure Committee report (27) develops tentative criteria for aluminum alloy construction of a bulk carrier, and in addition to specifying section modulus requirements determined by strength considerations it discusses the necessity for a midship moment of inertia value that will limit deflection. It is stated that, "The only guidance in this area at present is the ABS requirement that the hull girder deflection of an aluminum ship shall not be more than 50 per cent greater than that of a 'Rules' steel vessel, while Lloyd's and Bureau Veritas suggest no increase." The report itself does not agree, however. "It is concluded that no limits should be placed on the hull girder deflection of an aluminum bulk carrier, but that the effects of the deflection resulting from normal structural design should be considered in the areas noted above." A study of the report indicates that no consideration was given to the possibility that springing stresses would be aggravated by the increased flexibility (and hence longer natural period of vibration). It is felt that any elimination of deflection limits should be qualified by a provision that a study be made of the possibilities of serious springing.

A similar situation arises when extensive use of high strength steels is made. If full advantage is taken of their higher strength, then greater flexibility and hence the possibility of springing must be considered. A study of design procedures for high strength steels has been made (28), which accepts classification society limits on deflection.

In the present report, in which dry cargo ships are under consideration, deflection is not often a problem. Such ships are volume limited, and hence L/D ratios are quite low. This is especially true of container ships in which there appears to be a trend toward increasing depth in order to reduce the number of containers stowed on open decks. If high strength steels or aluminum is extensively used, a check should perhaps be made of stiffness and vibration frequency. No further detailed consideration of the problem is felt to be necessary for the present purpose of establishing hull load criteria.

A special case of objectionable deflection previously mentioned is the excessive distortion of hatches, resulting from torsional hull moments, which may cause loss of watertightness.

SUMMARY

The consideration of critical loads and hull deflections leads to the conclusion that information on the following loads is needed for rational longitudinal strength design:

Statical still water bending loads, mean values and variation.

Thermal effects on hull girder.

Wave bending loads, both extreme values affecting hull girder damage (or failure) and the cyclic loading picture affecting fatigue, including shear and torsion.

Dynamic loads, both extreme and cyclic, with phase relationships, durations and rates of application.

Each of the above will be discussed in turn in the succeeding chapters.

III. STILL WATER LOADS

INTRODUCTION

There were two aspects of the subject of still water bending moments studied in this research project on load criteria. One was a review of available procedures for calculating such loads and the other was a semi-statistical study of still water loadings on typical ships. Both of the above studies will be reviewed in this chapter.

CALCULATION OF STILL WATER BENDING MOMENTS

Broadly speaking, the techniques available for determining longitudinal static still water bending moments in ship hulls can be classed in two categories:

1. Approximate methods, used primarily in the early design stage for determining required scantlings before detailed lines and weight distributions are known, or used by ship's officers to determine changes in the bending moment caused by variations in the distribution of cargo and consumables aboard the ship.

2. Exact methods requiring detailed hydrostatic data (Bonjean curves) and weight distributions, used primarily by a design agent or shipyard to determine the bending moments expected in service and to produce loading guides for the ship's officers.

Approximate Methods

Many variations of approximate calculation techniques have been presented in the literature on longitudinal bending moments. Descriptions of the methods proposed by W. J. M. Rankine (1866), John (1874), Vivet (1894), Alexander (1905), Suyehiro (1913), and Foerster (1930) are given by Murray in his 1947 paper (29), in which he also develops a simplified method for calculating the bending moment at amidships for vessels of normal form. Mandelli (30) introduced the concept of "influence lines" which makes possible the quick tabular calculation of the midship bending moment for any condition of loading in still water.

He also extended these approximate methods to include calculation of the complete bending moment curve. It is worth noting that all of these methods, as well as the exact calculations, may be used to determine static wave bending moments as well as static still water bending moments. Indeed most of the techniques were developed for the express purpose of determining bending moments in some standard static wave profile.

Most of the tabular forms and graphs included in ship loading manuals and in instructions for the guidance of ships' officers, which they may use to compute midship bending moments, are based on the "influence lines" approach (30). Accuracy of the results is quite good (so long as the influence of trim on the buoyancy distribution is accounted for in the graphical data furnished) because the buoyancy and moment of buoyancy are known exactly for the completed ship. Less accurate calculations using the same techniques are possible without detailed hydrostatics by approximating the influence lines and giving their equations as functions of ship form (31). For the complete still water bending moment and shear curves to be determined without detailed hydrostatics, the Faresi "integral factors method" of approximation is also available (32).

Exact Method

Since the digital computer has come into general use in ship design, the detailed methods customarily used in final ship design have become almost as easy to use as the approximate ones. The latter remain useful only if,

(a) a computer is not available -- as on shipboard (usually),

(b) detailed data are not available -- as in early design.

For other purposes, exact calculations of still water bending moments in various conditions of loading are the rule. The basic method is well known and the principles involved are not at all complicated, but the numerical work is voluminous and tedious if done by hand.

Briefly stated, the still water shear (or static wave shear) at any point in the ship's length is calculated as follows:

$$V_x = \int_0^x W \, dx = \int_0^x w \, dx - \int_0^x b \, dx$$

where V_x = shear force at distance x from bow (or stern),

w = weight per unit length,

b = buoyancy per unit length,

$W = w - b$, load per unit length.

The integrations (summations) are performed from the bow (or stern) to station x.

For determining the bending moment at any point,

$$M_x = \int_0^x \int_0^x W \, dx \, dx = \int_0^x \int_0^x w \, dx \, dx - \int_0^x \int_0^x b \, dx \, dx$$

where M_x = bending moment at station x. The double integrals are the summations of the moments of weight and buoyant forces forward (or aft) of station x, taken about station x as an axis.

It is clear that the above equations can be easily evaluated numerically using a digital computer. In fact, the simplicity of the equations is the reason for the fact that a large number of programs to calculate still water (and wave) bending moment are available to the designer today. For example, nine firms and organizations have furnished abstracts of their bending moment computer programs to the SNAME index, T & R Bulletin No. 4-13 (33). In addition, various shipyards and ship operators are known to have operating programs.

The first step in evaluating the integrals is the "balancing" of the ship for a specific weight distribution, involving calculation of the displacement and the longitudinal center of buoyancy by integrating the area under the sectional area curve and taking first moments. The correct mean draft and trim can then be determined by trial and error. The only difference between the process for still water or for a static wave is the profile of the waterline, i.e., a straight line in the first case or a specified mathematical wave shape in the latter. The second step is evaluating the integrals for as many values of x as may be needed.

Another mathematically convenient program to calculate the above is one based on a mathematical description of the hull which requires very little input information and limits the numerical integration to the minimum necessary. Such a program has been developed at Webb Institute based on the use of mapping coefficients to describe the two-dimensional ship section (34). In this new method the computations are programmed to give the bending moment and shear force anywhere along the hull for any draft and trim (or for any mathematically-defined wave profile). Hence, comprehensive investigation of a wide range of still water loadings is possible with a short computing time. The program, designated WTS 130, is presently being documented.

Electrical Methods

We have learned about two electric instruments for calculating ship longitudinal stresses and/or bending moments:

Loadmaster - Kockums

Lodicator - Götaverken

The former is particularly good because it shows visually a graph of the bending moment distribution along the ship's length. One can see immediately the effect of a change in load on the bending moment curve.

STILL WATER BENDING MOMENT TRENDS

A pilot study has been made of still water bending moments for three ships of different types: a containership, a supertanker and a bulk ore carrier. The objective was to obtain enough actual still water bending moments for each ship in the outbound and inbound loading conditions to evaluate their statistical distributions, including mean values and standard deviations for outbound and inbound voyages separately.