SSC-124

A LONG-RANGE RESEARCH PROGRAM
IN
SHIP STRUCTURAL DESIGN

Edited by
Edward V. Lewis
and
George Gerard

SHIP STRUCTURE COMMITTEE

SHIP STRUCTURE COMMITTEE

MEMBER AGENCIES:

Bureau of Ships, Dept. of Navy
Military Sea Transportation Service, Dept. of Navy
United States Coast Guard, Treasury Dept.
Maritime Administration, Dept. of Commerce
American Bureau of Shipping

ADDRESS CORRESPONDENCE TO:

Secretary
Ship Structure Committee
U. S. Coast Guard Headquarters
Washington 25, D. C.

November 30, 1959

Dear Sir:

Early in 1957, the Ship Structure Committee initiated a study to produce a long-range research plan aimed at providing the information and knowledge which would lead to improvements in the structural design of ships. This study was undertaken by a group at Stevens Institute of Technology and New York University representing a wide range of competence in engineering and scientific fields. Their final report discusses the present state of knowledge and recommends specific areas for research and study.

The broad research program outlined is obviously beyond the resources of any one organization, and it will take long, continued effort by many groups to carry such a program forward. It is hoped that this report will encourage research in the areas indicated, and that it will be used by groups in addition to the Ship Structure Committee in shaping their research programs.

This study was prepared with the advisory guidance of the Committee on Ship Structural Design of the National Academy of Sciences-National Research Council.

This report is being distributed to those individuals and agencies associated with and interested in the work of the Ship Structure Committee. Comments concerning this report are solicited and should be addressed to the Secretary, Ship Structure Committee.

Yours sincerely,

E H Thiele

E. H. Thiele
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

Serial No. SSC-124

Final Report
of
Project SR-145

to the

SHIP STRUCTURE COMMITTEE

on

A LONG-RANGE RESEARCH PROGRAM IN SHIP STRUCTURAL DESIGN

by

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Washington, D. C.
National Academy of Sciences-National Research Council
November 30, 1959

FOREWORD

Since 1952, the Committee on Ship Structural Design has been providing technical guidance for the design research program of the Ship Structure Committee. In the initial stages of the work, certain unsolved questions regarding the brittle fracture of ships were in such sharp focus that immediate research projects were readily established. However, the Committee also realized early in its work that as soon as possible a broad but detailed study should be initiated to develop a continuing research program in a logical and comprehensive form. This report is the result of that study.

The recommendations contained in this report represent the results of a survey of the several pertinent fields by the authors, prepared for the use of the Committee on Ship Structural Design as a basis for planning future research. It is not likely that the Ship Structure Committee can sponsor even a major portion of the projects suggested; therefore, it is hoped that other groups will be able to carry out studies described in this report that are of particular interest to them. In this way, this report, which in draft form has already been of great value to the Committee on Ship Structural Design in planning the 1960 program, should be a stimulant and a guide toward the systematic improvement of ship structural design.

L. E. Grinter
Chairman, Committee on Ship
Structural Design

June 15, 1959

PREFACE

In September 1956, a prospectus was issued by the Executive Director of the Committee on Ship Structural Design, National Academy of Sciences-National Research Council, which stated in part: "Under the advisory guidance of the Committee on Ship Structural Design of the National Academy of Sciences-National Research Council, the interagency Ship Structure Committee is initiating a long-range research program aimed at improvement of structural design of ship hulls. It is expected that many groups representing a wide range of skills will participate in these studies during the next few years. The logical first need is thus the selection of a single organization to plan this research program on a full-time basis. After the program has been carefully planned, additional groups may be brought in to conduct investigations into specific phases of the problem."

Accordingly, arrangements were made for the staff of the Davidson Laboratory, Stevens Institute of Technology, and the Research Division, College of Engineering, New York University, to conduct a joint research study aimed at fulfilling the above stated planning objective. This report presents the results of the study, and is concerned specifically with research objectives and approaches aimed at the ultimate improvement in the design of ship hulls of conventional form. It presents a suggested long-range research program based on a critical review of past and current research, calling attention to problem areas where significant advances can be made by further research. The report is in no sense intended as a working design manual, nor does it cover the complete range of ship structural problems. The opinions and conclusions presented are those of the authors and not necessarily those of the Ship Structure Committee.

It is anticipated that this program will become out-of-date as research progresses. Simpler solutions to problems may be devised than those suggested, and new and unexpected areas may demand attention. It is hoped, however, that by pointing out the important gaps in knowledge as they appear today, thought and research action will be stimulated.

Attention should be drawn to two companion projects of the Ship Structure Committee:

Monograph on Ships at Sea, sponsored jointly with the Society of Naval Architects and Marine Engineers (seakeeping characteristics panel),

B. V. Korvin-Kroukovsky, Davidson Laboratory (Project SR-128)

Review of Ship Structural Design Methods,

Southwest Research Institute (Project SR-146)

Some ideas for needed research revealed by the first of these projects while in draft form have been incorporated into this report. The second report has not yet progressed far enough to permit this to be done.

July 15, 1959

E. V. L.
G. G.

Acknowledgments

The Design Planning Advisory Committee of the National Academy of Sciences-National Research Council Committee on Ship Structural Design provided guidance regarding the scope of the study and the form of presenting the research recommendations. Membership of the Committee is as follows:

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National Academy of Sciences-National Research Council

This project was discussed at various stages with a number of people in this country and abroad who are concerned with oceanography or ship structural design. The report was issued in preliminary draft form to them and to others in order to obtain comments and suggestions before the final draft was completed. The frank comments of all of these people were most helpful, for they led to the correction of several errors and omissions and resulted in the revision and clarification of a number of points. Accordingly, the assistance and encouragement of the following individuals is gratefully acknowledged:

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The assistance of many individual members of the staffs of the Davidson Laboratory, Stevens Institute of Technology, and of the College of Engineering, New York University, is also acknowledged. In addition, we appreciate the helpful suggestions of other individuals in the ship structural field not specifically mentioned by name.

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Abbreviations

ABS	American Bureau of Shipping
AGARD	Advisory Group for Aeronautical Research and Development
ATMA	Association Technique Maritime et Aeronautique
BSRA	British Shipbuilding Research Association
DHZ	Deutsche Hydrographische Zeitschrift
DTMB	David Taylor Model Basin
ETT	Experimental Towing Tank, now the Davidson Laboratory, Stevens Institute of Technology
IESS	The Institution of Engineers and Shipbuilders in Scotland
INA	Institution of Naval Architects, London, England
MARAD	U. S. Maritime Administration
MIT	Massachusetts Institute of Technology
NACA	National Advisory Committee for Aeronautics, now National Aeronautics and Space Administration
NAS-NRC	National Academy of Sciences-National Research Council
NATO	North Atlantic Treaty Organization
NECIES	North East Coast Institution of Engineers and Shipbuilders
NIO	National Institute of Oceanography, Surrey, England
NYU	New York University
QJRMS	Quarterly Journal of the Royal Meteorological Society
SNAME	Society of Naval Architects and Marine Engineers
SRAJ	Shipbuilding Research Association of Japan
SSC	Ship Structure Committee

SWOP	Stereo Wave Observation Project
SWRI	Southwest Research Institute
USCGC	United States Coast Guard Cutter
USN	United States Navy
WRH	Werft-Reederei-Hafen, Hamburg

CONTENTS

PART I - RESEARCH OBJECTIVES IN SHIP STRUCTURAL DESIGN

by

E. V. Lewis

Introduction

The purpose of the program described herein is to provide a broad but detailed long-range research plan aimed at the improvement of the structural design of ships. More specifically, the ultimate research objective is to provide the basis for more rational, less empirical, design procedures. To this end, research needs are discussed first in a general way, followed by specific recommendations of research projects. It is intended that the various recommended projects be specified in sufficient detail to enable the Ship Structure Committee--or other interested groups--to arrange immediately with laboratories and universities for the needed research. Several years will undoubtedly be required for the contemplated research to be substantially completed. However, when knowledge becomes sufficiently complete in all essential areas, it is anticipated that a big step can be taken toward the introduction of improved procedures in the design of ship structures.

The idea of long-range research planning is one that is particularly suited to engineering research, in which specific broad problems can often be clearly identified. Whereas much basic research in science must, by its nature, be free and unplanned, engineering research can be directed into specific projects that will contribute to the solution of the main problem. If this is done with care, there is a strong likelihood that important aspects will not be overlooked. This philosophy of research planning keeps the initiative in the hands of the sponsoring committee or agency, which can invite research proposals from laboratories and universities on particular projects. More rapid progress is assured by this approach than by passively accepting or rejecting random research proposals as they are submitted.

Current Design Methods

Current methods for the structural design of ship hulls are to a large extent empirical. For example, the determination of the sizes, or scantlings, of the principal structural members to withstand longitudinal wave bending loads is based on an empirical standard. A wave bending moment is calculated in a static manner for an assumed simple wave of arbitrary length and height. That is, the ship is assumed poised on a wave crest, or spanning two crests, in a condition of static equilibrium, as shown in Fig. 1, so that the loads at the various sections can be determined by computing the difference between the weight and buoyancy per unit length. No allowance is ordinarily made for the motions of the ship and wave, or for other hydrodynamic effects, although the effect of internal wave structure on pressures (the so-called Smith effect) is sometimes included.

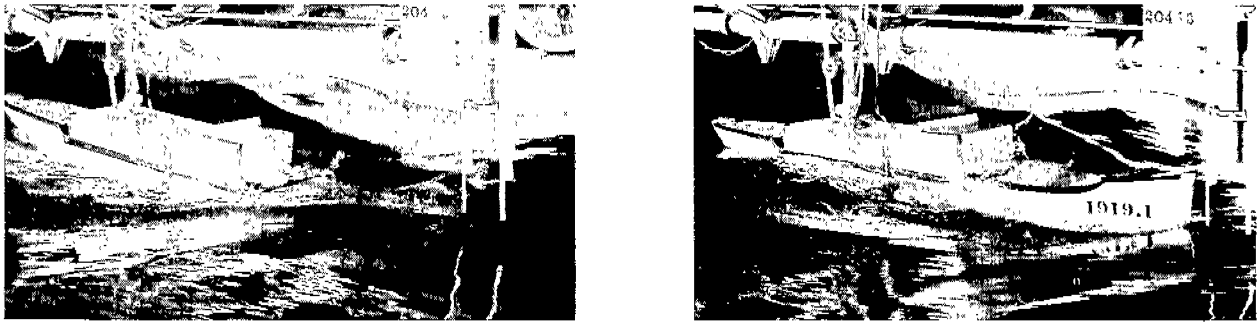
Figure 2, showing a ship model being towed in waves for measurement of bending moments, indicates the unrealistic characters of these static assumptions. However, the conventional static bending moment calculation does provide a standard design load which, in association with empirically derived allowable stresses, has resulted in a workable standard of longitudinal strength for both merchant and naval vessels. From the time of the introduction of iron and steel into shipbuilding nearly a century ago, this standard has been generally satisfactory for the many cargo ships and tankers (which until recently changed comparatively little in size and speed over the years) and even for many passenger ships and naval vessels.

The empirical factors have taken into account inadequacies in the method of calculating loads and in the assumed wave proportions, and also have tacitly allowed for other effects which are not explicitly considered, such as thermal stresses and superimposed impact loads caused by slamming. The static still-water bending moments, which may be of considerable magnitude, are usually allowed for separately in some manner. Combined loads, resulting from the fact that most structural elements simultaneously fill several functions, are allowed for in part directly and in part by the empirical factors.

a. Sagging Condition

b. Hogging Condition

Fig. 1. Assumed ship positions on wave for static bending moment calculation



a. Sagging

b. Hogging

Fig. 2. Typical photographs of a tanker model being towed in waves for the measurement of midship bending moments, Davidson Laboratory, SIT (Dalzell,[13] courtesy of American Bureau of Shipping)

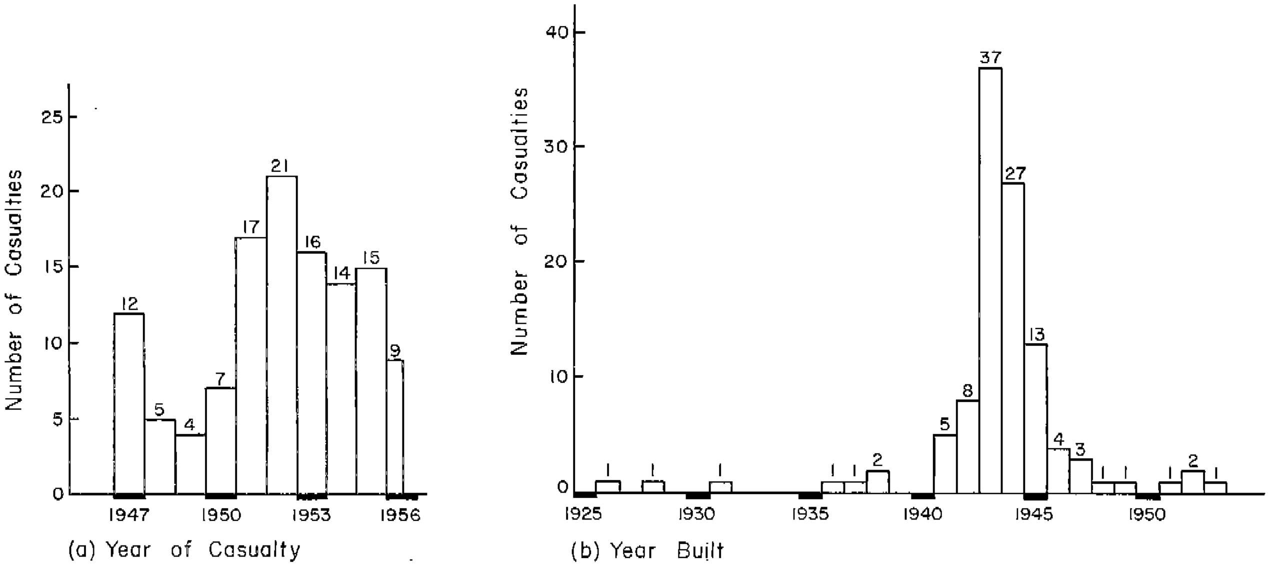


Fig. 3. Major structural failures at sea in ships of the world over 2000 gross tons (Turnbull[11])

The epidemic of fractures following the wartime introduction of welding into ship construction did not indicate the failure of the conventional empirical standard of strength, but rather a lack of understanding of the structural mechanics and metallurgy of welded structures. The situation has been brought under control as shown in Fig. 3a in part by improvements in design of details to minimize "notches," the provision of "crack arrestors," and in a few cases by adding longitudinal material. Improvements in the quality of materials have resulted in further success in the case of newer ships, as shown in Fig. 3b. Brittle fracture remains a problems, however, especially if further economy of structure is to be sought through better understanding of loads and use of higher working stresses.

Need for Improved Design Methods

The basic need for improvement in structural design procedures has arisen from the increase in size and speed of many types of ships built in recent years. It is here that the inadequacies of the current methods have become more and more evident. For example, the classification societies are in doubt as to how to extrapolate conventional standards to cover the ever larger supertankers and bulk carriers being built. Figure 4 shows how drastic this recent size increase of tankers has been with only moderate changes in speed. At the same time, naval designers are similarly puzzled as to the wave loads experienced by faster and/or larger naval craft. Figure 5 shows the trend of size and speed for one naval type--the destroyer--indicating again that perhaps size is more of a problem than speed. Dry cargo ships have shown much less increase in size, but a steady and significant upward trend in speed as shown in Fig. 6.

Studies are now under way on the feasibility of such radical developments as large submarine tankers and hydrofoil craft. Both of these ship types involve serious structural problems, but since they are of such a specialized nature they have been excluded from this research program. For surface ships there is every reason to expect two significant trends to continue:

(1) increasing size of bulk-cargo vessels (for both dry and liquid cargoes) with relatively small speed increase,

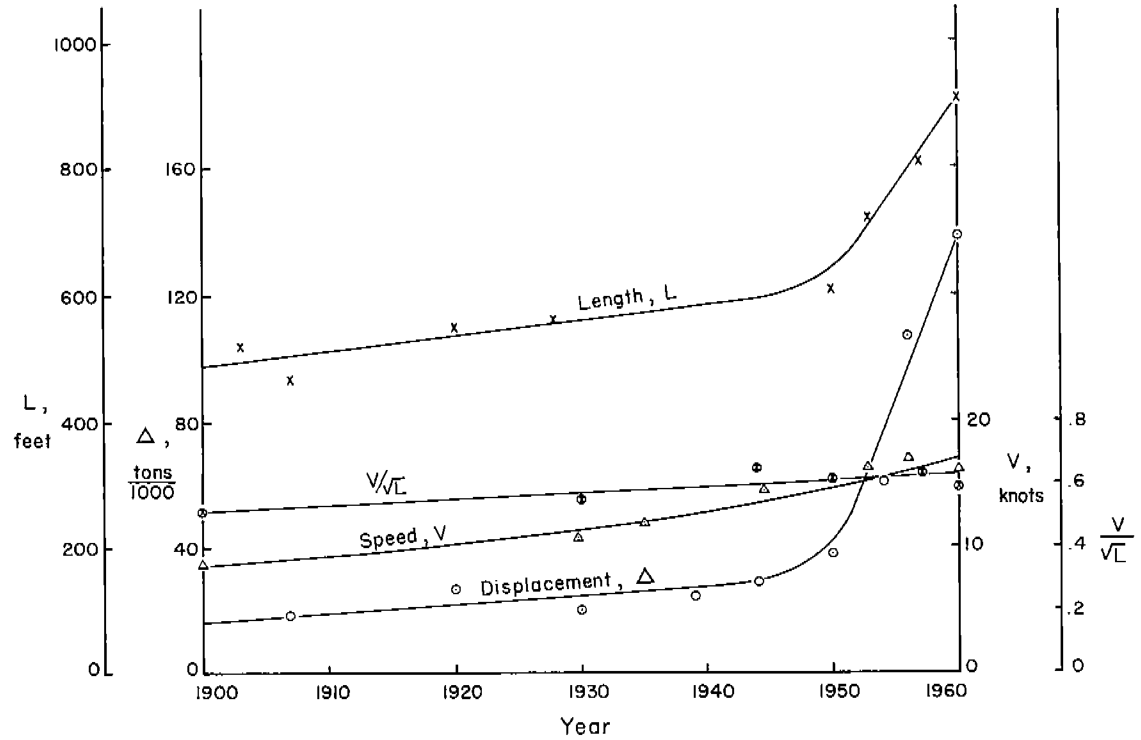


Fig. 4. Oil tanker size and speed trends (Largest tankers built in different years)

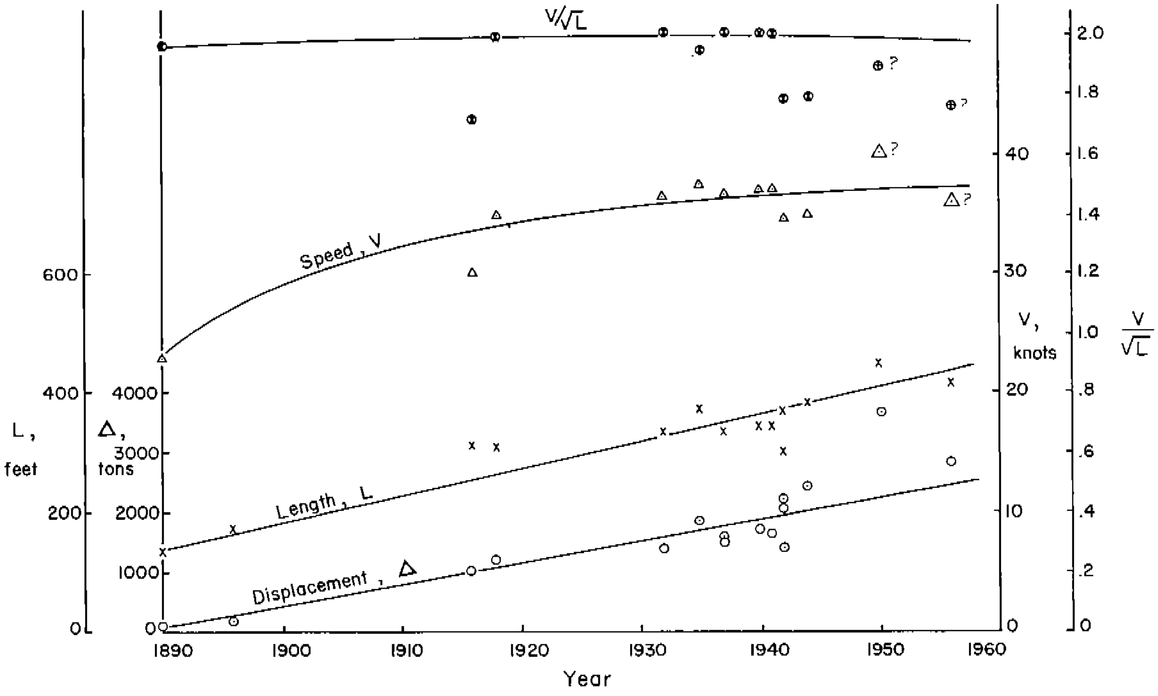


Fig. 5. U. S. destroyer size and speed trends

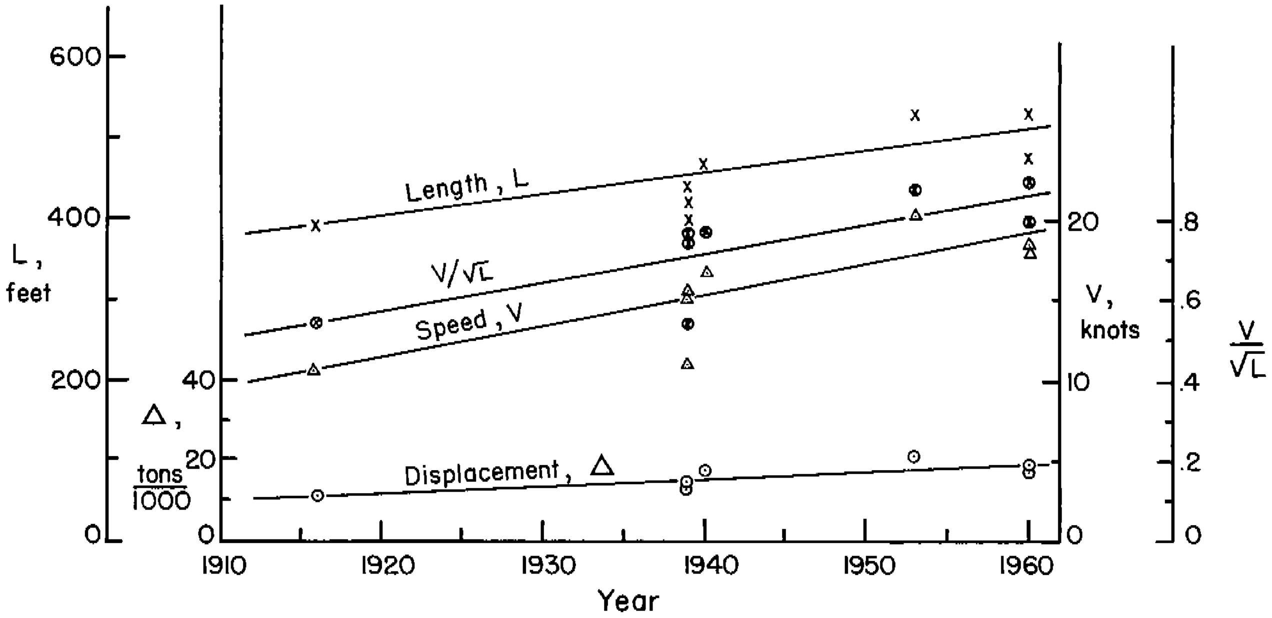


Fig. 6. U. S. cargo ship size and speed trends

(2) increasing speed of passenger ships, general cargo vessels and perhaps naval craft.

These continued trends are expected on the basis of the need for ever greater economy in the transportation of the heavy, bulk cargoes and the need for ever increasing speed in the transportation of high-value cargoes and passengers, as discussed by Davidson.[1*] There are indications that savings in port time and cargo handling costs obtainable by new types of container- or vehicle-carrying ships may call for corresponding increases in ship speed. The needs for speed in surface naval craft become obvious as submerged submarine speeds mount.

Both size and speed trends involve structural problems. In fact it has been suggested that, with radical new developments in power plants on the horizon, the structure may be the factor that places an ultimate limit on the size and speed of ships.

First let us consider size. It is a well-known fact that as the size of simple structures increases, the weight tends to become proportionately higher, providing the same kind of material is used. This results from the fact that

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*References are listed at the end of each section.

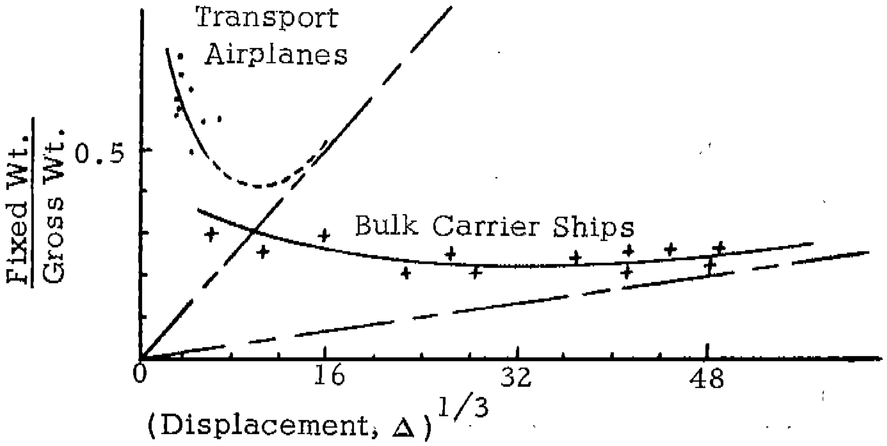

Fig. 7. Trends of structural weights (Davidson[1])

similar loads, such as the bending moment, on a series of geometrically similar hollow beams increase as the fourth power of linear dimensions, while the strength would increase only as the cube of linear dimensions. To provide equivalent strength, therefore, the material thickness and weight must be increased above those indicated by geometrical similarity. In complex structures such as aircraft, however, such an upward trend has not yet been detected, as shown in Fig. 7 from Davidson.[1] For ships this trend has only appeared in the case of the largest tankers.

Aircraft and ship structures have many redundancies which together with refinements in design have permitted successive advances in size without paying the expected penalty. As a result of better knowledge of loads, refined methods of stress analysis, better material quality, and more efficient use of materials, the newest and largest aircraft are still on the downward trend of weight coefficient. It has been suggested that perhaps the ship weight upturn might possibly be delayed by similar refinements and by allowing for wave-height reduction with length. Accordingly, an important area of study includes the problems involved in the design of still larger ships--which means consideration of such matters as the effect of size on the loads, possible structural refinements to save weight, potentialities of materials other than mild steel, and finally, indications of practical structural limits on size.

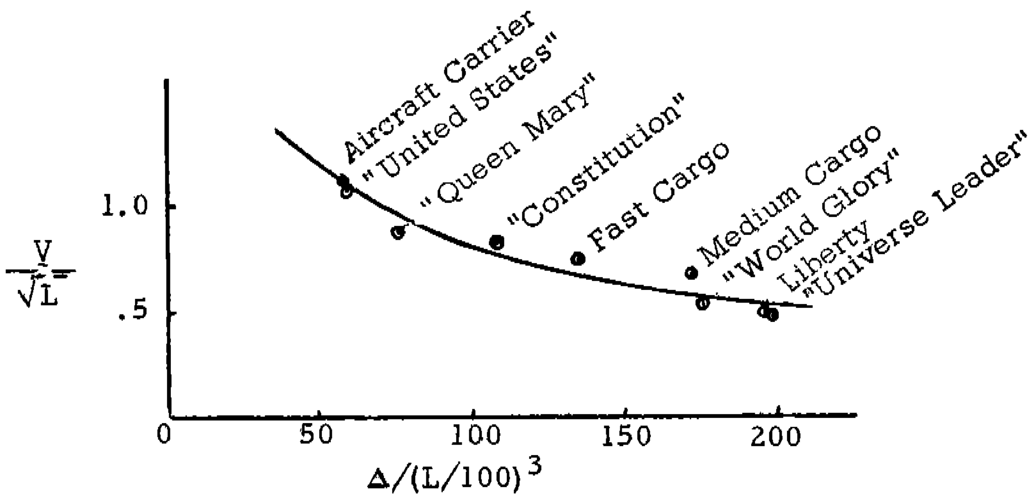

Fig. 8. Trend of $V/\sqrt{L}$ for ships of varying slenderness, $\Delta/(L/100)^3$

Considering speed next, one finds from available evidence discussed in Part II that there is a surprisingly small effect of speed, per se, on wave bending moments, until speeds are reached in head seas at which violent motions, slamming, and wet decks are experienced. Under such circumstances speed must usually be reduced for reasons associated with the motions rather than primarily to avoid large hull bending stresses. Therefore, the importance of speed in relation to structural design of future ships probably lies primarily in its effect on ship proportions. Fast ships have generally been more slender than slow ones, and a further trend in this direction appears probable. This trend is shown in Fig. 8, where the displacement-length ratio, $\Delta/(L/100)^3$, is used as an indicator of slenderness or fatness. Not only is the slender ship easier to drive in calm water, but, in general, it can maintain higher speeds in head seas as well, as discussed by Lewis.[2] Thus studies are needed to determine unusual loads experienced by slender ships and to investigate the use of lighter materials to avoid excessive structural weight. There is already evidence of increased dynamic whipping effects associated with increasing length/depth ratio, L/D, and the resultant increase in hull flexibility. Means for overcoming the difficulty or limiting the flexibility are needed. The latter approach may be difficult in the case of destroyers, for example, but it already has been accomplished in aircraft carriers by including the flight deck in the main hull structure, thus decreasing L/D from approximately 16 to 11.

Another objective of structural design research is weight-saving. There is reason to believe that the traditional methods are failing to produce the most economical structural designs, even for present-day ships. In ships carrying deadweight cargoes, each ton of steel eliminated could mean an additional ton of cargo. Hence, there is a double saving: lower initial cost and higher revenue. Typical figures for an oil tanker indicate that a 100-ton steel weight reduction would mean a reduced investment of about $60,000 and the following annual savings:

Capital charges, insurance, etc. on $60,000	$6,000
Annual income from 100 tons cargo (one way)	6,000
Total savings per year	$12,000

For a dry-cargo ship, in which volume is more of a problem than weight, the saving might be only in the initial cost, i. e., $6,000 instead of $12,000. But these are sizeable sums and a few hundred tons saved may amount to significant increases in profit.[3] Some possibilities for weight reduction without sacrifice of strength are apparent, for example, in the use of longitudinal framing in decks and bottoms of cargo ships. Reduction in the weight of expensive special steels in tanker decks and bottoms may be obtainable through more efficient structural arrangements involving thinner plating and heavier longitudinal framing. For possible future larger and faster ships, economical structural design, which implies minimum feasible weight of structure, becomes increasingly critical for the success of the design. Of course, to be fully effective such savings in weight must be achieved without increasing structural repair and maintenance costs.

Goal of Rational Design

In order to make possible the safe and economical structural design of larger and faster ships and to provide greater economy in conventional ships, a more rational method of design is essential. By a more rational method is meant one in which:

(1) The functions and requirements for the structure can be explicitly stated at the outset of the design.

(2) All of the loads to be expected in service can be determined and combined.

(3) The structural members can be arranged in the most efficient manner possible to resist the loads.

(4) Adequate but not excessive scantlings can be determined, using a minimum of purely empirical factors.

There can be no half-way measures. A more complete knowledge of seaway loads without an understanding of erection and temperature stresses, for example, would not justify a departure from traditional time-tested methods. Likewise, a complete understanding of all loads without accurate knowledge of the structural response of the hull in terms of stress distribution, load-carrying ability, etc., would not permit an advance to completely rational design. The particular significance of a research plan at this time is that it should insure that all facets of the problem will be considered. If no important aspect is overlooked, designers may confidently look forward to being able to take the big step to rational design after a reasonable period of time--perhaps five, perhaps ten years hence. This will provide the means to design the larger and faster ships of the future and to design both conventional and unusual ships more economically.

Fortunately, in recent years there has been considerable progress in various technical areas bearing on the ship structural design problem. Rapid progress has been made in the general field of structures, particularly under the stimulus of aircraft structural problems. At the same time research in oceanography and hydrodynamics is providing a much clearer picture of wave characteristics and of the loads imposed on ships in their natural environment; the sea. Other researchers are beginning to clarify the phenomena of brittle fracture, thermal stresses, structural response to impact loads, etc. The quality of shipbuilding steels has been improved to the point where the American Bureau of Shipping was able to announce recently that no serious fractures have occurred in American merchant ships built of steel manufactured to the new specifications (Fig. 3). A new approach to the superstructure problem has been obtained by the adoption of aluminum alloys with their low modulus of elasticity. But big gaps remain in the knowledge needed to apply these technical advances most effectively to structural design.

Requirements of Ship Structure The four steps in rational design mentioned above will be surveyed here in order to clarify the research problem. They will be discussed in greater detail in Parts II and III along with research recommendations. Some of the requirements for the design of a ship's structure are immediately obvious. Water must be excluded from the hull so that the ship will float. The hull must remain intact when subjected to seaway loads, thermal stresses, drydocking, and all other conditions of normal operation. And it will be agreed that ships intended for unlimited ocean service should be able to survive a hurricane, at least in the open sea. But should--or could--a ship be designed to survive very rare sea conditions, or a tidal wave in shoal water after an earthquake? What extent of collision or grounding damage should be assumed in design, and how bad a sea condition at the same time? No engineering structure is built to withstand the worst combination of unusual circumstances that might conceivably occur. Or, in the statistician's language, the probability of failure can be made to approach but never to reach zero. A line must be drawn between reasonable safety and practical usefulness.

Perhaps it can be tentatively suggested that a ship should be able to survive the worst sea conditions to be reasonably expected in its lifetime, including effects of shoal water, hurricanes, etc., but excluding phenomena such as waves caused by earthquakes. And the structure of a ship should, if possible, be able to hold together after any damage which does not result in the loss of its reserve buoyancy, and to do this in a moderately rough sea.

The structural design requirements will not be fully known, however, until the relative importance of factors such as the following are specified: weight, initial cost, operating cost (maintenance), reliability, expected life. The intended service of the ship must of course also be stated: unlimited ocean service, some special mission such as ice-breaking, or restricted service such as Great Lakes or coastwise runs.

Although these questions must be faced at the beginning of a rational ship design, they may be treated near the end of a research program, after the knowledge of loads has been clarified. At any rate, they will be discussed further in Part III of this report.

Nature of Loads on Ship Hulls The foremost problem in obtaining more rational structural design of ships is to obtain a better understanding of the loads. This was pointed out very strongly by the NAS-NRC Committee on Ship Structural Design in 1953. Typical or average figures for loads will not suffice. It is necessary to know not only the statistical distributions of each type of load, i.e., the frequency of occurrence of different levels of load, but ultimately the maximum load to be expected in the normal life span of ships on different services. Furthermore, the combined effect of many types of loading must be determined.

A ship at sea is subject to a variety of different loads, and it may be helpful before discussing structural research to describe the various types of loads. These loads act externally on the ship's hull, which may be considered initially as an essentially rigid body having a fixed geometrical configuration. The principal dimensions and form are determined mainly by non-structural factors such as buoyancy, stability, propulsion and maneuvering requirements, load-carrying capacity, and limitations of ports and drydocks.

First of all, a ship floating at rest in calm water is subject to certain local and overall loads as a result of unequal distributions of weight and buoyancy. A ship is in many respects like a building with the bottom structure (and to some extent side shell) forming the foundation which is supported by the vertical hydrostatic forces of buoyancy as shown in Fig. 9. In excluding the water from the interior, the bottom and side shell structure must resist the horizontal as well as vertical hydrostatic components. The pillars and frames

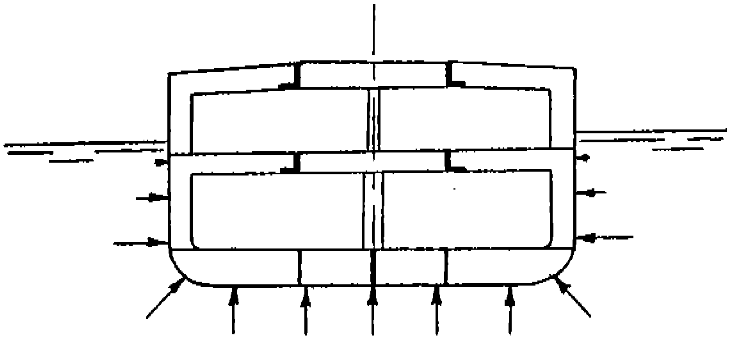

Fig. 9 Static loads on ship section

must support the decks which, in turn, support the cargo, liquids in tanks, machinery, personnel, and--on the weather decks--snow, ice, rain, and sea water. All of these produce local structural loads similar to those encountered in land structures. In addition, of particular importance are the overall shearing forces and bending moments on the hull resulting from unequal longitudinal load distributions which, under certain circumstances, may be of considerable magnitude, as shown in Fig. 10. This type of loading, in which the ship is assumed to behave like a simple beam, is fairly simple to calculate, and the computed changes in loads from one condition to another have checked out well with actual measurements on ships. However, superstructures and long deckhouses introduce complications that require special consideration.

Somewhat more difficult to evaluate are the thermal stresses caused by non-uniform temperature gradients. The underwater portions of the hull are essentially at the temperature of the water in which the ship floats, except when there are rapid changes in water temperature or heated liquids adjacent to the shell, while the above-water hull is subjected to varying air temperatures, combinations of solar radiation and shade, and internal heating and cooling. Stresses are induced that vary throughout the day as conditions change, the highest stresses often being at the waterline or at the intersection of the deck and side shell, as shown in Fig. 11. The latter stresses may be particularly important because they are superimposed on other longitudinal stresses.

Other types of loading experienced before the ship ever goes to sea are

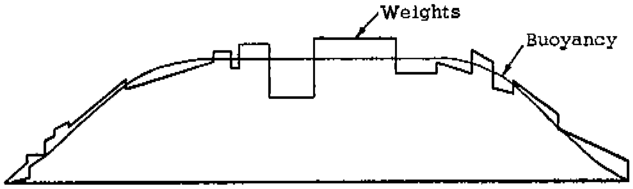

Fig. 10 Longitudinal distribution of static loads on ship hull

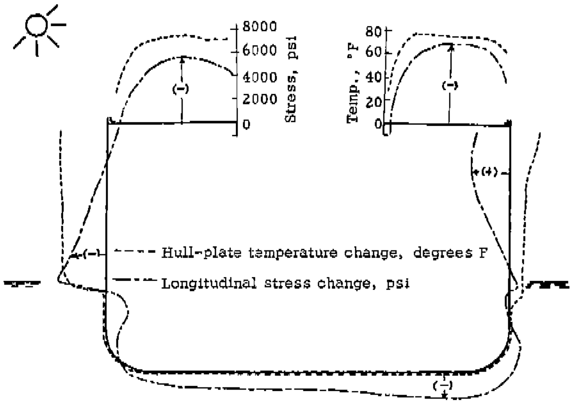

Fig. 11 Temperature gradients and stresses on a ship section (Meriam et al [12])

heating and cooling of the material during manufacture and the thermal effects of welding during the fabrication process. Welding involves the heating of the members being joined; the subsequent cooling of both the weld metal and the adjoining structure results in appreciable local stresses. Furthermore, as the erection and welding of the component parts of a complex structure such as a ship proceeds, each step may exercise restraints and induce stresses in previously completed portions of the structure. Other causes of built-in stresses are the use of heating and shrinking to fair plating, the uneven settling of building ways, and the completion of certain parts of the structure after launching. All of these built-in stresses are difficult to evaluate but, nevertheless, form an important part of the loading picture. They depend greatly on variables such as the quality of workmanship, effectiveness of weld inspection, and use of stress relief procedures.

A ship away from the open ocean is also subject to other loads. Coming alongside a pier may result in large local impact loads at the point or points of contact. Drydocking can produce large longitudinal and transverse bending loads as a result of uneven support, particularly in the overhanging portions of the ship. Grounding can produce very high loads for which design may not be feasible. Ships intended for navigation in ice must be specially strengthened against the side pressure of the ice and impact loads when ice-breaking.

Finally, when a ship goes to sea, a new set of loads is superimposed

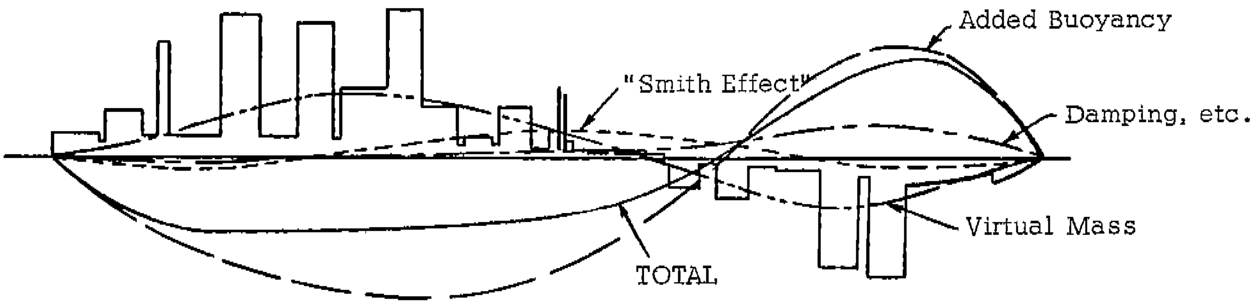

Fig. 12 Longitudinal distribution of loads on a ship hull in sagging condition in waves (Jacobs[14])

on many of those already discussed. The irregular surface of the sea results in further variations in the distribution of the water pressures over the surface of the hull, as shown in Fig 12. These pressure variations are the complex result of changes in hydrostatic head, in the motions of the wave particles, in the pitching, heaving, and rolling motions of the ship, and in the interaction between ship and wave particle motions. In addition, the accelerations involved in the motions of the ship result in significant mass-inertia effects. Until recently, attempts had been made to calculate some but not all of these complicated seaway loads, but model tests, as shown in Fig. 2, and new calculation methods are now helping to clarify the loading picture.

In attempting to calculate seaway loads, naval architects have long been baffled by the irregularity of the sea, and attempts to characterize irregular wave patterns by average characteristics cannot be considered satisfactory. In recent years new theories have been developed that permit the sea surface to be described as a spectrum of many component waves of different lengths, heights, and directions, all superimposed in random fashion (Fig. 13). Extensive observations now are needed on different sea routes within the framework of the theory. Professor B. V. Korvin-Kroukovsky of Stevens ETT has been engaged in the preparation of a monograph[4] surveying current knowledge of ocean waves, forces acting on ship hulls, and ship motions in waves,--a project under the joint sponsorship of the Ship Structure Committee and the Society of Naval Architects and Marine Engineers (SSC Project SR-128). His findings have

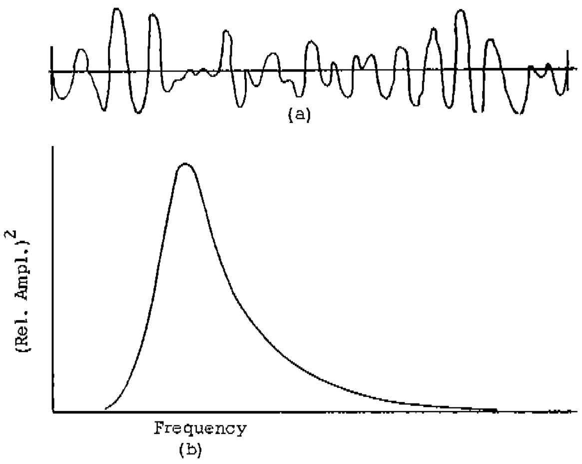

Fig. 13 Typical irregular ocean waves (a) Record (b) Energy spectrum

been used in considering needed research in the areas of forces acting on ships and their motions in waves.

The environmental situation in which an airplane operates is somewhat similar to that of a ship, for the atmosphere is subject to irregular fluctuations of velocity and pressure analogous to the variations in the surface of the sea. In aircraft design, however, it has been found possible to simplify the preliminary design problem by assuming that the fluctuating aerodynamic loads have a simple, known distribution over the wing, which is the main strength member, as shown in Fig. 14. In addition, the significant accelerations caused by gusts and maneuvers are those in a vertical direction relative to the plane of the aircraft, and they produce bending moments at the roots of the wings that can be easily calculated from the velocity of the atmospheric gusts. In the case of a ship, on the other hand, the main longitudinal bending loads on the hull, which is the main strength member, result from variations in the hydrodynamic and inertia loads along its length. Unfortunately, no suitable simplification of this problem appears to be practicable.

The seaway loads discussed up to this point can be resolved into a number of components: longitudinal bending in the centerline plane of symmetry, longitudinal bending in a lateral plane, torsion, transverse bending and "racking," and local loads. All of these are of relatively low frequency, governed by the period of encounter with waves that are long enough to have significant effects. In addition, the resistance to forward motion, even in calm

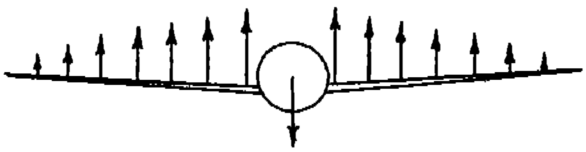

Fig. 14 Airplane wing loading

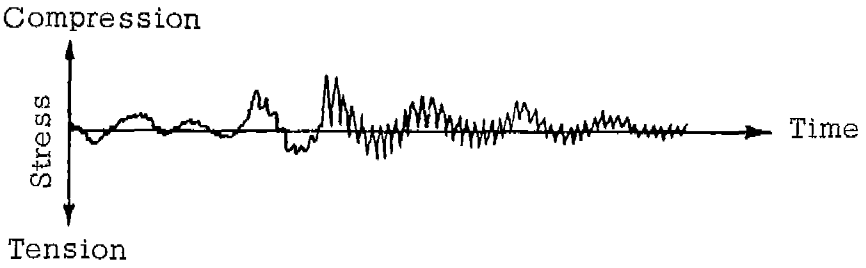

Fig. 15 Typical record of midship bending stress including effect of slamming (aircraft carrier) (Jasper and Birmingham[10])

water, must be balanced by the propeller thrust, which results in a small eccentric compressive load on the hull. As speed increases, a standing wave pattern also is created around the ship which changes the longitudinal distribution of buoyancy. Thus, a comparatively high sagging bending moment is caused at high speed. Waves breaking over the weather deck can produce pressure and impact loads on decks, superstructures, deckhouses, hatches, and fittings.

Another type of loading experienced at sea is that of high-frequency or impact loads. These result in the high-frequency response of the hull as a "free-free" beam, vertically, horizontally, and/or torsionally. These vibrations are caused by:

(1) impact forces usually in the forward part of the ship resulting from slamming or other large superimposed hydrodynamic forces arising from the sudden immersion of bow flare, waves breaking on deck, etc.

(2) periodic forces attributable to rotating or oscillating masses in the machinery and to the pressure fields around the rotating propeller blades.

These forces produce both local loads on the structure and elastic vibratory responses throughout the hull, as shown in Fig. 15.

In order to give some idea of the relative magnitude of all of the above loads, Table 1 gives typical values of the resulting stresses. Several types of loading appear to be of equal or greater magnitude than simple seaway bending

Table 1 - Typical longitudinal stress values in merchant ships

		Typical Large Values Observed (psi)*	
Residual stress in mild steel plate, as-rolled	At mid-thickness	4,000	T
	At surface	16,000	C
Local stress in weld metal[5]		Yield	
Reaction or locked-in stress in bottom structure during construction[6]		6,000	T
		17,000	C
Thermal stress at deck edge (or sheer strake), bright sun just before noon[7]		11,000	C
Static stress in calm water[8]		9,000	S
		15,000	H
Stress caused by wave pattern at high speed (calm water) for a destroyer[9]		2,200	S
Wave bending stress (low frequency)[8]		10,000	S
		8,000	H
Vibratory bending stress amplitude resulting from slamming[10]	Bottom impact	3,400	H or S
	Other impact (fast ships)	9,000	H or S

*T = tension
C = compression
S = sagging
H = hogging

NOTE: The above are extreme stress values which may be seldom, if ever, simultaneously superimposed. They represent variations from some unknown stress level rather than absolute values.

loads. It should be recognized, however, that all of these effects may seldom, if ever, occur simultaneously. At any particular time a certain load probably will predominate, and at any instant the phasing of the different loads may be such that they do not reach peak values simultaneously. Furthermore, some loads and stresses may be relieved and others aggravated by the concurrent application of other loads in service. For example, yield-point weld stresses may be relieved by plastic flow under a few reversals of load while, on the other hand, fatigue cracking or brittle fracture may be hastened by high-frequency stress reversal following slamming. Consequently, it is an important part of the present planning project to evaluate the importance of the different types of loads in order to determine where the emphasis should be placed in research. At the same time, attention must be given to means of determining the combined effects of the various loads, with the help of the theory of probability. All of the loads are considered in greater detail in Part II.

Structural Response In addition to examination of external loads, arrangement and size of structural elements that will enable the hull to maintain its shape and integrity efficiently under the influence of the loads. Actually there are two separate problems: the arrangement of structural members and the determination of scantlings.

All ships are basically hollow box beams, the strength deck (s) and bottom being the flanges and the sides the webs. These members also serve other purposes in excluding sea water, forming tank boundaries, supporting cargo and machinery, and enclosing the interior of the ship. Various other structures, such as intermediate decks, inner bottom, and bulkheads, are also part of the main hull structure. Their locations and extent are largely determined by their non-structural duties, but the designer may have some leeway in many cases. All of these structures are constructed of stiffened plating, and the structural designer has considerable freedom in choice and arrangement of stiffeners, provided he does not encroach on the intended usefulness of the various enclosed spaces. Thus there are transverse and longitudinal framing systems, and various combination systems. The spacing of beams and frames, and of supporting webs, stringers, and girders, can vary considerably. The problem is to obtain the optimum configuration, i.e., one that will provide the required strength, rigidity, and integrity with the least weight. Fortunately, techniques for determining optimum configurations of structural members are well-developed, particularly in the aeronautical field. Similar methods have been applied in naval ship design but only to a limited extent in the design of merchant ships. Research needs in the ship field are presented in Part III.

The other problem is the actual sizing of the members after the general layout has been determined. Methods of stress analysis are available and in general use, at least in the design of naval ships. A structural design monograph now being prepared by Southwest Research Institute (SR-146) is expected to summarize available methods of structural analysis in order to make them available to naval architects. But a full understanding of all the loads acting on a ship's hull and of the structural responses to them individually will not alone enable the designer to select the optimum structural layout or determine scantlings that will be adequate but not excessive. There are problems involved in determining the combined effect of loads on the selection of scantlings and these are considered in Part III. Another problem is that of allowances to be added for corrosion, which depends on the type of ship, the service, and the expected life. The final step is the reduction of the complex techniques applied in the research investigation to simplified procedures for practical design use.

It should be noted that although the development of simplified design methods is not part of a research program, it is essential for early application of the significant research findings to the design of ship structures. It is believed that this work divides itself into two distinct phases: the formulation of design rules and the formulation of design procedures by special groups. The classification societies and other regulatory bodies, ship designers, and research groups are all involved. These matters are discussed in the closing section of Part III.

Design Research Program

Many areas must be covered by a well-conceived research program in ship structural design. The program that has been prepared attempts to cover the field from the point of view of the researcher who looks ahead to the ultimate needs of the designer. Consequently, it considers a large number of problems in proceeding from consideration of environment and loads, through structural response, to the final determination of scantlings. This broad scope is made necessary by the current lack of knowledge. Once the ground has been thoroughly covered in research, it should be possible to apply the new knowledge to the development of simplified procedures for designing actual ships of the future.

The environmental factors in the research problem are considered in Part II, and include the seaway, loads caused by the seaway, static loads, and thermal gradients. The problems of determining structural response to seaway and static loads are discussed in Part III, along with recommendations for research under the categories of static and quasi-static response, impact and high frequency response, and thermal response. Consideration is given to both the arrangement of structures and the determination of scantlings, with improved rational design procedures as the ultimate goal. Attention is focused on the design of the main hull structure; however, the design of superstructures, subdivision bulkheads, and various structural details are not included.

The research program is broad in scope and covers both long and short-range projects. It includes some research areas that are already being covered to some degree. An attempt is made in every case to indicate such work in progress. Where projects can best be undertaken in a particular sequence, the recommended order is indicated. However, in general, it was not found feasible to suggest priorities for the research. It is hoped that, in addition to the sponsoring Committee, various groups, both in the U. S. and abroad, will be in a position to undertake some of the work.

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PART II - RESEARCH ON ENVIRONMENTAL FACTORS

Section 1. The Seaway

by

W. J. Pierson, L. J. Tick and G. Neumann

Background

Ocean-going ships regularly traverse many routes across the oceans, and the surface waves encountered constitute one of the most important environmental factors affecting their structural design. Although the technique of avoiding severe storms, whenever possible, is being developed along with the art of wind and sea forecasting, ships must still be able to survive, and if possible, pursue their courses under all sea surface conditions. In view of the fact that surface waves are one of the major causes of structural loads on ship hulls, it is of great importance to have a clear understanding of wave patterns and pressures in sufficient detail to permit calculation of these hydrodynamic loads. This requires that the irregularity of the sea surface, both in space and in time, be taken into account. It also implies that one needs to know about wave patterns not only under typical storm conditions in the open sea but also under extreme conditions such as hurricanes, shoal water, opposing currents and steep cross seas resulting from the superimposed effects of two or more storms.

Our knowledge of ocean wave patterns comes basically from sea observations, with the help of wave theories which are used to analyze and interpret the observed data. In cases where sea observations are not available, an indirect source of sea information is wave forecasting, or "hindcasting," from weather data. Accordingly, the status of our knowledge and research needs will be discussed here mainly in reference to sea observations and wave forecasting.

Present Status

Sea Observations Current available knowledge on the state of the sea and on wave heights and apparent periods is based mainly on visual wave observations taken from ships at sea, and in particular by the weather ships in the Atlantic and Pacific Oceans. However, there is some reason to doubt the reliability of these visual observations, particularly because the code used in international wave reporting by radio has an insufficient number of wave-height classifications. Similarly, there is considerable question as to the reliability of visually observed wave periods. Moreover, even if the average period were correctly observed, the usual law that the wave length in feet is 5.12 times the period squared does not hold in a random sea, and thus computed wave steepness cannot be precise. Hence, considerable error may be involved in using current data for ship design purposes. Some re-evaluation of such data and improvement in observation techniques are therefore needed. Furthermore, most information available on ocean waves is in the form of average or "significant" wave lengths and heights, which do not completely take into account the irregularity of the sea.[1÷3]

In recent years the application of time series methods, probability theory, and statistics, combined with classical hydrodynamics, has greatly increased our understanding of waves, as described by Pierson.[4] The new theories have made possible the description of irregular waves as a random superposition of many regular wave components of various lengths, heights and directions, and the relative importance of these components can be indicated by the directional spectrum of the sea.[5] By these methods the basic irregularity of the seaway can be described by a realistic mathematical model that provides a framework for more effective sea observations.

A certain amount of information is now available regarding the sea spectra to be expected under different conditions of wind strength, duration, and fetch, although there is some disagreement among different oceanographers regarding spectra. Neumann[6] derived a series of typical ideal spectra indirectly from observed wave heights and periods. Recently an operational shipborne wave recorder was developed at the National Institute of Oceanography (NIO) in Great Britain and was described by Tucker.[7] This recorder was deliberately designed not as a high precision instrument, but as a means of obtaining reliable measurements of waves in open sea conditions where no previously available instrument could be used. The fact that the instrument has recorded waves over 50 ft high from crest to trough is in itself an achievement, and, with refinements in design and calibration techniques, its accuracy and range of usefulness can be greatly enlarged. Nevertheless, the instrument has been used for making simultaneous ship-motion and wave records both in England and America, as reported by Cartwright and Rydill,[8] Jasper and Birmingham[9] and in a Liberty Ship project sponsored by the U. S. Maritime Administration and Bureau of Ships. Useful wave records also have been obtained from pressure recorders in shallow water, floating wave poles[10] and buoys,[11] and fixed recorders installed on the east coast radar platforms.

When actual records are available of the surface elevation at a point, techniques are available for obtaining the energy spectrum which describes numerous features of the wave pattern. At present, the wave theory on which these techniques are based lacks only the capability of treating nonlinear effects and some kinds of extreme conditions. As it stands at present, this linear theory may predict waves that are too steep for the conditions assumed, and thus a more satisfactory nonlinear theory may be needed to account for extreme conditions more realistically. These extreme conditions are of particular interest in connection with the problem of ship structural design.

In project SWOP, aerial stereophotography was applied to obtain a spectrum that gave values associated with both the direction and the frequency of the component waves of an irregular sea pattern in deep water.[5] In addition, Barber[12, 13] has demonstrated the use of an array of wave-height probes and NIO is now using a buoy that measures wave slopes and accelerations to obtain information on directional sea spectra.

Wave Forecasting New wave theories, described by Darbyshire,[14] Pierson, Neumann and James,[15] and Neumann and Pierson,[16] also have proved useful for wave forecasting. For example, various methods were applied by Rattray and Burt[17] to hindcasting sea conditions at the time of the structural failure and loss of the Victory cargo ship Pennsylvania in the North Pacific. A clear idea was thus obtained of an unusually severe storm.

At the present time there are numerous conflicting theories on all aspects of wave generation, wave forecasting, wave dissipation and wave propagation. These theories are supported by conflicting observations and conflicting analysis of the observations. Among the subjects under debate are the questions of:

(1) What is the correct theoretical form for the wave spectrum?

(2) How does the spectrum grow as the sea develops?

(3) How great a part do air-sea temperature differences play in determining wave height for a given fetch, wind direction and surface wind speed?

(4) Does viscosity play an important role in the decrease of the height of swell?

From the theoretical point of view, the possible factors that enter into the problem have not been well determined by observation.

The proper combination of empirical facts with theoretical views is the essential backbone of present-day wave forecasting methods. Even the most advanced theoretical results depend on empirically obtained information so long as questions of energy transfer from and to waves and energy dissipation are involved. Some of the more advanced theoretical results are not yet at a stage where they could be applied to the practical problem of forecasting waves at sea. By contrast, methods for forecasting wave generation for practical use are often called "empirical". However, these methods contain a sound substratum of theory and are based on observations of waves at various stages of development at sea. They are neither purely empirical nor purely theoretical.

Whether the theory of wave generation and propagation is derived correctly first and then verified against adequate observations or whether the observations are obtained first and then a theory is developed is of little consequence to the problem of ship structural design. Both will have to be done if for no other reason than to gather adequate statistics on extreme wave conditions.

Needed Research

Much remains to be learned about the sea. There are certain areas in the study of ocean waves that are basic in nature and therefore important to many others besides ship designers. Some of these problems may be considered to be outside the scope of ship structural research, for they undoubtedly will be solved in time as natural developments in physical oceanography. But their more immediate solution would permit more rapid progress in understanding seaway loads, and therefore it is believed essential that some such studies be included in this research program. Research progress can be best made by the cooperative efforts of all groups interested in a better understanding of the seaway. There are other aspects of the study of ocean waves that are of prime importance in the structural design problem, particularly those pertaining to severe sea conditions. These need special attention since they may not otherwise be undertaken for many years.

The ultimate objective of wave research, insofar as ship structural design is concerned, is to assemble data on sea conditions to be expected during the operational lifetimes of ships in different services. Several years of sea observations, resulting in recorded data that can be spectrally analyzed, can provide a foundation for such long-range predictions. If, in addition, improved wave forecasting methods are developed, available meteorological records can be used to determine by means of hindcasts the frequency of occurrence of the more extreme conditions over a ten or twenty year period in the past. On the basis of both observations and hindcasts, conclusions can ultimately be drawn regarding the expected frequency of occurrence of sea states of increasing severity for the lifetime of ships on various sea routes. Accordingly, needed research is discussed below under the following categories:

A. Sea Observations
   1. Observation methods
   2. Observations at sea
   3. Studies of steep waves
B. Wave Forecasting
   1. Wave generation and decay
   2. Application of wave forecasting methods

Specific projects mentioned by number are the recommended research projects described at the end of this section. A sequence has been indicated when certain work needs to be completed before other work can be undertaken.

A. Sea Observations

1. Observation methods: More reliable data on the sea surface are needed both for direct application to ship design problems and for developing ocean wave theory. The first step is to develop improved observation methods.

The possible unreliability of current methods of visually observing ocean waves, particularly those high waves of importance to ship design, has been mentioned. Consequently, one recommendation for future research would be a statistical study of the accuracy of such reported data and a study of whether or not the coding system now in use has resulted in biasing the data (Project 1). Such a study should lead to an improved coding system, to better ways of observing waves, and to an understanding of sources of error in current data. If some inexpensive device could be developed as an aid to visual wave height observations, the improved results obtained would be of considerable supplemental value to more precise instrumental observation.

According to H. U. Roll (private communication), "The importance of this project lies in getting exact knowledge of the reliability and accuracy not only of present wave observations but also of former ones. This will enable one to examine and possibly to use existing statistics of visual wave observations."

Improvements solely along the lines described above still will not give the naval architect the kind of data most useful for ship design nor will it answer many of the questions the oceanographer has about waves. Wave recording devices that would, at a minimum, give a record of the wave height as a function of time at a fixed point on the open ocean are therefore highly desirable. Only by having complete sample records of the sea surface can one obtain an adequate description in the form of an energy spectrum. If wave direction could also be recorded, it would be most helpful, but currently contemplated and operational recording devices do not have this feature.

One of the most promising types of wave recorder is the shipborne recorder recently developed at NIO. With some improvement in design and care in calibration, such devices could be used permanently aboard weather ships and other vessels to measure waves.

Other possibilities along the lines of work being done at Woods Hole Oceanographic Institute and the David Taylor Model Basin should also be considered. According to Farmer,[10] there is a whole range of possibilities between a highly damped wave staff to record the height of the sea surface as a function of time without moving up and down much itself, and a float to record vertical acceleration which is doubly integrated to obtain wave height. Perhaps some optimum design that would be a compromise between these two extremes can be found. This optimum design would be neither as cumbersome as the large wave pole at Woods Hole nor as subject to integration errors as the device described by Dorrestein.[11] Such a recorder perhaps could be so cheaply constructed that it would be expendable, and could be used for observation of hurricane waves.

Wave recorders are available or can be installed on all three of the east coast radar platforms and on some of the oil drilling rigs on the Gulf and west coast.

Thus, an essential field of investigation is that of deciding soon on the most practical types of wave recorder, and getting them in use (Project 2).

Wave records alone are not enough. A one-channel inexpensive spectrum analyzer should be used with each wave recorder so that the spectra could be transmitted to shore just like a radiosonde message. Thus, an important part of this project is the commercial development of a wave spectrum analyzer that would work directly from the output given by recorders on ships at sea.

2. Observations at sea: Ships follow certain trade routes over the ocean, and it is highly desirable to know the characteristics of the seas along these routes when designing new ships. This involves the study of waves on an oceanic scale in terms of a wave climatology; in other words, a historical series of large-scale synoptic studies is needed (Project 3).

Perhaps the most important single step in the history of meteorology was that of the establishment of a synoptic observation network. This means that complete weather observations are taken simultaneously by many reporting stations. Presently reported wave heights are synoptic, but a set of wave spectra determined from simultaneous observations would be of much more value in studying all kinds of problems. Thus, if weather ships could obtain the proper data, and if their observations could be coordinated with coastal swell observations in England, North Africa, Barbados, and Florida, and with observations taken on the east coast radar platforms where installations already exist, knowledge of wave systems would increase manyfold. Improved visual observations still will be needed as a supplement to fill in the gaps on the charts where no recorded wave data are available.

The development of a program for the routine collection and tabulation of wave spectra, wave observations, and associated meteorological data from all available sources on an oceanic scale is recommended. Such a large-scale undertaking would require the cooperation of the U. S. Navy, the Military Sea Transportation Service, the U. S. Navy Hydrographic Office, Coast Guard weather ships, the Weather Bureau, oceanographic institutions, universities, and other interested groups.

Given such data, methods developed by the U. S. Navy Hydrographic Office in depicting the current sea state and forecasting the future sea state by means of synoptic wave charts could be greatly extended and improved. The least-time track method for routing ships could also be greatly improved and the savings in cost might well be many times that of the cost of the program.

In addition, as was pointed out to the authors in a personal communication from Lyman: "in military oceanography there is hardly a tactical or strategic problem confronting the Navy in which wave conditions do not play an important part." Thus the above program should be supported for many other reasons besides those described herein.

The directional properties of the seaway would still be unknown, even if the above recommendations were accomplished. The determination of a directional spectrum is a difficult problem, and perhaps repeating the aerial stereophotographic procedures of Project SWOP one or two times more for higher wind speeds would be of value in this connection. Stereophotographs also could be taken from the radio masts on the east coast radar platforms. Another possibility is that of determining the directional properties of waves by simpler methods. Barber[13] has suggested a number of promising methods making use of arrays of wave-height gages, and he has actually applied several of them. However, there are many great difficulties present in applying Barber's results to waves in the deep ocean since five or six wave recorders have to be kept on a straight line at fixed distances from each other. Moreover, the whole spectrum is not determined easily by these techniques. It is understood from D. E. Cartwright (personal communication) that the National Institute of Oceanography, the National Physical Laboratory and the British Shipbuilding Research Association are undertaking joint experiments in England on the motions of ships in waves and that a buoy which sends vertical wave accelerations and slopes in two directions will be used. It is believed that cross-spectral analyses of the records will give much information about the directional spectrum. Analysis of some records made by the buoy is in progress.

After careful consideration of different methods of determining the directional properties of a seaway, one or more methods should be applied to the determination of a number of spectra for different typical sea conditions (Project 4). Both simple seas, in which a dominant direction is clearly present, and more complex cases, such as storm seas superimposed on heavy swells, should be included.

Since such a procedure will necessarily be complex, it can only be carried out for special cases. In those special cases, it would be well to have ships instrumented to record ship motions and stresses at the same time as the waves are being recorded. (See Section 2 of Part II.)

3. Studies of steep waves: The projects that are of particular interest in connection with the ship structure problem are those in which the emphasis is on extreme values of wave heights and steepness. The importance of unusually steep waves is indicated by the fact that unusually high waves have been known to do considerable damage to ships, as evidenced most recently by serious superstructure damage inflicted on the U. S. destroyer Manley off the coast of Portugal and the damage to the Liberte in December 1956.

Therefore, to supplement synoptic wave observations, there should be special sea observations designed to obtain direct data under the circumstances most likely to produce extremely high structural loads on ship hulls (Project 5).

These observations should be made under severe storm conditions both in the open sea and in locations where abnormally steep waves are encountered because of opposing currents, shallow water, cross seas, and "standing" waves caused by the reflection of an oncoming sea by vertical cliffs and breadwaters. It is also important to include hurricane sea observations. These records must be analyzed by suitable spectral methods.

The investigation should include the areas around east coast radar platforms, conditions over the Grand Banks, the continental shelf approaching the English Channel, and other places where dangerous sea conditions have been experienced. Field studies of the properties of wind-generated waves in shoaling water are essential for a better understanding of the effect of shallow water in producing extreme wave conditions. Wave records taken at different points along a line perpendicular to the coast, when an on-shore wind is blowing, would provide the necessary data for deriving the wave energy spectra on shallow water which can be compared with the spectra over deep water.

The steepness of a wave in a random sea is a difficult quantity to define. It is known that periodic progressive waves have a maximum steepness determined from non-linear considerations. Periodic standing waves can have a much greater steepness. In a random sea in which the spectral directions do not vary much, steepnesses may locally exceed the theoretical periodic values. For random seas reflected by vertical cliffs, for example, the vertical distance from one quasi-standing wave crest to the neighboring trough at any instant may be the same as the distances between instantaneous crests.

Along with observations of unusually high, steep waves, extension of existing wave theories should be carried out. Although adequate for moderately rough sea conditions, current random wave theories, i.e., those based on linearized equations, predict certain wave heights which are known to be unlikely under the assumed conditions, and certain height to length ratios which cannot actually occur. Consequently, an improved random model of the surface should be derived that in some manner does not lead to, or makes very unlikely, the appearance of certain unrealistic wave forms (Project 6). Furthermore, the current formula for the probability distribution of wave heights, based both on a random model of the sea surface derived from linearized equations and on a narrow-band assumption on the spectra, is inadequate. This is in part due to the linearizations which are weakest for high crests. A new distribution for wave heights based on an improved random model of the surface is therefore necessary. The non-linear random model devised by Tick[18] is a start in this direction. It also appears that some of the apparent contradictions and the disagreements mentioned above can be resolved on the basis of Tick's model and its planned extensions.

The use of potential theory in the derivation of a random model of a sea surface does not allow for a breaking wave. Certain conditions, e.g., speed of the crest being greater than the speed of the water beneath it, make for wave instability. The probability that these conditions will occur for any given random wave theory should be evaluated so that these waves, which in reality would break, can be removed or reduced in any study of the distribution of crest amplitudes.

So far, most of the random process models of the sea surface have been of a stationary character (in the probability sense). For a large class of oceanographic problems there is a change in the wave characteristics in space, as when the wind blows off shore. For another class of problems there is a change in the wave characteristic as a function of time, but at any given instant the structure is constant in space. The problem here is to formulate random representations in which the time and space coordinates enter in only a non-random way, and this randomness appears as coefficients of these functions as in a Fourier representation of the stationary case. Another case requiring special treatment is that of circular storms, such as hurricanes, in which the wind direction is continually changing and very steep waves are formed.[19]

B. Wave Forecasting

1. Wave generation and decay: Improvement in wave forecasting methods will be of help in the ship structural design program because it will then be possible to use past weather data to build up a more stable statistical description of wave conditions for design purposes. Improved wave forecasting

methods also will aid in ship routing and in numerous other applications. There are many currently available methods for forecasting waves. Given the improvement in observations outlined above, the many different methods could be sifted down to the one showing the most accuracy and promise for improvement. Thus another line of possible research consists of utilizing synoptic data and computed wave spectra as they become available for testing and improving wave forecasting methods. Since sea forecasting depends primarily on knowing the relationship between winds and the waves they produce, the first problem is to formulate better theories of the energy transfer from wind to waves. Since the mechanism of wave generation is only partly understood, the application of both theoretical and experimental methods to the study of the physical problem of energy transfer from wind to waves is needed (Projects 7 and 8).

To formulate a proper theory of this energy transfer, it is necessary to have a useful model of the energy source for the waves, namely the wind. There has been a continuing program of work on this subject, but up to the moment none of the models evolved has been completely satisfactory. Since the most useful description of the sea surface, particularly as it affects ship motions, is one based on probability theory, the greatest effort should be in this direction.

A concurrent problem to support the theoretical study of wave generation is the more accurate determination of the characteristics of the wind field in the lowest levels of the atmosphere. The study of anemometry problems and of determining wind shear with height in the lower levels of the atmosphere aboard weather ships therefore would be of value (Project 9). It is realized that this is a difficult problem owing to the presence of the ship, but certainly data better than the currently available Beaufort values should be obtainable.

The wind in the vicinity of the sea surface is a boundary layer phenomenon. If the sea surface is considered as a random process, then it is necessary to investigate random boundary layer conditions. The presence of this boundary modifies the wind profile above it. Since it is necessary to have some idea of the wind profile and the spectra of the wind fluctuations above the boundary in order to formulate an adequate wave generation theory, a set of simple probability procedures for dealing with random processes at the boundary is essential.

One of the major difficulties in establishing a useful air-sea interaction theory is the internal contradiction between using potential theory to describe the sea, i.e., no dissipation or addition of energy in the waves, and theorizing about the transfer of energy from the wind to the waves. With such a process the waves would grow indefinitely. Since potential theory has been found to produce a good approximation of waves, and because of its simplicity, it is recommended that a study be made to evolve a "sink" for the energy that does not destroy the irrotationality assumption of potential theory. In this way one can speak of steady-state solutions. This subject is discussed in Lamb[20] for a fluid of very low viscosity, but further study is needed.

The problem of initial wave generation also needs to be explored on the basis of probability theory. This involves the proper formulation of (1) the energy transfer from wind to waves by tangential stresses and normal pressure, and (2) methods for correctly randomizing these processes. A beginning has been made in this direction by Phillips[21, 22] and Miles.[23]

Small-scale experimental studies of air-sea boundary processes can provide valuable results for the wave-generation problem. The problem of the generation of initial waves under the action of wind can be studied, both in a wind-water tunnel and over natural bodies of water such as ponds, lakes, bays, and sounds (Project 8). Records of the wave motion at low wind speeds can be taken by a wave recorder. In addition to taking wave recordings in the gravity as well as capillary wave range, the vertical distribution of the wind over the wave surface should be measured along with the vertical distribution of temperature and humidity.

Some studies in wind tunnels and over small bodies of water have been carried out and more are underway. Studies of capillary waves by means of spectral computations are under way at New York University. Studies in a circular wind tunnel to provide a virtually infinite fetch have been carried out in Russia. Some work in a reservoir has been carried out in England, and studies are either planned or under way in Long Island Sound, Buzzards Bay and Chesapeake Bay.

More effective studies can be done in larger wind tunnels or by the modification of smaller tunnels. Wind tunnels with low ceilings so that the air space above the water is only one or two feet should be avoided because of the complexity of the modifications of the flow caused by the low ceiling.

Another important problem in ocean wave forecasting is that of energy dissipation both while the generating wind is blowing and after the wind ceases. It has been shown that for waves passing out of a storm area there is no detectable attenuation of swell by any effect other than dispersion and angular spreading. Thus, since there must be some dissipation effect in the generating area to provide steady-state conditions, it must be of a selective nature. For example, such energy dissipation might be caused by turbulence, internal friction, air friction, and breaking crests on the open sea. Of these possible causes, breaking crests appear to be the most likely as they would be most effective in the storm area.[22] The other possible causes should also be studied, however. Furthermore, such effects as shoaling water, opposing currents, opposing waves and atmospheric stability may have significant effects that require clarification. These effects are of interest also because of their influence on wave steepness. The modification of the energy spectrum of waves by shoaling water is caused by three important effects:

(1) dissipation of energy in the high as well as low frequency part of the spectrum owing to increased turbulence by the waves breaking and bottom friction

(2) increase in wave height and steepness caused by change of wave length with water depth and refraction

(3) refraction effects attributable to the change of phase velocity when the composite wave pattern approaches shallower water

The last effect has not yet been studied thoroughly for waves on the basis of wave spectra.

Experimental research in model tanks or small bodies of water should also be carried out along with theoretical studies of wave energy dissipation (Project 8).

2. Application of wave forecasting methods: Finally, it appears that more detailed studies should be made of the sea conditions at the time of past ship structural failures. Wave forecasting techniques can be applied to "hindcasting" the sea conditions from systematic meteorological records that are available for most sea routes (Project 10). More complete knowledge of the sea conditions at the time of actual structural failures should be of great value in assessing the significance of hydrodynamic loads in causing failures. This will require a detailed analysis of ship logs and weather logs, if available, as the presently abstracted data do not appear to be complete enough to be useful in forming valid conclusions. For example, the position of the Gulf Stream varies from day to day so that the possibility of a sudden temperature change needs careful study. In addition, information is needed to decide whether a ship was in shoal water or deep water.

To permit the results of all of the suggested research to be effectively applied by the designer, it is necessary to consider long-range forecasts or predictions. A project is therefore needed to assemble data on the sea conditions expected over the operating lifetime of ships or classes of ships on different trade routes, with particular emphasis being placed on severe sea conditions (Project 11). Through use of "hindcast" techniques, data on sea conditions can be extended far beyond the period covered by actual synoptic wave measurement, as described by Danielson, Burt, and Rattray.[24] Statistical methods and probability theory can then be applied to predicting the frequency of occurrence of different sea states, including the most severe sea to be expected, during a ship's lifetime.

Results Expected

It is anticipated that, after the completion of the program described above, knowledge of ocean waves, in general, will be much more complete. In particular, wave measurements are expected to provide information on extreme wave conditions, on how waves are generated by the wind and on how the waves propagate and dissipate after the winds die down. In addition, knowledge of non-linear wave features will have been increased. Finally, accurate information about the occurrence of the unusually severe conditions to be encountered by ships on different routes will become available for design use.

Summary of Recommended Research Projects

THE SEAWAY

Project No.	Title
	SEA OBSERVATIONS
	Observation Methods
1	Study of reliability of visual wave observations
2	Standardization and installation of operational wave recorders and spectrum analyzers
	Observations at Sea
3	Routine collection and dissemination of synoptic wave data
4	Determination of directional spectra of wind generated seas
	Studies of Steep Waves
5	Measurement of waves of extreme steepness
6	Development of non-linear theories for various wave features
	WAVE FORECASTING
	Wave Generation and Decay
7	Theoretical studies of growth, propagation and energy dissipation of ocean waves
8	Experimental studies of wave growth, propagation and energy dissipation in wind tunnels and over small bodies of water
9	Measurement of wind data for high winds in the lower levels of the atmosphere
	Application of Wave Forecasting Methods
10	Detailed studies of weather and sea conditions at the time of past ship structural failures
11	Long-range determination of expected sea conditions for ship design purposes

Project 1: Study of Reliability of Visual Wave Observations

Objective: To determine whether available wave height and period data reported in code by ships represent accurately the so-called "significant height" and some characteristic period; to determine whether an improved coding system can be devised.

Program: Study the available reported data on wave and heights periods for internal consistency and compare some visual reports with instrumental reports. Particular attention should be given to determining whether or not the proportion of high waves is correctly reported. Devise an improved coding method to provide more reliable wave data.

Suggested Techniques: Statistical analysis of data.

Research in Progress: None

Results Expected: Knowledge of the reliability and accuracy of present wave observations and means of improving them.

Project 2: Standardization on and Installation of Operational Wave Recorders and Spectrum Analyzers

Objective: To get wave recorders and spectrum analyzers in use on a routine synoptic basis on important trade routes.

Program: Make a study of available and potentially available wave recorders and decide on several that are suitable for routine observation. Build a fairly large number of them and install them on weather ships, on other ships on important trade routes, and on the east coast radar towers, including those in shoal water. The best recorder for a ship in deep water may not be the best for the radar towers. Obtain an inexpensive one-channel spectral analyzer for simultaneous operation with the recorders so that the spectra become immediately available. The wave records also should be preserved for the study of non-linear features. This project should be given high priority.

Suggested Techniques: Instrumental investigation and development.

Research in Progress: Various wave recorders are available or under development, such as NIO shipborne wave recorders,[7] an expendable buoy type recorder developed at DTMB, wave poles,[10] buoys or floats,[11] water elevation recorders on fixed radar and oil drilling platforms and pressure recorders in shallow water. Spectral analyzers are in use at NIO[26] and are being developed by Sperry Gyroscope Company.[25] The U. S. Navy Hydrographic Office has some plans for developing a shipborne wave recorder for obtaining synoptic data.

Results Expected: Means of obtaining adequate ocean wave data and analyzing them properly.

Project 3: Routine Collection and Dissemination of Synoptic Wave Data

Objective: To obtain long-range systematic data on ocean wave patterns on important trade routes.

Program: Record wave patterns regularly on weather ships, on east coast radar platforms, and on other ships on important trade routes. Obtain spectrum analyses and information on unusually severe seas from these records. The program would be a long-range undertaking, extending over many years. Devise a code to characterize the wave spectra and disseminate data by radio and teletype. Designate an organization to issue tabulations of the data on a monthly and annual basis, just as meteorological data are disseminated.

Suggested Techniques: Make use of wave recorders and spectral analyzers installed under the preceding project. Consult with the Weather Bureau, the Coast Guard, and the U. S. Navy Hydrographic Office as to practical procedures.

Research in Progress: None on the scale contemplated, although weather ships I, J and K are now taking wave observations with NIO recorders. The U. S. Navy Hydrographic Office has some long-range plans in this field. Some data are being obtained from east coast radar towers and Gulf coast oil drilling rigs. Data are also being recorded on a ship at sea by Centre Belge de Recherches Navales, in Belgium.

Results Expected: Properly collected and recorded ocean wave data for ready reference.

Sequence: Project 2 must be completed before Project 3 can be undertaken.

Project 4: Determination of Directional Spectra of Wind Generated Seas

Objective: To determine the directional spectra of seas generated by winds of 25 and 30 knots or more in deep water.

Program: Carry out several projects for the determination of directional spectra of the sea under typical storm conditions. Obtain ship motion and bending moment data concurrently. (See Project 18.)

Suggested Techniques: Use of either stereo wave photographs, antenna arrays or slope and acceleration measuring buoys, along with the wave height recorders described in Project 2 and available computational procedures.

Research in Progress: The work of Chase, Cote, et al[5] has been completed. Longuet-Higgins of NIO, Farmer[10] of Woods Hole, and Barber[12, 13] are working on other methods.

Results Expected: Information on typical directional wave spectra characteristics of different storm conditions. The results will also aid in the interpretation (in terms of wave direction) of routine data taken with ordinary wave recorders. (Projects 2 and 3)

Project 5: Measurement of Waves of Extreme Steepness

Objective: To obtain a large number of ocean wave records under conditions that would be expected to produce severe hull bending stresses; to analyze the results and make them available to researchers and ship designers.

Program: Make special observations of surface elevations at fixed points as functions of time over sufficiently long periods in order to obtain a large sampling of typical severe sea conditions. The following is a tentative list of specific cases for investigation:

- (a) hurricane seas off shore
- (b) storm seas off the U. S. east coast on the continental shelf (at radar platforms)
- (c) storm seas over the continental shelf approaching the English Channel
- (d) storm seas and swells over the Columbia River bar
- (e) the edge of the Gulf Stream where strong current shears occur
- (f) harbor entrances where breakwaters, cliffs and sea walls reflect the sea and cause patterns of steep "standing" waves

In addition, the severe cases obtained in the synoptic observations described in Project 3 would be studied.

Analyze wave records in order to obtain energy spectra and also to obtain extreme directly observable wave characteristics such as maximum wave height. Deduce wave length and steepness theoretically by the use of appropriate operations on the wave record.

Suggested Techniques: For open sea observations of rough seas the standardized recorders decided on in Project 2, or the expendable buoy being developed at DTMB, would be used. Wave recorders and equipment on east coast radar platforms would be directly applicable for case (b). Pressure recordings would be suitable over river bars, such as case (d). Statistics and probability theory should be applied to the analysis of the results.

Research in Progress: Some data are being recorded on east coast radar towers. Wave spectra in shoaling water are being studied by Roll and Walden in Germany.

Results Expected: Plots and tabulations obtained from analysis of wave records would be published, thus providing ready reference data on severe wave conditions.

Sequence: Project 2 must be completed before Project 5 can be undertaken.

Project 6: Development of Non-Linear Theories for Various Wave Features

Objective: To derive theoretically and verify experimentally corrections to the current linear wave theories that will explain how non-linear effects cause breaking waves and modify the wave spectrum, the linear Gaussian properties, and the wave heights and steepness.

Program: Study the non-linear features of waves theoretically and derive random representation of such features. Apply new computational techniques to the study of wave records, and verify the theoretical results by comparing them with observations.

Suggested Techniques: Apply and extend recently obtained, more generalized concepts for the representation of random processes.[18, 19] Verify against properly obtained data.

Research in Progress: Tick[18] at New York University, Phillips[22] at Johns Hopkins, and possibly others.

Results Expected: An understanding of the ways in which the linear theory may fail and a development of non-linear wave theories that may be applicable to the study of non-linear ship motions and loads in waves.

Project 7: Theoretical Studies of Growth, Propagation and Energy Dissipation of Ocean Waves

Objective: To find out what factors affect the growth, propagation, and energy dissipation of waves, particularly those generated under severe storm conditions.

Program: Have various groups analyze the new data obtained from the preceding projects on wind, waves and wave spectra and check the available theories against the data. Synoptic weather maps and all available supplementary information would be used. Extreme wave conditions would be of particular interest, including shoal water effects. Apply results to the development of theories of wave generation, wave propagation and wave energy dissipation.

Suggested Techniques: Make case studies of the records of hour-by-hour changes in the wave spectra and the winds and try to find consistant rules to describe what occurs.

Research in Progress: A limited amount of work, restricted by the amount of available wave data, is being done at NYU.

Results Expected: An explanation of how the sea develops and changes and improved procedures for wave forecasting, particularly under severe storm conditions.

Sequence: Project 7 can be started at once, but cannot be satisfactorily completed until Projects 8 and 9 are well advanced.

Project 8: Experimental Studies of Wave Growth, Propagation and Energy Dissipation Over Small Bodies of Water

Objective: To measure the waves generated by light winds over limited areas of water so as to aid in the development of theories of wave generation and propagation.

Program: Undertake several projects for the study of wave generation, propagation and energy dissipation under conditions where wind and wave data can be accurately obtained. Apply results to development of suitable theories.

Suggested Techniques: Continue development along the lines of procedures currently employed. A large long wind tunnel could provide wave data in a range where they are not currently available. Shallow water effects can be easily modeled. Waves should be measured as a function of fetch for different wind speeds, wind shears with height, and water-air temperature differences. Make spectral analyses in order to take into account the irregularity of wind-generated waves.

Research in Progress: Farmer is measuring waves in Buzzards Bay and Kinsman is measuring waves in Chesapeake Bay. Capillary waves have been measured by Cox in a wind tunnel at NYU.

Results Expected: A better understanding of the laws of wave generation, propagation and energy dissipation, as a basis for improved wave forecasting and rational determination of maximum wave heights and steepness expected at sea.

Project 9: Measurement of Wind Data for High Winds in the Lower Levels of Atmosphere

Objective: To study the turbulent features of storm winds and the shear with height of these winds.

Program: Instrument the masts of weather ships with sturdy anemometers at several heights, and record wind forces simultaneously at several heights. Wave observations also should be taken. This need not be a routine operation, but it should be carried out for a representative sample of wave and wind conditions.

Suggested Techniques: Consult experts on atmospheric turbulence and anemometry. Adapt methods used on land to the weather ships and take the presence of the ship into account theoretically.

Research in Progress: None at sea.

Results Expected: Data needed for the theoretical studies of wave generation described in the discussion.

Project 10: Detailed Studies of Weather and Sea Conditions at the Time of Past Ship Structural Failures

Objective: To find out the wave conditions present when structural failures of ships have occurred.

Program: Review records of ship structural failures and select a representative sample of cases in which weather and sea conditions appear to be contributing factors. Estimate carefully the wave, wind, and temperature conditions existing in each case.

Suggested Techniques: Determine the vessels to be studied from log data. Apply modern forecasting methods to "hindcast" the sea conditions from meteorological records. See Rattray and Burt,[17] Danielson et al,[24] and Project 7.

Research in Progress: Reports on ship structural failures issued by the American Bureau of Shipping and the Ship Structure Committee list available log data on sea conditions.

Results Expected: Reliable information on sea and weather conditions existing at times of a representative number of actual ship structural failures.

Sequence: This project can best be carried out after Projects 1 through 9 are well advanced or completed.

Project 11: Long-Range Determination of Expected Sea Conditions for Ship Design Purposes

Objective: To assemble data for predicting conditions of the sea to be expected over the operational lifetimes of ships for design use.

Program: To make an historical survey of the wave data collected, using improved wave hindcasting methods to determine the frequency of more extreme conditions. On the basis of this and available sea observations, make a long-range prediction of conditions to be expected over the lifetimes of ships on various sea routes.

Suggested Techniques: Results of the other recommended projects would be used. The wave data collected under Projects 3, 4, and 5 would be surveyed and expanded by means of the improved wave forecasting and hindcasting methods developed in Projects 7, 8, and 9 to determine the frequency of the severest sea states over the past ten or twenty years. Statistical methods could then be used to predict the expected frequency of occurrence of these conditions for the lifetime of ships on various sea routes in the future.

Research in Progress: None

Results Expected: Accumulation of data on the prediction of sea states that ships may be expected to encounter on various routes.

Sequence: This project can best be carried out after Projects 1 through 9 are well advanced or completed.

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Section 2. Low-Frequency Seaway Loads

by

E. V. Lewis and B. V. Korvin-Kroukovsky

Introduction

When a ship encounters waves at sea the most noticeable effect is the resulting ship motions which depend to quite an extent on the ship's speed and heading. Large hydrodynamic forces are of course involved in producing these motions, and the motions themselves, in turn, affect the forces. For convenience the seaway loads acting on a ship's hull can be classified under several categories: shear forces and longitudinal bending moments, both in the centerline plane of symmetry and in the lateral plane,* torsional moments, transverse loads which tend to bend or distort the section shape, and various local loads. Seaway loads also can be classified as low frequency (or quasi-static) and high frequency (including impact) which result in a vibratory response of the hull.

The low-frequency loads vary in an essentially smooth manner and are related to the rigid-body motions of the ship. The loads have irregular periods which correspond to the periods of wave encounter or sometimes to the natural period of pitching or heaving of the ship. Of particular importance is the longitudinal bending moment in the vertical plane, which is generally considered to be the basic load for consideration in hull design.

High-frequency loads arise primarily from impacts of portions of the hull against the irregular wave surface, or from other rapid variation of the hydrodynamic forces, which lead to vibratory hull response and corresponding superimposed high-frequency hull stress variations. High-frequency loads also are applied by rotating masses of machinery, propeller effects, etc. All of these high-frequency loads will be discussed in the next section.

Background

Knowledge of ship motions in waves and the accompanying hull loadings

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*For convenience longitudinal bending moments may be referred to as vertical when caused by vertical forces (ship upright) and horizontal when caused by horizontal forces.

are comprehensively surveyed in the monograph "Ships at Sea" being written by B. V. Korvin-Kroukovsky.[1] Needed research is also considered at some length. The following discussion includes some of the findings of the monograph.

The subject of longitudinal bending moments in waves has been studied intermittently ever since the beginning of iron and steel shipbuilding. In 1905, J. H. Biles[2] published the results of observations of hull stresses on HMS Wolf at sea as well as in dry-dock. A thorough review of other early work on full-scale observations of hull stresses or strains at sea, which have been interpreted roughly in terms of bending moments, is given in the Ocean Vulcan report prepared by the Admiralty Ship Welding Committee.[3] This early work was not systematic, however, and in most cases covered short periods of time--often only single voyages. The research by Schnadel[4] on the M. S. San Francisco was notable for its complete ship instrumentation and the fact that unusually severe sea conditions were encountered. Sea observations on the M. S. San Francisco first established clearly that the dynamic effects of ship motions in a seaway (excluding slamming) tend to reduce the longitudinal hull bending loads from those calculated by conventional static calculations, even with the so-called "Smith effect" included. Schnadel[4, 5] explained this additional reduction by the effect of accelerations on ship weights, the virtual mass of the water associated with the heaving and pitching motions, and the "disturbance of the wave by the ship itself." Damping forces apparently were not considered. This dynamic reduction in seaway loads has since been confirmed in model tests by Lewis[6] and Akita and Ochi[7] and by theoretical calculations by Jacobs.[8] However, this does not mean one can conclude that seaway loads are less than had been previously supposed. On the contrary, there is abundant evidence that waves much steeper than L/20, as assumed in conventional calculations, are experienced by ships at sea,[3] and this increased steepness may more than balance the hydrodynamic reductions.

More recent ship observations include the trials of the Ocean Vulcan[3] which were aimed specifically at determining the seaway loads. For this purpose, measurements were made of pressures over the surface of the hull and of vertical accelerations. Extensive stress (strain) measurements have been carried out by Jasper[9-11] on Coast Guard and naval vessels, some of which include seaway records. His comprehensive statistical studies based on both his own and other available data, have established statistical distribution patterns of stresses in a general way. These stress results give some indication of the bending load patterns. Information on extreme values of bending moments or stresses is obviously less complete than average values, but attempts at extrapolation to maximum expected values for design purposes have been made in the Ocean Vulcan studies[3] and by Jasper.[10] Unfortunately, the statistical methods do not yet give a satisfactory answer to the question of the maximum loads to be expected during the life of a ship.

Strangely enough, the experimental approach to wave loads in model tanks has been a very recent development. Apparently the first such tests were carried out in Japan by Sato[12] in 1945, but results were not published in English until recently. In Sato's tests a brass model representing the main structural features of an actual destroyer was used, with the number of transverses reduced for simplicity. Strains were measured at various points on the deck and bottom shell by means of resistance wire gages, and the corresponding bending moments were presented in his report for a station near the midship section.

Model tests sponsored by the Hull Structure Committee of the SNAME in the United States followed a different approach.[6] A five-foot wooden model was cut in half at the midship section and the parts were joined by aluminum alloy bars. The relative deflection of the two halves of the model was recorded by means of variable inductance pickups calibrated directly in terms of external bending moment, with the still-water moment considered as the zero reference. In this method, data could be obtained only at the cut section, but concentration on the problem of external loads resulted in a simplification of the model set-up.

Model tests of either type provide a powerful research tool which is advantageous on two counts:

(1) The wave conditions of the test--whether simple or complex--can be more easily measured than on ships at sea.

(2) Simplifying assumptions that are inherent in even the most advanced methods of analytical calculation can, in principle, be avoided.

The model test thus can be considered as an analog computer in which the external loading can be readily explored over a wide range of wave and ship variables. Furthermore, data can be accumulated much more rapidly than is possible on actual ships. Model tests also are of great value for checking and verifying theoretical methods of calculating bending moments.

Other model tests, using the above two basic techniques, have been carried out in Japan by Yoshiki et al,[13] Akita and Ochi,[7] and Ochi[14] and in the United States by Wachnik and Robinson[15] and Lewis.[16, 17] Recently the ETT experimental work has been extended to the case of oblique headings to waves. Bending moments in both centerline and lateral planes and torsional moments have been measured. Any desired regular wave proportions or irregular wave patterns can be investigated in this manner.

Valuable as model tests are for determining wave loads or bending moments, they can only provide the overall answer, not the magnitudes of the individual effects involved. The development of theoretical methods of calculation in order to account for experimental results and interpret their significance has been of great importance. The first refinement in the static method of calculating wave bending moments was suggested in 1883 by Smith[18] who showed that the effect of the actual pressure distribution in a wave was to reduce the calculated bending moments appreciably. The first complete formulation of the related problems of ship motions and bending moments was presented by Kriloff,[19, 20] who set up equations of motion for a ship that is assumed to be a rigid body pitching and heaving in regular waves. The "Smith effect" was included, but the effect of ship motions on the pressure distribution within the wave was neglected (Froude-Kriloff hypothesis). Constant coefficients were assumed in the equations, and allowance was made for damping in a rather crude form and for mass inertia effects, but not for virtual mass (entrained water).

Other work on bending moments was done by Read,[21] Alexander,[22, 23] Robb,[24] J. L. Taylor[25] and others. Horn[26] made a comprehensive study which, unfortunately, did not receive wide circulation. A particularly important analytical advance was made by Hazen and Nims[27] who made use of a mechanical computation device that permitted greater flexibility in bending-moment calculations.

Accordingly, they were able to evaluate the buoyancy forces and moments for successive positions of a ship on a wave, i.e., to use non-constant coefficients.

Further important advances were made in the analytical work forming a part of the Ocean Vulcan project[3] where the entrained water was taken into account. Refinements were introduced in the determination of damping forces (with the assistance of model tests for the determination of coefficients), and a numerical method of computation was adopted that permitted the exciting forces to be treated in a non-linear manner. However, pitch and heave were still treated as independent motions.

Meanwhile, refinements in the analytical treatment of ship motions were made without specific application to the bending moment problem by Kreitner,[28] Haskind,[29] Ursell,[30] Weinblum and St. Denis,[31] St. Denis,[32] Grim,[33] and Havelock.[34, 35] Finally, Korvin-Kroukovsky[36] treated the coupled equations of pitching and heaving and calculated the exciting forces by a method that took into account the interaction between ship and wave motions. At the same time his use of a numerical "strip" method of calculation was readily adaptable to the bending moment problem, where the longitudinal distribution of forces is of prime importance. The most significant finding was that the disturbance of the wave by the moving ship tends to intensify the Smith effect and reduce the bending moment further, as suggested by Schnadel[4] some 20 years earlier. Further refinements in the calculations have since been carried out by Korvin-Kroukovsky and Jacobs.[37] Direct comparison between calculated bending moments and those determined by model experiments were made by Jacobs.[8] Results were encouraging, and calculations are now being made at ETT on a destroyer for which model data are available. The bending moment has been found to be virtually a second order effect, involving the longitudinal distribution of the forces that produce the motions. Constant coefficients have been used for both the motions and the bending moment calculations, but Korvin-Kroukovsky's method will permit the introduction of non-constant coefficients into the bending moment calculation.

The theory of superposition presented by St. Denis and Pierson[38] provided a basis for the study of loads expected in irregular seas. In this theory the irregular patterns of the sea surface are described on the basis of superposition of many component waves of different periods and directions. It is assumed then that the seaway loads (as well as the motions) can be obtained by the superposition of the loads caused by each of the component waves. Good results have been obtained for irregular head seas by this approach, and the theory has been roughly verified within the limits of experimental accuracy, so long as the waves are not too severe.[17, 39]

Mention also should be made of systematic static calculations that have been made to determine shear and bending moment trends with wave proportions and such variables as ship fullness, proportions, and draft.[3, 40] In plotting these results use has been made of general expressions of the form:

$$M \propto \rho g L^2 BHC$$

where M is the bending moment, ρ is the mass density of sea water, g is acceleration of gravity, L is ship length, B is breadth, H is wave height, and C is a coefficient of fullness, i.e., waterplane or block coefficient or some modification thereof. The values of bending moment are found to depend also on secondary factors such as ship type, hull form, draft, etc. A wave of ship length gives the greatest, or nearly the greatest, bending moment value.

Attempts have been made to establish a wave height to use for static calculations of bending moments in ship design.[3, 41] It has been suggested that in lieu of the traditional L/20 value, a height/length ratio that is less for long waves and greater for short waves would be reasonable. Although this general trend may be correct, it does not appear that the actual values suggested have strong oceanographical data to support them.

Torsional loads and horizontal bending moments also have been calculated on a static basis by Vedeler[42] and the Admiralty Ship Welding Committee,[3] respectively. In addition, transverse loads on the sections of a ship have traditionally been computed on the basis of static assumptions.

Present Status

On the basis of past research, consisting of full-scale ship observations, model experiments, and theoretical studies, our knowledge of low-

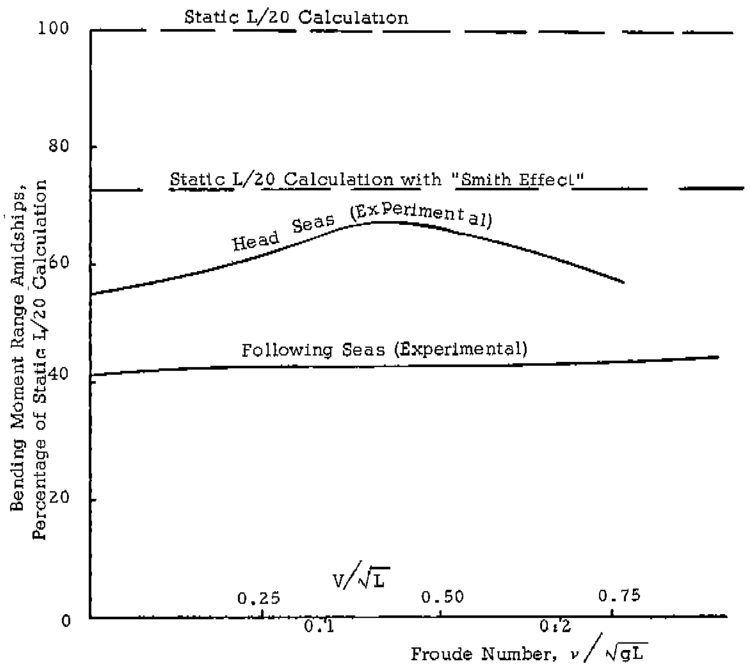

Fig. 16. Cargo ship bending moments in model length, L/20 waves

frequency seaway bending loads has reached an advanced but not yet satisfactory level. It is known that midship bending moments at moderate speeds in regular head or following seas are consistently lower than those calculated for the same wave height by conventional static methods, even with the Smith correction included, as shown in Fig. 16. Model tests show moderate bending moment peaks as speed is increased in waves of various lengths. But these peaks also correspond to speeds for severe motions, shipping of water, and slamming. Therefore it is doubtful that, in very high storm seas, a ship would attain the speed at which these bending moment peaks occur. Within the limits of reasonable speed, the variation of bending moment with speed is smaller than had been anticipated (Fig. 16). Hence, speed does not appear to be a major variable as far as the low-frequency wave bending loads are concerned. This contrasts sharply with the superimposed high-frequency slamming loads, which have been found to be strongly dependent on speed.

Bending moment trends established by conventional static calculations have been partially confirmed by model tests which show ship proportions and fullness, along with wave proportions, to be the dominant factors. For example,

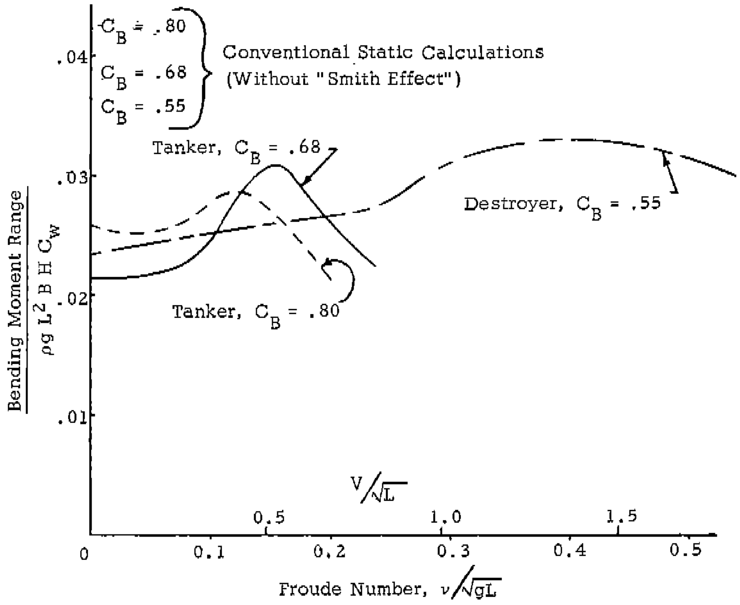

Fig. 17. Calculated and experimental bending moments in model length waves (neglecting slamming effects)

in Fig. 17 it can be seen that such extreme ship types as a tanker and a destroyer can be brought into rough agreement by assuming that the wave bending moment, excluding slamming effects, is proportional to $\rho g L^2 B H c_w$. (Here c_w is the waterplane coefficient.) This plot suggests that bending moment trends can be determined by conventional static calculations, but that actual magnitudes are generally much lower. Further confirmation is needed, however, especially if ships of unusual form or proportions are being considered. At moderate speeds the trend of model bending moments with block coefficients from 0.68 to 0.80 have been found to be in the same proportion as that given by static calculations.[43] As previously noted, the fact that waves are sometimes steeper than L/20, particularly in irregular storm seas, warns against undue optimism regarding the magnitude of actual seaway loads.

A wide range of wave lengths, 0.5 L to 2.0 L, has been found in model tests to produce large bending loads, with the peak value occurring at approximately the length predicted by static calculations (Fig. 18). For waves up to L/20 in height, the bending moments are roughly proportional to wave height, provided the wave crests do not go over the deck. But theory and experiment

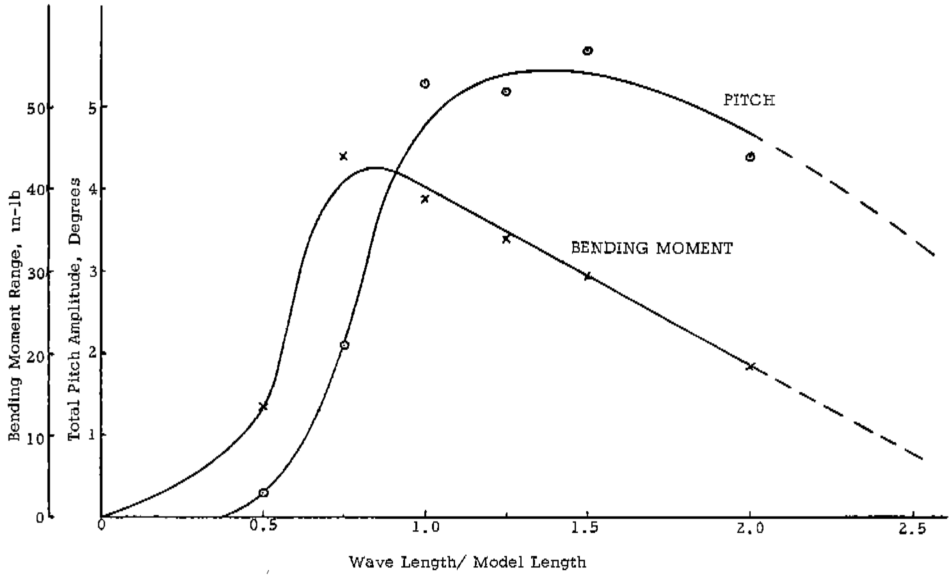

Fig. 18. Typical variation of pitching motion and bending moment with wave length destroyer model at 20 knots (full scale) wave height = L/48 (Data from Lewis and Dalzell[39])

suggest that bending moments may increase at a slower rate in steeper waves.

Other important variables are ship form, heading to the waves, freeboard, and distribution of cargo, fuel, etc. Results by Ochi[14] show a variation of 15 to 30% between extreme U and V-shaped bows. These differences conform roughly to those obtained by static calculation.

Recent exploratory work on the effect of ship heading by Numata for the Hull Structure Committee, SNAME (as yet unpublished), showed little change in the vertical component of the longitudinal bending moment with heading, when the effective wave length remained constant. However, horizontal bending moment components in steep waves reached large values and require further investigation because the combined effect of the two components was to increase the stress at the deck edge. Torsional moments were quite small but not negligible. The trends, but not the magnitudes, of both lateral and torsional moments with heading agreed closely with those predicted by static calculations.

The effect of the longitudinal distribution of cargo, fuel and other weights may be appreciable, particularly in bulk cargo vessels. First of all, the weight distribution affects the still-water bending moment. Then it determines the longitudinal radius of gyration, which, in turn, affects the motion amplitudes and hence the hydrodynamic loads. Finally, it affects the distribution of mass inertia loads. The dynamic effects of weight distribution are now being studied by Norske Veritas by means of model tests.

Freeboard is important because it determines when waves will break over the deck. There are indications that waves on deck do not change the range of bending moment much, but modify the distribution between hogging and sagging.[44] However, this effect requires further clarification.

Knowledge of extreme wave bending moments in irregular storm seas for design purposes is restricted, as explained above, to a limited amount of full-scale ship observations. Theoretical methods presently available are limited to moderate wave heights in which effects are roughly linear, but they can probably be extended to steeper waves. A promising approach to extreme conditions is the use of models in very steep tank waves. An exploratory study has been carried out by Dalzell in connection with the project leading to this report (Fig. 19).

In this exploratory study, a model of a T2 tanker was tested at zero and low speeds in head waves of model length and average heights ranging from L/20 to L/8.5. Although nominally regular, the steeper waves showed considerable irregularity. Plotting individual measurements of bending moment amplitude against actual local wave height showed considerable scatter in the higher waves, as shown in Fig. 20. Two significant conclusions were drawn, namely:

(1) There was a tendency for the bending moment on the average to fall off from a linear relationship as wave steepness increased.

(2) The highest recorded bending moments in head seas up to L/8.5 in steepness were 12 and 20% greater than conventionally calculated static values in sagging and hogging, respectively. (Static calculations were made for a model length wave of height L/20, without the "Smith" correction.)

These conclusions suggest the strong possibility that maximum values of bending moments can be definitely established experimentally by similar tests covering the various other important variables, such as: wave length, possibly still steeper waves (resulting from conditions such as shoal water, reflection from

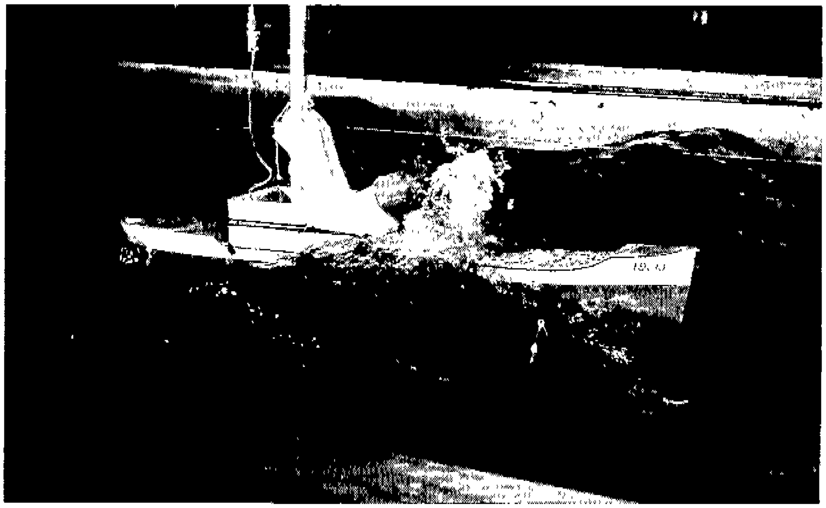

Fig. 19. Tanker model in steep waves (length/height = 9)
Davidson Laboratory, Stevens Institute of Technology

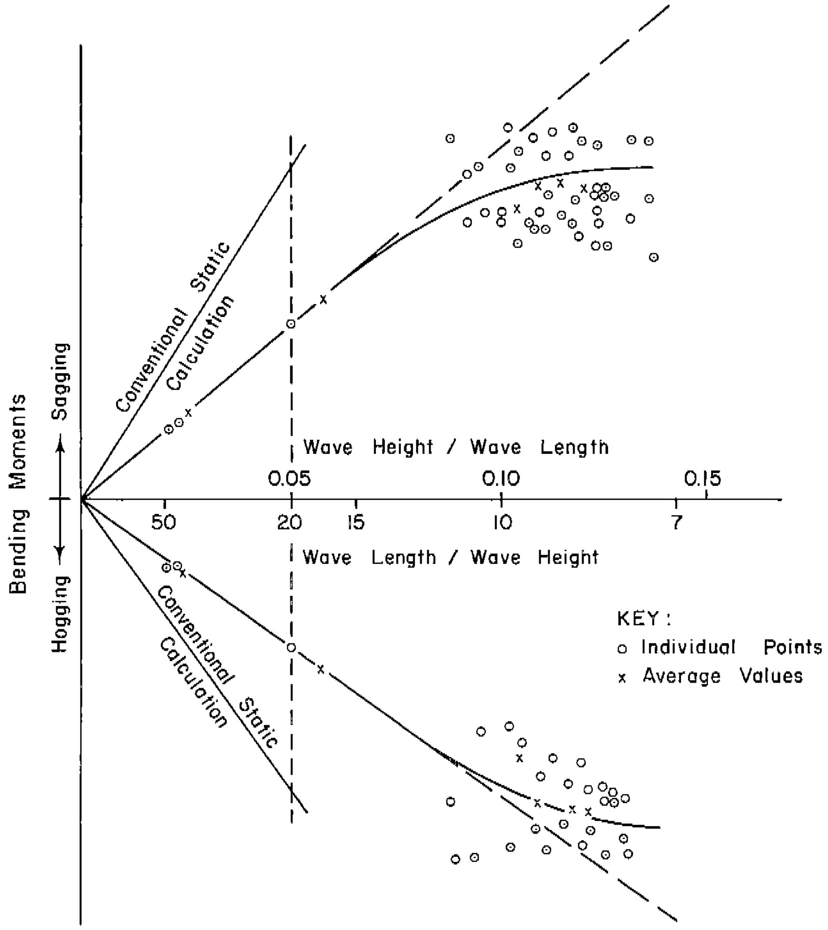

Fig. 20. Trend of midship bending moments with wave steepness
T-2 tanker model at zero speed (model length = wave length)

a sea wall, cross seas, etc.), irregular waves, hull proportions and form, freeboard, heading to waves, loading (draft and weight distribution), and other sections of ship than amidships.

Very little research has been carried out on other dynamic seaway loads, such as those on transverse sections of a ship, on tank boundaries resulting from the surging of internal liquids, effects of heel and roll, and various local loads. Most of the work has consisted of calculations on the basis of simple static assumptions. Further research is needed in these areas to complete the picture of seaway loads. However, inertia loads on masts, machinery foundations, etc., are well understood and can be calculated if accelerations are known. The longitudinal compression loads resulting from propeller thrust and ship resistance are comparatively small, and it is believed that they can be estimated satisfactorily from available information.[3]

Needed Research

As noted before, research needs in seaway loads, as well as in the related field of ship motions, are discussed in much more detail in the monograph being written by Korvin-Kroukovsky.[1] The specific projects recommended in this research program and described in the following pages are those that should contribute directly to a reasonably complete understanding of seaway loads. Although further research on the subject of ship motions will, of course, be helpful in increasing the understanding of loads, it is believed that such research should be covered in other programs.

Research on longitudinal bending and torsional loads on the main hull structure will be considered, both for regular and irregular waves, after which other seaway loads will be discussed. The main headings will be:

A. Trends of Longitudinal Loads in Regular Waves
B. Trends of Longitudinal Loads in Irregular Storm Seas
C. Extreme Values of Seaway Loads
D. Miscellaneous and Combined Loads

A. Trends of Longitudinal Loads in Regular Waves The logical starting point for a long-range research program on low-frequency hydrodynamic loads on ship hulls in waves is the consideration of a simplified case of regular waves of constant period (length) and moderate height. Studies of ship hull loads in regular waves are of necessity limited to model experiments and theoretical investigations, since truly regular waves are not found in nature--even in the case of apparently regular swells from a distant storm. Not only are such regular waves easier to investigate theoretically and experimentally than the irregular patterns actually found in nature, but there are three distinct reasons for studying regular waves, namely:

(1) to obtain direct comparative information on trends of seaway loads with wave proportions, ship characteristics, loading, and speed
(2) to increase our understanding of the nature of the hydrodynamic loads on ship hulls by correlation with theory
(3) to make it possible to investigate irregular and extreme wave conditions by superposition of regular wave effects.

It can be argued that suitably planned model experiments can provide all the needed information on trends of seaway loads and that, therefore, theoretical work on the same subject is unnecessary. It is believed, on the contrary, that parallel theoretical and experimental work can provide the greatest progress in the long run. First of all, theoretical work,when checked against experimental studies, can explain the experimental results, thereby increasing our understanding of loads and permitting a generalization of the results and extrapolation to new and unusual cases. Secondly, theory can guide experiment by suggesting the form in which results should be presented, detecting areas needing experimental study, identifying possible experimental errors, etc. Hence, a long-range plan should include coordinated theoretical and experimental research in order to obtain a more complete understanding of the phenomena of seaway loads.

Finally it appears that undoubtedly the best approach to cases of irregular waves and unusually steep waves is by the superposition of regular wave effects as described by St. Denis and Pierson[38] and Lewis.[17] It is essential, therefore, to have adequate experimental data and theoretical formulations for the simple regular wave case. Consequently, it is felt that the first step in the program should be a group of correlated experimental and theoretical studies in regular waves. Of course, the case of meeting waves at right angles to the crests, either head or following, is the simplest situation for study. The principal load on the main hull structure is longitudinal bending as a result of the variation in distribution of the vertical hydrodynamic and inertia forces. This means shearing force variations reach maximum values at the quarter lengths from the ship's ends and bending moment variations reach their maxima very close to the midship section. Investigation of these effects is therefore recommended for a wide range of variables, including possible higher speed ships (Projects 12 and 13). It may be expected that an accurate knowledge of shearing forces will become increasingly important if high-efficiency structures come into more general use, as has been the case in the history of aircraft structures.

Ships do not often meet waves exactly at right angles, and consequently it is important to consider the effect of meeting waves at oblique headings. Shearing forces are then asymmetric and are modified by torsional loads, which at present appear to be of comparatively small magnitude. Midship bending moments will act in a plane that continually changes its slope or angle to the ship's vertical centerline plane, and, for convenience, can be considered as made up of vertical and horizontal components having a specified phase relationship to one another. These forces and moments can be measured in model tests on oblique headings to waves, and theoretical calculation methods can readily be extended to cover this situation (Project 14).

Since it depends on the instantaneous values of vertical forces along the length of a ship's hull, the calculation of bending moments is more sensitive to small inaccuracies than are motion calculations which involve integrations with time. Hence, further refinement of the present theoretical methods is needed in the form of more accurate information on virtual mass and damping coefficients, including methods of allowing for the fact that the flow does not follow simple two-dimensional paths about ship sections as assumed by strip theory. Water pressures, which determine the ship motions and bending moments, are known to be affected by the flow interaction between neighboring strips. It probably will be desirable also to introduce non-linear coefficients into the moment calculations (Projects 15 and 16).

When refinements in the theory have brought about satisfactory agreement within the linear range between calculated and experimental loads for a number of ship types, then the scope of the purely experimental trends can be greatly extended by carrying out systematic computer calculations for a still wider range of variables (Project 17).

B. Trends of Longitudinal Loads in Irregular Storm Seas For realistic answers to the problem of seaway loads, research must be extended to the irregular wave patterns actually observed in the ocean. The most direct approach is to obtain strain data from ships at sea, which can be interpreted in terms of loads if desired. This involves two types of observations:

(1) statistical data obtained from many types of ships instrumented as simply as possible and operating for long periods of time on various trade routes

(2) short-range data obtained from a few ships fitted with more elaborate instrumentation and means for recording the accompanying wave patterns.

The first type of project is discussed later as a means of obtaining statistical data on extreme values of the basic vertical longitudinal bending moments at the midship section. It is believed that secondary effects can be studied over shorter periods and compared with basic loadings.

Listed below are some of the important secondary effects that do not require long-range statistical treatment:

(1) The relative magnitude of the hogging and sagging moments which make up the observed range of loading. It may be possible to instrument some ships to measure hogging and sagging separately with reference to a zero base line established by taking the mean stress level at periods of relative quiescence.

(2) Possible higher loads at locations somewhat ahead or astern of

the section usually used for measurement (near midships). Additional gages should be employed within the range of 10% of the ship length forward and 5% aft of the midship section. Deflection measurement also should be considered.

(3) Shear forces near the quarter lengths. Additional gages can be provided on some ships to obtain this information.

(4) Torsional loads and horizontal bending moments.

(5) Superimposed slamming loads (Section 3).

Hence, short-range investigations aboard ship (Project 18) should be aimed at obtaining very complete data on the above effects, along with accompanying ship motions. If records of the irregular ocean patterns also are obtained, the possibility will be opened up for the correlation of full-scale observations with experiment and theory. This is of particular importance for establishing the validity of model tests and theoretical methods of predicting seaway loads in irregular waves. Such a correlation has until recently been impossible because of the lack of a satisfactory method of recording the sea pattern that accompanied the observed hull stresses or loads. Cartwright and Rydill[45] have shown how a shipborne wave recorder and a suitable spectrum analyzer can make such correlations possible. Simultaneous wave and stress data have been obtained by Jasper and Birmingham[11] in a joint MARAD-DTMB project. Because of the difficulty of obtaining a directional sea spectrum, it is anticipated that these model-to-ship correlations will be attempted mainly for head seas, in which case the directional properties, i.e., short-crestedness, will not seriously affect the longitudinal bending loads (Project 19). However, when directional sea data are obtained, as discussed in the previous section, it would be highly desirable to obtain ship motion and bending moment data concurrently.

For a general study of bending loads at any heading to short-crested irregular head seas, experimental and theoretical methods must be applied. First, it will be necessary to determine the extent of applicability of the superposition principle by carrying out model tests at oblique headings to long-crested irregular seas (Project 20). Such wave patterns are preferable to more realistic short-crested seas since they are much more readily analyzable.

Having established the range of conditions in which experimental and/or theoretical techniques can be applied with validity in determining seaway loads in irregular seas, the next step will be the investigation of trends of load with ship size, proportions, speed, heading, etc., in irregular waves (Project 21). The effect of ship size is of particular interest because of the current trend to larger and larger ships and the difficulty of extrapolating scantlings on a purely empirical basis. It is generally believed that relatively severe loads occur less frequently for large ships, since moderate storms affecting small ships are more frequent than severe storms. On the basis of probability theory, it would be expected, therefore, that the larger the ship, the lower the probable maximum load during the ship's lifetime. Application of the method of superposition to predicting the statistical properties of bending moments in irregular storm seas has confirmed this trend in a general way. Further work is needed to establish how rapidly the extreme values of bending moment fall off with increasing size (Project 22). It should be noted that it is easier to determine the trend of any given statistical parameter with ship size than to establish the maximum load expected in the lifetime of any given ship. The former problem requires only a representative sampling of spectra for typical severe storm sea conditions.

C. Extreme Values of Seaway Loads Unfortunately, it is the maximum attainable bending moment values that are of particular significance in ship design, and it is these values that are most difficult to determine, whether one makes use of statistical observations aboard ships, theoretical calculations, or model experiments. Nevertheless, by approaching this crucial problem from several directions, satisfactory answers can be expected within a reasonable time.

First, considering statistical methods for dealing with extreme values, one finds that, although there may be a theoretical trend toward infinite loads as the observation time increases, the upward trend in loads is very slight within a ship's lifetime. For example, it might be expected that a typical North Atlantic cargo ship might encounter about 8000 hours of gales of Beaufort force 8 or greater during a 25-year lifetime. This corresponds to about 10^7 stress reversals. If one assumes a Rayleigh distribution of stresses in force 8 gales,[10] it may be estimated roughly that the highest load expected during the ship's lifetime is about twice the highest value yet actually observed at sea. This simple example is, of course, not the whole story, but it does demonstrate that statistical methods alone do not necessarily lead to astronomically high loads or stresses. With the accumulation of statistical data over longer periods of time for various ship types in different services, maximum anticipated seaway loads can be established with increasing reliability.

Accordingly, Project 23 is proposed to obtain long-range statistical data on the symmetrical component of longitudinal midship bending moments, which are considered to be the basic seaway load. Data can be obtained by means of strain cycle counters or automatic recording instruments calibrated in terms of bending moment by loading the ship in still water. If possible, hogging and sagging moments should be separated. The emphasis should be placed on extremely high bending loads, since the distribution patterns of moderate loads have been well established. Statistical methods should be applied to the analysis and interpretation of the observed data, making particular use of extreme value theory. The accumulation of statistically reliable data on extreme values will be a long, slow process, however, since the larger the loads, the less often they occur, and therefore it will be difficult to obtain a satisfactory sample. No statistical method or theory can extrapolate safely beyond the range of available data into the "tails" of the distribution curves. In the analogous case of aircraft design, for example, the maximum gust velocity assumed for design on the basis of statistically derived data has steadily increased as more data have accumulated. Nevertheless, it is felt that statistical research of this sort should be encouraged on a larger scale than at present, even though it may take years for useful conclusions to be reached regarding extreme loads.

Another important effect should also be included in a long-range statistical study of basic longitudinal midship bending moments, if simplicity of the instrumental set-up can be maintained. This is to determine the degree of asymmetry in the longitudinal bending moment, leading to above-average loads at one deck edge or bilge. Such statistical data could be obtained by installing a few additional strain gages. If this is not feasible in the long-range project, it should be incorporated in the short-range project (Project 18).

Meanwhile, there are other approaches to the problem of maximum seaway loads that should be followed concurrently in order to extend the usefulness of statistical data and obtain engineering answers within a reasonable length of time. One of these is to make use of model tests for statistical studies, where advantage can be taken of the fact that in a 1/100 scale model, for example, the time scale is compressed 10 times. Since severe storm conditions can be generated continuously in a model tank, the severe weather expected in the lifetime of a ship can be compressed into a comparatively short time. Thus, the 8000 hours of Beaufort force 8 previously mentioned, is equivalent to 800 hours of tank testing. This is definitely within the realm of possibility in a small tank, although a shorter time probably would suffice. Such a statistical model study of extreme values of midship bending moments is recommended primarily as a means of determining the form of the distribution function for extreme values (Project 23).

Another approach is to attempt to ascertain directly the physical upper limits of longitudinal bending moments. Attention would be focused on regular waves of various lengths and maximum attainable steepness, and also on unusually steep waves of irregular wave patterns. Both model tests in waves and theoretical methods can be applied to the solution of this problem (Project 24). Experimental methods have been discussed previously, and it is believed that theoretical methods can be extended to extreme non-linear regular wave conditions by superposition of stokes wave components. All possible phase relationships between wave and ship motions must be considered, as was proposed by Hazen and Nims.[27] For study of the effects of individual waves in an irregular pattern, the methods of Fuchs and MacCamy[46] may be applicable. Having determined the maximum load physically possible, it remains to establish from oceanographic data the probability of obtaining the extreme wave steepness considered (see Section 1).

Still another approach to be followed is the extension of the superposition method of predicting behavior in irregular seas to the case of extreme irregular wave conditions. After extension of the bending moment theory to include nonlinear effects, it will then be necessary to develop the theory of response to irregular waves to a point where extreme, nonlinear conditions can be adequately taken into account (Project 25). In due course, these developments may permit, in combination with data on extreme sea conditions, the reliable prediction of maximum expected bending moments at sea. This is a difficult approach, and the goal is still some years in the future. However, it is believed that it will lead to increased understanding of the extreme value problem and should be actively pursued.

D. Miscellaneous and Combined Loads In addition to the basic longitudinal and torsional loads on a ship hull in waves, there are other loads to be considered. One type that is not too well understood is that of transverse loads experienced by a rolling ship in a beam or oblique sea. These loads tend to bend and distort the transverse sections of the ship. Not only are there large hydrodynamic forces, but inertia loads also may be considerable. Experimental and theoretical studies of these transverse loads are recommended as the most satisfactory method of evaluating them for both regular and irregular sea conditions (Project 26). Data can also be obtained at sea (Project 18).

Another important load is that caused by the surging of liquids in internal tanks as a result of ship motions. A project on this subject is also recommended (Project 27).

A more general area for investigation is the careful study of cases of ship structural failures in order to determine as much as possible about the loads causing the failures, as well as the behavior of the structure. A great deal of work of this sort is regularly done by the classification societies and naval authorities, and it is mentioned here in order to encourage further work, particularly directed at loads, and publication of results for the guidance of designers. It is important that these studies include structures other than the main hull girder, as for example superstructures, deck houses, and decks subjected to wave impact. Many such local loads are not amenable to theoretical or experimental determination (Project 28).

Special attention should also be given to drawing conclusions regarding speed and heading conditions which have favorable or unfavorable effects on structural loads under different sea conditions. Such results should be of value to shipmasters handling ships in rough seas (Project 29).

Finally, all of the above investigations of maximum anticipated loads must be correlated and interpreted with the aid of probability theory and statistical methods. In particular, consideration must be given to methods of determining the combined effects of torsional moments, transverse loads, and bending moments in centerline and lateral planes. Following the completion of research to clarify the nature of seaway loads acting on a ship's hull, it will be essential to develop simplified methods of calculating loads for design use. These might take the form of graphs and tables or simple factors that are applicable to familiar "standard" static bending moment values, or perhaps certain "equivalent" wave heights that can be used with standard calculations (Project 30).

Results Expected

It is anticipated that the program described above and detailed in the following pages will in time lead to a reasonably complete understanding of seaway loads, i.e., how they vary with ship proportions, size, speed, heading, and sea conditions. It will also provide information on maximum seaway loads to be used for design purposes, as well as convenient short-cut methods for their calculation in everyday use by ship designers.

Summary of Recommended Research Projects

SEAWAY LOADS

Project No.	Title
	Trends of Longitudinal Loads in Regular Waves
12	Experimental trends of bending moment in regular waves
13	Experimental trends of shearing force in regular waves
14	Experimental trends of bending, torsion, and shear loads at oblique headings to regular waves
15	Coefficients for equations of motion, longitudinal modes
16	Coefficients for equations of motion, lateral modes
17	Computed bending moment trends in regular waves
	Trends of Loads in Moderate Irregular Storm Seas
18	Case studies of seaway loads aboard ship
19	Correlation of full-scale bending loads with model and theoretical predictions
20	Theoretical and experimental methods for study of hull loads in irregular, oblique seas
21	Trends of bending and shear loads in irregular seas
	Extreme Values of Seaway Loads
22	Statistical studies of seaway loads aboard ship
23	Statistical investigation of maximum bending loads by model tests
24	Maximum physically possible bending loads
25	Theoretical techniques for study of hull loads under severe irregular head sea conditions
	Miscellaneous and Combined Loads
26	Transverse bending loads
27	Loads due to motion of internal liquids
28	Analysis of cases of ship structural damage
29	Methods of avoiding severe loads at sea
30	Specification of extreme seaway loads for design purposes

Project 12: Experimental Trends of Bending Moment in Regular Waves

Objective: To determine longitudinal wave bending moment trends by model tests in regular head and following waves and to compare these trends with results obtained by available theories.

Program: Carry out model tests and parallel theoretical calculations for several different representative ship types in order to determine midship bending moments in regular head and following seas. A wide range of ship proportions and forms should be covered, from a full bulk cargo ship to a long slender ship of $\Delta/(L/100)^3 = 25$, representing a possible high-speed ship of the future. The following variables should be studied:

Block coefficients: 0.55 to 0.85
Ship speed: 0 to design speed
Wave lengths: 0.75 to 1.5 L
Wave heights: L/50 to L/20
Longitudinal weight distribution including
    large concentrated weights
Freeboard, especially forward.

Compare theoretical and experimental results and devise suitable empirical correction factors that can be applied to theoretical calculations, if necessary.

Suggested Techniques: Experimental work: Measure midship bending moments on suitable self-propelled or towed models in various regular wave trains. The tests should be conducted preferably in a wide tank so that tank wall reflection at low speed will not interfere with results. Trends of hogging and sagging moments should be determined and plotted for reference, after fairing out any vibratory effects of slamming (see Section 3).

Theoretical work: Employ the strip theory developed by Korvin-Kroukovsky and Jacobs[37] for the calculation of motions, shearing forces, and bending moments; use constant coefficients but include the effects of coupling between pitch and heave.[8] Use would be made of new data obtained under Project 15 as they become available.

Research in Progress: A project dealing with both theoretical and experimental aspects, applied to a typical destroyer, at ETT; experimental work sponsored by the American Bureau of Shipping at ETT (Dalzell, [43]); work sponsored by Norske Veritas in Trondheim, Norway; work sponsored by British Shipbuilding Research Association in England; work at the Netherlands Ship Model Basin in Wageningen, Holland; and model tests on Series 60 models at Delft Technical University.

Results Expected: More complete information on the variation of longitudinal bending loads with wave and ship proportions, hull form, speed, and weight distribution; further indications of the relative importance of these various factors; and determination of the range of applicability of available linear theories for the calculation of shear and bending moments at the midship section in regular waves.

Project 13: Experimental Trends of Shearing Force in Regular Waves

Objective: To determine trends of shearing-force amplitudes by model tests in regular head and following seas and to compare the trends with computed values.

Program: Carry out model tests in regular head and following seas and parallel theoretical calculations for several different representative ship types in order to determine the magnitude and location of maximum shear force in the vicinity of the quarter length from each end. Several model speeds, weight distributions, wave lengths, and wave heights should be considered. Compare theoretical and experimental results and attempt to devise suitable empirical correction factors to apply to the theoretical calculations, if necessary.

Suggested Techniques: Experimental measurement of shear forces on suitable models self-propelled or towed in regular waves. Use the strip theory developed by Korvin-Kroukovsky[37] for the calculation of shear.[8]

Use may be made of calculations and/or tests carried out under Project 12 or perhaps the two projects can be combined.

Research in Progress: By Norske Veritas in Trondheim, Norway.

Results Expected: Trends of shearing force amplitudes with wave and ship proportions, hull form, speed, and weight distribution; indications of the relative importance of the various factors; and confirmation of available theories for the calculation of shearing forces in regular waves for several ship types.

Project 14: Experimental Trends of Bending, Torsion and Shear Loads at Oblique Headings to Regular Waves

Objective: To determine trends of torsion and longitudinal bending moments, both vertical and horizontal, with heading to regular waves, and to develop satisfactory methods for the theoretical calculation of these loads.

Program: Carry out model tests and parallel theoretical calculations for several different ship types to determine longitudinal bending moments amidships, both vertical and horizontal, as well as torsional moments, at oblique headings to regular waves. Basic work should be at moderate wave amplitudes, but experiments should be extended to steep waves in order to determine the extent of any nonlinear effects. Ship speeds from zero to designed sea speed should be covered, and wave lengths should vary from 0.5 L to 1.5 L, the values selected at each heading being those that produce the highest loads.

Compare theoretical and experimental results and devise suitable correction factors to apply to the theoretical calculations, if necessary.

Suggested Techniques: Experimental work: Measure midship bending moments and torsion on suitable instrumented models in regular waves of various lengths and heights. The tests should be conducted in a wide tank where oblique headings can be obtained and wave reflections from tank walls at low speed will not interfere with results.

Theoretical work: Extend to three dimensions the strip theory developed by Korvin-Kroukovsky and Jacobs[37] and include hydrodynamic and inertia effects of forward speed and ship motions. The theory may be limited to linear conditions with constant coefficients, but the important couplings among the different modes of motion should be included.

Research in Progress: An exploratory study on a T-2 tanker model at ETT under SNAME sponsorship; similar work is planned at ETT on tankers of other fullness under ABS sponsorship and on a destroyer under Bureau of Ships sponsorship; theoretical studies of ship motions in three dimensions at ETT; experimental and theoretical work on destroyers and Series 60 models at the Netherlands Ship Model Basin, Wageningen, Holland.

Results Expected: Trends of bending and torsional moments with speed and heading to regular waves for various ship types, and methods for determining these loads by calculation.

Project 15: Coefficients for Equations of Motion Longitudinal Modes

Objective: To obtain more complete data on coefficients appearing in the equations for longitudinal ship motions and bending moments, including experimental verification of theoretical values for a variety of ship shapes in two-dimensional flow and consideration of three-dimensional effects.

Program: Theoretical work: Compile available data on virtual mass and damping coefficients for various ship shapes in two and three-dimensional flow and extend ship motion theory to include other two-dimensional and three-dimensional forms that are of interest, taking free-surface effects into account. Concave shapes representing flared ship sections should be included.

Experimental work: Use model tests for confirmation of the theoretically determined coefficients for two-dimensional flow, idealized three-dimensional bodies, and typical ship forms; confirmation of cross-coupling coefficients and exciting forces for typical ship forms, as calculated by Korvin-Kroukovsky and Jacobs;[37] investigation of the effect of forward speed.

Suggested Techniques: Theoretical work: Potential theory as applied by F. M. Lewis,[47] Ursell,[48] Grim,[33] Havelock,[34] Haskind,[29] and Korvin-Kroukovsky and Jacobs.[37]

Experimental work: Two-dimensional studies involve the forced oscillation of cylindrical bodies spanning a long, narrow tank and recording of the time history of motions and forces. Coefficients can be obtained by analysis to separate the in-phase and out-of-phase components.[49-51]

Three-dimensional studies involve the forced oscillation of idealized bodies and ship forms in heave, pitch, and combined heave and pitch at various speeds in calm water in a wide tank, and measurement of forces on restrained models in regular waves. In order to determine three-dimensional effects, i.e., longitudinal distributions of forces, the models must be jointed or surface pressure measurements must be made and integrated, in addition to the measurement of forces and motions.

Research in Progress: Theoretical work by Kaplan at ETT under the sponsorship of the Bureau of Ships, DTMB. Experimental work on Series 60 models, Shipbuilding Laboratory, Delft Technical University. Experimental work on the longitudinal distribution of virtual mass and damping at Colorado State University, under the sponsorship of Panel S-3, Hull Structure Committee, SNAME.

Results Expected: Complete virtual mass and damping data in graphical form for a wide variety of ship sections, with methods for allowing for three-dimensional and free surface effects. Evaluation of methods for calculating cross-coupling coefficients and exciting forces, with suitable empirical correction factors.

Project 16: Coefficients for Equations of Motion Lateral Modes

Objective: To obtain more complete data on coefficients for equations of ship motions with six degrees of freedom, with particular attention given to the lateral modes of roll, yaw and sway not covered in Project 15.

Program: On the basis of the equations of motions utilized in Project 14 compile available data on virtual mass and damping coefficients for lateral motions and on coupling coefficients that express the interaction among all the various modes. Extend the theoretical work where necessary to provide data on the most important coefficients and on exciting forces. Carry out experimental confirmation for the important coefficients and exciting forces, and determine empirical correction factors if necessary.

Suggested Techniques: Theoretical work: Employ potential theory as applied by F. M. Lewis,[47] Ursell,[48] and Landweber.[52]

Experimental work: Make measurements on suitably instrumented ship models restrained in certain modes and on cylindrical bodies under forced oscillation representing two-dimensional flow.

Research in Progess: Landweber at the University of Iowa; Kaplan at ETT

Results Expected: Data in graphical form for the most important coefficients involved in the lateral motions of ships, including indications as to means of allowing for three-dimensional flow; compilation of methods for calculating cross-coupling coefficients and exciting forces.

Project 17: Computed Bending Moment Trends in Regular Waves

Objective: To apply electronic computers to further systematic study of trends of longitudinal bending moments and shear in regular waves, considering the effects of hull form and proportions, wave length, speed and heading.

Program: After theoretical methods for the calculation of wave bending moments and shear have been improved and tested (Projects 12 to 16), develop suitable electronic computer programmings for the calculations. Carry out a systematic program of computer calculations to establish further trends of longitudinal bending moments (both vertical and horizontal) with variations in hull form and fullness, proportions, weight distribution, wave length, ship speed, and heading.

Suggested Techniques: Employ standard computer programming methods, making use of the "extended theory" developed by Korvin-Kroukovsky and Jacobs[37] and Jacobs.[8] Include lateral as well as longitudinal modes and nonlinear effects. Refer to the work of Hazen and Nims[27] which used a cinemaintegraph.

Research in Progress: R. Stevens at NYU has been working on the computer solution of ship motion problems, based on Korvin-Kroukovsky's linear treatment. Computer solutions of ship motion problems are also being obtained at MIT.

Results Expected: A much more complete picture than has been hitherto available of the variation of longitudinal bending moments and shear with all important variables. Furthermore, a programming would be made available for determining hull bending loads for possible new and unusual ship designs.

Sequence: Project 17 should follow Projects 15 and 16 rather than proceeding concurrently.

Project 18: Case Studies of Seaway Loads Aboard Ship

Objective: To obtain data on the relative importance of different types or components of seaway loads by detailed observation of several typical ships at sea, and to obtain correlated data on seaways, motions, and loads.

Program: Carry out measurements of seaway loads, together with accompanying ship motions or accelerations and ocean wave patterns. This should be done on several different ship types for periods of several months each. Take similar measurements concurrently with Project 4 for determination of directional sea spectra.

The particular types of loading to be measured and compared are longitudinal bending, both vertical and horizontal, shear at the quarter length, torsion, and transverse bending. Pressure measurements on the hull surface also may be desirable, as was done in the Ocean Vulcan trials.[3] Sufficient measurements should be made to ascertain the fore and aft location of the maximum bending moment, and special attention should be directed toward distinguishing between hogging and sagging moments. (Over-all hull deflections, local stresses at critical points and slamming stresses also may be observed for use in connection with structural projects discussed in Part III.)

Suggested Techniques: Shipboard installation of a large number of electric resistance strain gages, suitably arranged to separate bending stress components and torsion and to measure shear; installation of accelerometers and angular motion pick-ups; and installation of shipborne wave recorders which should be supplemented by buoy-type sea-state recorders as a check. All data should be recorded on suitable oscillographs, operated continuously during rough weather. Still-water tests should be carried out to calibrate the ship in terms of loads.[3]

Research in Progress: Sea observations on naval vessels, DTMB;[11] joint MARAD-DTMB Liberty ship project.

Results Expected: Indications regarding the relative importance of different seaway load components; and correlated data on seaway, motions, and loads, for support of current theoretical and model studies (Project 19).

Project 19: Correlation of Full-Scale Bending Loads with Model and Theoretical Predictions

Objective: To obtain several direct comparisons of longitudinal bending moments and shear, determined by full-scale measurement at sea, with values predicted by model tests and by theoretical calculations.

Program: When satisfactory full-scale data become available (Project 18) for not only ship bending stresses and motions, but also for the accompanying wave patterns, carry out experiments on a model in similar irregular head or following seas. Make spectrum analyses of both ship and model records, and for comparative purposes "correct" the model bending moments and shear spectra to correspond to the actual spectra obtained at sea. Apply purely theoretical methods also to the calculation of these spectra. Finally, compare all three results and determine the extent of applicability of model and theoretical techniques, with attention given to the problem of separating hogging and sagging moments.

Suggested Techniques: Measure motions and midship bending moment variations on a suitably instrumented model in irregular head seas. Full-scale ship stresses or strains should be interpreted in terms of longitudinal bending moments and shear by calibration of the ship in calm water (Project 18). Means for quick spectrum analysis is desirable. Theoretical work should be based on the work of Korvin-Kroukovsky and Jacobs[37] for regular wave responses, while superposition theory should be used for irregular waves.[17, 38]

Research in Progress: None. However, some ship data have been obtained, as discussed by Jasper and Birmingham.[11]

Results Expected: A direct comparison between model, theoretical, and full-scale bending moments and shear, with conclusions regarding the validity of model tests and theoretical techniques and, if necessary, empirical correction factors.

Project 20: Theoretical and Experimental Methods for Study of Hull Loads in Irregular Oblique Seas

Objective: To apply methods for predicting the statistical characteristics of bending loads to the case of oblique headings to short-crested irregular waves and to determine the extent of their applicability.

Program: Compare predicted and observed spectra for models of one or more typical merchant ships at various speeds on oblique headings to irregular waves of several degrees of severity for the following loads:

Longitudinal bending moment, vertical
Longitudinal bending moment, horizontal } at the midship section
Torsional moment
Shear force at quarter lengths from the ship's ends.

Suggested Techniques: Experimental work: Take measurements on suitably instrumented models, self-propelled at various headings to long-crested irregular waves. (Long-crested waves are suggested as a means of obtaining irregularity which is analyzable rather than to obtain exact realism.) Either jointed models with suitable dynamometers, or scaled metal or plastic models with strain gages, can be used.

Theoretical work: Employ the method of superposition presented by St. Denis and Pierson[38] based on the application of probability theory to short-crested irregular waves. Characteristic model responses to different wave lengths as a function of speed and heading should be determined by model tests in regular waves.[17] Suitable means of making spectrum analyses should be utilized.

Research in Progress: Exploratory work on a T-2 tanker model is in progress at ETT under the sponsorship of the S-3 Panel, SNAME, and similar studies on a destroyer are planned at ETT under Bureau of Ships (DTMB) sponsorship.

Results Expected: Verification of the theory for predicting loads on ship hulls in the general case of any heading to short-crested irregular seas, with indications of empirical correction factors if necessary.

Project 21: Trends of Bending and Shear Loads in Irregular Seas

Objective: To investigate general trends of longitudinal bending moments for several ship types when more complete information is available on ocean wave spectra, particularly for severe sea conditions (Project 5).

Program: For different typical directional wave spectra, determine for several ship types the trends of the average of the highest 10% longitudinal bending moments and shear values as a function of ship proportions, size, speed and heading. Hull forms for which model data on bending moments in regular waves are available should be used. It should be noted that the intent of this project is not the study of the maximum anticipated bending moment values. (See Projects 24 and 25.)

Suggested Techniques: Employ the superposition method of St. Denis and Pierson[38] to the extent verified under Project 20, using empirical correction factors if necessary. Experimental data on bending moments and shear in regular waves should be used as the "response amplitude operators" until advances in theoretical methods (Project 17) permit the entire process to be done by calculation.

Research in Progress: None

Results Expected: To establish on a comparative basis how the loads in irregular seas vary with ship size, proportions, speed, and heading, in order to assist in the determination of scantlings for large tankers, fast cargo ships, and passenger vessels.

Sequence: Project 21 should follow Projects 18 and 19, and it also depends on additional sea data from Project 5.

Project 22: Statistical Studies of Seaway Loads Aboard Ship

Objective: To obtain statistical records of vertical longitudinal wave bending moments experienced by various types of ships operating on different trade routes, with the emphasis being placed on extreme values of external loads.

Program: Carry out a long-range statistical study of longitudinal wave bending moments on approximately 15 to 20 ships of different sizes, speeds and types operating on important routes. Sea and weather data should be compiled concurrently. Reports of accumulated results in tabular and graphical form should be issued periodically. Statistical studies should be made, leading primarily to information on distributions of extreme load values. (Short-range case studies entailing more complete seaway load measurements and measurement of wave patterns are covered in Project 18.)

Suggested Techniques: Two strain gage installations mounted on the strength deck amidships, one port and one starboard, should be installed on all ships. They should be temperature-compensated and connected in series in order to give a mean reading. Calibration of each ship in terms of vertical longitudinal bending moment would be obtained by filling and emptying ship tanks in calm water to provide known bending moments. Records at sea would be obtained by suitable instruments designed to require a minimum of attention, such as strain-cycle counters, automatic sampling recorders, or instruments for recording average and maximum values during fixed time intervals. The instruments should be designed so as not to respond to high-frequency strain variations caused by slamming, engine vibration, etc., for such effects should be considered separately under another project.

Statistical analysis should be made of all load data; in particular, "extreme value" theory should be applied to the study of trends of maximum values. (See also Project 23.) If sufficient data are obtained, analysis of trends should also be obtained in the manner of Jasper.[10]

Research in Progress: Some stress data are being obtained by the Hull Structure Committee of the SNAME (Panel S-10), DTMB, British Shipbuilding Research Association, the Swedish Ship Research Institute, the Laboratory for Ship Structure Research, Delft Technical University, and the Association Technique Maritime et Aeronautique, France (de Leiris[53]). The Ship Structure Committee has initiated a project (SR-153) with Lessells and Associates, Inc., for a portion of this study.

Results Expected: Further supporting data on statistical trends of hull bending moments. After five or more years, statistically valuable information on extreme loads for different services and different ship types should emerge.

Project 23: Statistical Investigation of Maximum Bending Loads by Model Tests

Objective: To obtain statistical information on the maximum bending loads expected under severe storm conditions on the basis of model tests in random irregular waves.

Program: Carry out a series of long-term model tests in random irregular waves, using models of several ships for which full-scale load data have been obtained (Project 22). Apply statistical "extreme value" theory to the interpretations of model and full-scale results.

Suggested Techniques: Experimental work requires the generation of random, irregular waves having an essentially constant energy spectrum but continually varying wave pattern. (This contrasts with the repeatable irregular patterns now produced in some model tanks.) By generating comparatively severe seas continuously in a tank it will be possible to reproduce several seasons of full-scale bad weather behavior in a reasonable time, provided a small model scale is used. Attention should be focused on midship bending moments, which would be measured on suitably instrumented models. Methods for routine spectrum analysis of wave and bending moment records are essential.

Statistical "extreme value" theory should be applied to the analysis, plotting, and interpretation of the model test results. The aim should be to establish the distribution function of extreme values for several specific sea conditions. These would then be compared with full-scale statistical data, and, if possible, used for extrapolation of statistical results.

Research in Progress: None

Results Expected: Definite indications of the distribution of extreme values of longitudinal bending moments for several ship models in particular sea states over a long period of time. Use of these model results in extrapolating full-scale statistical data on seaway loads.

Project 24: Maximum Physically Possible Bending Loads

Objective: To determine on a physical rather than statistical basis the upper limit of longitudinal seaway bending moments and shear forces expected on various type ships.

Program: Determine the maximum wave bending moment in the hove-to condition for several types of ships having various values of freeboard, draft, superstructure length, and longitudinal weight distribution. Model tests supplemented by theoretical methods should be used both in irregular and regular wave conditions. Determine trends of limiting bending moments in order to obtain simple relationships for design guidance. Finally determine from oceanographical data (Section 1) the probability of the occurrence of the most severe waves attained in the model tests as a function of ship size.

Suggested Techniques: Conduct model tests in regular waves of varying steepness up to maximum attainable values covering a range of wave lengths sufficient to establish the most severe conditions. Standing waves obtained by reflection should also be included, and the effects of bow emergence and shipping of water should be considered. Different phase angles should be obtained, if possible, by testing at different speeds in regular head and following seas. Runs also should be made in severe irregular waves with breaking crests in order to determine whether or not more severe bending moments can be obtained. Statistical theory should be used as a guide in determining the number of runs required and in interpreting these results.

Theoretical work can be based on the methods developed by Korvin-Kroukovsky and Jacobs,[37] with allowance being made for nonlinearities by making use of non-constant coefficients. It is believed that the motions and bending moments can be calculated for a ship poised on the crest of a steep Stokes wave of finite height (120-degree crest), or on a standing wave (90-degree crest) obtained by reflection.[54] This method involves superposition of the effects of perhaps three Stokes wave harmonics. The effects of emergence of the ends of the ship and water on deck should be taken into account. For the determination of extreme conditions in irregular waves, application of the Fuchs-MacCamy[46] techniques should be considered, as well as superposition of a finite number of Stokes waves. Slamming effects should not be considered. (Indications regarding extreme bending moments might also be obtained by the method of Schade.[55])

Research in Progress: A pilot experimental study was carried out at ETT as groundwork for this report. The Ship Structure Committee is initiating a project (SR-157) at ETT for this work.

Results Expected: Definite information on the upper physical limits of longitudinal bending moments, as influenced by ship proportions, freeboard, draft, length of superstructure, and phase relationships with motions; indications of the probability of attaining these limits on ships of different sizes on different sea routes.

Project 25: Theoretical Techniques for Study of Hull Loads Under Severe Irregular Head Sea Conditions

Objective: To extend methods for predicting the statistical characteristics of bending moment variations in irregular head seas to extreme conditions in which nonlinear effects are encountered; to verify these methods by model tests.

Program: Make a survey of available techniques for dealing with bending moments under extreme irregular wave conditions. This involves the following types of nonlinearities, separately and in combination:

(1) nonlinearities in the wave patterns,[56] including the effects of breaking crests and shoaling bottom (Project 6)

(2) nonlinearities in the response of a ship to simple regular waves, arising from such factors as sloping sides, bow emergence, and shipping of water on deck, all of which invalidate the direct superposition of responses to component waves.

Apply available bending moment theory (Project 19) and extend it as necessary to determine average and extreme values of midship bending moments for a typical ship in severe irregular waves. Carry out tests in severe irregular tank seas on a model of the ship studied theoretically. Compare experimental and theoretical results, make refinements if possible in the theoretical calculations, and introduce correction factors if necessary.

Suggested Techniques: The starting point for theoretical work is the basic linear superposition method presented by St. Denis and Pierson,[38] based on the application of probability theory. New developments by Tick[56] for treating nonlinearities of the sea should be applied along with other developments in nonlinear vibrations and time-series techniques. Experimental work should make use of a suitable model that can be towed in irregular tank wave patterns and on which measurements can be made of midship bending moments. Means of recording data and making spectrum analyses should be available.

Research in Progress: None

Results Expected: Suitable theories developed and checked against model tests that permit prediction, perhaps with the help of empirical factors, of the bending response of ships to irregular seas beyond the present limit of linear assumptions for both the seaway and the ship's response.

Sequence: Project 25 requires parallel development of nonlinear, irregular wave theory (see Section 1).

Project 26: Transverse Bending Loads

Objective: To determine the nature and magnitude of dynamic transverse bending loads on a ship caused by waves and ship motions, and to develop a satisfactory method of calculating these loads.

Program: Determine by model tests the loads on a transverse section of a typical ship caused by rolling and other motions in waves. Calculate these loads by methods analogous to those used for longitudinal bending. Compare the results obtained by theoretical calculation, experiment and full-scale measurement and refine the calculation method as necessary.

Suggested Techniques: The theoretical calculations should take into account wave and gravitational forces exerted on the rolling ship, and inertial "forces" associated with accelerations, including the effects of concentrated cargo and machinery weights. Experimental techniques should make use of a ship model in beam or oblique waves, with its transverse sections instrumented to measure loads directly. However, if a structural model is used, the stresses can be measured. In the latter case, the distortion of the transverse section resulting from the loading can also be measured. Full-scale data would be obtained from Project 18.

Research in Progress: None

Results Expected: A method of calculating the transverse bending loads on a ship caused by rolling motions and waves in a beam sea, and indications of their magnitude.

Project 27: Loads Resulting from Motions of Internal Liquids

Objective: To determine the magnitude of the dynamic loads on ship tank boundaries as a result of the surging of the liquid contents, and to develop a satisfactory method of calculating these loads.

Program: Determine experimentally the loads on tank boundaries within a tanker hull for several typical tanks that are subject to surging as a result of ship motions. Determine trends of the loads with different sizes and shapes of tanks, different amplitudes of motions, and different levels of liquid in the tanks Compare these results with theoretically determined values and modify the theoretical methods as necessary. Estimate the effect of combined motions in two planes, i.e., rolling and pitching.

Suggested Techniques: Experiments should make use of scale model tanks arranged so that they oscillate to simulate pitch-heave-surge or roll-yaw-sway motions of suitable amplitudes and periods. Theoretical calculations should make use of hydrodynamic theory, assuming an ideal potential flow.[57] If purely theoretical methods do not prove feasible, semi-empirical formulations may be used to express trends.

Research in Progress: Det Norske Veritas in Norway and the S-10 Panel of the Hull Structure Committee, SNAME, are planning projects of this sort. Work is in progress on fuel tanks in missiles, which may be applicable to ship tanks.

Results Expected: Trends of dynamic liquid loads on tank boundaries under different conditions, and theoretical or semi-empirical methods of determining such loads.

Project 28: Analysis of Cases of Ship Structural Damage

Objective: To investigate cases of structural damage in order to determine as much as possible about both the loads and the structural response, and to make the results available for use by designers.

Program: Carry out thorough investigations of cases of ship structural damage, including both cases of failure by fracture or buckling and the less serious damage which is indicative of slightly excessive loads. The latter can be of particular value if used to work backwards from the observed deformation to an estimate of the load that caused it. Conclusions regarding loads, structural responses, and recommended design improvements should be published for the guidance of designers. Damage to superstructures, deckhouses, weather decks, bulwarks, bulkheads, etc., should be included as well as damage to the main hull structure.

Suggested Techniques: Survey of actual damaged ships, with measurements, photographs, and drawings being taken of each. Employ conventional methods of analysis for plastic deformation, supplemented by tests of full-scale structures if necessary.

Research in Progress: This type of work is regularly done by the classification societies and the navies of various countries, but publication of the gathered data is not complete. (Exceptions are Vedeler,[58] Turnbull,[59] Gibbs and Boyd,[60] and Reference 61.)

Results Expected: An accumulation of information regarding loads, particularly those that are difficult to calculate, and structural responses, all for the guidance of designers.

Project 29: Methods of Avoiding Severe Loads at Sea

Objective: To provide information to ship operators and masters on means of minimizing structural loads at sea.

Program: After other research projects are sufficiently advanced, review the results in order to obtain indications as to the effects of changes in speed and heading on hull bending loads. Prepare a report outlining possible means of reducing hull bending loads at sea.

Suggested Techniques: Comparative study and plotting.

Research in Progress: None

Results Expected: A simple report for the guidance of ship operators and masters on means of minimizing structural loads at sea.

Sequence: Project 29 depends upon considerable progress in all of the preceding projects.

Project 30: Specification of Seaway Loads for Design Purposes

Objective: To devise simplified means of specifying loads that should be considered in designing a ship. This should be done after other projects for the purpose of evaluating seaway loads on ship hulls have progressed sufficiently.

Program: Review results obtained in other research projects with the objective of determining trends of extreme seaway loads with ship form, speed, trade route, etc. These trends should then be expressed in simple form for design use, perhaps expressing the seaway loads in the form of effective static wave heights (comparable to the present "standard" L/20 wave), or possibly directly as functions of ship dimensions and fullness by means of graphs or tables. Combined effects of different simultaneous loads should be considered, including static loads, in vertical and horizontal bending, torsion, longitudinal compression, and other loads considered in the various projects.

Suggested Techniques: Graphical plotting, dimensional analysis, and comparison of elaborate calculations with simplified methods of determining loads. Use of probability theory and statistics.

Research in Progress: None

Results Expected: Simplified procedures for determining seaway loads for design use.

Sequence: Project 30 depends upon considerable progress in all of the projects preceding 29.

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Section 3. Impact and High-Frequency Loads

by

S. F. Borg and E. V. Lewis

Introduction

The dynamic loading on ship structures may be separated into three broad types as follows:

(1) comparatively low-frequency loading resulting directly from the interaction of waves and ship motions

(2) loading resulting from slam impacts, or other sudden hydrodynamic pressure variations, which are followed by vibration

(3) high-frequency loading caused by vibratory masses such as machinery and propellers.

Item (1) was discussed in Section 2 and will not be considered further. Items (2) and (3) are similar in that both result in high-frequency vibratory hull responses. They differ fundamentally, however, in type of loading, since the former is transient and the latter is a steady-state phenomenon. In addition, a ship may be subject to occasional impact loads during docking or berthing. The significance of all these loads in relation to bending stresses, buckling, brittle fracture, and fatigue will be discussed in Part III.

Present Status

Slam Loading

The present status of knowledge on slam loading is discussed in detail in a seakeeping monograph by Korvin-Kroukovsky.[1] Complete understanding of the problem involves answering the following:

(1) What are the conditions leading to slamming and how can slamming be ameliorated?

(2) What are the forces or loads induced by slams, or other sudden changes in loading?

Physically, bottom slams are caused by the pitching and heaving motions that sometimes cause the bow to emerge and then re-enter the water. Upon reentering the sea, sudden impact-type loads may be applied to the ship hull if the relative velocity is sufficiently high. These loads cause a sudden change in the vertical acceleration, generally felt as a shudder or a series of shudders or vibrations that constitute the response to the slam loading. It has been demonstrated by Szebehely[2] that there is usually negligible change in the vertical velocity of the bow at the time of a slam. It is possible also for lateral wave impacts to cause slamming, thus involving horizontal as well as vertical vibrations. And for ships with broad, flat sterns, such as destroyers, slamming may occur aft.

Korvin-Kroukovsky,[1] Warnsinck and St. Denis,[3] Jasper and Birmingham,[4] and Lewis and Dalzell[5] have called attention to the fact that slender, lightly built ships that are comparatively flexible (as destroyers and older aircraft carriers) may experience vibratory hull responses without the severe impact usually associated with slamming. In fact, it may not be necessary for the bow to emerge. Comparatively sudden changes in hydrodynamic pressures are undoubtedly responsible, arising not only when the bow re-enters the water, but when the flare enters and when water is shipped on deck. Jasper has calculated the loads resulting from flare immersion for comparison with observations made on the carrier Essex.[4] The calculations confirmed that very high loads occur, as indicated by full-scale stress measurements.

Szebehely[2] has shown that the occurrence of bottom-impact type slamming, which is particularly important in commercial ships, depends on:

(1) emergence of forefoot

(2) relative vertical velocity greater than a minimum value that depends on shape

(3) very small angle of incidence between keel and wave slope.

All of these conditions depend on ship motions and the phase relationships between motions and waves. It has been clearly established by Szebehely[2] and others that bow emergence and high relative velocity occur characteristically at speeds leading to synchronism between the natural period of pitching and the period of encounter with regular waves or component waves of an irregular pattern. At these times the amplitudes and phase relationships are such as to make slamming likely. However, bow emergence also depends on draft forward, and therefore bottom slamming can usually be avoided if sufficiently deep draft can be obtained.[6] The designer can help this situation by providing adequate ballast tank arrangements.

Hull form has a large effect on the incidence of slamming because it affects the motions, and because the forward hull shape determines the magnitude and location of slamming pressures. Ochi[6] and others have shown that peak pressures are less on a V-form than U-form hull, and that, with increasing fineness, larger vertical velocities are required to produce slamming. Thus, slamming is to some extent under the control of the designer, in a qualitative way at least. Tests carried out at ETT for the Bureau of Ships have shown that bow fins that reduced the amplitude of pitching in waves also reduced the superimposed vibratory bending moments, provided the fins did not emerge.

Furthermore, it has been shown by Lewis and Dalzell[5] and others that in irregular storm seas, where synchronism with certain components cannot be avoided, frequency and severity of slamming increase rapidly with increasing speed. This is in distinct contrast to the low-frequency bending loads discussed in Section 2 that show comparatively small variation with ship speed. Hence, slamming is generally under the control of the ship master, as shown in Fig. 21.

Ship-motion calculations can be applied to the prediction of slamming, since a complete knowledge of motions and phase relationships permits the determination of bow emergence, vertical velocities, and angle between keel and wave slope. In fact, Tick[7] has shown that, if the minimum vertical velocity and maximum angle of incidence for slamming can be specified for a particular ship, the frequency of occurrence of slamming can be predicted for any irregular sea condition.

The present status of knowledge about forces and loads produced by slamming is roughly as follows. Most methods of calculating slam loadings are based upon wedge-entry solutions. One class of such solutions is based upon Wagner's[8] original researches utilizing an expanding-plate type of analysis. These solutions have generally been employed in slamming research at DTMB.[2] A second method is the Wagner "spray root" theory which accounts for the high pressures at the edge of the entering surface but is difficult to apply to the ship slamming problem. Another form of solution has been presented by Borg[9] and is currently being extended to include various ship shapes that are of interest to ship designers. The

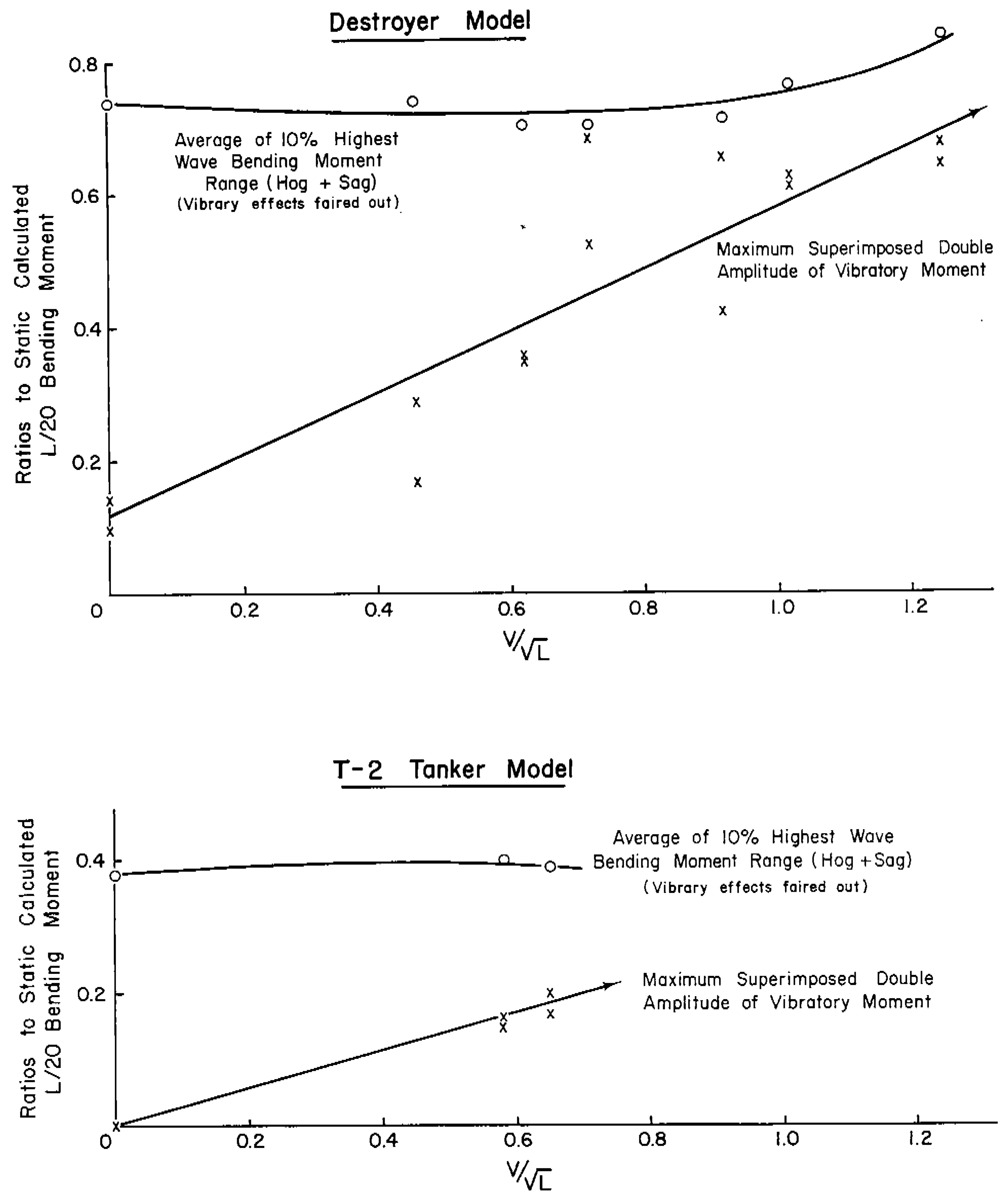

Fig. 21. Trends with speed of quasi-static wave bending moment and superimposed vibratory moment caused by slamming. Models towed in moderate irregular tank waves.

calculation of slamming pressures by M. A. Todd,[10] making use of Wagner's method for a simplified case, agreed with experimental values when properly interpreted. However, three-dimensional effects need to be taken into account, since the angle of the keel to the wave slope will influence both the local pressures and the total integrated load on the hull.

Work has been in progress for some time at DTMB in calculating the loads on the bow of an aircraft carrier as the flare enters the water.[4] The DTMB method involves determining the step-by-step change in virtual mass as the bow and flare enter the water.

Loads Resulting From High-Frequency Forces The effects of vibrating machinery and propeller blade forces have been studied extensively, but primarily with the aim of reducing the immediately objectionable effects of the vibration rather than of considering the structural loads they induce. Although these high frequency forces are believed to be small, they do constitute a part of the total load picture, particularly if the excitation coincides with a natural hull vibration frequency. They may be exaggerated by the superposition of slamming effects in bad weather. Hence, high-frequency loads are of some significance.

Needed Research

Research needs in connection with impact and high-frequency loads can be determined on the basis of the following design considerations:

(1) It is desirable to be able to design ships in such a way as to minimize the loads acting on the hull as a result of slams, other suddenly applied hydrodynamic effects, vibrating machinery, and rotating propeller blades.

(2) It is essential to obtain satisfactory methods for determining the maximum loads caused by slamming and vibratory forces.

Research recommended to attain these ends will now be discussed.

A. Slam Loading As far as the designer is concerned, the first point to consider in attempting to avoid slamming is to devise a design that will produce minimum motions. This involves questions of ship proportions and hull form which have been dealt with by Korvin-Kroukovsky and Jacobs,[11] Lewis,[12] Niedermair,[13] and others. Experimental and theoretical techniques are already available to evaluate specific designs, and consequently this aspect does not come within the scope of the project. Another need of the designer is for further guidance in producing hull forms that lead to reduced pressures when slamming does occur. Accordingly, it is recommended that both theory and experiment be applied to the investigation of optimum hull shapes and the consideration of possible modifications of typical ship lines that might reduce slamming pressures (Project 31).

Another problem to be solved by future research is the determination of maximum slam loads to be considered for design purposes. Because of the influence of operating conditions, namely ship speed and draft, on the slamming loads, this is a particularly difficult problem to solve. In principle, it appears that if any ship is driven at sufficiently high speeds at light draft in a severe storm, excessive slamming loads will eventually be reached. One approach to the problem of maximum impact loads is to determine from actual observations on different types of ships the minimum operating drafts forward and the maximum speed actually attainable in storms, particularly in head or bow seas. If speed is reduced, data should also be obtained on the reasons for the reduction such as high accelerations, shipping water over bow, slamming, or propeller racing (see Project 34). With such information available for different ship types, methods of calculating motions could be applied in the case of a new design. Knowing the motions, one can find for the case of regular waves quantities such as relative vertical velocity at the bow and angle between keel and wave slope.

On the basis of data on velocity and impact angle, further extension of Wagner's[8] theory or Borg's[9] method, or some entirely new theory, is needed in order to permit calculation of the resulting impact loads. In particular, it is necessary to devise means of dealing with the typical flat, low deadrise, and rounded shapes of ship bottoms and flare (Project 31), and with the effect of the angle between the keel and wave slope (Project 32). Further sea observations (Section 1) should provide information on the spectra of typical extreme storm sea wave patterns. The remaining research problem would then be the extension of the probability methods of Tick[7] to predicting the probable maximum impact loads expected at minimum drafts and maximum speeds in different storm sea spectra (Project 33).

Since slamming is in itself an indication that ship speed should be reduced, a short-cut approach to the problem of slamming loads is the observation of the maximum loads that shipmasters allow vessels to sustain. Direct observations can be made on various types of merchant and naval vessels of slamming pressures, which can then be integrated to obtain either local or overall hull loads. Alternatively, pressures and loads can be calculated by the methods discussed previously, i.e., from observed vertical bow velocities. Since slam loads differ from low-frequency wave bending loads in that they are mostly under a shipmaster's control, it is to be expected that, in general, maximum slam pressures will depend more on a shipmaster's skill in gauging his vessel's performance than on the severity of the sea. Consequently, long-range statistical studies are unnecessary for determining maximum slamming loads. Instead it is only necessary to obtain sufficient data on ships of various types to take into account the differences in the personal traits of individual shipmasters (Project 34). At the same time, it is desirable to obtain data on ship speed, vertical velocities, and the frequency of occurrence of slamming.

B. Loads Resulting from High-Frequency Forces Reduction of vibration is an important subject for research on its own account. Therefore, it is believed that research in this area under this program should be limited to determining the magnitude and frequency of the loads on a typical ship hull caused by normal vibrations. Since these loads can best be determined indirectly by strain measurements, it is recommended that a research project be undertaken to determine the magnitude of vibratory strains in different locations in typical ships, with particular attention being given to conditions of resonance (Project 35).

Results Expected

It is anticipated that the research described above will provide the information and calculation methods for (1) designing hull forms to minimize slamming loads, and (2) determining maximum slam and vibration loads for use in design of hull structures.

Summary of Recommended Research Projects

IMPACT AND HIGH-FREQUENCY LOADS

Project No.	Title
31	Optimum hull shape for minimizing slamming load (two dimensions)
32	Theoretical calculation of slamming loads (three dimensions)
33	Calculation of slamming loads in irregular seas
34	Observation of slamming loads at sea
35	High-frequency loads

Project 31: Optimum Hull Shape for Minimizing Slamming Loads (Two Dimensions)

Objective: To determine theoretically and experimentally the optimum section shapes for hulls subject to slamming loads.

Program: Extend available two-dimensional analytical methods for determining the theoretical pressures and loadings on typical ship hull sections subjected to slamming loads. Flat bottom and low deadrise shapes, as well as flaring sides, should be included. Investigate the effect of variations in shape on the peak and total pressures in order to determine optimum shapes for various degrees of hull fullness. Make two-dimensional water entry tests for measurement of pressure distributions as a function of impact velocity for a series of ship section models, including the optimum shapes determined on the basis of theory. Determine the rate of rise in pressures.

Suggested Techniques: Use theoretical methods developed by Wagner,[8] Szebehely,[2] and/or Borg.[9] Build scale models that can be dropped or mechanically driven into a tank over a range of impact velocities. Have pressure gage pick-ups at various points in the model, and employ suitable instruments for recording rapid fluctuations.

Research in Progress: Projects at SWRI and DTMB. Work is planned by the S-14 Panel, SNAME.

Results Expected: It is hoped that this study will determine possible modifications in hull bottoms and flare that will reduce appreciably slamming loads when impact velocities are specified. At the same time it may establish a satisfactory method of calculating impact pressures in the two-dimensional case.

Project 32: Theoretical Calculation of Slamming Loads (Three Dimensions)

Objective: To develop theoretical three-dimensional methods of determining the pressures and loads on ship hulls caused by slamming, when the relative vertical velocity and angle between the keel and wave slope are specified.

Program: Extend available analytical methods, as developed in Project 31, to determine the theoretical slamming pressure distributions on typical ship hull shapes, taking into account three-dimensional effects, particularly the angle between the keel and the water surface (wave slope). Carry out model tests to clarify the nature of hydrodynamic impact loads and to check theoretical calculations. Models of typical merchant ships and slender, flexible hulls such as a destroyer should be included. Investigate the cases of side impact on the bow and shipping of water on deck.

Suggested Techniques: Employ the strip theory in combination with "water entry" theories of Wagner,[8] Szebehely,[2] or Borg.[9] Model tests should be carried out in regular waves, with instruments for recording pressures on the hull, motions and phase relationships.[6] Moving pictures should also be taken to assist in determining the relative vertical velocity at bow, the angle between the keel and wave slope, and the extent to which flare entry and shipping of water on deck produce significant dynamic loadings.

Research in Progress: Work by Ochi is planned at DTMB. Experimental work on a destroyer model is planned at ETT.

Results Expected: It is hoped that improved methods will be developed for the theoretical determination of slamming pressures and loads when velocity and angle of entry are specified.

Sequence: This project should not be initiated until Project 31 has been completed.

Project 33: Calculation of Slamming Loads in Irregular Seas

Objective: To develop methods for theoretically determining the maximum pressures and loads expected on hull structures caused by slamming in irregular seas.

Program: Using analytical and statistical procedures, develop methods of determining theoretical pressures and load distributions on typical ship hull forms at specified speeds in irregular seas.

Suggested Techniques: For calculation of ship motions in irregular seas make use of the strip theory developed by Korvin-Kroukovsky and Jacobs[11] and superposition of responses to component waves as described by St. Denis and Pierson.[14] For analyzing pressures and forces use methods described by Wagner,[8] Szebehely,[2] or Borg[9] (Projects 31 and 32). For statistical procedures, employ methods similar to those described by Tick.[7]

Research in Progress: None

Results Expected: It is hoped that methods will be developed for theoretically determining the maximum slamming pressures and loads in irregular seas when a ship's speed is specified.

Sequence: This project should not be initiated until Project 32 has been completed.

Project 34: Observation of Slamming Loads at Sea

Objective: To measure the pressures and loads on hull structures caused by slamming at sea, and to obtain associated sea and motion data.

Program: Make measurements of actual pressure distributions on a number of ship hulls subjected to sea slamming loads, and note the frequency of slamming. At the same time record data on sea conditions and ship motions, particularly vertical velocities or accelerations at the bow. The speed of the ship should be obtained and the reason for any reduction in speed noted. Calm water drafts forward and aft should also be recorded.

Suggested Techniques: Use pressure gages at various points on the hull, and employ an oscillograph for recording the rapid fluctuations in the pressures. Gages should be designed to read integrated pressures over plating panels rather than "point" pressures. They should be located on the flaring sides, on the ship bottom, and on the forward deck. Sea conditions should be recorded if possible by a suitable instrument (see Section 1), or otherwise the significant wave heights and periods should be observed by a trained observer. Ship motions should be recorded by means of accelerometers at bow and stern. Speeds should be obtained from log books and/or by Loran observations. Slamming stresses also should be recorded for use in connection with research covered in Part III.

Research in Progress: DTMB is currently conducting research on aircraft carriers rounding Cape Horn.[4]

Results Expected: The main results would be as follows:

(1) The theoretical predictions of slamming loads could be checked and the validity of the theoretical methods determined.
(2) The actual pressure values will give data on the magnitude of loads which can be expected on different ship types in irregular storm seas, as well as data on maximum vertical velocities.
(3) Data on upper limits of speed will become available for different ship types in different sea conditions.
(4) Data will be obtained on the frequency of slamming for different ship types in different services.

Project 35: High-Frequency Loads

Objective: To determine the magnitude of loads on hull structures as the result of rotating masses of machinery and propeller blade forces.

Program: Make measurements of vibratory strains on actual ships having different types of propulsion machinery and power. Interpret the data in terms of loads. Consider both local loads and loads on main hull structure, as well as effects of heavy concentrated masses. Investigate combined effects of slamming and high-frequency loads.

Suggested Techniques: Employ strain gages and oscillographs for recording the high-frequency variations aboard ship. Calibrate against known variable exciting forces produced by an exciter in order to facilitate interpretation of ship test results. For shipboard techniques see Carrol[15] and Russo and McGoldrick.[16]

Research in Progress: Measurements on a 16,000-ton tanker by the Laboratory for Ship Structure Research, Delft Technical University.

Results Expected: Data on the magnitude of stresses and loads resulting from high-frequency forces acting on a ship.

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Section 4. Static Loads

by

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Background

Static loads on ship hulls result from the combined effects of (1) the downward forces caused by weights of the structure, cargo, stores, machinery, etc., and (2) the fluid pressures on the outside of the hull and within ship tanks. Many of these loads are local in nature, and can be calculated by conventional methods. Most of them contribute also to the overall bending loads on the hull as a beam or girder. Since the downward-acting weight forces and the static buoyancy forces can be readily calculated for any condition of the ship, it is not difficult to construct a longitudinal load curve and integrate in order to obtain shear and bending moments. The still-water bending moments under different loading conditions must be considered along with wave bending moments and other loads in determining the scantlings of the main hull structure. In addition, for completeness, static bending moment calculations should be carried out for flooding conditions following possible collision damage to the ship. The extent of assumed flooding of the hull should correspond to the worst conditions under which the ship is designed to remain afloat.

Another type of static loading is that experienced by ships in dry-dock. There are, of course, local loads in the vicinity of keel blocks and shoring, but there may also be transverse bending loads and, of particular importance, longitudinal bending moments when the ends of a ship overhang the supports. All of these loads are amenable to calculation and are customarily allowed for in structural design.[1]

Residual or locked-in stresses resulting from steel manufacture, fabrication, and erection procedures will be considered as static "loads" since they are not caused by any external loading. Residual stresses may be defined as those existing in structures when no external forces are acting on them. They develop during various stages in the construction of the structure. During plate manufacture the cooling of the metal after hot rolling causes residual compressive stresses near the edges and on the surface of the plate, and tensile stresses near the center and mid-thickness. Welding and burning during construction cause residual tensile stresses of yield-point magnitude along welds and burned edges. In the heat-affected zone adjacent to the weld, longitudinal compressive stresses of about one-fifth yield strength are reached. Residual or reaction stresses also result from the restraint placed on one part of the structure by the surrounding parts, from heating and shrinking to fair plating, from uneven settling during building, or from completion of some parts of the structure after launching.

The primary significance of residual stresses is their relation to the problem of brittle fracture. It has been shown by Osgood[2] that residual stresses can be a contributory cause of fracture, along with other factors such as low temperature, poor material quality, thick plating, and notch effects. But if conditions are not conducive to brittle failure, a high load applied in service and then released or reversed will tend to relieve the residual stresses. Hence, it does not appear necessary to assume that residual stresses, which sometimes are at the yield point level, are superimposed directly on longitudinal bending stresses. Just how important residual stresses are remains to be determined. However, there is no doubt that to reduce the likelihood of brittle fracture residual stresses should be minimized, and/or some means of relieving them should be employed, if possible.

Present Status

The standard longitudinal strength calculation for a ship in still water is described in any Naval Architecture text (for example, Arnott[3]) and the method described may be used for any loading condition. Good general agreement between calculated and observed bending moments in static tests in still water has been obtained many times. The static bending moment depends, of course, on the distribution of the cargo, fuel, and other variable loads in the ship. Hence, designing to one particular loading condition, as for instance a full homogeneous load of cargo, overlooks the possibility that other loading conditions might produce higher bending moments as well as more severe local loads. This variability of loading is important both for tank vessels and dry cargo ships, especially when carrying heavy cargoes which require that some tanks or holds be slack or empty.

The need to investigate variations in static longitudinal bending moments by calculation has been realized by ship designers and classification societies, and there have been several papers pointing out the danger of improper distribution of liquid cargoes. One of the first of these was a paper by Thompson,[4] while a more comprehensive treatment of this subject by McDonald and MacNaught[5] presented data on the bending moments and stresses for nine typical tankers with a great variety of cargoes and loadings. The latter paper included specific recommendations for cargo distribution and sequence of loading of these vessels to avoid excessive still-water and static wave bending stresses. Uneven longitudinal distribution of cargo may also be dangerous for general cargo ships. Tashiro[6] discussed uneven loading and its effect on the bending moment for several general cargo ships, and more recently Abrahamsen[7] has discussed loading effects on dry cargo ships. A study of the loading for both Liberty cargo ships and T-2 tankers was presented in Reference 8. For naval ships the Bureau of Ships has a form for making routine bending moment calculations and also makes use of analog computers. In addition, several instruments are on the market for determining mechanically the change in bending load or stress in a particular ship in any possible condition.

The effect of residual stresses on the performance of various kinds of structures, particularly ships, and the contribution of these stresses to fracture has been discussed at length in some of the papers contained in the monograph edited by Osgood.[2] In this monograph, Ffield reports on several cases of ships being instrumented to determine residual stresses during fabrication. Most measurements were made in the vicinity of welds, except in the case of two heavy cruisers in which the effect of lifting of the bow section from the building blocks was studied. Watson[9] measured residual stresses in a tanker during construction, but the number of gages employed was limited and the extended time that the gages were used (eight months) may have had some influence on the accuracy of the results. Low-temperature stress relief procedures have been used on welded ships, but their success in reducing the magnitude of the locked-in stresses is in doubt.[10,11]

Needed Research

Since the static still-water loading problem has received more attention than other types of loading mentioned previously, the needs for research in this area are somewhat more limited. For most ships the only important variable still-water load is that of longitudinal hull bending. Some of the factors in addition to cargo loading that affect the still-water bending moment are the location of and weights in the engine room, position of the bridge and other deckhouses, extent of the cargo spaces, position of the ballast tanks and pump rooms, block coefficient, and amount of sheer. These factors have been discussed by Abrahamsen and Vedeler[12] and by McDonald and MacNaught.[5]

Nevertheless, the variable loads such as cargo and fuel are the main problem in operation. Either the hull should be designed for the worst possible loading or for a limiting condition that is not to be exceeded. In some cases the first approach may be satisfactory to the operator, but in many tankers, bulk carriers, and even general cargo carriers the latter may be preferable. A program of systematic calculations of still-water bending moments for various types of ships in order to determine the possible range of bending moments should be undertaken for reference in designing ships by the first approach (Project 36). Such calculations are already in use on a routine basis for naval vessels and often for oil tankers, but not for all merchant ships.

If a limiting condition is imposed on the loading, as in the other suggested approach, the ship's cargo officer must have means at his disposal to determine the bending loads or stresses quickly and easily for any loading condition. This may be accomplished either by means of calculation forms, graphs, tables, or by some mechanical calculator (Project 37).

To learn more about the magnitude of the locked-in stresses accompanying fabrication and erection of the structure, a systematic program of instrumentation of ship components during fabrication and assembly in various shipyards would be valuable. A thorough examination of the residual stresses in a laid-up ship should also be undertaken (Project 38). An important part of the project would be to develop practicable methods of fabrication and erection that would minimize residual stresses. Evaluation of low-temperature stress relief methods and measurement of residual stresses after these methods have been applied should also be included.

Results Expected

The first result of this research should be a better understanding of the range of possible still-water bending moments for different ship types, from which conclusions can be drawn regarding the need to restrict service loadings. The second result should be the development of quick, easy methods of determining bending moments for any given ship loading condition. These methods would be used by the operating personnel to avoid dangerous loading conditions. Finally, a more thorough knowledge of the stresses accompanying fabrication and erection, and means of reducing them, would complete the static loading picture.

Summary of Recommended Research Projects

STATIC LOADS

Project No.	Title
36	Variation in still-water bending moments for different ship types
37	Determination of still-water bending loads in service
38	Statistical data on fabrication and erection stresses

Project 36: Variation in Still-Water Bending Moments for Different Ship Types

Objective: To determine the possible range of static still-water bending moments for different types of ships.

Program: Make a series of calculations of still-water bending moments for different types of ships, such as tankers, bulk ore carriers, general cargo ships (machinery amidships and aft), and passenger-cargo ships. Various extreme conditions of cargo and fuel distributions should be assumed, as well as conditions of damage in which compartments are flooded.

Suggested Techniques: Employ elementary static bending moment theory, as applied in the case of tankers by McDonald and MacNaught.[5] Allowance should be made for possible large secondary bending of portions of the structure such as double bottom panels.

Research in Progress: Det Norske Veritas in Norway on both dry cargo ships and tankers; Bureau of Ships on naval vessels.[7, 12, 13]

Results Expected: Definite conclusions regarding possible range of still-water bending loads to be expected in different types of ships if no loading restrictions are imposed.

Project 37: Determination of Still-Water Bending Loads in Service

Objective: To make available and encourage the use of methods for quickly determining longitudinal still-water bending moments in ships of various types.

Program: Survey available methods of determining still-water bending moments by calculation, and by use of tables or graphs and instruments. Investigate methods of improving all of these and making them more generally available.

Suggested Techniques: Library research, simple calculations, and perhaps instrument development.

Research in Progress: Det Norske Veritas in Norway.

Results Expected: Available methods for quickly determining longitudinal still-water bending moments in service.

Project 38: Statistical Data on Fabrication and Erection Stresses

Objective: To collect statistical data on residual stresses resulting from the fabrication and erection of ship hulls and to devise means of reducing residual stresses.

Program: Instrument ships of several types during erection to determine the magnitude of the built-in stresses formed at each stage of the construction. Attention should be given to stresses near welds and away from welds, and at points of stress concentration, with emphasis placed on locations subject to overall longitudinal bending. Investigate effects of variation in welding sequences and fabrication techniques in order to determine practicable means of reducing residual stresses. Evaluate effectiveness of low-temperature stress relief procedures.

Suggested Techniques: Use strain gage techniques and other non-destructive methods for measuring residual stresses during construction. Also use trepanning methods on steel plates as-rolled and on laid-up ships to determine residual stresses remaining in a ship after long service has allowed structural "shake-down" to take place. Strain gage measurements before and after low-temperature stress relief methods have been employed would assist in evaluating these procedures.

Research in Progress: Stresses and deformations of ship plates during construction are being measured by the Centre Belge de Recherches Navales, Belgium.

Results Expected: Quantitative data showing magnitude of fabrication and erection residual stresses and means of reducing them.

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Section 5. Thermal Gradients

by

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Background

Temperature changes and gradients play an important part in the loading on ship structures. Several factors combine to produce temperature differentials in a ship's hull that are often the cause of significant structural loadings: the temperatures of the surrounding water and air, the intensity of solar radiation, the effects of shading from the sun, the temperature of air and liquids within the ship, and the effects of wind and waves in dissipating heat. Another important source of temporary temperature gradients in structures is the extremely high temperatures reached in the welding process during fabrication.

If they are uneven in distribution, the temperature gradients produced by the thermal environment can contribute to the state of stress in the structure, so that parts of the structure exercise mutual restraints on other parts. Similarly, the high welding temperatures during construction cause residual stresses that may be of considerable magnitude. Thermal stresses are discussed in Part III, Section 4 and residual stresses in Part II Section 4.

Present Status

The theory for computing stresses resulting from known thermal gradients is well established, and has been applied specifically to the problem of thermal stresses in ships. (For more details and references see Part III, Section 4.) All investigators have, however, started with either assumed or measured temperature distributions. No one has attempted to compute the temperature distribution in a structure for a given thermal environment. Nevertheless, the general subjects of heat transfer and the resulting temperature distributions have been well covered in the literature; for example, see McAdams[1] and Jakob.[2] Much of this information could be applied to ships, and preliminary exploratory studies of this type have been made by Meriam and Seban at the University of California.

In order to calculate thermal gradients, the environments to which ships are subjected in service must be known. Except for information on solar radiation, the necessary oceanographic and meteorological data are available from such sources as the U. S. Navy Hydrographic Office and the Weather Bureau. However, solar radiation intensity can be deduced from theoretical considerations based on current weather observations. Hence, if solar radiation were measured and correlated with the cloudiness, time of day, time of year, ship position, and other pertinent data, these observations could be used to determine solar radiation intensity from available weather data. Work of this nature has been done at land-based weather stations.

Needed Research

Available information on the thermal environment that ships encounter at sea should be gathered and analyzed. Reports from weather stations at sea, combined with new data taken on ships operating on the major sea routes, should be gathered in order to determine the most adverse conditions a ship may encounter. Data collected should cover a period of several years and some should include hourly reports in order to give a good indication of diurnal as well as seasonal changes. Results should then be published for ready reference by designers (Project 39).

Research in the determination of hull temperature gradients can be of three types: theoretical development, full-scale measurement, and model tests. All three types of research should be aimed at obtaining satisfactory results by theoretical means, i.e., a reliable analytical method of calculating the temperature distribution in a complex structure from the known thermal environment (Project 40). Available theories and methods of calculation of heat transfer must be applied to the complex geometry and boundary conditions of ships. Conduction within the structure, convection to and from the surrounding air and water, and radiation to and from the ship must be considered. Correlation of the results of theoretical calculations of thermal gradients with observations on properly instrumented ships in service will be necessary to test the theory (Project 41). The development of model tests would also be extremely valuable in checking theoretical methods for the prediction of temperatures from artificially produced extreme environmental conditions. An advantage of model tests is that the structure can be simplified in order to permit easier calculations.

For more immediate indications of the extreme temperature gradients expected in ships, a project to measure hull temperatures on several ships in services where extreme thermal environments are likely to be encountered should be carried out (Project 41). These data, if taken in conjunction with meteorological and stress data, would also serve to correlate and verify the calculations of temperature gradients (Project 40) and thermal stresses (Project 56). Specific attention should be directed to certain local conditions that may cause steep temperature gradients, such as the gradient through a web frame or stringer immersed in heated oil and connected to the hull moving in a cold sea. In addition, shadow effects under conditions of intense solar radiation may produce extreme temperature gradients locally.

Results Expected

Research in thermal gradients should provide the necessary data and theoretical methods to enable a ship designer to determine the extreme temperature gradients expected in a ship in any service.

Summary of Recommended Research Projects

THERMAL GRADIENTS

Project No.	Title
39	Compiling data and observing sea and air temperature, solar radiation on various trade routes
40	Calculation of extreme temperature distributions in ship hulls from ambient conditions
41	Statistical data on extreme temperature gradients in ship hulls

Project 39: Compiling Data and Observing Sea and Air Temperatures, Solar Radiation on Various Trade Routes

Objective: To collect and analyze existing data and to obtain new data on the following for various sea routes:

1. sea temperature
2. air temperature
3. solar radiation intensity
4. humidity
5. cloudiness
6. wind velocity and direction
7. precipitation
8. date, time, location and heading of ships

Program: Survey and analyze meteorological data from weather ships and the Hydrographic Office. In addition, ships on various major sea routes should be instrumented to record the above-listed data over a period of at least one full year on each sea route. Since presently available meteorological data do not include information on solar radiation intensity, the emphasis of new data-taking should be on this factor. Correlation should then be made between radiation intensity and the other items normally recorded, for the purpose of "hindcasting" solar radiation intensity from past records. Results of the survey of meteorological records, plus hindcasts of solar radiations, should be compiled and summarized for ready reference.

Suggested Techniques: The survey of meteorological data should be made for enough different locations and over a long enough period so that a statistical analysis of the data will yield valid quantitative results on mean and extreme values. Ship instrumentation should be simple but reliable. Combination gages in which one faulty gage can nullify the results of others should be avoided. Readings should be taken over at least one full year so that seasonal variations can be established and at one-hour intervals on a representative number of days throughout the year so that diurnal variations can be determined. Emphasis should be placed on measurement of solar radiation.

Methods used for correlating meteorological data with solar radiation intensity should be similar to those developed and applied in studies at land weather stations.

Research in Progress: None

Results Expected: A statistical analysis of the data collected should yield reliable information on mean and extreme thermal environmental conditions that a ship may be expected to encounter in any particular service.

Project 40: Calculation of Extreme Temperature Distributions in Ship Hulls From Ambient Conditions

Objective: To develop theoretical methods of calculating the temperature distribution in the hull from given ambient conditions, and to compare the results so obtained with measured values from ships in service and from model tests.

Program: Survey available methods of calculating heat transfer in plates and structures that are applicable to the ship problem. With assumption of known ambient conditions, calculate heat transfer to and from a ship's hull by conduction, radiation and convection, and determine the resulting temperature distribution in the hull. Check the validity of the theory by comparing calculated results with actual ship measurements, and also with measurements from model tests using suitably simplified box-girder models. The effects of internal heating and cooling should also be included.

Suggested Techniques: The development of a satisfactory theory will require a thorough search of heat transfer literature to determine the applicability of various methods of calculation, including three-dimensional effects.[1, 2] Some of the complicating effects that will have to be considered are: the effect of ship speed and wind on film coefficients; of wind, clouds, fog and angle of incidence on solar radiation; of shadows; and of hull color. Electronic computer solutions may be required for the three-dimensional case, but possibilities of numerical solutions and simplified procedures should be considered.

Full-scale ship instrumentation to check calculations should be done on the same ships as those instrumented for meteorological data mentioned in Project 39. Portable thermocouples could be used to obtain temperature data on outside and inside plating where possible, and also on decks, girders, tank tops, bulkheads, and other members. A sufficient number of readings should be made on each transverse section to construct valid temperature-distribution curves. This will entail extra readings in the vicinity of sharp thermal discontinuities (such as waterline of ship and refrigerated hold spaces).

A simplified box girder model with provision for applying various temperature gradients by means of liquid baths or radiant heaters could be constructed and instrumented to check theoretical calculations.

Research in Progress. The S-10 Panel of SNAME is sponsoring a study at the University of California on the calculation of thermal gradients for comparison with observations aboard a laid-up ship.

Results Expected: The result should be a reliable theoretical method of calculating the temperature gradients in a ship's structure associated with any given ambient conditions. The method should if possible, be concise enough to be easily used by design offices.

Project 41: Statistical Data on Extreme Temperature Gradients in Ship Hulls

Objective: To collect statistical data by use of thermocouples in order to establish extreme temperature gradients in ship hulls in service.

Program: Instrument several ships on routes where extreme temperature conditions are known to exist, such as Arctic seas in clear winter weather (cold sea, hot solar radiation on the side of a ship) or "cold cargo" ships (reefers, liquid-gas carriers) in tropical seas. Attention should be directed to local steep temperature gradients.

Suggested Techniques: For recording hull temperatures, portable thermocouples could be used, and measurements should be taken only under extreme conditions. For correlation with meteorological data, more permanent thermocouple arrangements could be used in conjunction with Project 39. A statistical analysis of the data would provide information on the extreme conditions to be expected at sea.

Research in Progress: None

Results Expected: Statistical data on extreme temperature gradients in ship hulls on various sea routes.

General References for Part II, Section 5

Churchill, R. V., "Comparison of Temperatures in Solid Bodies and Their Scaled Models," Proceedings, Heat Transfer, A Symposium. Ann Arbor: Research Institute, University of Michigan, 1952.

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Investigation of the Temperature Ranges Encountered by Ships in Normal Service (Admiralty Ship Welding Committee Document FE4-292), London: Her Majesty's Stationery Office, 1949.

Gatewood, B. E., Thermal Stresses. New York: McGraw-Hill Book Company, 1958.

Weather Reports. Washington: Weather Bureau, U. S. Department of Commerce.

World Atlas of Sea Water Temperatures (Publication No. 225), Washington: U. S. Navy Hydrographic Office, 1944.

References for Part II, Section 5

1. McAdams, W. H., Heat Transmission. (Third Edition). New York: McGraw-Hill Book Company, 1954.
2. Jakob, M., Heat Transfer. New York: John Wiley and Sons, Inc., 1950.

PART III - RESEARCH ON SHIP STRUCTURAL DESIGN AND ANALYSIS

Section 1. Introduction

by

George Gerard and E. V. Lewis

Background

The ship hull as a structure has been discussed in an introductory fashion in Part I. There the basic elements in the design of a successful and efficient ship structure were listed as follows:

(1) The functions and performance requirements for the ship shall be explicitly stated at the outset of the design. This information constitutes the design criteria from which the structural design can proceed.

(2) All of the loads to be expected in service should be rationally determined and suitably combined. These loads multiplied by suitable factors of safety constitute the design loads for the ship structure.

(3) The structural members shall be arranged in the most efficient manner possible to resist the loads.

(4) Adequate but not excessive scantlings shall be determined, using a minimum of purely empirical factors.

It was tentatively concluded in Part I that for most seagoing ships the primary design criterion should be that the ship be able to survive the extreme environmental conditions expected on a statistical basis during the lifetime for which it is designed. These conditions might include hurricanes, steep waves in shoal water, the lowest and highest temperatures encountered on any trade route, ice conditions, and even the effects of collision damage that does not result in complete loss of reserve buoyancy. Extraordinary phenomena such as tidal waves caused by earthquakes and the effects of severe grounding would undoubtedly be excluded.

The structural design is confined within the external geometrical features of the hull which are determined largely by "performance" considerations such as stability, resistance, propulsion, seaworthiness, cargo capacity, port limitations, and dry-docking. However, the geometry is also determined by economic factors, since a long ship is more expensive to build, for example, than a short ship that will carry the same load. On the other hand, a long ship may be cheaper to drive in both calm and rough seas, and therefore an economic balance must be determined in each design to satisfy the conditions to be specified by Item 1.

The proper balance between performance and economic considerations in ship design is outside the scope of a research program. It is important to note, however, that there are important economic aspects involved in the improvement of ship structures. The ultimate aim of structural research should be to obtain more efficient use of materials. This means that more expensive design procedures, methods of fabrication, or materials must ultimately pay for themselves in greater earning power for the ship and/or reduced repair and maintenance expenses.

Once the functions and performance requirements of the design have been explicitly stated, it should be apparent that the design of the ship structure requires a knowledge of environmental loads acting upon the external geometrical features of the hull (Item 2). Thus, it appears that significant improvements in the economical design of the hull must be based upon a more complete understanding of the loads produced by environmental factors. As a consequence, considerable attention was devoted in Part II to research programs designed to achieve this goal.

Although our knowledge of hull loads generated by the seaway and other environmental factors is still incomplete, methods of structural design and analysis have been under continual development (Items 3 and 4). While particular environmental conditions are unique to ships, the methods of structural analysis required in ship design are common to other structural fields: aircraft, civil engineering and solid mechanics. Thus, there is a great body of knowledge encompassed by these fields from which to draw in the design and analysis of hull structures.

It is noteworthy that the advent of all-metal aircraft design in the 1930's was substantially aided by existing literature on buckling of plates and shells drawn from the field of ship construction. The impetus for, and the continued interest in, buckling problems prior to 1930 can be directly traced to the transition from wood to iron in ship construction of the 1880's. More recently, the performance demands of modern aircraft have placed tremendous importance on buckling problems with the result that during the past 25 years a substantial theoretical and experimental literature on buckling and failure of plates and shells, as well as advanced methods of stress analysis and minimum weight analysis, have become available.

In the area of brittle fracture, the ship structures field has led in research as a result of first encountering the catastrophic effects of this phenomenon. After the Comet disasters, the aircraft field was quick to utilize this body of knowledge in evolving the fail-safe design of modern transports, i.e. design in which any crack is contained so that the remaining structure can carry the load.

Organization of Part III

Structural problems are discussed in a general way in this first section of Part III. The structural responses to different types of main hull loads are then considered in detail in Sections 2, 3 and 4 which lead to specific research recommendations. There are also many types of response to local loads that will not be considered in this report. These loads include cargo and machinery weights, static pressures on tank boundaries and watertight bulkheads, vibratory effects on machinery foundations and stern frames, and forces on masts and deck structures caused by ship motions. Such problems are either already understood or research to clarify them can be or is being planned by structural designers.

Finally, in Section 5, a structural design philosophy is tentatively proposed, directed toward applying the new knowledge to be gained under this research program to new procedures in the design of actual ships. A major problem discussed in Section 5 is the combined effect of the different loads acting on the hull at widely different time rates; these range from essentially static loads varying slightly throughout an entire voyage as fuel is consumed, through diurnal thermal stress variations and low-frequency (T = 5 to 10 sec) wave bending stresses, to high-frequency (T = 1/2 to 1 sec) vibratory stresses following a slamming impact. The combined effect depends on both the environmental conditions and the phase relationships of the various loads. Probability theory offers interesting possibilities in coping with this problem, as well as those questions concerned with factors of safety and extreme loads to be used for design purposes.

Ship Structural Problems

Recent structural difficulties encountered in ships, such as brittle fracture, formation of cracks at points of stress concentration (such as hatch corners), and buckling of bottom plating, must be viewed not simply as problems of improving material quality or avoiding local structural damage but as symptoms of inadequate design. If the weak links in the design can be strengthened, it should be possible to obtain more efficient utilization of material and hence to increase the mean working stresses with safety. Any equalizing of the stress levels will improve the overall structural behavior, which will permit economies both in the initial design and during subsequent service.

One of the serious problems that has been partly but not completely solved is how to reduce the probability of brittle fracture and fatigue failure. These are much more than local problems, for a local crack can propagate until it becomes a disastrous failure. Until the probability of fracture can be reduced to an acceptable level, a fail-safe philosophy must be adopted at the design stage. For example, the number and location of crack arrestors should be determined on such a basis that if cracking should occur between any pair of arrestors, the remaining structure would be adequate to permit the ship to return to port. The attainment of fail-safe design is considered in Section 2.

High stress concentrations at locations such as hatch corners serve not only as points for initiation of fatigue or brittle cracks; they represent uneconomical distribution of structural material. Plastic flow cannot be counted on to relieve these stress concentrations in a ship, since reversals of loads will usually cause the stress concentrations to reappear. In fact, alternating stresses in the plastic range are undoubtedly a source of fatigue cracking at hatch corners. Consequently, attention is directed in Section 2 toward a more vigorous attack on improved design details to reduce stress concentrations drastically as a means of increasing the efficiency of the structure as a whole. Section 3 considers the effect of stress reversals in the presence of stress concentrations.

It has been pointed out that there is a considerable body of opinion among ship owners that it pays to have very low stress levels because there is then less need to dry-dock vessels for structural repairs. This is believed to be a tacit admission of inadequate design. The inherent difficulty with this low mean working stress theory is that it means, in effect, arbitrarily adding material throughout the main hull girder in order to maintain low stress levels at critical points. It neglects the fact that cracks invariably initiate at stress concentrations which may be increased by the addition of material. Furthermore, added thickness in the plating increases the danger of brittle fracture as a result of size effects. Above all, this theory neglects the possibility that improved structural arrangements and details should be more beneficial at no greater cost or weight.

The buckling of inner bottom and shell plating amidships in transversely framed ships is another indication of inadequate and uneconomical structural design, since the plating cannot carry loads beyond the load at buckling. With suitably designed longitudinal framing it is possible to withstand the same load with much less structural weight. Hence, the background is presented in Section 2 for a study of possible layouts of main hull structural members to determine optimum configurations, using as a starting point the data on optimum design now available.

Structural Trends of Ship Hulls

In the design of structures, the external geometrical and overall loading features are generally fixed by design conditions over which the structural designer has little control. Thus it has been noted that in the design of a hull structure, the length, beam and depth are generally governed by the performance considerations of stability, resistance, seaworthiness, cargo capacity, and docking, and by economic factors.

Once the overall geometry is established, the structural designer is somewhat restricted by the necessity of subdividing the hull by means of decks and bulkheads in a manner suitable for the efficient arrangement of cargo and passenger spaces, machinery, fuel tanks, etc. However, he is relatively free, within such limits, to divide the structure into components by selecting suitable framing. By proper division of the structure, it is possible to achieve efficient structural designs within the confines of a prescribed geometry.

Since the external geometrical features basically define the structures problem it is of some significance to consider typical values of certain dimensional ratios for ship hulls. In Fig. 22 the trend of the ratio structural length of hull girder L to maximum depth D is shown for various types of ship hulls. It can be observed that L/D has been relatively constant over the years in the range of 14 or less, primarily in order to limit hull deflections.

The ratio L/D is an overall "slenderness ratio" for box beam types of structures. It is directly related to the overall deflections of the beam under load. Since an aircraft wing is also a box beam subject to loadings similar to a ship hull, it is interesting to note that L/D values of 40 are employed in current transport aircraft designs. Thus, from a strength standpoint, there could be substantial increases in L/D ratio beyond the value of 14 currently used in ship design providing that increased flexibility is permissible. Furthermore, improved design should permit some increase in L/D without loss of stiffness.

The question naturally arises as to what factors should determine the allowable flexibility of ship hulls. From a purely structural point of view, quite large deflections might be acceptable, as for example in an aircraft wing. However, no clear statement of the reasons for limiting deflections of ship hulls has been found. Presumably the bending of propeller shafts, piping, etc. may be a consideration, but flexible couplings could certainly cope with much larger deflections than are ordinarily experienced. The present investigation has revealed only one clearcut reason for limiting flexibilities and that is to avoid excessive vibratory slamming stresses. This matter is discussed in Section 3.

A second geometrical feature of beam type structures is the structural thickness ratio, the depth D to beam B. The trend of this ratio over the years is shown in Fig. 23 for tanker hulls. The downward trend indicated probably reflects

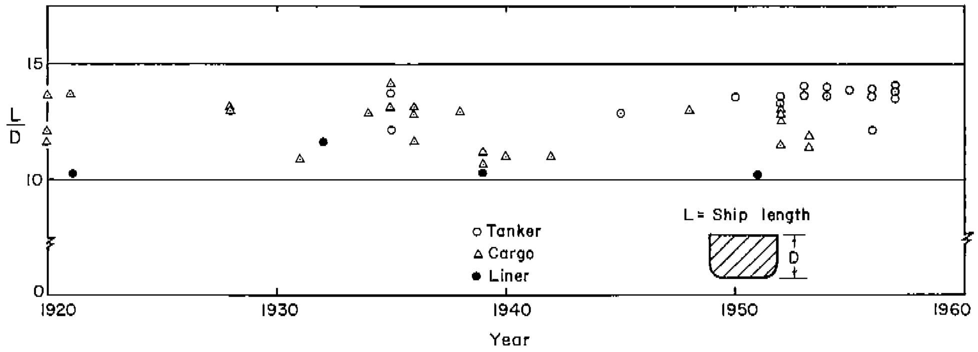

Fig. 22. Trend of L/D ratio for ship hulls

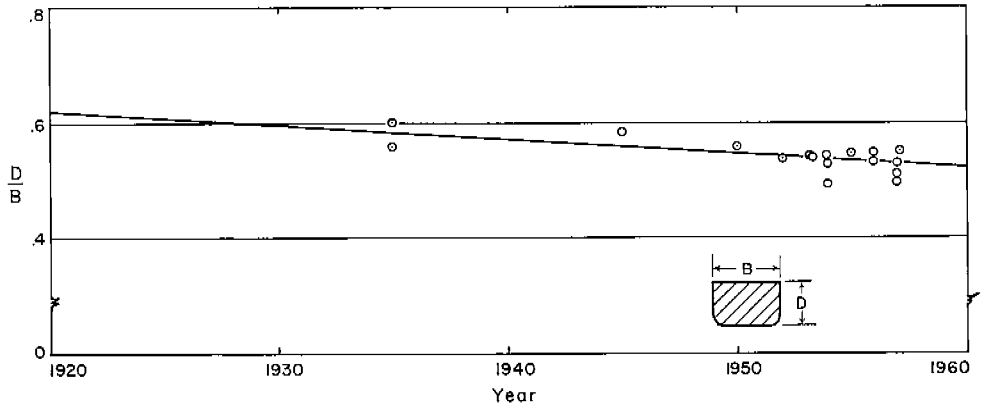

Fig. 23. Trend of D/B ratio for tanker hulls

the influence of draft restrictions as tankers have increased in size.

Loading Trends

In addition to considerations of flexibility, the loads to which ship structures are subjected also depend upon the geometrical ratios presented in Figs. 22 and 23. In the following, an attempt will be made to estimate those loading trends that substantially influence the type of construction and the strength level of materials required to obtain efficient structural designs.

When a box beam is subjected to simple bending, most of the load is taken by the flanges. Hence, the basic layout of plating and stiffening of the compression flange depends greatly upon the load to be carried per unit breadth of flange. This loading per unit breadth is given by

$$N = \frac{M}{B\,D} \qquad (1)$$

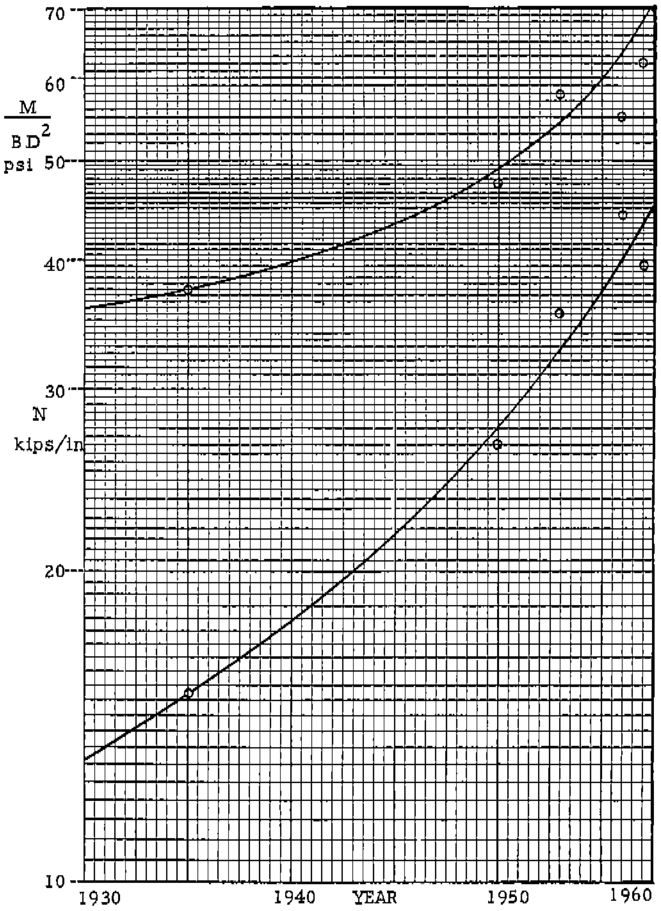

Fig. 24. Maximum loading trends for tanker hulls

where: M = bending moment, B = breadth, and D = depth. Typical values of N that have been plotted in Fig. 24 for tanker hulls, based on nominal design bending moment, indicate an upward trend with time. As discussed below, this trend reflects increases in tanker size and is consistent with the increased thickness of steel plating required in decks and bottoms of modern super-tankers.

If one considers specifically the bending moment caused by waves, use can be made of the expression for the ideal bending moment in regular waves of ship length given in Part II,

$$M = \rho g L^2 BHC \tag{2}$$

where: ρg = density of the water, L = length of ship and wave, H = wave height, and C = a constant depending partly on hull fullness.

By use of Eq. 1

$$N = \rho g\, C_2 H \left(\frac{L^2}{D}\right) \tag{3}$$

If H/L is assumed constant, which can be true only for small changes of L,

$$N = \rho g C_3 \left(\frac{L^3}{D}\right) \tag{4}$$

Both Eqs. 3 and 4 show that L/D is an important factor in determining the loading on the structure. However, indications are that L/D can be assumed to remain constant for a particular ship type on the basis of Fig. 22 and considerations of hull deflection and freeboard. Therefore,

$$N = \rho g C_4 L^2 \tag{5}$$

This indicates the very significant effect of ship length on the loading on the flanges. Hence, the trends to larger ships and faster ships which tend to be more slender (see Part I) must inevitably bring increased structural loads.

In order to design efficiently the compression flanges of box beams, it is convenient to use a structural loading index. This index combines the bending moment M with the external geometrical features of beam B and depth D in the following form

$$\frac{M}{BD^2} = \frac{N}{D} \tag{6}$$

As shown in Section 2, the structural loading index can be used to determine the most efficient arrangement of plating and stiffening system for the flanges in compression.

The trend of M/BD^2 for tanker hulls is shown in Fig. 24. The current value is roughly 60 psi. For purposes of comparison, more lightly loaded ships such as passenger ships and destroyers have values of roughly 15 psi and 5 psi, respectively. On the other hand transport aircraft wings have M/BD^2 values as high as 400 psi. The significance of these values in relation to design will be discussed in Section 2.

Section 2. Static and Quasi-Static Response

by

George Gerard and Herbert Becker

Basic Structural Design

Structural response to static or quasi-static loads will be considered first. These are the loads discussed in Part II, Sections 2 and 4 that result mainly from uneven longitudinal distribution of buoyancy and have constant or slowly changing values which do not involve vibratory effects. The basic structural design of the hull logically proceeds from a knowledge of the overall geometrical and loading features which are set by functional requirements. Once the basic structural layout of the hull has been decided upon, local load distributions can be determined and the detailed structural design should follow as an iterative process as indicated in Fig. 25.

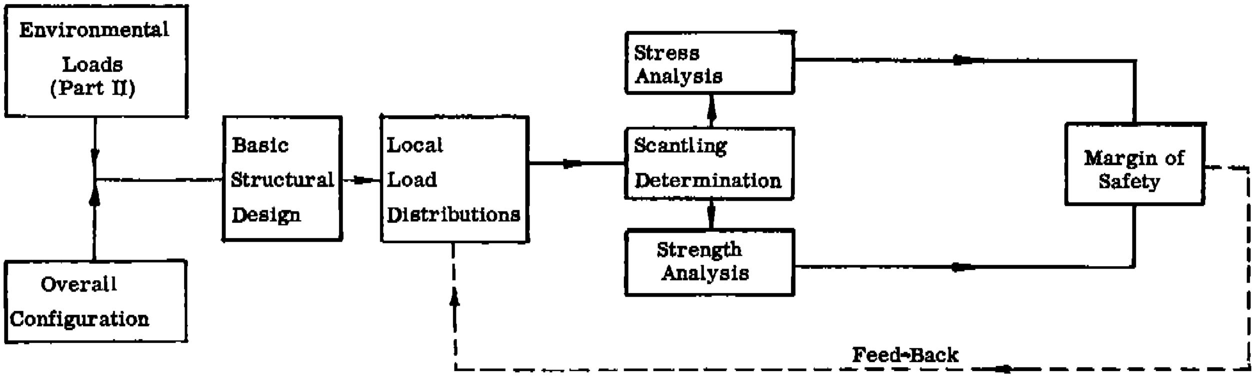

Fig. 25. Structural design cycle

Since the hull is basically a box beam subject to hogging and sagging moments, the upper and lower surfaces of the beam are designed on the basis of compressive and tensile considerations while the sides of the box are designed primarily for shear loads. The preliminary determination of scantlings of the hull structure particularly at the midship section is based primarily upon longitudinal bending strength considerations. In general, the plating and stiffening arrangements for the strength deck and hull bottom should be governed by design for compression strength. In tension, on the other hand, almost all longitudinally continuous material can be designed to be effective and adequate nominal tension strength can be generally obtained with a structure designed for compression. While in principle, tension considerations may be relatively unimportant in the determination of scantlings, experience has indicated that such considerations are of prime importance in details such as hatch corners and continuity of longitudinal members. Brittle fracture and fatigue strength are vitally affected by details of the tension structure as discussed subsequently.

In current ship designs, other external loadings such as horizontal bending, torsion, shear and transverse loads generally have a secondary effect upon the structural design. While such loads may be decisive as far as local details are concerned, the preliminary sizing of the shell and strength deck can generally proceed from longitudinal bending strength considerations. Hence, at this point consideration is given only to the overall compression and tension loads acting on the flanges of the box beam.

Compression Structural Design In the design of the hull bottom and strength deck for compressive loads, buckling considerations play a governing role. Basic information on buckling and failure of plates and shells has been comprehensively reviewed by Bleich[1] for ship construction and more recently by Gerard and Becker[2] for aircraft construction.

The plating serves a contouring function as well as a load-carrying function, and in order to minimize buckling which will lead to ultimate failure a stiffening system of longitudinals and/or transverse framing is required. When the combined plating-stiffening system is considered as a unit, it is usually possible to determine the optimum distribution of material between the plating and stiffening on the basis that the plating and stiffening fail simultaneously.

As shown by Gerard,[3] the optimum design for a particular plating-stiffening system depends upon the loading index M/BD^2, which expresses the design requirements in terms of the bending moment M, beam B, and depth D as discussed in Section 1. As a necessarily brief example of the application of minimum weight principles to a structure similar to a deck, longitudinally stiffened plating supported by transverse frames was considered for a range of M/BD^2 values. The results are

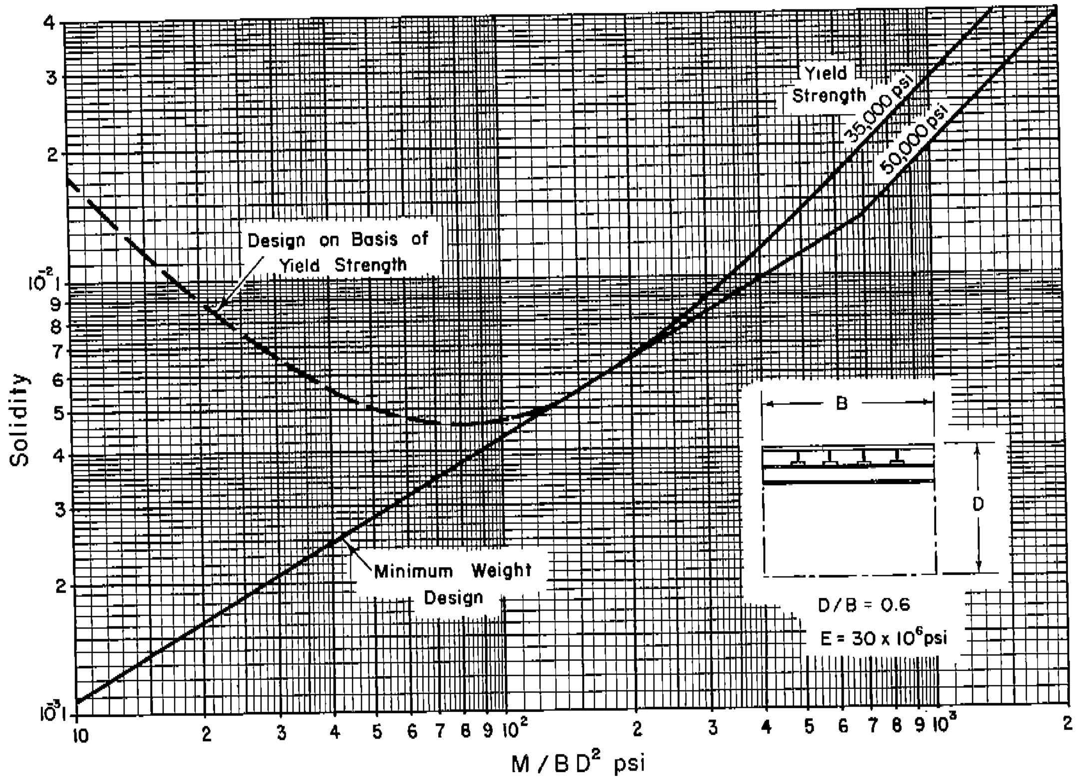

Fig. 26. Minimum weight design chart

shown in Fig. 26 in terms of "solidity" which is the ratio of the weight of the plating-stiffening system relative to the weight of a long solid box of beam, B, and depth, D. The lower curve refers to a plate-stiffening system designed according to structural efficiency principles while the upper one refers to a system designed for a stress level equal to the yield strength of the material. It is apparent that for values of M/BD^2 below 100 psi, which appears to be the range of current ship design practice as shown in Fig. 24, a considerable increase in efficiency is possible through use of the structure of optimum design.

Although this is only one illustrative example, structural efficiency studies can be of further value. For example, the optimum distribution of material between the plating and stiffening can be arrived at for different systems as shown in Table I. It is to be noted that results presented by Gerard[3] prove that transverse stiffening systems are considerably less efficient than longitudinal stiffening systems.

Table I. Optimum distribution of material

Element	Longitudinal plus transverse stiffening	Transverse stiffening only
plating	33%	75%
longitudinals	47	--
transversals	20	25

Further, various stiffening systems can be compared to determine the configuration of minimum weight in particular cases. In addition, the desirability of using materials of higher yield strength in such applications can be readily investigated. As shown in Fig. 26, for values of M/BD^2 less than 160 psi* there is no advantage in using a steel with yield strength above 35,000 psi since buckling is elastic in this range and depends upon the elastic modulus. Only when M/BD^2 is in the range of 500 psi* would the use of a 50,000 psi yield strength steel be desirable. In addition, the desirability of using other types of materials can be investigated with these procedures.

In this brief review, some of the significant contributions of structural efficiency principles to structural design of compression structures were presented. This approach requires extension to the types of construction employed in hull design, particularly for the range of variables encountered in ships. Considerable increase in structural efficiency, particularly in the design of large ships, should result from such a research program and therefore Project 42 is recommended. The possibility of using high-strength steel or aluminum for weight saving also requires consideration. This problem is covered by Project 43.

Tension Structural Design The design of the structure on the basis of compression generally provides adequate tension material to sustain the nominal tension loads if all longitudinal material is continuous. However, the presence of various types of stress concentrations requires considerable attention to structural details to

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*These values apply to the specific details of the problem analyzed in Fig. 26.

insure adequate protection against brittle fracture and fatigue crack initiation and propagation. The load carrying ability under service conditions of the deck or bottom depends primarily upon these weak links. Although specific aspects of this problem are discussed further in this section, it is important at the basic structural design stage of the design cycle shown in Fig. 25 to plan structural details which minimize stress concentrations. This is not a minor consideration to be decided upon in the later stages of structural design. For example, it appears particularly desirable to design areas such as hatch corners in a manner that will permit the critical regions to be fabricated in the shop under closely controlled welding conditions.

Stress concentrations are basically of two types: those of a determinate nature that arise at structural discontinuities such as hatch corners and other cut-outs, and those of an indeterminate nature such as occur at undetected flaws resulting from welding. Stress concentrations constitute high local stress areas where cracks can initiate and ultimately propagate under the reversed loading and variable temperature conditions experienced by the ship in service (see Project 46).

Although there are distinct possibilities of greatly reducing the determinate stress concentrations to insure satisfactory strength for brittle fracture and fatigue, it seems unrealistic from a design standpoint to assume such a possibility for indeterminate stress concentrations.

Every effort must be made to design details in a manner that minimizes the possibility of welding and fabrication flaws. In addition, attention must be devoted to continual improvements in welding and fabrication techniques as well as the development of more satisfactory inspection procedures.

Since these procedures cannot be assumed to be foolproof, there is considerable wisdom in designing the basic structure of the hull in such a manner that cracks can be contained locally to avert catastrophic failure of the complete structure resulting from uncontrolled crack propagation. This is the leading idea in the current development of the fail-safe design philosophy which recognizes undetected cracks as an inevitable consequence of fabrication and service experience.

The proper number and configuration of crack containments introduced into the basic structural design to avoid catastropic failure of the hull requires considerable investigation. The use of crack arrestors must be viewed not solely as a corrective measure for bad designs, but as an essential feature of good design. The design of dual path structural elements as well as efficient crack containment structures constitutes an important aspect of structural design for containment of brittle fracture and fatigue fractures. Research in the area of crack containment design goes hand in hand with the significant metallurgical advances in ship steel during recent years, and therefore Project 44 is recommended.

Shear and Torsion Structural Design Although the design of the hull sides for shear loads requires particular attention in thin-shell ships, it does not appear to present any particularly important problem areas for research. Design methods for stiffened plating under shear loads are available in texts such as Bleich[1] and Kuhn.[4]

Vasta, on the basis of test data presented in Reference 5, concluded that a structure satisfactory for longitudinal bending generally possesses adequate torsional strength. For ships with large hatch openings, however, a design problem may exist in providing adequate torsional strength and rigidity. In such cases, the use of closed cells (such as a double bottom) provides a substantial increase in torsional rigidity.

Local Loads

The basic structural design just discussed is based upon overall loads. Before the structure of a ship can be analyzed, it is first necessary to compute the loading on each component of the structure. This is done from a knowledge of the external loads on the overall structure and the detailed internal design of the structure. Consequently, the determination of local loads follows the calculation of overall environmental loads and the basic structural design as shown on the flow chart of Fig. 25.

Once these local loads have been found by application of available structural analysis techniques it is possible to make initial local scantling determinations. As shown on Fig. 25, this is followed by the stress and strength analysis of the structural components of the ship for the first time around the structural design cycle. The result of this work generally reveals the need for structural redesign, thus requiring redetermination of local loads and scantlings as indicated by the feedback line of Fig. 25. This redesign and analysis process continues until a satisfactory margin of safety is obtained. The subsequent sections describe some of the stress analysis problems, which are then followed by a section on strength analysis.

Factors included are effects of changing section with length, discontinuities and openings, transverse restraints, shear lag, superstructures and deckhouses and torsion problems.

Stress Analysis

In this section a number of problems are discussed which occur in the stress analysis cycle of ship structural design (Fig. 25). A large number of engineering structures can be stress analyzed by use of the elementary methods involving normal stress, bending stress, transverse shear stress and torsional shear stress. These are frequently characterized by their appropriate formulas, P/A, Mc/I, VQ/It and $T/2At$. However, in shell structures that involve the extensive use of plating, such as ships and airplanes, it is necessary to examine structural behavior in more detail than is usual when applying the elementary formulas.

The first problem is termed shear lag* which generally occurs in the type of structure in which the flexibility in shear of the plating prevents rapid diffusion of local loads into the structure. In a second case, the local loads which are applied to frames

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*In this report the term "shear lag" is used to include all those types of structural behavior in which the shear flexibility of the plating influences the stress distribution. This may deviate from the usage in naval architecture in which the term appears to be restricted to the effect on the section modulus for primary hull girder bending stress computations.

attached to shell structures are prevented from developing large bending moments in the frames because the plating acts to resist the tendency for motion of the frame. A third case involves the analysis of a ship under torsion loading where, in addition to the basic shear distribution, shear lag problems may occur and frame action is involved. A basic source on this subject is the text by Kuhn.[4]

Longitudinal Bending The design problem for hull longitudinal bending was discussed previously. However since a ship hull is generally a wide box beam, the problem of shear lag should be considered. Also, shear lag plays a role in hatch stress analysis and hull-deckhouse interaction problems.

Local load redistribution occurs at cutouts such as hatches. This is apparent when one considers a continuous panel under uniform tension. If a section of this panel were removed from the interior, the loads initially in the plating and stiffeners at the cutout would be diffused. This leads to shearing stresses in the deck adjacent to the cutout corners where a stress concentration problem already exists. The problem of stress concentration is treated in detail in a later portion of this section.

It is also necessary to determine the stress distribution resulting from the diffusion of loads into the hull to determine if there is any loss of section effectiveness through shear lag. For ship designs of current proportions, little loss of section effectiveness because of shear lag may be expected as indicated in the data presented in Vasta's paper.[5] However, shear lag considerations may appear in ship designs that depart significantly from the range of current proportions.

Now consider a ship with a deckhouse or superstructure. Obviously at the fore and aft deckhouse ends none of the house structure could be considered as acting to help resist bending in the ship. However some of the structure at the middle of the house could be effective. Consequently, it is necessary to determine the effect of the deckhouse side and top plating in transmitting deck strains into the house.

The factors involved in the hull-deckhouse interaction are the length and height of the deckhouse, the material of which it is constructed, its location fore and aft, and the relative rigidities of the house and hull together with the manner of connection to the deck. Many theoretical and experimental studies are available in the literature. Since the application of these analyses requires a knowledge of relative rigidities that are difficult to determine, recourse to model tests is advisable at the design stage. Suitably instrumented scale models and photoelastic models are recommended as a design procedure rather than as an overall research program.

Torsion Torsion loading can be induced in a ship by running at oblique headings to the seaway. If the ship were to be idealized to an unstiffened shell of constant section with the torques applied to the ends, the torsion loading would be transmitted from one end of the tube to the other by uniform circumferential and longitudinal running shears, $T/2A$. In an actual ship the stress distribution is considerably more complex because of the variations in cross section, cutouts in the plating, the presence of longitudinal and transverse framing, and the structural interaction that usually results when the box beam is subjected to torsion. Furthermore, the shear lag problem is found here also.

A simple rectangular box beam subjected to torsion will generally deform in such a manner that cross sections initially plane before application of torque will not remain plane when torque is applied but will warp. In a constant cross section box, warping will be constant along the box length. If the ends are tapered as in a ship, the effect is to restrain this warping action and to set up bending stresses in the intermediate region of the box.

In addition to these overall effects, torsion-bending effects may be generated when large cutouts occur. The cutout panel is the shear equivalent of the cutout problem in a box beam under bending moment loading.

The complication introduced by the longitudinal and/or transverse framing arises from the interaction of flat plating and stiffening system in diffusing shear loads into the decks and sides of the ship. This corresponds to the diffusion problem for normal loads. It is made more complicated by the shear lag effect that occurs in all diffusion problems in plate-framing structures.

It is apparent that the torsion problem can become quite complex on a ship although the loading may be simplified to concentrated end torques. Actually the water load will vary along the ship and will give rise to a varying torsion loading. This may tend to reduce the region affected by torsion. However, it also imposes requirements on the transverse framing since these components exercise a large measure of control over the diffusion of the twisting action throughout the hull.

Since torsional loads are usually low in hulls of normal proportions, no overall research program on torsional stress analysis is recommended since it is believed that available methods of analysis are generally satisfactory in such cases. In confirmation of the analysis, suitably instrumented scale models and photoelastic models are advisable when unusual torsional problems are encountered in design.

Frame Behavior Available methods of analysis for single frames (including effective breadth of plating) under various types of loading in the plane of the frame are generally satisfactory. However, the common practice in stress analysis of analyzing individual frames for the loads applied to them may be unduly conservative since the supporting effects of the plating are neglected. If there is a stiff transverse bulkhead not far from the frame the tangential deflection of the plating (shown in Fig. 27) is suppressed at the bulkhead. Thus, the plating between the frame and the bulkhead is subjected to shear loading that counteracts the tendency of the frame to deflect parallel to the plating. The result of this action is a reduction of the bending moments in the frame. This effect can be considerable, as shown in Fig. 27 which depicts theoretical and experimental stresses for a frame-stiffened circular cylinder. Although this configuration and loading may not pertain directly to surface vessels, the example illustrates the magnitude of the correction that can be obtained.

As may be seen in Fig. 27, the bending stresses are reduced to a fraction of those obtained from elementary theory in which the shear flow along the frame is determined from VQ/It. Furthermore, the shears are increased in the region of the load to values much larger than VQ/It. The sketch of the deflected frame

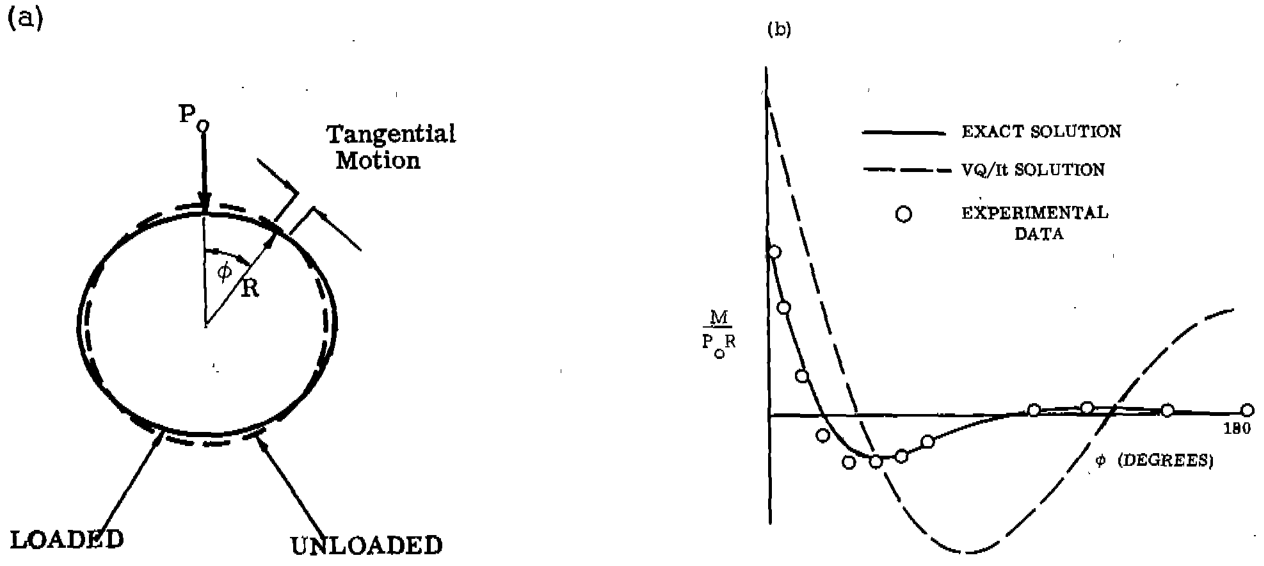

Fig. 27. Bending in a shell supported frame

illustrates how this occurs. At a little distance on either side of the concentrated radial load P the frame has a tendency to move tangentially as well as radially. When the loaded frame lies in a bay between two fairly stiff transverse bulkheads, the plate is unable to accept this tangential motion without resistance to the frame deformation. The result is less tangential motion, greater shear stresses in the plate near the load, and consequently a highly localized bending reaction applied to the frame from the localized plate shear.

An exploratory study appears to be indicated for the problem of frame behavior. Photoelastic models could be built representing typical ship designs. Stresses from these models would be compared to those predicted by the elementary frame theory. If large departures are found between these results, then a detailed research project could be initiated to yield the design data. These approaches are discussed in Project 45.

Cutouts The stresses at a cutout or opening depend upon the in-plane loads near the cutout, the manner in which this loading is distributed in the region of the cutout, and the nature of the reinforcement at the cutout. The first factor controls the average stress while the other two control the magnitude of the stress concentration factor.

For example, a uniform thickness plate would be expected to induce

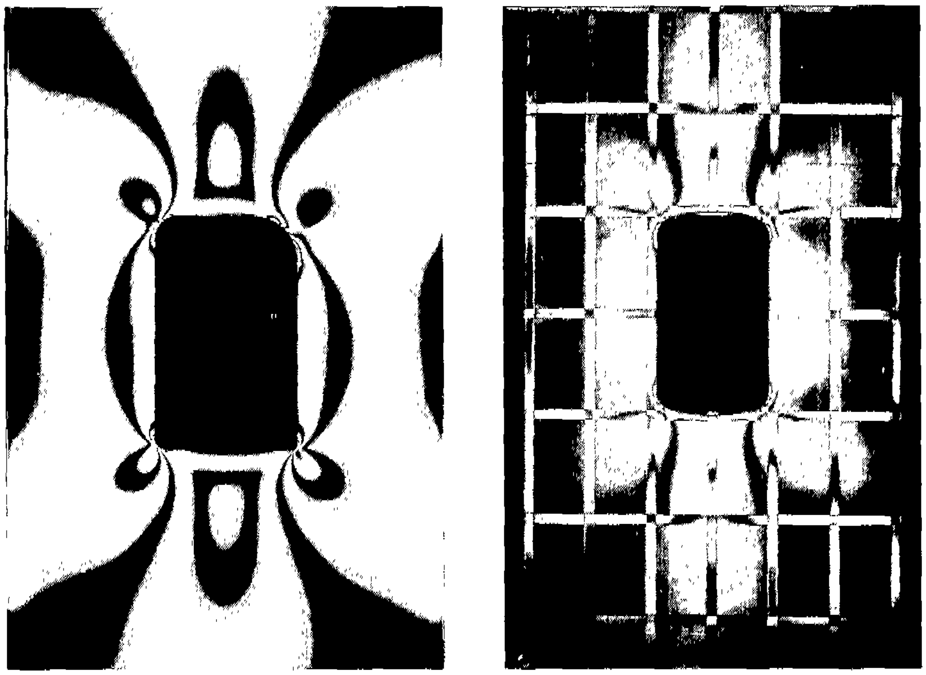

Fig. 28. Photoelastic patterns of stresses around a hatch in a uniform plate (left) and a stiffened plate (right).

higher stresses at a hatch corner than would a structure with a reinforced corner. In addition, a small radius corner would naturally result in a higher stress concentration factor than a large radius corner. The significance of these effects is portrayed in Fig. 28, which contains photoelastic fringe patterns for a uniform flat plate and a stiffened plate. The latter represents an idealized model of a deck stiffened longitudinally and transversely.

The corners of the flat plate are fabricated with four radii which correspond to ratios of radius to hatch width, r/b, equal to 0.04, 0.08, 0.15 and 0.3. The variation of stress concentration with radius is evident in the figure. The corners on the stiffened plate model were formed to $r/b = 0.15$. The concentration factor for the uniform plate was 3.7 for $r/b = 0.15$ while that for the stiffened plate was 1.9. This resultant halving of the concentration factor in the stiffened plate appears to be a result of shear lag effects.

As this exploratory investigation demonstrates, photoelastic investigation of possible hatch designs appears to be a worthwhile research project. It would be a simple matter to study elliptic and spiral arc corners, as well as different types of built up construction. Furthermore, the proper placement of strain gages for full scale structural tests is clearly indicated by the photoelastic fringe patterns. For example, Fig. 28 reveals that the maximum stress is near the tangent points to the corner radii on the hatch sides. There is considerable stress reduction at the centers of the corner arcs and consequently little useful data on peak stresses would be obtained for such a structure from a strain gage placed at that point.

The stress field that is made visible in a photoelastic fringe pattern may be used to determine the stress gradients near hatch corners and also permits calculation of energy distribution near the corner. Both types of information may be useful in brittle failure analysis. Furthermore, the structural performance of a crack arrestor can be observed in relation to the total deck behavior.

Various hatch corner details have been studied under simple tension loading,[6] and some have been shown to be superior to others. However, studies are needed of more effective means of drastically reducing stress concentrations. For example, the deck can be raised between hatches to form a continuous trunk, or aluminum alloy plating might be used between hatches. Many other discontinuities occur in ship structures besides hatch corners, and special photoelastic tests are recommended in dealing with these in the design stage.

As a result of the relatively recent development of new photoelastic materials and modeling techniques, it is a simple matter to construct hatch corners of various configurations ranging from simple flat plates with circular radii to a raised deck between hatches of different material from the main deck, with almost any amount of complexity in the corner detail. The manufacture of such a complex model is made possible as a result of the machinability and cementability of photoelastic models to a degree of refinement that permits reproduction of welding details. The photoelastic research program on hatches is Project 46.

Strength Analysis

Compressive Strength Vasta,[5] in reviewing longitudinal bending static tests on several hulls, reported that failure in all cases occurred by compressive instability:

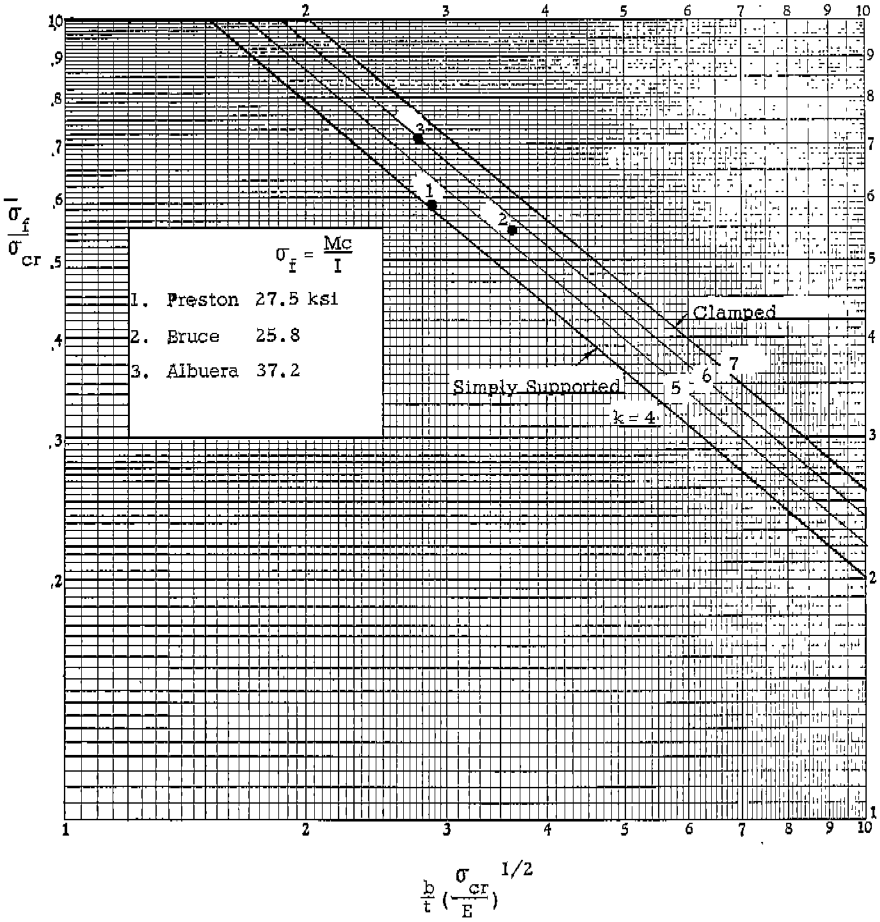

Fig. 29. Compressive instability failure of three ships and relation to predicted values.

one deck failure and two bottom failures. It is most significant that Vasta obtained relatively good agreement between the average compressive stress in the hull at failure (calculated from Mc/I) and the crippling strength of plates that failed after elastic buckling. In all cases, the longitudinal stiffeners along the unloaded edges of the plate must be of a slenderness ratio corresponding to the compressive yield strength.

The results of a rather extensive semi-empirical analysis in Reference 2 concerned with the crippling strength of plates after elastic buckling are shown in Fig. 29. The buckling coefficient values (k) correspond to simply supported (k = 4) and clamped (k = 7) unloaded edges as well as intermediate values of elastic restraint (k = 5, 6). Also shown are the three hull test results summarized by Vasta. It can be observed that the test results are in substantial agreement with the semi-empirical curves particularly when it is recognized that the large longitudinals used in the hull bottoms corresponding to points 2 and 3 contributed appreciable elastic restraint and effectively raised the buckling coefficient k into the range of 5 to 6.

The important conclusion to be drawn here is that it is apparently possible to predict the longitudinal bending strength of hulls to a high degree of accuracy by rather simple methods. The degree of success obtained for the compressive instability case strongly suggests that the methods presented by Kuhn[4] can be used to determine the shear strength of the stiffened plating at the sides of the hull.

In connection with the application of semi-empirical results on laboratory tested plates to the prediction of failure of actual ship hulls, certain problem areas require investigation:

1. The effect of lateral loads (such as hydrostatic pressure) in combination with axial compression upon buckling and crippling strength of plates (Project 47).
2. The typical boundary conditions along the edges of stiffened plating in terms of the buckling coefficient k. This problem is of direct importance in determining the crippling strength of longitudinally stiffened plating. It is believed that sufficient theoretical studies are available to provide a reasonably good engineering answer in most cases.
3. The effects of unfairness (particularly prevalent in welded ships) upon the buckling and crippling strength of plating. Although it is anticipated that a small degree of unfairness would have a negligible influence upon crippling strength, it is important to establish an upper limit of unfairness that can be tolerated in a welded hull (Project 48).
4. The effects of residual stresses caused by rolling of the plating as well as welding upon the buckling and crippling strength of plating. Again, while it is anticipated that a certain level of residual stress may negligibly influence the crippling strength, it is of some im-

portance to establish quantitatively the significance of residual stresses upon compression strength (Project 49).

Tensile Strength In considering the tensile strength of hulls, it must be recognized that the tensile strength measured in a static test is not necessarily representative of tensile strength under service conditions of reversed loading and low-temperature environment over years of operation. Thus, even if failure under test of a hull design in both the hogging and sagging conditions occurred as a result of compressive instability, this cannot be taken as an indication of satisfactory tension strength in service.

Service conditions place particular emphasis on the tensile strength of structural elements containing determinate and indeterminate stress concentrations under reversed loading conditions over protracted periods of time. Because of an embrittlement tendency of steels, special importance is attributed to the strength under low-temperature service conditions, as well as to size effects. The elastic energy available in the structure to cause fracture increases with ship size. Furthermore, the absolute thickness of plating affects its tendency to brittle behavior.

Of major importance in establishing the adequacy of the tensile strength of the hull under service conditions is the tensile strength of structural elements containing indeterminate stress concentrations such as weld flaws. Some of the significant factors included in Project 50 are as follows:

1. Fracture strength required to initiate crack propagation in specimens containing small cracks
2. Fracture strength of such specimens following compression to various nominal stress levels
3. Fatigue strength of such specimens under various cycles of reversed loading
4. Fracture strength of such specimens of various sizes to establish size effects
5. Fracture strength of such specimens under various low-temperature conditions

Stress concentrations of a determinate nature such as occur at hatch corners were covered in the section on stress analysis. It is believed that much can be accomplished to reduce such stress concentrations by proper design. Therefore, determinate stress concentrations do not place an inherent limitation on tensile strength as do those of an indeterminate nature. Thus the principal area of research is one of design and verification by strength tests of complete components including reversed loading and low-temperature conditions, as discussed further in Section 5.

Residual Stresses Residual and locked-in stresses were discussed in Part II. Although their magnitude may reach yield point intensity, they differ from the other static loads or stresses in being essentially local in character and acting in one direction only. Hence, it is expected that they will be at least partly relieved by application and release of load (tension or compression). However, there is a possibility of their influencing the buckling strength, and therefore research is recommended on this point. The extent to which they are relieved in tension loading also requires attention, but it appears tentatively that they are only serious in respect to the possibility of brittle fracture in the presence of a crack or weld defect (Project 50).

Summary of Recommended Research Projects

STATIC AND QUASI-STATIC RESPONSE

Project No.	Title
	Basic Structural Design
42	Application of principles of efficient structural design
43	Investigation of material properties for efficient structures
44	Investigation of fail-safe structures
	Stress Analysis
45	Structural evaluation of hull frame behavior
46	Design of low stress concentration hatch corners
	Strength Analysis
47	Effect of hydrostatic loads on compressive strength
48	Effects of unfairness on compressive strength of plating
49	Effect of residual stresses on compressive strength
50	Effect of small cracks on tensile strength

Project 42: Application of Principles of Efficient Structural Design

Objectives: To apply and extend structural efficiency design principles to the forms of construction and range of geometric variables experienced particularly in the design of the midship section.

Program: Perform theoretical calculations covering a pertinent range of variables and forms of structural arrangements of interest in hull design covering longitudinal and transverse stiffening systems for single and double plating.

Suggested Techniques: Use available theories and extend results (Reference 3) in the form of design charts for use in hull design.

Research in Progress: None known

Results Expected: Rules for the proper proportioning of plating and stiffening to result in efficient structures for the prescribed loading. Comparative efficiencies of various forms of stiffening systems used in hull design.

Project 43: Investigation of Material Properties for Efficient Structures

Objectives: To relate the yield strength levels required to improve the efficiency of structures of various configurations subject to compressive loads.

Program: The importance of using a higher strength steel and other materials such as aluminum to achieve weight reduction in structures subject to buckling depends upon the loading and geometry of the beam as well as the configuration of the plating--stiffening system. Consequently, it is of importance to perform calculations for a typical range of ship variables to determine the conditions under which use of material of increased yield strength or lower density results in a significant weight advantage. This can be accomplished using the approach presented in Fig. 26.

Suggested Techniques: Theoretical calculations

Research in Progress: None

Results Expected: Design charts relating the desirable yield strength of the material to the design conditions.

Project 44: Investigation of Fail-Safe Structures

Objectives: To investigate various approaches to the design of fail-safe structures that will act to contain brittle fracture and fatigue cracks so as to avoid catastrophic failure of the complete hull.

Program: Establish basic engineering design principles for the containment of cracks that originate at various stress concentrations in hulls. Determine optimum configurations for various types of hull designs so that high structural efficiency is obtained.

Suggested Techniques: Develop analytical approaches to the subdivision of tension structures into crack-containing elements.

Research in Progress: None known in the ship structures field that approaches this problem from the design standpoint.

Results Expected: The establishment of basic engineering principles for the design of fail-safe ship structures.

Project 45: Structural Evaluation of Hull Frame Behavior

Objectives: 1) To determine the accuracy of present theory for hull frame stress analysis.

2) In the event of significant disparity between present theory and actual structural behavior, to develop an adequate theory for hull frame stresses.

Program: 1) Perform an exploratory investigation of framed construction representative of present ship design practice by comparing theory with experimental data.

2) Augment present theory, or develop new theory where necessary.

Suggested Techniques: Theory:

1) Elementary frame theory

2) Theory including the deflectional interaction of the frame with the plating

Experiment:

1) Photoelastic models during the exploratory stage and during development of the theory

2) Scale model metal structures to check the theory as applied to prototypes

Design: Construct charts for designer and stress analyst if new theory is developed.

Research in Progress: None

Results Expected: Check adequacy of existing methods of frame design and development of reliable procedure if they are inadequate.

Project 46: Design of Low Stress Concentration Hatch Corners

Objectives: To develop hatch and other cutout designs that minimize stress concentrations.

Program: Make a review of the literature of this problem and evolve efficient structural details that drastically reduce stress concentrations and lead to the most favorable structural behavior, particularly in the vicinity of cutouts. Evaluate alternative solutions economically.

Suggested Techniques: Through experimental stress analysis, supported by elasticity theory where possible, develop hatch design and other cutout details. Upon completion of design program, construct metal prototypes to check results of study by test under reversed loading.

Research in Progress: Some work has been sponsored by the Ship Structure Committee.[6]

Results Expected: Development of sound hatch-corner and cutout details from the standpoint of basic design to minimize the tendency for cracking at hatch corners and permit higher mean stress levels.

Project 47: Effect of Hydrostatic Loads on Compressive Strength

Objectives: To determine the effect of hydrostatic loads in combination with axial compression upon the buckling and crippling strength of long flat plates.

Program: Perform a series of tests covering a range of width-thickness ratios pertinent to ship design on long flat plates under edge compression and lateral pressure.

Suggested Techniques: Although the primary emphasis is on the ultimate strength of the plating, a sufficient number of strain and deflection gages should be employed to indicate the region of accelerated lateral deflections under the combined loads.

Research in Progress: Lehigh University under Bureau of Ships sponsorship.

Results Expected: Test data that can be used to account for the effect of lateral loads upon crippling strength.

Project 48: Effects of Unfairness on Compressive Strength of Plating

Objectives: To determine the effects of initial geometrical imperfections associated with lack of fairness upon the buckling and crippling strength of long flat plates.

Program: Perform a series of tests covering a range of initial geometrical imperfections characterized in terms of variables pertinent to ship fabrication practice.

Suggested Techniques: Introduce characterized initial imperfections of various magnitudes into flat plates and load by edge compression to failure. Use strain and deflection gages to determine the buckling characteristics of the plates.

Research in Progress: None

Results Expected: Test data that can be used to indicate the effect of unfairness upon crippling strength as well as to establish an upper limit of unfairness that can be tolerated in ship design.

Project 49: Effect of Residual Stresses on Compressive Strength

Objectives: To determine if residual stresses attributable to rolling of plating and welding significantly influence the crippling strength of plating.

Program: Conduct a screening program to determine the effect of residual stresses caused by rolling and welding upon the failure of plates in axial compression.

Suggested Techniques: Determine typical values and distributions of residual stresses present in rolled or welded plates and load adjacently located plates in edge compression to failure.

Research in Progress: None

Results Expected: Test data that should indicate the significance of residual stresses upon crippling strength and permit judgement of the importance of a research program in this area.

Project 50: Effect of Small Cracks on Tensile Strength

Objectives: To determine the influence of small cracks upon the fracture strength of various steels used in ship construction under various conditions simulating service experience.

Program: Introduce characterized cracks in specimens of various ship steels and determine the following characteristics under extreme temperature conditions pertinent to ship operation:

a) static tensile strength
b) tensile strength following compression to various nominal compressive stress levels
c) fatigue strength under various cycles of reversed loading
d) effect of size of specimen upon (a)

Suggested Techniques: Laboratory tests of steel specimens under tensile and reversed loading.

Research in Progress: Much of this program is in progress under sponsorship of Ship Structure Committee and at Naval Research Laboratory.

Results Expected: Data indicating the inherent tensile strength of specimens containing small cracks for application to ship structures.

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Section 3. Structural Response to Impact and Reversed Loading

by

S. F. Borg and E. V. Lewis

Background

Impact When a ship is subjected to slamming impact loads, as discussed in Part II, the structural response may be one of large deflection, high stress, and frequently actual damage to the forward bottom that may require expensive repair. However, impact loads are not entirely a local problem, and solutions by improving the structure locally are not only difficult but may actually be dangerous. There is ample evidence that, at least in fast ships, the vibratory hull response following a slam can add appreciably to the hull bending stress. Furthermore, the high strain rate associated with this superimposed stress may have a direct bearing on fatigue and the probability of brittle fracture. Consequently, local stiffening of the forward bottom structure to enable it to withstand greater local slam loadings may increase the likelihood of damage to the main hull structure by adding to the bending stress. Hence, the impact problem must be considered both on a local and overall basis. As in the case of other types of structural response, there are questions of both the optimum layout of the structure and of actual determination of suitable scantlings.

The hull bending stresses amidships following wave impact or slamming can be sizeable. Indeed, because slamming occurs in rough seas, when the wave bending loads are high, it is impossible to consider one type of load without the other. Full-scale ship observations and model experiments have indicated that the structural response to impact loads depends greatly on the elastic properties of the hull, particularly the overall rigidity. A relatively long, shallow, lightly built vessel like a destroyer will generally deflect more under seaway loadings and will have a lower natural frequency of vibration than a cargo ship or passenger ship. It also appears that it is easier for serious superimposed vibratory stresses to develop on a ship like a destroyer, perhaps because of the relationship between duration of impact and natural period of vibration. Considering that these high-frequency stresses are superimposed on the wave bending

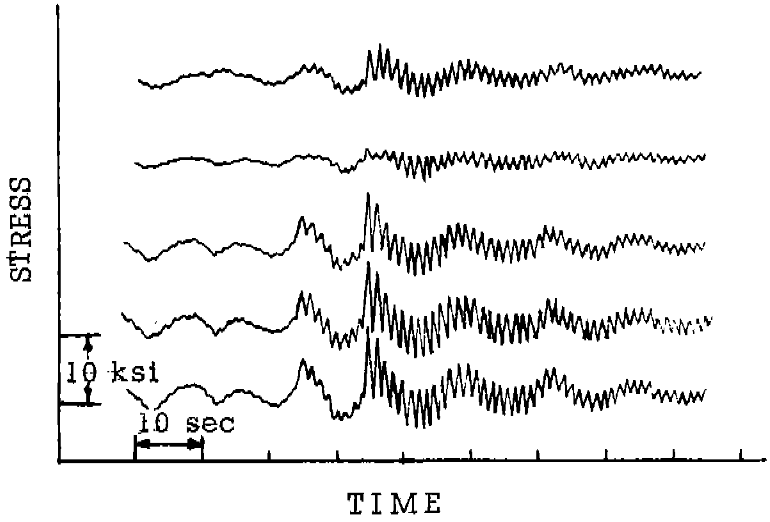

Fig. 30. Extreme case of superimposed slamming stress (records from several points on ship) (Jasper and Birmingham[3]).

stresses, the combined effect may be quite high in a destroyer[1, 2] or in an aircraft carrier[3] (Fig. 30). Although these remarks apply particularly to vertical vibrations, lateral or horizontal vibrations are known to be excited also at sea, with resulting lateral bending.

The seriousness of slamming depends to a large extent also on how the vibratory response is superimposed on the wave bending stresses. Bottom slams, for example, generally do not occur at the instant of maximum wave bending moment. The magnitude of the combined peak stress therefore depends greatly on how quickly the vibratory stress is damped out. The first vibratory mode is most prominent, but vibratory response in other modes may increase the peak value. Strain records obtained on ships at sea show that the damping is much greater for merchant ships than for more flexible naval craft. This is another reason why the superimposed stresses are generally less serious for merchant vessels.

Many ship fractures have occurred under rough sea conditions while slamming was taking place. Because of the importance of a high strain rate on brittle fracture it appears that the rate of application of the slamming load, as well as the overall stress magnitude, may be of considerable significance.

Investigation has shown that the early response of a hull structure to an impact is a complex phenomenon which can best be analyzed in terms of different "periods". Thus, immediately after an impact there is the "period of localized effect", during which the stress and deformation characteristics of the slamming load are predominantly localized in plate panels, floors, girders, etc. and can only be accounted for by considering the separate effects on these structural components. For large slamming loads, the problem may be one of inelastic or plastic action with large deformations.

Following this initial period, there is what may be called a "period of transition". During this period the stress wave is traveling down the hull but the entire structure is not as yet aware of the slamming load. The response is a combination of localized effects and transient longitudinal wave effects, with possible reflections from the near end as well. Therefore, an exact analysis is extremely difficult.

The final period, "period of overall effect," is the usual one for which solutions are given in the literature. The stress wave has had time to be felt by the complete hull structure and vertical or lateral vibrations have become established. These vibrations are sometimes referred to as whipping.

To summarize, the problem of response to impact loads involves, questions of optimum design or layout of the local structure to cope with impact loads and of scantlings for the various members subject to impact. Even more important are questions of layout and scantlings of the main hull to provide for the superimposed vibratory loads. The effect of variation in overall hull rigidity on the vibratory response requires attention, because significant changes in rigidity can be made by changes in depth. Assuming that suitable values of impact loads can be determined (as discussed in Part II), the discussion that follows will concentrate on research studies that will make possible the more efficient design of a structure to withstand these loads.

Reversed Loading In addition to impact loads and stresses, consideration must be given stress reversal, which was discussed in the previous section. The vibratory stresses following a slam are alternating stresses of comparatively high frequency, and in some cases may involve reversal of the combined stresses. A ship's hull is subject to many other stress reversals, and a study of the frequency of occurrence of stresses of different magnitudes and frequency recommended in Part II should help clarify the nature of the fatigue loads. Even long-period variations such as those caused by cargo loading should not be considered as static. And diurnal thermal stress variations and medium-frequency wave bending stresses all contribute to the stress reversal pattern. Although smaller than stresses resulting from wave impact, stresses resulting from vibrating machinery have been known to be of serious magnitude when their frequency corresponded to a natural mode of hull vibration. At present it appears that the fewer very high stress reversals are more serious than the many low or medium-level cycles. In all cases, however, stress concentrations are an important factor. The research problem is to clarify the nature of structural response to the entire spectrum of reversed and alternating stresses and to provide means for allowing for these in design.

Present Status

Impact Our knowledge of the local structural effects upon impact, both in the elastic and plastic range, is limited. However, some work has been done by Greenspon[4] and full-scale data have been obtained by Jasper and Birmingham[5] on the Unimak, but the effects of compressibility of water and elastic deformation of the structure are still in doubt. Considerable advance has been made recently in the field of aeroelasticity, which may prove of value in relation to the hydroelastic problems. More theoretical work is needed, however, and experimental verification is essential.

Little attention has been given to the problem of response in the period of transition, i.e., while the elastic stress wave is traveling through the structure. However, some preliminary work has been done at DTMB and at ETT.

The structural analysis of the overall ship structure subject to a slam, i.e., the ship's response during the "period of overall effect," has been treated as a problem in vibration analysis. The general, elementary idealized theory of vibration has been well known for some time and was described by Rayleigh.[6] A large amount of literature that exists on ship vibrations caused by steady harmonic excitation is primarily directed toward the evaluation of the vibration frequencies.[7-9] The slam analysis, however, is a complicated problem, since it involves pulse-type loadings and is complicated by the effects of virtual mass of the water and damping of the vibrating structure.

The existing state of knowledge of hull vibration strains following an impact is briefly summarized in the monograph by Korvin-Kroukovsky.[10] Theoretical work has taken three general directions. In one, discussed by Mathewson,[11, 12] and McGoldrick et al,[8] the time histories of vibrations are traced computationally, using step-by-step integration. In the second, a detailed mathematical analysis of the process is attempted by considering the resultant vibration as composed of a number of characteristic vibrations. This process has been described by Frankland,[13] Ormondroyd et al,[14] and Ochi.[15,16] The third is based upon conservation of energy considerations and has been developed by Borg[17] at ETT. It is applicable to the elastoplastic as well as the elastic range.

In the first approach it is necessary to assume a constant damping value. This approach is in opposition to the experimental results reported by Lockwood Taylor[7,18] and Kumai[19] which show a rapid increase of damping with increasing frequency. Although this approach was reported to have given good results in the analysis of steady-state ship vibrations, it appears to be less suitable for studying the conditions immediately following an impact. A UNIVAC program is available at DTMB for solving problems in detail, however, with the constant damping limitation.

Because it is sufficiently detailed, the second approach has the potential to explain rationally all aspects of ship vibration. Solutions are available for the damped vibrations of any mode. However, the practical application of these solutions requires:

(1) further consideration of how to apportion the effects of the exciting impulse to various modes

(2) greater knowledge of the damping at different frequencies.

Ochi[15, 16] applied two different methods of dynamic analysis to item (1), while Kumai[19] has recently given some useful contributions to item (2). In general, this second approach starts with the fundamental equation of a vibrating beam, either in its most approximate form, with shear and rotary effects neglected, or in its more exact form which includes these effects. The authors then consider the different simplified control conditions, boundary conditions and loading conditions, and obtain their solutions.

Borg has made an investigation at ETT of various portions of the overall slamming problem including time-effect, damping, model scaling, and elasto-plastic effects. In addition, he has developed a third method of analysis based upon energy considerations which enables one to determine the slamming response in the period of transition as well as in the period of overall effect. Borg's method[17] utilized strain energy concepts and, by apportioning strain energy in various symmetric and anti-symmetric modes, any response characteristic such as shear, moment or deflection can be obtained approximately in a relatively simple manner. However, none of the methods can solve the problem during the period of localized effect.

Solutions by the various methods give different results.[20] Indeed, one of the major problems in the field of slam analysis is determining which of the many different solutions is the most satisfactory. Actual evaluation can only be obtained by comparing the various results with actual test data.

Because of the importance of damping, special consideration must be given to the state of knowledge on this subject. A slam introduces energy into the ship hull and the resulting vibrations would exist indefinitely if damping were absent. Because of damping, energy is withdrawn from the system, which in turn reduces the amplitude of vibration. There seem to be four possible major modes of dissipation of energy from a vibrating ship hull, namely:

(1) internal friction in the steel hull subjected to alternating stress cycles

(2) fluid friction in the boundary layer adjacent to the ship hull

(3) wave or ripple formations on the surface of the ocean

(4) friction and slip in the lap and butt-riveted joints of the hull. (This factor, of course, does not enter into modern welded ship analysis.)

Calculations of the energy losses in these different modes has confirmed experimental results that internal friction or hysteresis damping accounts for the major part of the damping.[7]

The problem of determining the energy loss from internal friction in a stressed member is probably most thoroughly discussed by Zener.[21] In the case of a vibrating ship hull, one may formulate the problem in terms of the so-called internal friction, tan δ. It can be shown for small values of internal friction that,

$$\tan\delta = \delta = \frac{1}{2\pi} \frac{\Delta E}{E}$$

where E is the strain energy in a transversely vibrating member when the strain energy is at its maximum, i.e., when the deflection is at its maximum, and ΔE is the strain energy dissipated per cycle.

The most accurate determination of δ for steel probably has been given by Bennewitz and Rotger, as noted in Zener.[21] It is shown that δ is a function of frequency of vibration. Nevertheless, the fundamental mechanism of hysteresis is not fully understood, and it appears that the damping in a complicated ship structure differs greatly from that indicated in tests on simple bars.

Reversal of Loads Figure 31 taken from Low,[22] shows the typical behavior of mild steel under reversal of load. It shows that a comparatively small number of load reversals can seriously affect the endurance when the elastic limit is exceeded. This situation occurs in ship hulls at points of stress concentration, as described by Vasta,[23] and it also might occur elsewhere in the structure if high safety factors were not maintained. In simple tensile loading a stress concentration can be re-

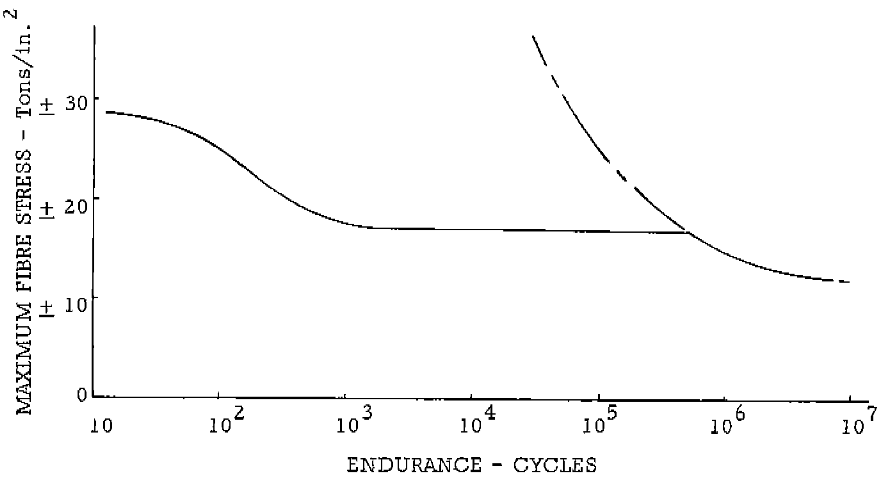

Fig. 31. Typical endurance curves for mild steel (Low[22]).

lieved by plastic flow, but if a sufficiently high compressive load is applied to cause plastic flow in the opposite direction, the relief will be only partial and/or temporary. Also, a fairly small number of stress reversals in the plastic range can cause failure. In fact, some writers maintain that all fatigue failures involve plastic flow on either a macroscopic or microscopic level. Comparatively little attention has been given to this problem of so-called "low-cycle" fatigue.[24]

High-cycle (low-stress) fatigue in ships has been discussed by Weck,[25] who concludes that it probably has not been a serious factor in ship fractures, though it should not be neglected. Extensive literature exists on the subject of fatigue in general, and a great deal of work is in progress that undoubtedly has a bearing on the ship problem. This work covers such important topics as the basic mechanism of fatigue, corrosion fatigue, effects of residual stresses and stress concentrations, and the effect of impact or strain rate.

Needed Research

It is believed that research should be directed at increasing understanding of the response of ship structures to impact loads and stress reversals. The ultimate objective is to provide adequate methods for designing ship structures so that they can withstand these local and overall effects.

Since exact theories for various slamming problems are extremely complicated and can be solved if at all, only by electronic computers, experimental results must play an important part in the overall study of slamming phenomena. Two major reasons for the experimental work are:

(1) to verify approximate theories where these have been proposed

(2) to obtain useful design data in those cases where no theory is available

Model testing is preferable to full-scale testing from many standpoints, providing it is possible to properly scale a model for impact conditions. Considerations of scale effect indicate that, in general, it is possible to properly scale models for the studies of slamming responses. However, internal damping introduces great difficulties. There are significant differences in the time histories of the slamming strain recorded on ships at sea and on models tested in towing tanks. In ships, the strain maxima last from 30 to 60 cycles. High vibratory stress values therefore are superposed on several consecutive wave bending moment cycles. In models, on the other hand, the vibratory strain sometimes seems to be attenuated so rapidly that its superposition on the wave bending moment strain is of minor importance. Investigation of the phenomenon of damping in structures generally indicates that there is a frequency dependency that introduces an appreciable scale effect in the models tested. Since the use of models is evidently necessary if rapid progress is to be made, a complete rational understanding of the above phenomenon is needed. Results obtained by Zener[21] on the vibration of bars indicates that a reduction in damping takes place at very high frequencies, and this discovery may provide an answer to the scaling problem.

Full-scale measurements are also needed on specially instrumented ships--either laid up or in service--to establish the relationship between measured loads and structural responses, thus testing the validity of current theoretical and experimental studies. However, long-range statistical studies are not believed necessary as in the case of the study of simple wave bending loads.

A. Local Impact Methods should be developed for analyzing the local structural components in the elastic and elasto-plastic ranges of dynamic response both to obtain an optimum structural layout and to determine the necessary scantlings

(Project 51). The possibility that a more flexible structure might be more effective in resisting impact loads than a very rigid one also should be investigated. To explore this possibility certain refinements must be introduced in the usual treatment of impact loads. The effect of the deflection of the plating panels, girders and floors on the local pressures must be included, as well as the energy absorption ability of the structure and the effect of the small compressibility of the water. These hydroelastic considerations are probably of particular importance in the case of flat or very nearly flat bottoms. Once the best arrangement of the structure to withstand impact loads has been determined, the experimental and theoretical results can also be applied by the designer to the determination of scantlings required.

B. Overall Response A graded approach to the problem of a ship's overall response to a slam including the "period of transition" is suggested. It is believed that most rapid progress will be made by comparing the results of theoretical reasoning with experimental data for a simple case first, and then proceeding to the ones of increasing complexity. Attempts to compare the results of incompletely developed theories prematurely with the experimental data on a body as complex as a ship are not considered advisable. In fact, such a procedure is considered dangerous because of the probability of false conclusions resulting from an incomplete understanding of the subject.

On the basis of the above reasoning, a laboratory project is suggested (Project 52). Tests on full-scale ships are cumbersome, and the conditions of testing are so complicated that the correlation of theoretical and experimental data is uncertain. Such tests are necessary, however, as an overall check of experiment and theory, and it is recommended that a full-scale project be planned and carried out after experience with laboratory procedures has been obtained (Project 53).

It is tentatively suggested that four basic models be used in the experimental work. A steel bar of uniform rectangular or round section would serve as the first model. Theoretical data appear to be developed mostly for such a simple body, and its use is expected to provide the most direct correlation with the theory. However, the relationship of shear and flexural deflection may be an important part of the impulse response theory, and this relationship may be different in a ship-like structure than in the solid bar model. As an intermediate step in the development, the use of a moderately thin-walled tube for the second model is suggested.

The use of a built-up box girder is recommended for the third model. This is expected to reproduce the important structural properties of a ship's hull, without attempting to reproduce the details. Particular attention should be paid to the relationships between the area of the structural material to the overall section area, the relationship between width and height, and the proportion of the material in the skin and the longitudinal stiffening members.

A complete ship model would serve as the fourth test model. Ochi's[16] description of model construction can be taken as a practical example of a structure that is simple but which, nevertheless, preserves the important properties of a true ship. Modifications in size and structural detail must be made, however, to provide correct scaling of structural responses. The calculation of vibration responses of a model so complex in sectional properties and weight distribution may prove to be beyond the power of available analytical methods. Experimental results will provide an indispensable target for further analytical development. Furthermore, the test data and analysis procedure will serve as a valuable guide in planning experiments on full-scale ships.

C. Damping Since hysteresis damping plays such an important role in the ship structural response to impact loads, further investigation is needed of the fundamental mechanism involved. A suitable theory should be developed for determining the damping which can be verified by comparison with ships and/or model experiments. If models are used, particular attention must be given to the scaling of damping effects (Project 54). Since lateral impacts or irregular forces are known to cause lateral vibratory responses, these tests should include measurements of lateral as well as vertical components.

D. Reversal of Loads It is felt that research on the subject of high-cycle fatigue is well covered in the structural field, and therefore no specific projects should be included in this program. However, low-cycle fatigue appears to be of particular importance in ship structures, because of the possibility of local high stresses at points of stress concentration and residual stresses. It will become increasingly important if attempts are made to develop more economical structures. Consequently, it is believed that <u>experimental work on reversed loading</u> of specimens representing ship components with stress concentration should be an important part of the research program (Project 55).

<u>Results Expected</u>

On the basis of the research described, it should be possible to arrive at satisfactory methods of determining the local and overall response of a ship to slamming loads. These methods can then be applied to selecting L/D ratios, improving structural layouts and determining design details and scantlings.

Summary of Recommended Research Projects

STRUCTURAL RESPONSE TO IMPACT AND REVERSED LOADS

Project No.	Title
51	Investigation of local structural response to impact loads
52	Prediction of elastic response of ship structures to variable hydrodynamic loads
53	Full-scale observations of elastic response of ship hulls
54	A study of the hysteresis damping of hull vibrations
55	Tests of ship structural members under load reversals

Project 51: Investigation of Local Structural Response to Impact Loads

Objective: To obtain information on optimum layout of structures subject to im-impact loading and to devise suitable design methods.

Program: Carry out tests of typical and modified sections of ship bottoms in order to determine loads, deflections, and stresses at impact with the water surface. The following cases are tentatively suggested:

(1) a typical section of a merchant ship bottom (preferably one in which slamming damage has been experienced)

(2) the same section with increased plating support obtained by additional longitudinals

(3) an alternative design to (1) in which large areas of plating are supported in such a way as to have comparatively large deflections under load

Attention should also be given to the expected gain in strength of plating panels built with some initial concavity or dishing.

Theoretical methods should then be applied to the calculation of the stresses for comparison with observed values. Empirical correction factors and compressibility effects should be introduced as necessary to obtain agreement between theoretical and observed data so that design methods will be provided. An attempt should be made to ascertain the extent to which the elastic limit is raised at critical points by high strain rates associated with impacts.

Suggested Techniques: A portion of a full-scale ship bottom or a large-scale model should have a section instrumented with suitable pressure and strain gages from which loads can be obtained by integration. Bottom structures should be dropped on the water surface to obtain measurable impact loads. Recording equipment, as well as gages, must be capable of accurately recording data at the high speed of the impact.

Research in Progress: Project SR-154, being initiated by the Ship Structure Committee at the University of California, Berkeley, will include these studies on large models.

Results Expected: Conclusions regarding the most suitable structural layout to resist impact loads, and methods for determining scantlings when impact loads are specified.

Project 52: Prediction of Elastic Response of Ship Structures to Variable Hydrodynamic Loads

Objective: To establish methods of evaluating the time history of a ship's deflections and stresses during vibrations following a slam, taking cognizance of the various vibration modes and of the different damping in each mode.

Program: Closely coordinated theoretical and experimental studies of three or four simplified models of successively increasing complexity, perhaps as follows:

(1) a steel bar of uniform rectangular or round section, in approximately "free-free" condition
(2) a thin-walled tube, both in air and floating on water
(3) a built-up box girder, reproducing important structural properties of a ship's hull but not details, properly scaled for slamming response
(4) a complete ship model, reproducing a ship in essential details, i.e., in plating and wide-spaced stiffeners, bulkheads, inner bottom, decks, properly scaled for slamming response

Measurements of strains or deflections resulting from a known impulse should be made at several positions along the model length. Analysis should be directed at (1) the evaluation of damping coefficients and comparison with theory, and (2) a detailed comparison of the time history, after the application of the impulse, with that calculated by various available theoretical methods. Conclusions should be drawn as to the most suitable methods of predicting the transient elastic response of a ship to hydrodynamic loads, and as to the effects of the relative rigidity of the hull.

Suggested Techniques: The steel bar can be tested in a "free-free" condition by suspending it on a number of long springs of very low spring constant. The thin-walled tube can be tested in the same condition and also floating half-immersed in water. The other models can be tested afloat and measurements of strain or deflection made at several positions along the length, avoiding nodal points in all modes as much as possible. The gages and recording equipment must have a sufficiently high frequency response. Methods of recording data should be such as to simplify analysis.

For theoretical work, the various methods discussed in Part III, Section 3, can be applied. Allowances for scale effects should be made in comparing theoretical with experimental results.

Research in Progress: Theoretical work at DTMB, ETT and NACA. Ship model tests at NSMB, and planned at DTMB. The Ship Structure Committee is initiating Project SR-154 at the University of California, Berkeley, which will include Items (1) and (3) of the program.

Results Expected: A better understanding of the nature of the transient elastic response of ship hulls of differing rigidity to an impulse, and conclusions regarding the most suitable method of predicting response for design purposes.

Project 53: Full-Scale Observation of Elastic Response of Ship Hulls

Objective: To obtain full-scale data on the elastic response of ship hulls to impact loads for comparison with theory and experiment.

Program: Observations of superimposed hull bending stresses and shear at various locations following slamming should be made aboard a number of different ships. This work can perhaps be combined with the project for measuring impact loads discussed in Part II, Section 3. Measure lateral bending stresses also when they occur. In addition, tests should be made on ships in port, in which known impact loads are applied and the response recorded by means of strain gages. These should provide information on damping for comparison with model tests and theory.

Suggested Techniques: Strain gages should be installed at a number of points in the ship and connected to recording instruments capable of making accurate continuous records of high- and low-frequency responses, including the 6th to 8th modes. When sea data are taken, provisions should be made to turn on the recording instruments when slamming is imminent. Pressure data should be obtained over shell plating panels in order to permit an estimate of the impact loading.

Research in Progress: DTMB is making measurements aboard ship and comparing them with calculations.

Results Expected: A more complete picture of the nature of elastic response of a ship hull to impact loading, both vertical and lateral, and a compilation of data suitable for comparison with theory and model experiment.

Project 54: A Study of the Hysteresis Damping of Hull Vibrations

Objective: To develop an acceptable method for determining the damping of hull structures subjected to slam loading.

Program: (1) Make theoretical studies directed toward obtaining a more complete knowledge of the hysteresis phenomenon and develop theoretical expressions for internal damping that are applicable to ship structures. (2) Using full-scale ships and/or properly scaled models, perform vibration tests to check methods for determining damping in the various modes, including rotation. (3) On the basis of tests, develop design methods that are suitable throughout the range of frequencies important in vibration analyses of ship hulls.

Suggested Techniques: Theoretical investigation of internal damping should start with consideration of loss of energy in internal friction in solid bars and then extend to the case of stiffened shell structures such as ships.[21] A thorough study of pertinent literature will, of course, be essential at the beginning of the project.

Experiments for verification involve the application of a known impact load and comparison of the damping coefficients observed with those predicted. In the case of full-scale tests, vibration generators may perhaps be used for consideration of damping in the steady-state condition. In the case of model tests, simplified models can be used to facilitate comparisons with theory, but scale effects must be taken into account. (Data obtained in Project 52 can also be used.)

Research in Progress: Much work has been done on damping lately as part of the broad field of "solid state physics" and it is very likely that techniques used in this field will be applicable to structural damping.

Results Expected: To provide basic information that will permit damping effects to be correctly included in the structural analysis of a vibrating hull.

Project 55: Tests of Ship Structural Components Under Load Reversals

Objective: To obtain a better understanding of the response of ship structural components to stress reversal beyond the elastic limit.

Program: Carry out laboratory tests of simplified ship structural components under alternate tension and compression for the following cases:

(1) geometric stress concentration (as at a corner)
(2) residual stress (as along welded seam)[26]
(3) plate panels subject to buckling

Suggested Techniques: Large specimens should be subjected either to reversed tension and compression loads or to reversed bending loads at low frequency. Different load amplitudes should be applied, providing local peak stresses varying from yield point to the ultimate strength. Means should be provided for evaluating the local stress concentrations or residual stresses. Theoretical methods should be applied to the test results in order to obtain generalized conclusions regarding the endurance strength in relation to the initial stress and applied load. Attempts should be made to correlate results with experimental data on tests of steel specimens in low-cycle fatigue.

Research in Progress: A project at the University of Illinois for the investigation of low-cycle endurance strength of steel; fatigue testing of plates with holes at bracket connections, JJW Nibering, Delft Technical University.

Results Expected: Basic information regarding the behavior of ship structures under load reversal and conclusions for improved design.

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Section 4. Thermal Response

by

R. B. Zubaly

Introduction

Temperatures affect ship structures in three ways, namely:

(1) Residual stresses result from temperature-induced expansions resulting from welding, burning and flame-straightening during construction or repair. (See Part II, Section 4 and Part III, Section 2.)

(2) The probability of brittle fracture is increased by the metallurgical effects of low temperatures on many structural steels. (See Part III, Section 2.)

(3) Thermal stresses result from uneven temperature gradients in the structure.

The temperature distributions or gradients in a ship hull resulting from its thermal environment have been discussed in Part II, Section 5. If the structure is completely free to deform, these gradients will result in expansion or contraction of the structure without creating stresses, as in the case of an unrestrained steel bar immersed in a hot or cold fluid. Because of the complex nature of a ship structure, each part of the structure exercises some restraint on the expansion or contraction of adjacent structures. Therefore, when uneven temperature gradients are imposed on the structure, not only deformations but also thermal stresses result. This section will deal with the theoretical and experimental determination of these stresses and their verification by full-scale measurement.

Present Status

A theory has been established for the calculation of thermal stresses in girders and ships if the temperature gradients in the structure are known, and a number of methods of calculating them have been developed. The methods of

Hurst,[1] Corlett,[2] Jasper,[3] and Timoshenko and Goodier[4] all have been applied to ship structures. Hechtman[5] has reviewed these methods and other current literature on thermal stresses and strains in ships and has listed an extensive bibliography. These thermal stress calculations have all been for two-dimensional cases, i.e., longitudinal gradients were neglected. However, according to Meriam a three-dimensional theory is available.

Correlation of theoretical calculations with model tests have been found to be good by Corlett[2] and Jasper,[3] and a significant amount of full-scale experimental work on a laid-up ship has shown rather good agreement with theory according to Meriam et al.[6] However, no measurements of ship temperatures or thermal stresses have been made on ships at sea.

Hechtman[5] calculated the thermal stresses existing in a number of ships at the time of structural failures and estimated the probable contribution of these stresses to the failure.

Needed Research

The two-dimensional thermal stress theory has been successfully verified by observations, but it is believed that stresses may be appreciably greater if longitudinal thermal gradients are included. Longitudinal gradients can result from heating of oil in tanks, steam cleaning of tanks, refrigerated spaces, etc. Accordingly, a method should be developed to calculate the stresses for the case of three-dimensional steady-state temperature gradients, including the longitudinal variation of temperatures. The effect of bulkheads and web frames on thermal stresses must also be investigated since they restrain thermal expansion in transverse directions. The development of models and techniques of applying known thermal gradients to them should be done in order to check the theory (Project 56).

Three-dimensional calculations can also be verified by a limited amount of full-scale measurement. Such tests would best be carried out on a laid-up ship having gages disposed longitudinally on the hull and on bulkheads, tank ends, and other members, rather than only on a single transverse section

(Project 57). In addition, means of minimizing thermal stresses should be considered.

It has been generally noted that many major failures of ship structures occurred at a time when the temperature was changing rapidly. That is, temperature gradients in time as well as in space were present. However, it is believed that the resulting space gradient is the significant factor rather than the rate of change of temperature.

Thermal stresses can reach significant levels, and they were reported by Hechtman[5] to be a significant factor in nearly half of the ship failures he studied. An extension of his work of determining the contribution of thermal loads and stresses to past ship structural failures should prove valuable for comparing the conditions causing failures with those predicted by theory (Project 58). Data from ship logs, weather stations and solar radiation data by hindcasts as mentioned in Part II, Section 5 should be used to determine the environmental conditions at the time of the failure. The thermal gradients could then be calculated by the methods stated in Project 40, and the thermal stresses could be determined by the methods described in Project 56.

Results Expected

As a result of this research, knowledge of the effects of temperature gradients on the stresses in ship structures will be more complete. Design methods to minimize thermal stresses will be developed.

Summary of Recommended Research Projects

THERMAL RESPONSE

Project No.	Title
56	Stresses resulting from thermal gradients (steady-state)
57	Full-scale thermal stress measurements
58	Analysis of cases of ship structural failures

Project 56: Stresses Resulting from Thermal Gradients (Steady-State)

Objective: To develop a satisfactory method for calculating the stresses in a ship hull resulting from temperature gradients in three dimensions, with particular attention being given to the effects of lateral restraint and local heating.

Program: Extend available two-dimensional thermal stress calculation methods to the three-dimensional case where longitudinal temperature gradients are included. In addition, take into account the effect of bulkheads and heavy web frames on restraining free thermal expansion in the transverse direction. Carry out model tests where possible and compare the results with theoretical calculations. Apply these methods to possible means of reducing thermal stresses.

Suggested Techniques: The extension to the three-dimensional case should use current theoretical methods along with an electronic computer to facilitate the solution. Calculations for the effect of lateral restraint should be included. A simple structural model with several bulkheads and means of heating various sections may be useful for verification of the three-dimensional calculation. Use may also be made of photo-thermoelasticity techniques.

Research in Progress: The S-10 Panel of the SNAME has suggested a study to develop three-dimensional stress calculations as part of its six-phase program, but the study has not yet been started.[7]

Results Expected: The program should yield a reliable theoretical calculation method for temperature stresses, including the effects of longitudinal temperature gradients and lateral restraints. Hence, means of reducing thermal stresses may be suggested.

Project 57: Full-Scale Thermal Stress Measurements

Objective: To measure thermal stresses in a laid-up ship in order to verify the theoretical calculation of stresses resulting from temperature gradients in three dimensions and having lateral restraint effects included.

Program: Instrument a laid-up ship in order to obtain temperature and stress readings on several transverse sections, on bulkheads, and other members. Compare the measured stresses with those obtained by using the calculation methods developed in Project56 for the same given temperature distribution.

Suggested Techniques: The instrumentation should consist of thermocouples to measure temperature and SR-4 resistance wire strain gages to measure strains for the calculation of the stresses. In addition to instrumenting the transverse sections, enough gages must be disposed in a longitudinal direction in order to establish the longitudinal temperature gradient so that the three-dimensional theory can be checked. Additional gages should also be installed on bulkheads and on the shell in the vicinity of bulkheads to check the lateral restraint effects, and at points of structural discontinuity to check the effect of stress concentrations. Measurements should be made in heated or cooled compartments and nearby to determine the effects of heating or cooling oil or other cargo.

Research in Progress: University of California recently completed two-dimensional work which covered measurements at only one transverse section.[6]

Results Expected: A limited amount of full-scale measurement of temperatures and stresses in a laid-up ship should be sufficient to provide a good check on the theoretical calculation of thermal stresses, including three-dimensional gradients and lateral restraint.

Project 58: Analysis of Cases of Ship Structural Failures

Objective: To determine thermal environmental conditions attending past cases of ship structural failure, and to calculate the thermal stresses that existed at the time of the failures.

Program: Survey the records of past ship structural failures to determine in which cases thermal stresses may have been instrumental in causing the failure.[8] Determine the environmental conditions present in each case and calculate the thermal stresses that would result.

Suggested Techniques: Sea and air temperatures, wind direction, and ship heading can be taken from ship logs at or near the time of the fractures. Cloudiness and solar radiation intensity may be deduced by the hindcast method described in Project 39. From these known environmental conditions, the temperature distribution in the hulls can be calculated by the method described in Project 39, and the stresses by the method mentioned in Project 56. Analysis of the thermal stresses in the vicinity of the fracture may reveal the possible importance of temperature conditions in ship failures.

Research in Progress: None

Results Expected: An analysis of meteorological and other thermal conditions present at the time of major ship structural failures. From these the resulting thermal stresses can be determined and used in future design work.

Sequence: This project can proceed when accurate methods of hindcasting solar radiation intensity are developed. (See Project 39 and Part II, Section 1.)

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Section 5. Structural Design Philosophy and Procedures

by

George Gerard

Introduction

In the process of translating loads experienced during the anticipated service life of a ship into an efficient structural design, there are several major problem areas to be resolved:

a) determination of design loads and stresses separately and in combination
b) factors of safety
c) structural integrity tests

From a broad standpoint, successful resolution of these problem areas can have a considerably more profound effect upon structural integrity and efficiency than many of the individual research projects discussed previously. These problems were reserved for the last section because it appeared to be most desirable to present as complete a picture as possible of the various aspects of ship structural design before discussing the inter-relationship of these aspects.

It is important to recognize at the outset that many of these problem areas cannot be resolved in the predictable future by research alone. A suitable combination of research, experience and balanced judgement is required. Above all, a devoted attempt must be made to resolve clearly each of the problem areas that are involved in the ultimate goal of a rational approach to the structural design of ships. It is believed that considerable progress has already been made in this area in the design of naval vessels.

In an attempt to make this discussion more meaningful, certain procedures are offered as suggestions rather than as concrete proposals. They are offered as a means of focusing attention on critical problem areas in order to provide a basis for deliberation. If they stimulate discussion, they will have served the function intended. Somewhat different from the previous sections of this report, the discussions of this section do not readily lead to definite research projects that can provide decisive answers. The resolution of many of these problem areas requires approaches other than research, and consequently no specific projects are recommended.

The environmental factors leading to loads were discussed at considerable length in Part II and in order to avoid extensive repetition here the reader may be well advised to review Part II at this point. The research program of Part II is directed toward obtaining a reasonably complete knowledge of environmental loads. It is the intention here to deal with certain aspects of structural design philosophy in translating these environmental loads into design loads by use of suitable factors of safety.

For this purpose, we shall treat those factors, that can be best considered in terms of loads (seaway, static, and slamming loads) separately from those best considered in terms of stresses (thermal, residual, fabrication and erection stresses). In addition, it is necessary to distinguish between single loads of extreme value determined on a probability basis and repeated and reversed loads represented in a spectral form. Finally it is important to account for the loads caused by natural phenomena (seaway loads) as distinct from those to some degree under the control of the ship's master (cargo and slamming loads).

Design Philosophy

A tentative scheme of design requirements is given in Fig. 32. It expresses the general philosophy that a well-designed ship shall not fail in any of the following ways:

A. Overall failure by compressive instability under extreme loads.

B. Extensive plastic flow under extreme tensile loads.

C. Low-cycle fatigue cracking under reversals of extreme loading at points of stress concentration.

Each of these items will be discussed in turn, followed by an additional case to be avoided:

D. Propagation of brittle fractures and/or local high-cycle fatigue cracks.

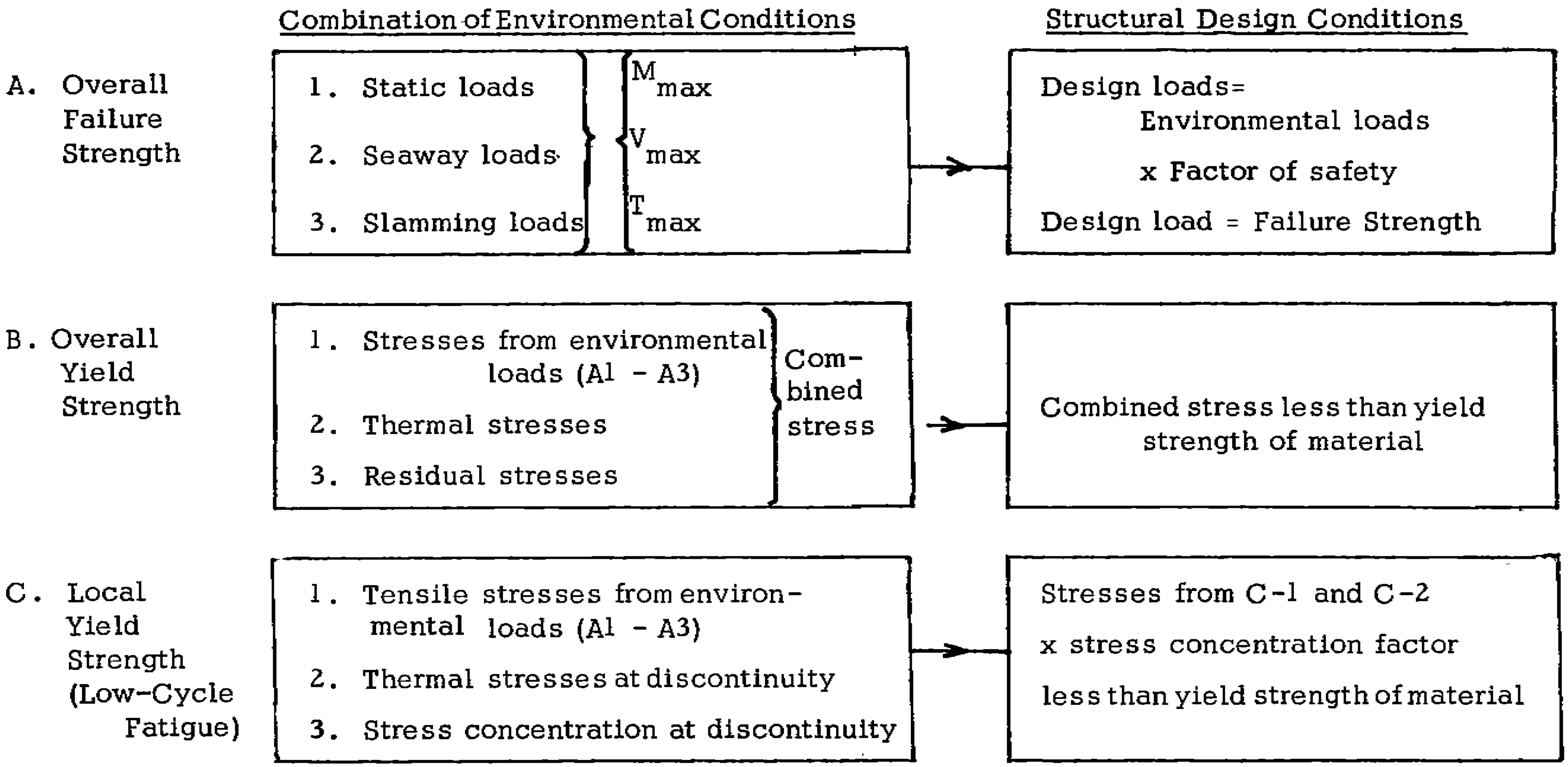

Fig. 32. Structural design philosophy

A. <u>Failure Strength Under Extreme Loads</u> Following the research program described in Part II, it can be assumed at this point that we will have a reasonably complete knowledge of the extreme environmental loads and stresses. There are many possible methods of combining these loads and stresses into structural design conditions. The approach offered here is primarily for the purpose of discussion.

We are concerned first with extreme values and their relation to failure of the hull, which in static tests generally occurs by compressive instability. Items such as thermal stresses, residual stresses and stresses associated with lateral loads and unfairness of plating affect buckling. However, in all probability they have a negligible influence upon ultimate failure by compressive instability and, therefore, only the main environmental loads need be considered in relation to overall failure strength. In order to clarify the effect of the various stresses upon the compressive strength of plating, however, several projects were recommended in Part III, Section 2.

Following the general outline presented in Fig. 32, the static and still-water loads (which are readily determined) should be combined with seaway loads (which are statistical in nature). Also included should be the contribution to longitudinal bending resulting from slamming. Although it may be contended that slamming is controllable by the ship's master, overall structural integrity considerations demand that the maximum probable slamming contributions to longitudinal bending be included.

The environmental loads can now be combined as discussed in Part II in terms of maximum bending moments, shears and torques distributed over the ship's length. As shown in Fig. 32, the structural design loads can be obtained by multiplying the environmental loads by a suitable factor of safety. Local loads on main structural components must also be considered, as discussed in Section 2. In an efficient structural design, the design load and failure load should be equal throughout the structure.

It is certain that the choice of suitable factors of safety for various structural components of the ship encompasses a great area of controversy which requires considerable study and deliberation. There is no point in engaging in an extended discussion here because it does not appear that research alone can provide the required answers. However, it may be noted that with a reasonably complete knowledge of loads, adequate quality control of materials and fabrication procedures, relatively exact methods of stress and strength analyses, and suitable structural integrity tests, the aircraft industry has successfully used a factor of safety of 1.5. For aircraft, the stringent procedures associated with a safety factor of 1.5 are completely justified in terms of the economic value of a pound of weight saved.

In the design of large and/or fast ships where weight may assume the importance that it does in aircraft, there can be economic justification for using the procedures necessarily associated with a factor of safety of 1.5. For most merchant ships, considerations of maintenance and repair, such as discussed in Part III, Section 1, must be included in obtaining a balanced judgment of the most economical design under a prescribed set of design requirements.

In addition, special safety considerations are involved in the design of those portions of the structure subject to corrosion. Again, economics will dictate whether a weight penalty in the form of a corrosion allowance is justified in place of protective methods such as the use of stainless steel, stainless clad steel plating, or special coatings.

It is believed that in analyzing the various factors involved in arriving at suitable factors of safety, statistical methods will be of great significance. In particular, the use of probability theory in determining environmental loads has been discussed in Part II. Likewise, it can be used to determine allowable strength levels for materials and for quality control of fabrication.

B. Yield Strength Under Extreme Loads In addition to failure strength in compression, it is necessary to consider overall yield strength in tension, in order to avoid extensive permanent distortion of the major hull structure. It is at this point that thermal and residual stresses enter the picture.

As shown by item B in Fig. 32, the combination of environmental conditions considered here includes the stresses resulting from the previously discussed environmental loads (not including a factor of safety) plus those thermal stresses and residual stresses resulting from fabrication and erection that have an effect on main structural components. In all cases, we are concerned here with overall stresses rather than highly localized stresses such as those that occur in weld zones.

The pertinent structural design condition is that the combined stress resulting from all these component stresses should not generally exceed the yield strength of the material. Should it be determined that considerations of yield strength in tension rather than failure strength in compression govern, then it would certainly be advisable that design measures be employed to reduce thermal and/or residual stresses.

C. Local Strength under Reversed Loads While overall yield strength considerations are important in terms of permanent distortion, local yield strength considerations (item C in Fig. 32) in regions of stress concentration are of considerable significance to low-cycle fatigue, as pointed out in Section 3. In order to avoid low-cycle fatigue problems, it appears desirable to limit the maximum tensile stresses to the yield strength level at structural discontinuities, cut-outs, hatch openings and hull-deckhouse locations. Methods of stress analysis to determine local stresses at critical points in the structure are discussed in Section 2. The effect of indeterminate stress concentrations such as weld flaws can only be evaluated at present by suitable tests on large-scale structural components as discussed in a later paragraph.

As shown in Fig. 32, the pertinent environmental conditions for local yield strength include stresses caused by environmental loads (static, wave and bending) plus thermal stresses, all of which involve reversals about different mean values. The tensile stress multiplied by the appropriate stress concentration factor at a discontinuity should not exceed the yield strength of the material as a design condition. It appears necessary to establish the value of the stress concentration at the discontinuity at the design stage by photoelastic studies or suitably instrumented scale model tests. Residual stresses are not believed to be significant here because local plastic flow sufficient to relieve them will not contribute to low-cycle fatigue.

Slamming loads are generally recognized to be controllable to a large extent by the ship's master. Since local bow damage generally does not affect the overall structural integrity, it appears possible to design the forward structure for pressure loads considerably less than possible extreme values. This may be permissible if suitable restrictions for limiting slamming are prescribed. In such cases the local design load should include the controllable level of integrated environmental pressure multiplied by a suitable factor of safety.

D. Life Expectancy Considerations In contrast with failure strength under extreme loads which primarily depends on compressive instability, questions concerning life expectancy of the structure are governed by tensile considerations. In dealing with brittle fracture, the pertinent environmental condition is the ambient temperature. In fatigue* considerations, the cyclic loading spectrum, such as can be obtained from load investigations discussed in Part II, consititutes the significant environmental condition.

Both brittle fracture and fatigue focus particular attention on material characteristics, on determinate stress concentrations associated with structural discontinuities, and on indeterminate stress concentrations such as at weld flaws. Research is needed to clarify many aspects of these problem areas, including continued studies of structural mechanics, metallurgy, welding techniques, inspection methods, and design details (all of which are included in the Ship Structure Committee's research program). Nevertheless, it appears that structural integrity tests of full scale components containing structural discontinuities are a necessary adjunct to structural design. Although this approach may at first glance appear revolutionary, it should be noted that testing of typical ship structural components is by no means uncommon.

In this connection the following tests appear to be desirable as steps in rational structural design:

a) Establish validity of crack containment structural design by testing at low temperatures representative large-scale models containing typical weld flaws. A realistic cyclic loading spectrum should be used.

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*Here "fatigue" is considered in the conventional or high-cycle sense.

b) Establish life expectancy of full scale components containing structural discontinuities using the pertinent cyclic loading spectrum. These components should be constructed utilizing typical shipyard welding procedures, since weld flaws in the high-stress regions at structural discontinuities are of particular importance here. It is necessary to use full scale components because of the significance of size effects in brittle fracture and fatigue.

Rational Ship Design Procedures

In order to bridge the gap in years between research and its application in design, it is essential that work be undertaken to formulate new design rules and design procedures after research discussed in this report has progressed significantly. This process of interpreting research results in terms of a workable design philosophy requires a concerted effort if significant results of research are to be realized quickly.

It is anticipated that the classification societies and other established regulatory bodies (as well as naval design establishments) will continue to keep abreast of research developments in the ensuing years. Furthermore, it is hoped that the uncertain areas of knowledge will be sufficiently clarified by research to permit steps to be taken at the appropriate time toward the formulation of new, more rational design rules. Some suggestions may be offered at this time as to steps that may prove to be desirable. First, the requirements for the structure of ship hulls can undoubtedly be formulated in more explicit terms than in the past. Some of the requirements can probably be very definite regarding conditions the structure must be able to withstand in service, as for example the possible distribution of cargo in still water. Others pertaining to weather and sea conditions may have to be expressed in statistical terms, such as a probability of one serious structural failure in so many thousand ship years of service. The latter approach is being developed in various structural fields and is tacitly accepted in the ship field where a certain small number of ships are lost per year for various reasons, including structural failure.

Next, methods of determining explicitly and combining all the environmental loads for design purposes should be adopted. For conventional or normal ships, formulas and graphs can be prepared that will give the most extreme values of total bending moment, shear, and torsion to be assumed, as well as maximum thermal and residual stress values. For unusual ships, theoretical calculations and model tests can be applied to the determination of suitable values of environmental loads.

On the basis of this more exact knowledge of the environmental loads, less conservative but more reliable factors of safety can be selected to obtain the design loads. Methods used for determining structural arrangements and scantlings appropriate to the design loads are not believed to fall exclusively within the cognizance of the classification societies. (Hence, this point is discussed below.) However, the means of verification of the design, or the determination of whether or not the structure can be expected to meet the design loads, certainly does fall within their province. Perhaps in the future such verification can be based on a suitable presentation of structural analysis data, supported by full-scale and/or laboratory experimental results. Obviously an entire ship cannot be subjected to a proof-test, but critical components or standard details can be.

As a distinct separate phase of rational ship design, consideration should be given to the problem of practicable and efficient structural design procedures to implement the design philosophy outlined; these procedures should be related to the new type of design rules recommended (see Section 2). Knowledge gained from this research program must ultimately be assimilated and incorporated into actual design use in simplified form. To this end it is recommended that a special group be formed representing designers, shipbuilders, classification societies, other regulatory bodies, and research investigators. The objective of this group would be to devise and continuously improve design procedures. In doing this a distinction should be made between conventional or normal designs and unusual ships requiring more individual treatment. The first problem to consider will be convenient methods for determining optimum arrangements of structure, i.e., spacing of beams and stiffeners, balance between plating and stiffener sectional areas, etc. The second problem will be methods for determination of scantlings of individual members. Both of these steps involve an iterative process such as suggested in Fig. 25 in Part III, Section 2.

This long-range research program in ship structural design will have achieved its purpose if it stimulates the research necessary to permit the clarification of a new and rational design philosophy, which in time will be implemented by new design rules and procedures.

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APPENDIX

LIST OF RECOMMENDED RESEARCH PROJECTS

List of Recommended Research Projects (Continued)

COMMITTEE ON SHIP STRUCTURAL DESIGN
Division of Engineering & Industrial Research
National Academy of Sciences-National Research Council

<u>Chairman</u>:

N. J. Hoff
Head of Department of Aeronautical Engineering
Stanford University

<u>Vice Chairman</u>:

M. G. Forrest
Vice President-Naval Architecture
Gibbs and Cox, Inc.

<u>Members</u>:

G. F. Carrier
Division of Engineering & Applied Physics
Harvard University

C. O. Dohrenwend
Dean of Graduate School
Rensselaer Polytechnic Institute

J. M. Frankland
Consultant, Mechanics Division
National Bureau of Standards

L. G. Straub
Director, St. Anthony Falls Hydraulic Laboratory
University of Minnesota

Dana Young
Dean, School of Engineering
Yale University