

SHIP STRUCTURAL DESIGN

A Rationally-Based, Computer-Aided Optimization Approach

OWEN F. HUGHES

*Department of Aerospace and Ocean Engineering
Virginia Polytechnic Institute and State University,
Blacksburg, Virginia*



Published by
The Society of Naval Architects
and Marine Engineers
601 Pavonia Avenue
Jersey City, New Jersey 07306

Copyright © 1988 by The Society of Naval Architects and Marine Engineers.

The opinions or assertions of the authors herein are not to be construed as official or reflecting the views of SNAME or any government agency.

It is understood and agreed that nothing expressed herein is intended or shall be construed to give any person, firm, or corporation any right, remedy, or claim against SNAME or any of its officers or members.

Library of Congress Card Catalog No. 88-62642
ISBN No. 0-939773-04X

Previously published by
John Wiley & Sons, Inc., 1983

*To my parents,
Earl and Marion*

PREFACE TO THE SNAME EDITION

As noted in the first Preface and also on page 3 of the text, this book was intended primarily as a textbook, but at the time of its first edition there were two factors that largely prevented it from fulfilling this role. Firstly, there is the need for low cost, so as to fit within a student's budget; but for a large book of a technical nature and with a relatively small number of students, this is simply not possible. I believe that the publishers of that first edition, Wiley/Interscience, did an outstanding job, and I am deeply grateful to them for the obvious skill and high standard of quality which they devoted to it. But precisely because it was a first edition, with all the associated setup costs, combined with the small market, it was quite impossible to produce the book as a "low price" item.

The second factor that has limited the book's role as a textbook is the lack of tutorial and review problems at the ends of chapters. But this was the direct result of the economic situation described above; from their experience the publishers knew that the primary market for a higher priced book of this type would be libraries, government agencies, and other large organizations involved in ship structural design, all of whom would use the book mainly as a reference rather than a textbook, and adding tutorial material would have just increased the cost still further. Having assessed the market, the publishers selected the number of copies to be printed accordingly, and when the last copy was sold in December 1987, the sales profile showed that they had judged it perfectly. They therefore declined to go to a second printing, whereupon the copyright reverted to the author.

This opened up an opportunity to overcome the two obstacles to the book's intended role as a textbook. To

overcome the cost obstacle the author donated the book negatives and the copyright to SNAME, without royalty, and SNAME on its part agreed to make a second printing on a non-profit (cost recovery) basis. However, it was obvious that much of the cost savings would be lost if the book were to be altered either by adding tutorial problems, or by updating various chapters (although fortunately, it has been possible to correct the errors that had been found in the first printing).

Therefore, in order to supply both the tutorial problems and the updating, Professor J.B. Caldwell and the author have begun collaborating on the first of a series of small, low-price booklets, each dealing with a specific topic and containing updated material, worked examples and problems with answers. The booklets will be published by SNAME, and it is hoped that some of them will involve other authors as well.

Although the book's title is *Ship Structural Design*, nearly all of its material is directly applicable to "marine structures" in general. Therefore the booklets will include examples and problems relating to other types of marine structures as well as ships, and the series will be entitled *Marine Structures: Selected Topics, Examples and Problems*.

To the acknowledgements in the first edition, I now wish to add my thanks to those students and colleagues who took the trouble to point out errors, and I am grateful for this opportunity to rectify them. Special thanks in this regard are due to M. Dominique Beghin of Bureau Veritas.

OWEN F. HUGHES

Washington, D.C.
July 1988

PREFACE

For a structure as large and as complex as a ship there are three levels of structural design, the second and most central of which is the subject of this book. Concept design deals with the topology or overall geometry of the structure; preliminary design establishes the scantlings (structural dimensions) of all principal structural members; and detail design is concerned with local aspects such as joints, openings, and reinforcements. Overall structural geometry is generally determined by overall design requirements rather than by structural requirements, while detail design is largely guided and constrained by fabrication methods and requirements. Also, since local structural details are numerous and basically similar among various structures they lend themselves to standardization and to design from handbooks and structural codes. Thus, it is in preliminary design where the structural designer has the largest number of significant decisions and options, and the greatest scope for optimizing the structure so that it best fulfills the objectives and satisfies all of the various constraints and requirements.

Rationally-based design is design from first principles using the tools of modern engineering science: computers and the methods of structural analysis and optimization which computers have made possible. Thus, the rationally-based approach is ideally suited for preliminary structural design, and it is this approach and this level of design that is the subject of this book. As shown by some examples in Section 1.3, this type of design offers substantial benefits to all parties concerned: owner, designer, builder, and operator.

Designing from first principles requires two separate and very extensive analyses: a response analysis to ascertain the true and complete response of the structure to all loads and load combinations, and a limit state analysis to ascertain all of the possible limit or

failure values of these responses. Taken together these two analyses are by far the dominant part of rationally-based design, and this is reflected in this text in which 15 of the 17 chapters are devoted to various aspects of analysis. Because of this predominance of analysis, rationally-based design is necessarily computer based and this is the key to many of its benefits: speed, accuracy, thoroughness, economy, easy modification, and so forth. Also, as explained in Section 1.3, the necessary computer programs are already available and the hardware and software costs are quite moderate.

Of the many different topics and aspects in preliminary structural design some are an inherent part of rationally-based design (e.g., the aspects pertaining to response analysis and limit analysis) while others are more distinct and external (e.g., the selection of materials) or are simply constraints in the optimization process (e.g., the avoidance of some natural frequency). One of the advantages of the rationally-based approach is that it unifies and coordinates these many different aspects. Even for the more distinct or external aspects the rationally-based approach provides a framework by which each can be better coordinated with the other aspects.

Because there are so many aspects to preliminary design it is simply not possible to treat all of them in detail in one book. Therefore, the author's plan is that the subject should be covered in two books, of which this is the first. This book deals with the methodology of rationally-based design and with its two major components; response analysis and limit analysis. These aspects are presented in such a way that this first book is complete in itself, and does not rely on or require the second book for understanding.

PREREQUISITES, LEVELS OF STUDY, AND TIME REQUIREMENTS

The material in this text is suitable for either graduate or undergraduate study, or a combination of both. The only prerequisites are knowledge of mechanics of solids, strength of materials, and the basic aspects of matrix algebra and of statistics. If necessary, the latter two could be covered in a few introductory classes or in outside reading. The total time required to cover all of the topics in this book is about eight semester hours. For undergraduates and for persons with only the basic

prerequisites a six semester hour course can be achieved by omitting chapters 4, 6, 10, 15, and 17 and skimming chapters 8 and 16. For persons who have already completed some courses in structural analysis (covering, say, columns, plate bending and buckling, frame analysis, and the finite element method) all of the remaining topics could be covered in four semester hours, by omitting chapters 5, 7, 9, 11, and 12 and skimming chapters 6 and 10.

*Sydney, Australia
June 1983*

OWEN F. HUGHES

ACKNOWLEDGMENTS

I would never have been able to write this book without the kind help and encouragement that I have received from many people—both within and outside of the field of ship structures—through the many years of its preparation. So many persons have helped in various ways that it is simply not possible, in this limited space, to acknowledge and thank each of them individually. To all of them I would like to offer my most sincere and heartfelt thanks. I am deeply grateful for their help, and even more for the kindness and generosity which motivated and accompanied it.

But there are some persons who deserve a very special thanks and acknowledgment. I am deeply grateful to Professor Farrokh Mistree, now at the Georgia Inst. of Technology, for his generous and cheerful friendship, for his many valuable suggestions and unstinting help and encouragement, and in particular for the many valuable contributions which he made in the computer implementation of the design method presented herein. Special thanks are also due to Dr. Vedran Zanić of the University of Zagreb, who also contributed in all of these ways. Other academic col-

leagues to whom I am also grateful for reading drafts of chapters and offering valuable suggestions and corrections are Professors J. R. Paulling (Berkeley), J. B. Caldwell (Newcastle), M. K. Ochi (Florida), and P. Terndrup Pedersen and J. Juncher Jensen (Tech. U. of Denmark).

I am also very grateful to Mr. Stanley Stiansen and the senior research staff of the American Bureau of Shipping for the strong encouragement and support which they gave at a relatively early stage in the development of the design method. This early and sustained support was of immense help.

And finally I wish to offer special thanks to Mrs. Diane Augée for having unfailingly provided such speedy and flawless typing of the manuscript through all of its many drafts and revisions over the past six years. Her outstanding professional skill, and the characteristic thoughtfulness, patience, and cheerful enthusiasm which she has contributed throughout have been of immeasurable help, and constitute a major contribution to the work.

O.F.H

CONTENTS

1. Rationally-Based Structural Design, 1
2. Loads, Response, Limit States, and Optimization, 51
3. Hull Girder Response Analysis—Prismatic Beam, 78
4. Wave Loads—Statistical, Dynamic, and Nonlinear Aspects, 129
5. Matrix Stiffness Analysis: Frames and Grillages, 180
6. Hull Girder Response Analysis—Nonprismatic Beam, 218
7. Basic Aspects of the Finite Element Method, 242
8. Hull Module Modeling and Elastic Analysis, 267
9. Plate Bending, 332
10. Orthotropic Plate Bending and Application to Double Wall Panels, 368
11. Buckling and Ultimate Strength of Columns, 390
12. Buckling and Ultimate Strength of Plates, 404
13. Elastic Buckling of Stiffened Panels, 440
14. Ultimate Strength of Stiffened Panels, 465
15. Structural Instability: Nonlinear Frame and Finite Element Analysis, 487
16. Plastic Frame Analysis, 508
17. Ultimate Strength of a Hull Module, 541

Ship Structural Design

RATIONALLY-BASED STRUCTURAL DESIGN

1.1 INTRODUCTION

We are at present in the midst of a gradual but profound change in the philosophy and practice of ship structural design. The growing demand for more efficient marine transportation has already produced significant changes in ship sizes, types, and production methods. For example, since 1960 many new ship types have appeared, such as lng carriers, multihull vessels, barge carriers, ro/ro vessels, surface effect ships, and hydrofoils. This process of change will almost certainly continue because there are so many factors which give rise to it and stimulate it. Some examples are:

The need for adequate protection against pollution and for adequate safety with respect to dangerous cargoes

New trade patterns, cargoes or tasks, which introduce special problems or lead to unusual ship geometry or proportions

The development of designs for standard ships which are to be produced in larger numbers and hence require a greater degree of cost efficiency

The development of a wide variety of other types of floating structures for the extraction of ocean resources and for other uses of the sea

The complexities of modern ships and the demand for greater reliability, efficiency, and economy require a scientific, powerful, and versatile method for their structural design. In the past, ship structural design has been largely empirical, based on accumulated experience and ship performance, and expressed in the form of structural design codes or "rules" published by the

various ship classification societies. These rules provide simplified and easy-to-use formulas for the structural dimensions, or "scantlings," of a ship. This approach saves time in the design office and, since the ship must obtain the approval of a classification society, it also saves time in the approval process.

However, there are several disadvantages to a completely "rulebook" approach to design. First, the modes of structural failure are numerous, complex, and interdependent, and with such simplified formulas the margin against failure remains unknown; thus one cannot distinguish between structural adequacy and overadequacy. Therefore, such formulas cannot give a truly efficient design and in some cases the extra steel may represent a significant cost penalty throughout the life of the ship.

Second, these formulas are only aimed at avoiding structural failure, but there are usually several ways of achieving this and the particular way which is implied in the formula may not be the most suitable in regard to the specific goals of the ship owner or the particular purpose or economic environment of the ship. A true design process must be capable of accepting an objective, of actively moving toward it, and of achieving it to the fullest extent possible.

Third, and most important, these formulas involve a number of simplifying assumptions and can be used only within certain limits. Outside of this range they may be inaccurate, and the history of structural design abounds with examples of structural failures—in ships, bridges, and aircraft—which occurred when a standard, time-honored method or formula was used, unknowingly, beyond its limits of validity.

For these reasons there is a general trend toward "rationally-based" structural design, which may be defined as

Design which is directly and entirely based on structural theory and computer-based methods of structural analysis and optimization, and which achieves an optimum structure on the basis of a designer-selected measure of merit.

Thus rationally-based design involves a thorough and accurate analysis of all of the factors affecting the safety and performance of the structure throughout its life, and a synthesis of this information, together with the goal or objective which the structure is intended to achieve, to produce that design which best achieves the objective and which provides adequate safety. This process involves far more calculation, but that can be more than offset by using computers. For this reason, rationally-based structural design is necessarily computer-based, semiautomated design.

This type of design was first developed and applied for aircraft and aerospace structures and it continues to have its greatest application in these areas because of the predominant economic significance of structural weight, and hence structural efficiency, coupled with the obvious need for very high structural reliability. In land-based structures the move toward this approach was given strong impetus in the 1970s by a series of structural failures of steel box girder bridges, which showed that for the larger and more slender bridges the existing empirically based design codes were inadequate. In the ocean environment, an elementary form of this approach is already used for the design of offshore structures, partly because there is little or no previous experience on which to rely, and partly because of the high economic stakes involved. In this area, as well as in ship structures, the classification societies have encouraged and contributed greatly to the development of rationally-based methods.

Rationally-based design is definitely not fully automated design, that is, a "black box" process in which the designer's only role is to supply the input data, whereupon the process presents him/her with a finished design. This type of design requires that all design decisions—objectives, criteria, priorities, constraints, and so on—must be made before the design commences, and many of these decisions have to be built into the program, making it difficult for the designer to even be aware of them, much less to have control over them. Rather, of its very nature rationally-based design must be interactive. The designer

must always remain "in charge" and be able to make changes—in his/her objectives, criteria, constraints, priorities, and so on—in the light of intermediate results. Therefore, a rationally-based design process should allow the designer to interrupt, go back, make changes, call for more information, skip some steps, and so forth.

From all of the foregoing it is obvious that rationally-based design gives the designer much more scope, capability, and efficiency than ever before. But it does require a computer—either a workstation or a modern PC—and it requires a basic knowledge of structures (e.g. the fundamentals of finite element analysis, and the basic types of structural failure) together with some experience in structural design (theory alone is not enough). Given these requirements, then the deciding factor in choosing the rationally-based approach is whether and to what extent a product and/or a performance (economic or operational or both) is desired that goes beyond what is obtainable from the rule-based approach. The latter is simpler, but it is non-optimal and non-adaptable. Thus the two approaches are complementary and a good designer will use whichever is more appropriate for a given situation.

Preliminary Design and Detail Design

In a ship structure, as in most structures, the principal dimensions are usually not determined by structural considerations but rather by more general requirements such as beam and draft limitations, required cargo capacity, and so on. For this reason structural design usually begins with the principal dimensions already established, and the designer must determine the complete set of scantlings that provide adequate strength and safety for least cost (or whatever other objective is chosen). Structural design consists of two distinct levels:

1. Preliminary design, which determines the location, spacing, and scantlings of the principal structural members[†]
2. Detail design, which determines the geometry and scantlings of local structure (brackets, connections, cutouts, reinforcements, etc.)

[†]For naval vessels this is termed "contract design."

Of these two levels, the rationally-based approach has more relevance and more potential benefits in regard to preliminary design because:

- a. This level has the greatest influence on the structural design and hence offers very large potential savings.
- b. This level provides the input to detail design and the benefits of the latter are strongly dependent on the quality of this input.

In fact, rationally-based preliminary design offers several kinds of potential benefits. The economic benefits are illustrated by the tanker example quoted in Section 1.3, in which the rationally-based approach gives a 6% savings in ship structural cost compared with current standard designs (which for a large tanker represents a savings of over one million dollars) and an even greater amount of extra revenue from the increased cargo capacity arising from weight savings. Naval vessels can obtain greater mission capability by a reduction of weight and/or vertical center of gravity. Ship designers gain a large increase in design capability and efficiency, and are able to concentrate more on the conceptual and creative (and more far-reaching and rewarding) aspects of design. And finally, there are also substantial benefits to be gained in ship structural safety and reliability.

This is not meant to imply that detail design is less important than preliminary design; it is equally important for obtaining an efficient, safe and reliable ship. Here also there are many benefits to be gained by applying modern methods of engineering science, but the applications are different from preliminary design and the benefits are likewise different. Since the items being designed are much smaller it is possible to do full-scale testing, and since they are more repetitive it is possible to obtain the benefits of mass production, standardization, methods engineering, and so on. In fact, production aspects are of primary importance in detail design.

Also, most of the structural items that come under detail design are similar from ship to ship, and so in-service experience provides a sound basis for their design. In fact, because of the large number of such items it would be inefficient to attempt to design all of them from first principles. Instead it is generally more efficient to use design codes and standard designs which have been proven by experience. In other words, detail design is an area where a rule-based approach is very appropriate, and the rules that are

published by the various ship classification societies contain a great deal of useful information on the design of local structure, structural connections, and other structural details.

Aims and Scope of the Book

As indicated in the Preface, this book is the first of a coordinated pair of books on ship structural design, and it presents a methodology for rationally-based design and all of the analysis aspects of such design. Now that we have defined the term "rationally-based" and have noted the distinction between preliminary design and detail design, we can give a more specific statement of the aims and scope of the two books. The aim of the first book is twofold:

To present the fundamental and essential aspects of rationally-based preliminary ship structural design in a complete and unified treatment that assumes only basic engineering subjects such as mechanics and strength of materials

To present a methodology for rationally-based design that is practical, efficient, and versatile, and that has already been implemented in a computer program, tested, and proven

The aim and approximate scope of the second book is:

To provide information on other basic aspects of ship structural design such as choice of configuration, design of particular substructures, structural optimization (especially practical design-oriented aspects), material selection, vibration, design for production, welded connections and some aspects of detail design (especially fatigue), and in all of these areas pay particular attention to computer-aided aspects

This first book is entirely self-sufficient and self-contained; that is, it covers all of the basic aspects of rationally-based design that are required by a designer, even aspects as basic as frame analysis and the finite element method. This has been done for two reasons. First, because this book is intended primarily as a textbook, and in the field of ship structures such books are few and far between. For too long, students in this field have had to consult a large number of different books and other sources in order to obtain the theory and methods that they need, and these are often in a

form that is not suited for ship applications. Because of the greater complexity and sophistication of rationally-based design, the lack of a unified and comprehensive text would constitute a correspondingly greater difficulty for students, and a serious obstacle to further progress in this field.

The second reason is that rationally-based design, both in general and in the particular method presented herein, is radically different from the traditional rule-based method, and although many of its features are familiar to designers (such as frame analysis, finite element analysis, and elastic buckling) other features are either relatively new (such as nonlinear finite element theory and statistical prediction of wave loads) or totally new (such as the use of a hull module as the basis or subject of the design, some new techniques for structural modeling, and the method for ultimate strength analysis of a hull module).

For this reason the book is also intended for practicing designers who wish to become more familiar with this alternative method of design. In fact, the book's role here is of particular importance because rationally-based design of its very nature requires at least a basic knowledge of its underlying theory and methods. Once this is acquired the method's enormous capability (some of which is demonstrated in Section 1.3 and in the references given there) becomes available to the designer. Moreover, the method's breadth of application and the benefits gained from it increase in proportion to the knowledge of it. It is the author's hope that the presentation of the underlying theory and analysis methods in this text will assist designers to obtain the maximum possible benefits from this new approach.

Also, the author would like to emphasize that the design method presented herein is not the only possible method, at least not in regard to the particular component methods for achieving the basic tasks, such as the structural modeling techniques and the methods of member limit analysis. The methods presented herein have been selected or developed on the basis of their suitability for rationally-based design, but this type of design involves so many different areas that there are bound to be some particular methods and techniques that are as good or better than those given here. Moreover, as further progress is made in such areas as structural theory, numerical methods, and computer hardware and software, still better methods will be developed. But the important point is that now, as the result of many years of effort by many persons and organizations both inside and outside of the field

of ship structures, all of the required ingredients for rationally-based design are available.

Applicability to Naval Design

Another important feature of the design method presented herein is that it applies equally well to naval vessels and commercial vessels. Because classification rules are intended for commercial vessels and are not suitable for warships, various navies and naval design agencies have developed their own methods of structural design. Like the classification rules, these methods have evolved over a long period and many of them have been systematized and codified into some form of *design manual*—a sort of naval counterpart to the rules. But because of the need for greater structural efficiency and other special requirements, naval design methods have generally been more thorough and rigorous than rule-based design, and have shown a stronger trend toward a rationally-based approach. Thus in addition to the design manuals many current methods of naval design already include some of the basic features of rationally-based design, although not as a single integrated design method.

Section 1.2 gives a brief overview of the basic features of rationally-based design, including a discussion of the different aims, measures of merit, and design criteria in commercial ships and naval ships. Section 1.3 considers the capabilities, applications, and some sample results. Once these aspects have been treated it becomes apparent that the method presented herein applies equally well to both ship types, and that it matches the needs and challenges of naval design particularly well. Because commercial vessels are much more common, most of the explanations and figures in this text refer to this type. Therefore it seems desirable at this point to briefly summarize the reasons why the rationally-based method presented herein is so well suited for naval design, even though a full appreciation can only be obtained after covering Sections 1.2 and 1.3.

First of all, naval ship structures are subject to many special requirements and constraints. For example, they must be capable of withstanding specified levels of blast, shock, and other special loads. Also, they must be damage tolerant, that is, capable of sustaining some structural damage without loss of main functions. As discussed in Section 1.2 the mission requirements of naval vessels make it extremely important to minimize the weight and vertical center of gravity of

the structure to the extent allowed by the various constraints (such as cost, adequate strength and safety, and damage tolerance). Hence there is a paramount need for structural optimization, which is one of the basic features of rationally-based design.

But also, in order to achieve a truly optimal structure, the other aspects of rationally-based design are also required. In particular, rationally-based design explicitly calculates each load effect and each limit value, and imposes the stipulated safety margin for each individual limit state. In contrast, current naval design methods utilize specially defined "design loads" and some typical or representative limit states (which are simplified in order to preserve generality and facilitate computation) together with some general requirements such as maximum permissible stress. Since the actual individual load effects and limit values are not evaluated, the actual safety margins are not known precisely. Hence it is necessary to use larger safety margins in the representative limit states in order to achieve a sufficiently high probability that none of the margins in the actual limit states will be zero or negative. This inevitably results in some excess material. In contrast, since rationally-based design considers each limit state explicitly, it can achieve the same degree of safety without excess material.

Finally, it is worth noting that the ability of rationally based design to deal with both commercial and naval ships can also help to unify the field of ship structural design, which until now has been largely split into these two separate areas.

Applicability to Other Types of Structure

In this text the rationally-based approach is described purely in terms of ships. However, because this approach represents the most fundamental and most general type of engineering design, the material presented herein is also applicable to a wide variety of other steel structures, both fixed and floating.* All of the basic principles and most of the analysis methods for other steel structures are the same as for ships, and the scope of this text could have been extended to include these other structures without requiring any fundamental change of approach. However, this would have required the consideration of additional types of loads

*For example, in Reference 1 the method presented herein was used for the structural optimization of a large steel box girder bridge.

and failure modes, plus some new examples to illustrate these other applications, and this would have increased the book's length unduly.

Practicality of the Method

Rationally-based design is necessarily computer-based and this raises a number of practical questions in regard to computer implementation, accuracy, cost-effectiveness, availability, ease of use, documentation, and so on. These are important questions and they are dealt with fully in Section 1.3. But since practicality is so essential in a design method it is appropriate to mention here that this method has been developed over a period of 10 years and that during all this time a computer program based on it has been developed simultaneously. The program is called MAESTRO[†], and a cruder and partially completed forerunner was called SHILOPT. The latter was used for thoroughly testing and demonstrating the basic features, and the results have been documented in the technical literature, showing MAESTRO to be extremely powerful, versatile, cost-effective and easy to use. The published ship design applications include a 14,000 tonne cargo ship, a 96,000 tonne tanker, a 140,000 tonne bulk carrier, and a destroyer. In all cases the program produced an optimum structural design in a matter of minutes and at very low cost. In addition to its use for optimum design, the analysis portion of MAESTRO can be used to evaluate a given design, to assess proposed changes to a design or to an existing ship, or to evaluate the seriousness of damage incurred by a vessel. The program is also a valuable tool for ship structural research and for the teaching of ship structural design. Further details of all these aspects are given in Section 1.3 and in the references cited there.

1.2 BASIC ASPECTS OF STRUCTURAL DESIGN

One of the most familiar and fundamental concepts in engineering is that of a system, which may be anything from a simple device to a vast multilevel complex of subsystems.

A ship is an obvious example of a relatively large and complex system, and in most cases the ship itself is a part of an even larger system. The ship consists of

[†]Method for Analysis, Evaluation and STRuctural Optimization.

several subsystems, each essential to the whole system, for example, propulsion subsystem, cargo-handling subsystem. The structure of the ship can be regarded as a subsystem, providing physical means whereby other subsystems are integrated into the whole and given adequate protection and a suitable foundation for their operation.

In general terms the design of an engineering system may be defined as:

The formulation of an accurate model of the system in order to analyze its response—internal and external—to its environment, and the use of an optimization method to determine the system characteristics that will best achieve a specified objective, while also fulfilling certain prescribed constraints on the system characteristics and the system response.

Translating this to the case of preliminary ship structural design, a rationally-based design procedure can be described as follows:

1. The external loads are predicted as accurately as possible, using statistical methods where appropriate.
2. The load effects and limit values of load effects are calculated accurately throughout the structure for all loadcases.
3. The minimum required margins between the load effects and their limit values are all selected on the basis of a required degree of safety.
4. The resulting strength requirements are expressed in the form of mathematical constraints on the design variables (in most cases nonlinear constraints).
5. The designer is left free to specify the measure of merit of the structure, that is, the criteria that is to be used in achieving the *best* structure, and the influence of each design variable on the measure of merit. Also the designer is able to specify any number of other constraints on the design, of any form whatsoever, in addition to the strength-related constraints.
6. An optimization method automatically and efficiently solves for the values of the design variables which give the maximum value of the measure of merit while also satisfying all of the constraints.

From this description of a rationally-based design procedure it is possible to identify six essential tasks:

1. Calculation of environmental loads.
2. Overall response analysis.
3. Substructure response analysis.

4. Limit state analysis.

5. Formulation of reliability-based structural constraints.

6. Solution of a large nonlinear optimization problem.

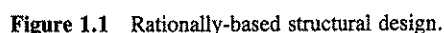
Figure 1.1 illustrates the overall design process, consisting of these six tasks. All of them are inherently very large tasks, especially for structures as large as ships, and the principal difficulty or challenge in developing a rationally-based design procedure is to develop methods that can perform these tasks to the required degree of accuracy and thoroughness, within acceptable amounts of total manhours and total computational cost. Each of these tasks is now considered briefly, in order to define it more precisely and to explain broadly what it entails.

Calculation of Environmental Loads

The environmental loads are the loads, both static and dynamic, that come from the ship's environment (mainly due to gravity and fluid pressures) and from its motion. Most of these loads are relatively independent of the structural design, that is, they are not much affected by the structural layout or by the scantlings. Rather they are more a function of hull shape, the type and distribution of cargo, and other nonstructural factors. Therefore, although the calculation of these loads is the first step of structural design, and one of the most crucial aspects of the entire process, it is essentially a separate initial task. Some of the loads can be readily calculated and controlled by the designer (e.g., those arising from cargo distribution). Other loads, particularly wave loads and other hydrodynamic loads (slamming, sloshing, etc.) are sufficiently complex that their calculation is not regarded as part of the designer's task but rather that of hydrodynamicists and other specialists. In contrast, the other two types of calculations—response analysis and limit state analysis—are inherently and totally structural in nature.

Overall Response Analysis

This analysis entails the calculation of the effects of the environmental loads on the overall structure (bending moment, deflection, stress, etc.). For reference the load effects will be represented by the symbol Q (or Q_i if referring to the i th load effect).



*The "response" of a structure is simply the group of load effects that is caused; the two terms are essentially the same and they are used interchangeably throughout this text.

forces and moments which are dealt with in beam theory: vertical shear force F_y , longitudinal bending moment in the (ship's) vertical and horizontal planes M_z and M_y , and longitudinal twisting moment M_x . Of these, the most significant is the vertical bending moment M_z , that is, bending about the z-axis in Fig. 1.2. This load effect is caused mainly by the unequal distributions of weight and buoyancy along the length of the ship, accentuated by waves. Horizontal bending (i.e., bending about the y-axis) occurs when the ship is in an inclined condition, due to rolling, and also arises from quartering seas in which wave crests on one side of the ship are in phase with troughs on the other. In most ships the maximum value of M_y is much smaller than the maximum value of M_z (typically 20% or less) but in large tankers and some other cases it can rise to as high as 50%. For simplicity we here consider only

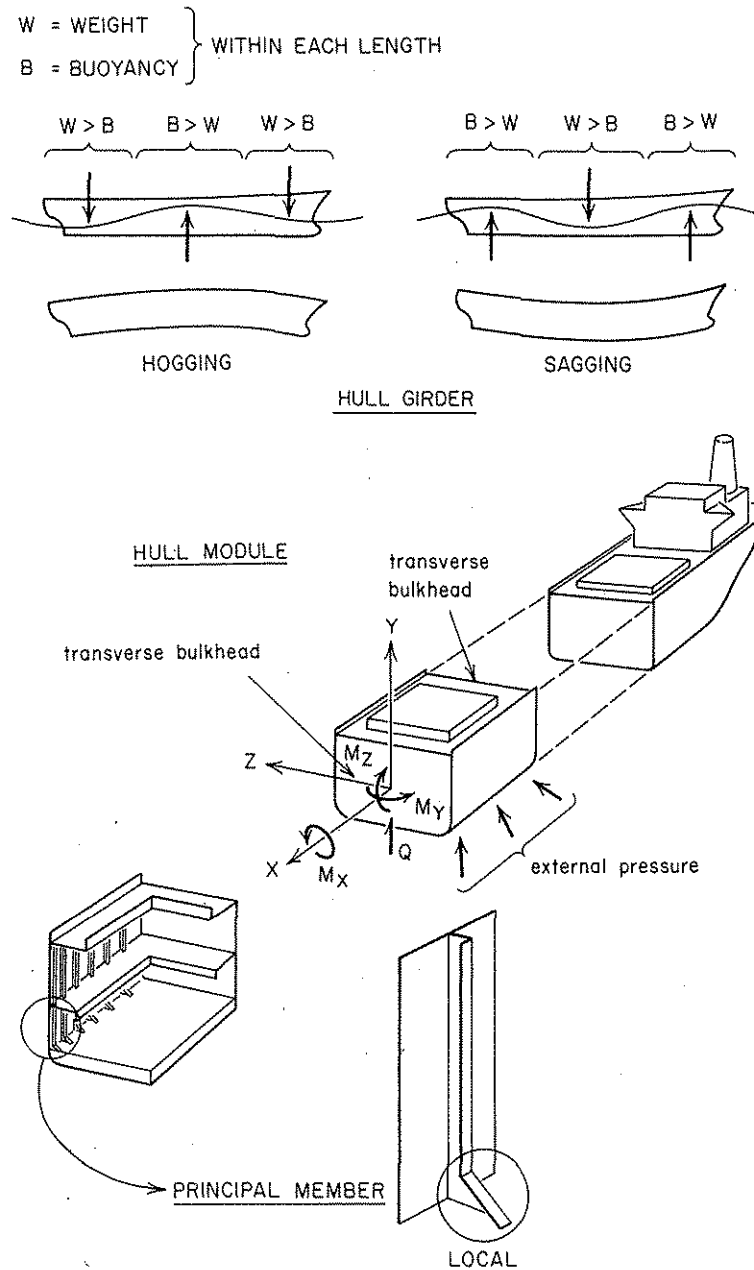


Figure 1.2 Levels of structural analysis.

vertical bending; horizontal bending and its relation to vertical bending is considered in Section 3.6.

The bending moment varies along the length of the ship, being zero at the ends and having a maximum value which usually occurs near the midlength of the ship. The maximum value of hull girder bending moment is the single most important load effect in the analysis and design of ship structures. Hull girder bending is referred to as either "hogging" or "sag-

ging," depending on the sense of curvature which it causes, as shown in Fig. 1.2.

The hull girder analysis assumes that hull girder bending satisfies simple beam theory (Bernoulli-Euler), which implies the following assumptions:

1. Plane cross sections remain plane.
2. The beam is essentially prismatic (no openings or discontinuities).

elongated length $(R+y)d\theta$

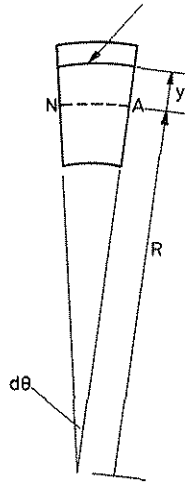


Figure 1.3 Strain distribution in simple beam theory.

3. Other modes of response to the loads (e.g., transverse and longitudinal deflection and distortion, caused by shear and/or torsion) do not affect hull girder bending and may be treated separately.
4. The material is homogeneous and elastic.

The first assumption is illustrated in Fig. 1.3. Under the action of a bending moment a beam undergoes curvature of radius R locally and, if plane cross sections remain plane, the longitudinal strain ϵ_x varies linearly in the vertical direction and is related to R as follows:

$$\epsilon_x = \frac{(R+y)d\theta - R d\theta}{R d\theta} = \frac{y}{R}$$

The horizontal surface where y , and hence also the strain, is zero is referred to as either the neutral surface or the neutral axis. The material is assumed to be homogeneous and elastic, and so the longitudinal stress is

$$\sigma_x = E\epsilon_x = E \frac{y}{R} \quad (1.2.1)$$

If there is no external axial force equilibrium requires

$$\int_A \sigma_x dA = 0$$

which reduces to

$$\int_A y dA = 0$$

and this indicates that the neutral surface coincides with the horizontal centroidal axis of the cross section.

Equilibrium of moments requires that the external moment M_z is balanced by the moment of the internal stress forces

$$M_z = \int_A y \sigma_x dA$$

which from (1.2.1) reduces to

$$M_z = \frac{EI}{R} \quad (1.2.2)$$

where I is the moment of inertia of the cross section, defined by

$$I = \int_A y^2 dA$$

Equation 1.2.2 relates the curvature to the external bending moment and if this is used to eliminate R from (1.2.1) the result is the familiar equation for bending stress at a height y from the neutral axis

$$\sigma_x = \frac{M_z y}{I} \quad (1.2.3)$$

SECTION MODULUS

Equation 1.2.3 indicates that σ_x is greatest when y is greatest, that is, at the extreme upper or lower edge of the section. When y corresponds to one of these extreme values the quantity I/y is called the *section modulus* and is usually denoted by Z . Since the neutral axis is not generally at half-depth there will be two extreme values of y : y_D for the deck and y_K for the keel, and there will thus be two values of Z : $Z_D = I/y_D$ and $Z_K = I/y_K$. The bottom structure is usually sturdier than the deck and so the neutral axis is usually below the half-depth. A height of $0.4 D$ above the keel is typical, but the location varies widely between different ship types. Thus the largest hull girder stress usually occurs in the deck rather than the bottom. More precisely, it occurs in the uppermost member which is longitudinally effective, that is, which is of sufficient length and has a sufficiently rigid attachment to the rest of the hull girder to act as part of the hull girder. In most cases this is a deck and that deck constitutes the

uppermost flange of the hull girder. If the side shell extends up to this deck then it is referred to as the *strength deck*.

Since the hull girder bending moment is essentially independent of the scantlings, the section modulus gives a direct measure of the change in hull girder bending stress arising from a change in scantlings. Therefore in each cycle of the rationally-based design procedure of Fig. 1.1, the new values of hull girder stress are obtained directly by calculating the new location of the neutral axis and the new value of I ; there is no need to repeat the hull girder analysis.

Section modulus is also useful whenever it is desired to assess or control the maximum hull girder stress (wave-induced, stillwater, or total) by itself, separately from the stresses arising from hull module and principal member response. For example, because the wave-induced hull girder stress is cyclic it is necessary to restrict its amplitude in order to guard against fatigue failure.

DEPARTURE FROM SIMPLE BEAM THEORY

Equation 1.2.3 states that the stress is constant across horizontal decks and varies linearly in the sides. There are several factors which can cause the actual stress distribution to differ from this idealized distribution. Firstly, because of transverse shear there is some longitudinal distortion of the cross section of the hull girder; this is referred to as "warping" of the cross section. This means that the first assumption is not fulfilled, at least not perfectly. Likewise, the second and third assumptions are not fulfilled because the hull girder is not prismatic, having large openings and other discontinuities and discrete elements (transverse bulkheads). Also, it is a complex assembly of members, transverse as well as longitudinal, and there are several other modes of response, in addition to warping, which affect the hull girder bending response. For ships in which there are no major changes in cross section other than in-line hatches (for which the intermediate portions of deck may be ignored) the longitudinal stress due to hull girder bending generally follows the idealized distribution quite closely (ignoring stress concentrations and other local effects) as shown in Fig. 1.4. For such ships the effects of shear and of other responses, of transverse structure, and even of openings and discontinuities, can be calculated separately (or at least estimated) in order to assess their importance and to apply corrections where necessary. In some cases superposition can be used. This structurally prismatic type of hull girder is considered in

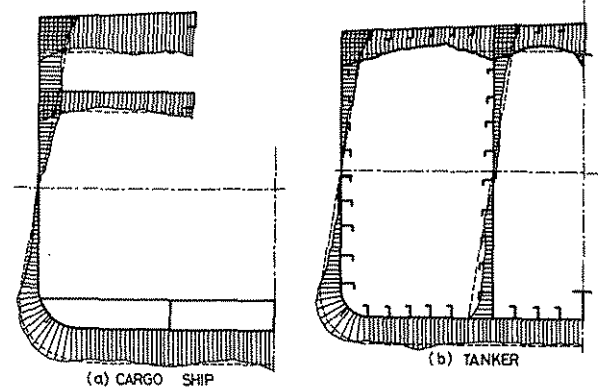


Figure 1.4 Typical hull girder bending stress distribution for structurally prismatic ships.

Chapter 3. For ships with significant changes in cross section most of the load effects can only be obtained at the hull module level. The boundary conditions for the hull module analysis can be obtained from a non-prismatic hull girder analysis using a "hull segment" element. The latter is presented in Section 6.3.

Shear force can be quite significant with some cargo types and distributions (especially bulk cargoes) and both shear force and twisting moment can be significant if the hull girder has low torsional rigidity. This occurs in vessels with large and numerous deck openings, such as container or barge-carrying vessels. Shear force and its effects are treated in the latter part of Chapter 3. Torsion is dealt with in Chapter 6.

Hull Module

SIGNIFICANCE AND ROLE OF A HULL MODULE

Ideally a structure should be designed as a single unit; that is, all of the steps of rationally-based design should be applied to the structure as a whole, in order to be sure to account for all of the structure's interactions and other characteristics. This is essential if the design is to be truly optimal. However, present day computational means are not yet adequate for the complete procedure to be applied to a structure as large and as complex as a ship. Therefore it is necessary to subdivide the overall structure and to achieve its design by means of a coordinated series of rationally-based designs of these substructures. If these separate designs are to still produce the true optimal overall design it is necessary to continue to account for all of the structure's interactions and other characteristics. Obviously, this includes all types of interactions between the substructures: in response, in limit states, and in overall optimality. Therefore the division into substructures must not prevent, omit, or inaccurately

portray any of the structure's responses, limit states, or optimality tradeoffs.

On practical grounds this can only be achieved if the substructures can be defined such that their interactions are few, localized, and easily calculated and accounted for. Hence there are two main requirements which a substructure must meet:

1. It must be sufficiently small, cohesive, and regular as to make its rationally-based design both feasible and practical.
2. It must be sufficiently large and sufficiently autonomous in its response, its limit states, and its effect on the overall optimality, such that no significant characteristic of the overall structure is lost, and such that all significant interactions which do exist can be fully accounted for.

For a ship structure the second requirement can only be satisfied by making each substructure a complete segment of the hull girder. In this text such a substructure is referred to as a *hull module* (see Fig. 1.2). A smaller substructure could never adequately represent all of the characteristics of the overall structure; nor would it have sufficient autonomy in the three required areas: response, limit states, and optimality tradeoffs.

Taking each hull module as being a complete segment largely eliminates interactions in the last two areas. If all of the hull modules are of reasonable length then any form of overall (hull girder) failure will occur wholly within a hull module. And because of the need for longitudinal continuity there can be no appreciable tradeoffs in structural cost (or other measure of optimality) between one hull module and another, especially if they are all reasonably long.

Structural interactions between hull modules cannot of course be eliminated, but they can be minimized by always locating the hull module boundaries at transverse bulkheads. But it is also necessary to be able to analyze each hull module in isolation, and therefore each of them must be defined such that a complete set of boundary conditions can be established for it from the hull girder analysis. It is this need for boundary conditions, together with the need to correctly portray the structural response, which determines the minimum length of a hull module.* These two require-

ments must always be fulfilled by each and every hull module. The actual length that is required depends on the overall layout of the vessel, the arrangement and geometry of its holds or major compartments, and the location and size of all large openings.

In certain rare cases these requirements may preclude subdivision; that is, the entire ship must be modeled. This would be the case, for example, with a completely open-deck ship because for such a vessel the torsional response is important and the hull girder analysis is not sufficiently detailed to determine accurate boundary conditions anywhere within the ship length. For a similar reason there are some container ships for which the structural model must extend over all of the cargo holds, from the forepeak bulkhead to the engine room bulkhead. For other container ships it is possible (by means of a special type of hull girder analysis presented in Chapter 6) to obtain suitable boundary conditions at intermediate bulkheads, thereby allowing the use of isolated hull modules. For bulk carriers it will be shown that the hull module must extend over at least three cargo holds. For some other ship types it can be a single hold. A further and more detailed discussion of the minimum length of a hull module is presented in Section 2.3.

Apart from minimum length there are no hard and fast rules for choosing the number, location, and length of the hull modules. The choice depends on many factors and it varies according to the situation and the circumstances surrounding each design. This is just one of many aspects of structural design which must be left to the judgement of the designer. Some examples for particular ship types are given in References 16 and 17. If the vessel consists of a number of basically similar cargo holds it is usually desirable to use identical scantlings for all of them for greater simplicity and economy. In this case the designer defines a hull module which satisfies the minimum length requirement (and which may therefore need to include more than one hold) and he proceeds to design that hull module using a number of different *loadcases* (combinations of loads which occur together). Each loadcase consists of the loads that act on one of the hull modules which make up the hull girder.

In other cases a ship may have very little repetition in its layout so that there is no automatic advantage in using a minimum length hull module. Here the choice of subdivision into hull modules depends mainly on how much the layout and geometry varies among the different portions of the ship, and how much commonality or variation the designer wishes to impose on the design. Perhaps surprisingly, the amount of com-

*More correctly, the need for boundary conditions determines the minimum length of the *finite element model*, which may consist of any number of hull modules, and the minimum length of a *hull module* is determined by the need to correctly portray the structural response; i.e. by the second of the two requirements listed at the top of this page.

putation is not a principal factor in this decision, because in the design method presented herein the total amount of computation is only moderately increased if the ship is divided into several short hull modules instead of a few long ones, assuming that in all cases a full design is performed for each hull module.

In fact, although there is some savings if there are fewer hull modules, and although the theoretical ideal is to design the complete structure all at once, there are practical limitations and disadvantages in trying to represent the ship with very few hull modules. From sheer practicality the computer program which implements the design method must necessarily incorporate and rely on some degree of regularity in the geometry and structure of the hull module; otherwise either the programming task becomes too large or the program itself grows too large to be efficient, or even manageable. Because of this regularity in the hull module the inclusion of more and more different portions of the ship in one hull module requires more and more modeling simplifications. These constitute artificial constraints on the design, thus limiting the extent to which it can approach the true optimum. Therefore in general a separate hull module should be defined for each portion of the ship that has substantially different geometry, subject to the minimum length requirement.

However it is not always necessary to perform a complete design for every portion. In some ships there may be a few portions that are of greater economic or operational importance and it may be sufficient to design these first and then obtain the scantlings of the other portions by a judicious choice of intermediate values, or even the same values in order to obtain greater simplicity and regularity of structure and the cost savings which this often brings.

In the design process of Fig. 1.1 the first two steps refer to the ship as a whole and therefore they only need to be performed once, whereas the design cycle consisting of steps 2 to 6 must be performed in its entirety (including however many cycles are needed for convergence) *for each hull module*.

By way of summing up these basic considerations regarding the rationally-based design of ship structures, we may list the three aspects which are crucial for its achievement:

A suitable choice of the hull modules

The use of a true rationally-based procedure for the hull module design

A careful and thorough synthesis of the hull module designs with each other and with the other aspects of structural design

HULL MODULE RESPONSE ANALYSIS

For purposes of structural definition, analysis, and optimization it is necessary to subdivide the hull module into further substructures. In the design method presented herein there are two further levels of substructure: principal member and local structure. These are illustrated in Fig. 1.2. Although we are further subdividing the hull module, it is still analyzed and designed as one unit, and so the manner in which this further subdivision is done does not greatly affect the optimality of the resulting hull module. However, it has a very strong influence on the speed and efficiency of both the analysis and the optimization of the hull module.

The hull girder analysis provides the boundary conditions—both supports and loads—for each of the hull modules. From this point on, each of the hull modules is designed separately, though of course there must be coordination between them and a final synthesis, which often includes standardization. The design process begins with the response analysis of the hull module. We note here that the load effects that are calculated in the hull module analysis become the loads and the boundary conditions for the member analysis, and the load effects for the latter become the loads and boundary conditions for the local structural analysis. Thus the same physical quantity or phenomenon can be referred to as either a “load” or a “load effect,” depending on whether one wishes to indicate a cause or an effect.

The importance of the hull module analysis cannot be overemphasized. The purpose of structural response analysis is to calculate all of the significant load effects in all of the principal members, and the main purpose of the hull module analysis is to provide the boundary conditions which are required for the analysis of the principal members. Because of the complex three-dimensional geometry and loading in a hull module, and the consequent high degree of statical indeterminacy, it is not possible to determine the boundary conditions of the principal members except by performing a hull module analysis. Putting it another way, the principal structural members cannot be analyzed or designed in isolation, but rather only in conjunction with a hull module analysis. The point is emphasized here because most earlier methods of ship structural design did not include a hull module analysis, mainly because the computational means were not available.

Another result of the statical indeterminacy of the hull module is that the distribution of loads among the principal members and the pattern of internal forces in

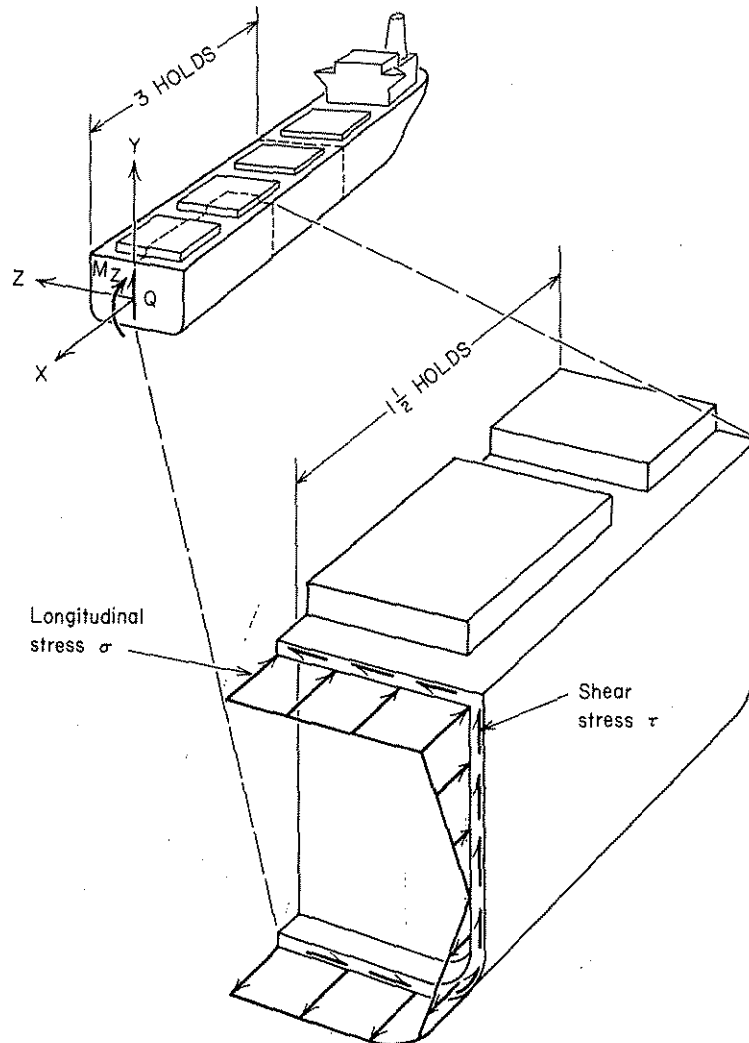


Figure 1.5 Application of hull girder load effects.

each of them is dependent on the structural dimensions of the principal members. As the design proceeds and these dimensions change so also do the internal forces change, and for this reason the design of the hull module and its constituent principal structural members is necessarily an iterative process, as shown in Fig. 1.1.

The loads on the hull module which come from the hull girder analysis are the hull girder stresses in the ship's cross section that are "exposed" by "cutting" the hull module away from the rest of the ship. Unless a special hull girder analysis has been used, this cut must be made at a transverse bulkhead (either just forward or just aft of the bulkhead, so that only the longitudinal material is cut) because the ordinary hull girder analysis assumes that there is no transverse deformation of the cross section. There are two types of applied

stresses—longitudinal stress σ which acts normal to the cross section, and shear stress τ which acts in the plane of the cross section. These are illustrated in Fig. 1.5. When applied to the hull module as external forces they account for the effect of the rest of the ship structure and they provide the reaction forces which place the hull module in equilibrium. (It will not be perfect equilibrium and so sufficient restraints must be applied to the module to prevent rigid body motion, but the reaction forces at these support points will be small.) Wherever there is symmetry in the hull module only half of the structure in that direction needs to be modeled (even though the loads may not be symmetric). Hence for a doubly symmetric hull module only a one-quarter model is required, as shown in Fig. 1.5.

This procedure of isolating the hull module and applying the hull girder stresses as loads assumes that

these stresses are independent of and unaffected by the structural response which occurs at the hull module level. This assumption is valid because the longitudinal structure of the hull girder is essentially orthogonal to the transverse structure and so the athwartships loads, which are ignored in the hull girder analysis, do not have any appreciable effect in the longitudinal direction (and at the ends of the vessel, where the taper is larger, the stresses themselves are much smaller). Of course, one way in which the hull girder stresses could be affected by the hull module response is that if the combined loads acting on the hull module were to cause buckling or yielding of any longitudinal member, then that member would no longer be longitudinally effective, thereby reducing the hull girder moment of inertia below the value that was used in the hull girder analysis. However, the check for this ineffectiveness occurs in the formulation and evaluation of the constraints (step 5 in Fig. 1.1) in which every member is checked regarding yielding, buckling, and all other possible forms of failure or unserviceability. If a member is found to be inadequate, it is redesigned in step 6. But before the members can be checked the hull module analysis must be performed because there are some longitudinal stresses at this level which must be added to the hull girder stress. Also, the check against buckling requires first that the buckling loads be calculated for all of the relevant members. Thus the structural modifications which are required in order to preserve the validity of the hull girder analysis can only be made after the hull module analysis has been performed. But the design process is necessarily iterative anyway, due to the statical indeterminacy of the structure and the nonlinearities in most of the ultimate strength constraints. As the design proceeds, each of the members will be made to satisfy all requirements and in this way the validity of the hull girder analysis will be guaranteed. Therefore, it is both permissible and logical to analyze the hull module separately and subsequently to the hull girder.

LOCAL STRUCTURE

At the most detailed level are those elements of structure which are local in extent: components of principal members, brackets, connections, reinforcements, foundations, fittings, and so on. Basically, a structural element can be classified as local if it does not have any appreciable effect on the load distribution within the hull module; in other words, it is local if it does not affect the magnitude and overall distribution of inter-

nal forces in nearby principal members, but rather has only a local effect on the internal force distribution in these members.

Because of the irregular geometry of local structure its analysis usually represents a significant computational task. Obviously the analysis and design of local structure can only be done after the structural dimensions of the principal members have been determined. But as noted previously and as illustrated in Fig. 1.1, the design of the principal members is an iterative process, and it would be inefficient to include the design of local structure as part of this process. Rather, the design of local structure—detail design—is a separate process which comes after the preliminary design process shown in Figure 1.1. Reference 2 contains a great deal of information on detail design, as do the rules and other publications of the classification societies. Moreover, most of the items that come under the heading of local structure are not unique to ships, and there are many design manuals and handbooks for land-based steel structures which contain useful information.

Limit State Analysis

A *limit state* is any condition in which a structure or a structural member has become unfit for one of its intended roles, due to one or more loads and/or load effects.* There are two broad categories of limit states: the *ultimate* or *collapse* limit states, in which the structure or member has failed in its primary, load-carrying role; and the *serviceability* limit states, which involve the deterioration or loss of other, less vital functions. The *limit values* are the values of the loads or load effects which produce or correspond to a limit state. A limit value is denoted by the symbol Q_L . The symbol Q_L represents the values of a group of loads and/or load effects which produce a limit state. A limit state analysis consists of the calculation of the limit values, perhaps in various combinations and sequences, which correspond to a specified limit state, either in a member or in the overall structure. An ultimate limit state is often referred to as the *ultimate strength* of the

*For the overall structure it is loads, whereas for a member it is usually load effects. For simplicity we often use the term "load", even when the term "load effect" might be more accurate. The symbol Q denotes whatever agent is causing a limit state; hence Q can represent either a load or a load effect. Where a distinction is important the symbol F will be used for a load and the symbol Q for a load effect.

structure or member, and the two terms are used interchangeably throughout this text.

Serviceability limit states arise from the fact that some members are designed on the basis of a form of failure other than structural failure. For example, as shown in Chapter 9, laterally loaded plating is usually designed on the basis of a maximum allowable "permanent set" (plastic dishing). The limit value is the load which causes this limit state, whereas the ultimate load is that value at which the plate can no longer support the load.

There are three basic types of structural failure, plastic deformation, instability, and fracture, and within these there are several different modes of failure, some of which are more serious than others; these are explained in Section 2.4. Moreover, these various failure modes can combine and also interact, depending on the member properties and on the loading. And finally, there are always several different loading arrangements and load combinations which must be considered (hogging and sagging, deep draft and light draft, various distributions of cargo, etc.). Hence for each structural member there are usually several limit states, not all of which have the same degree of seriousness. In general, rationally-based design requires that each and every relevant limit state be examined, and those which interact should be examined together. There should be no *a priori* assumptions as to whether some limit state will or will not govern the design.

Thus, to take a very simple example, the laterally loaded plate referred to above should be examined for both types of limit state. The limit load for ultimate failure is much larger than the limit load for allowable permanent set. But because of the far greater degree of seriousness there must be a much greater margin between the ultimate load and the expected service load, and so either requirement may govern the required thickness of plating. In order to determine which is the governing requirement it is necessary to perform both limit state analyses.

The level of seriousness of a limit state corresponds approximately to the level or extent of structure which has failed: overall, substructure, or local. For the preliminary design of a ship structure the appropriate levels are hull module and principal member. The hull girder level is here redundant because the hull module is a complete segment of the hull girder and failure of the hull module is failure of the overall ship. Hence in this text the terms "overall failure" and "structure failure" refer to failure at the hull module level, unless noted otherwise. Failure of local structure is not

sufficiently serious to be included with the other levels. Also, as noted earlier, this level of structure is usually dealt with in detail design rather than preliminary design.

Thus there are two levels of structure that can reach a limit state: the structure as a whole (the hull module) and the principal members. Ideally the limit analysis of the overall structure should include the limit analysis of the individual principal members. However the limit analysis of a hull module is a very large computational task and the total amount of computation can be reduced by performing the two separately: a hull module limit analysis which uses a simplified structural model of the hull module; and a separate limit analysis of each different principal member, for each different load combination which that member faces. The member limit analyses provide the values of a member ultimate strength which are used in the hull module limit analysis, and the latter specifies the load combinations which are to be used in each member limit analysis. The determination of these load combinations is crucial for rationally-based ship structural design. At the member level it is not possible to adequately account for the interaction between members. Hence it is not possible to know the true loads that are acting on each member as the structure approaches collapse. Moreover, most large structures have a high degree of statical indeterminacy, and also alternative paths through which loads can be transmitted. It is unusual—and undesirable—for large structures to have a member that is so vital that collapse of the member would mean collapse of the structure. In most cases structure collapse requires a large number of individual failures in various members. Some of those failures occur within the same members and cause them to collapse; others are more widely distributed and therefore do not cause member collapse. It is even possible for a structure to collapse by a mechanism involving several members, none of which has undergone complete collapse. Hence it is absolutely necessary to examine the strength of the structure as a whole, in order to identify any and all mechanisms which may cause collapse.

An example of member collapse is the collapse of a stiffened panel in the deck of a ship. In this case the load is the hull girder bending stress σ_x . The collapse could be caused by any of the three basic types of failure (for simplicity we here ignore combinations and interactions). Hence there are (at least) three separate limit values of σ_x , and the panel collapses when σ_x reaches the lowest of these three values. The mag-

nitude of each of these limit values is determined by the design of the panel—its geometry, scantlings, material, and so on. Expressing this in more general terms, we say that each limit value Q_L is a function of the design variables X , and when we wish to indicate this dependency we shall write $Q_L(X)$. Thus, the limit values are under the control of the designer, and the safety of the structure is achieved mainly by choosing X such that each of the limit values $Q_L(X)$ exceeds the corresponding load Q by a satisfactory margin.

Safety, Uncertainty, and Structural Constraints

(A) STRENGTH CONSTRAINTS

Almost every design involves constraints, that is, conditions or requirements which must be satisfied. In structural design the most important constraints are the strength constraints—those which are aimed at providing adequate safety and serviceability. Structural safety is inherently probabilistic, it is the probability that a structure will not fail. The risk of failure arises from the various uncertainties which are involved: uncertainties in loads, load effects, and limit values of load effects, the latter being due to variations in material quality, workmanship, fabrication, and so on. There are two broad types of uncertainty, statistical and nonstatistical. The first type arises from genuine statistical randomness and can therefore be treated using statistical theory. The second type arises from subjective elements and from events which are not truly random and are difficult to predict. Wave loads and material properties are examples of statistical uncertainties; these can be dealt with adequately by statistical methods. Examples of nonstatistical uncertainty are those arising from the operation of the ship, such as operating errors (improper loading, mishandling, etc.) or a change of service.

Obviously, a rationally-based design procedure must be able to deal with both types of uncertainty in such a way that the required degree of safety (which is ultimately decided by society as a whole, through the medium of regulatory authorities and insurance rates) is achieved in a clear and explicit manner. The first type—statistical uncertainty—is dealt with by statistical methods. For all loads, load effects, and limit values which are probabilistic, statistical theory is used to estimate suitable values to be used for design. If the quantity involves a large number of peak values, such as wave-induced bending moment, then the cal-

culation is based on *extreme values* of that quantity, and the particular extreme value which is selected for design is referred to as the *characteristic value*. In this text an extreme value is denoted by the symbol $\hat{\cdot}$ placed above the quantity (e.g., $\hat{M}_w$ for wave-induced bending moment) and the characteristic value is denoted by a subscript c (e.g., $\hat{M}_{w,c}$).

Besides dealing with statistical uncertainty, a rationally-based design procedure must also provide some means whereby the designer (or the regulatory authority) can explicitly allow for the other uncertainties. This is done by specifying a minimum value of the margin between $\hat{Q}_c$ and Q_L . In practice this margin is usually specified in terms of a *safety factor* γ_0 which is the minimum factor by which Q_L must exceed $\hat{Q}_c$. In terms of γ_0 the constraint is of the form

$$\gamma_0 \hat{Q}_c(X) \leq Q_L(X) \quad (1.2.4)$$

But in addition to accounting for uncertainty, it is also necessary to utilize some further safety factors in order to allow for the degree of seriousness of each type of failure, both in regard to safety (loss of life) and serviceability (loss of revenue or loss of mission capability). Likewise it is also necessary to apply some factors to account for particular circumstances such as the type of ship (passenger, cargo, naval, hazardous cargo, etc.) and the cost and the operational importance of the ship. These various factors are known as *partial safety factors*. The required degree of safety is provided by the total factor of safety, which is the product of the partial safety factors. Thus in (1.2.4) γ_0 denotes the total factor of safety.

Strength constraints are very often nonlinear, for a variety of reasons. First, two of the three basic types of failure are generally nonlinear: instability in typical ship structural members is usually inelastic, and plastic deformation is inherently nonlinear. Therefore most of the limit value expressions $Q_L(X)$ are nonlinear, and hence most of the structural constraints, even those involving only one load, are nonlinear. Modes of failure that involve more than one load and/or more than one structural member are even more nonlinear. Also in a statically indeterminate structure the load effect in a member $Q(X)$, can be a nonlinear function of the design variables X .

Failure Involving Multiple Loads. For simplicity we have thus far considered limit states which involve only one load. For a limit state which involves two or more loads one of the loads is selected as the principal

independent variable and an expression for its limit value is obtained as a function, not only of the design variables, but also of the other loads. For example, in the failure of deck plating due to plate buckling, the primary load is the longitudinal compressive stress σ_x . The limit value is the value of σ_x that causes buckling; in buckling terminology this is referred to as the "critical" stress $(\sigma_x)_{cr}$. If there is also a transverse stress σ_y acting on the plate this constitutes a second load and it influences the value of $(\sigma_x)_{cr}$. From plate buckling theory (Chapter 12) one can obtain an expression for this influence; in general form it is

$$(\sigma_x)_{cr} = f(X, \sigma_y)$$

Hence the constraint equation takes the form

$$\gamma_0 \sigma_x \leq f(X, \sigma_y)$$

and in the design of the plating the design variables must be such as to satisfy this inequality.

(B) OTHER (NONSTRENGTH-RELATED) CONSTRAINTS

As shown in Fig. 1.1, besides the strength constraints there are other constraints on the structural design arising from (1) operational requirements (e.g., minimum size of hatches, limitations on distortion and on vibration, etc.) and (2) fabrication considerations (e.g., maximum plate thickness for cold rolling, minimum spacing between stiffeners for welding, etc.).

These other constraints are relatively straightforward because they are expressed directly in terms of the structural design variables, being either minimum or maximum values of design variables or of ratios of design variables. An example of the latter is the fabrication constraint that the height of the transverse frame h_f must be sufficiently larger than the height h_s of a stiffener which passes through it, so that the cutout does not interfere with the flange of the frame. Thus, for example, if it were desired to restrict the stiffener height to no more than 80% of the frame height, then the constraint would be $h_s \leq 0.8 h_f$. Constraints of this type are important, but there is no need to give them any further treatment in this book because they are straightforward and are already contained in structural design manuals and structural codes, such as the rules of the classification societies. Also, since they have a very simple mathematical form (linear inequality) it is a simple matter to incorporate them in any mathematical algorithm or computer program for rationally-based structural design.

Definition of the Objective in Structural Optimization

Rationally-based design, of its very nature, must have a goal or objective, and there must be some measure for assessing the merit of a design vis-a-vis that objective. Hence in a rationally-based design process the designer must be able to nominate and quantify the objective of the design, and the design process must be capable of actively and automatically achieving this objective to the fullest extent possible, subject to the constraints. This in turn means that the design process must include an optimization method which is capable of solving an optimization problem involving a large number of constraints of various types (linear and non-linear, equality and inequality) and in which the measure of merit is totally flexible. That is, the optimization method should not restrict the measure of merit to linear expressions or to special cases (such as "least weight") since these may not suit the designer's needs.

Mathematical optimization of any kind requires that the measure of merit be defined as a mathematical quantity which is to be maximized (or minimized) and which is expressed as a function of the design variables. The measure of merit is therefore also referred to as the "objective function." In the overall design of a ship the structural design interacts with the other aspects of design, and something which is beneficial from a structural point of view may be detrimental in some other regard. Therefore the structural design objective should reflect the overall goal and the objective function should account for the results of interactions between the structural design and the other aspects of ship design. The goal depends first of all on the basic purpose of the ship, and in this regard the two principal categories are commercial vessels and naval vessels. In this section we consider the measure of merit for a ship structure, first for commercial vessels (while keeping in mind that many of the factors relating to this are also relevant to naval vessels) and then for naval vessels.

(A) COMMERCIAL VESSELS

For commercial vessels the objective is profitability, either of the ship itself or of some larger system. The principal factors which determine a ship's profitability are shown (in greatly simplified form) in Fig. 1.6, taken from Ref. 3. The quantities that are strongly influenced by the structural design are outlined, and it is clear that the structural design can affect profitability

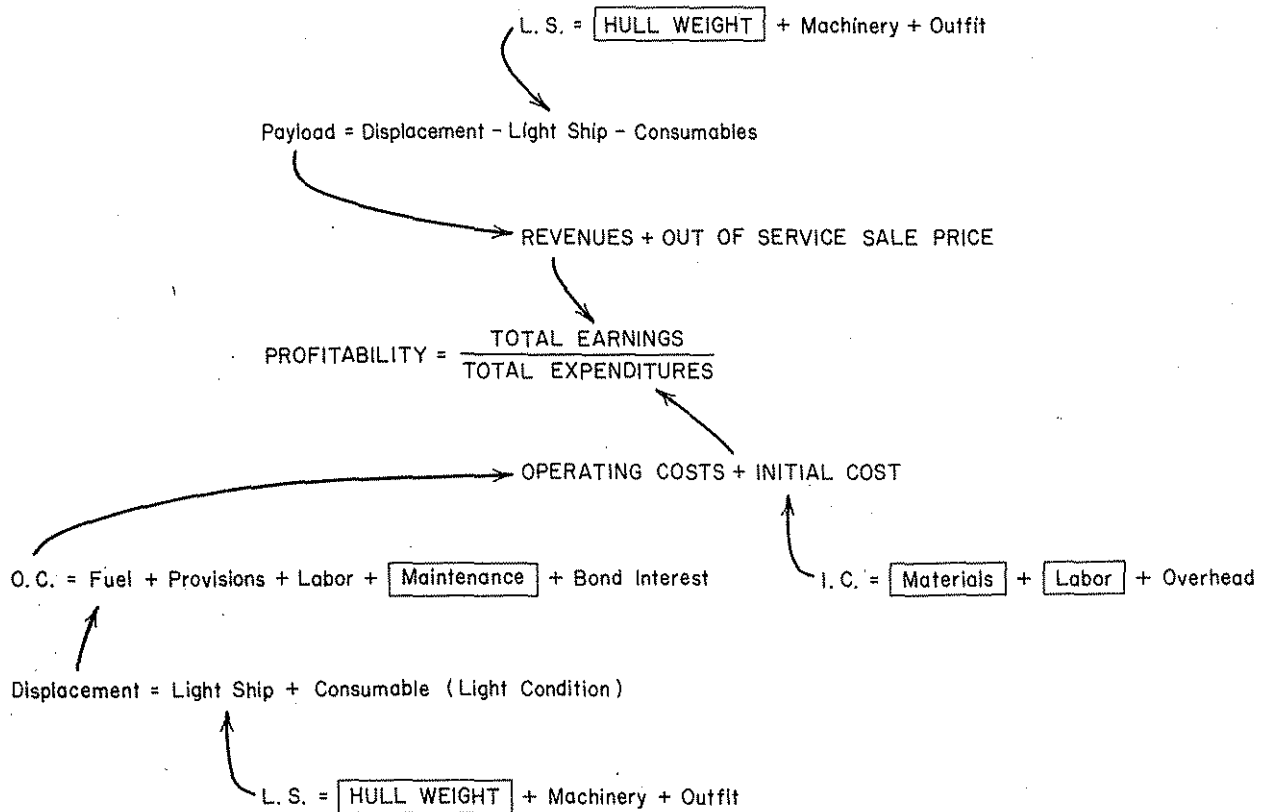


Figure 1.6 Principal factors in ship profitability.

at various levels and in various categories: payload, initial cost, operating cost, and so on.

The choice of the objective function also depends on which person or agency has the authority to decide; that is, it depends on whose behalf the designer is acting. In most cases it is the ship owner, but it may be the ship operator or the shipyard or the controller of some larger system in which the ship is to operate. For example, a shipyard which is responsible for the design as well as the construction would probably give greater importance to initial cost than would a ship owner, whereas the latter would have a greater interest in operational aspects and life-cycle economics.

Also, the factors and influences shown in Fig. 1.6 have different degrees of importance, and not all of them need to be included in the objective function. In many cases the only strong influence which the scantlings have on profitability is their effect on initial cost, and in such cases "least initial cost" is a sufficiently accurate objective.

Alternatively, with small weight-critical vessels such as hydrofoils and surface-effect ships, profitability or performance is determined almost entirely by

hull weight because decreased structural weight allows a direct and corresponding increase in the payload. Therefore in these cases the weight of the structure is included in the objective function, as a different type of cost. Moreover, even very large vessels can be weight-sensitive, such that a savings in hull weight gives an increase in payload, as well as reductions in cost. The ways in which this occurs are indicated in Fig. 1.6, from Evans [3].

The question then arises as to what is the proper combination of the two goals of weight reduction and initial cost reduction. This question can only be answered by a careful study of the economic life cycle of each ship, to determine the trade-off between initial cost and increased revenue from weight savings. As an approximate means of allowing for this combination, Caldwell [4] has proposed a useful nondimensional objective function which combines weight and cost in the form

$$U = \nu \frac{W}{W_0} + (1 - \nu) \frac{C}{C_0} \quad (1.2.5)$$

where W_0 and C_0 are the weight and initial cost of some

basis or standard design, W and C are the weight and initial cost of a proposed design, and ν is a number which varies between zero (where least initial cost is the objective) and unity (where weight-saving is the objective). It can be shown that if the weight saved in structure can be taken up by cargo then the best value of the weighting factor ν in (1.2.5) is

$$\nu = \frac{1}{1 + R_c/R_w} \quad (1.2.6)$$

in which

$$R_w = \frac{\text{weight of structure}}{\text{weight of cargo}}$$

in the basis design and

$$R_c = \frac{\text{annual costs arising from initial cost}}{\text{total annual cost}}$$

in the basis design.

For a large tanker R_w and R_c are typically 0.2 and 0.4, respectively, giving $\nu = \frac{1}{3}$, whereas for a small general cargo vessel the values are typically 0.25 and 0.25, giving $\nu = \frac{1}{2}$. Equations (1.2.5) and (1.2.6) thus indicate that increasing ship size and specialization will increase the importance of initial cost in the objective function. Obviously, more direct factors, such as increased labor costs relative to material costs, will have an even greater effect.

Savings in Fabrication Cost. For this reason, one of the most effective ways of reducing the initial cost of a large structure is to reduce the work content, and this can be achieved by simplifying the design and by increased standardization. There are opportunities for both of these measures at all levels of ship structural design, as shown by the following examples:

1. Overall hull structure.

a. Simplifying the geometry of the hull. The work content in producing curved panels is many times that for flat panels. This has led to greater use of straight line sheer and camber (or their elimination altogether), greater use of knuckles, chines and flat surfaces, or plating with single, rather than double, curvature.

2. Hull module.

a. Arranging the major structural elements such as decks, bulkheads, and frames so as to maximize the use of standard panels.

b. Simplifying the structural arrangements in complicated modules, such as those at the fore and aft ends of the ship. Some examples are fore ends incorporating cylindrical bows, or frames mounted normal to the plating and greater use of flat areas and knuckles near the stern.

3. Principal members (girders, frames, stiffened panels).

a. Selecting unidirectional stiffening, even when on the basis of the strength : weight ratio cross-stiffening is more "efficient."

b. Use of corrugated plating to avoid stiffening.

c. Use of straight flanges on the web frames of curved shell plating, even though such frames may protrude further into the hold.

4. Local structure.

a. Standardization of dimensions of plates and stiffeners to facilitate automated production and to achieve savings due to large batch ordering.

b. Design of structural connections so as to reduce the work content and perhaps also to facilitate inspection and maintenance.

Decisions about the overall hull structure—the first level—are more a part of the overall design of the ship rather than the structural design as such. And the fourth level—local or detail design—is basically similar for all welded steel structures, and hence there are a number of references and design manuals already available for this level of design. Therefore this book focuses mainly on levels 2 and 3; it is at these levels that rationally-based ship structural design *per se* can provide the greatest benefits.

Savings in Operating Costs. In spite of its importance, initial cost is seldom the only significant cost that is affected by the structural design. Operating cost can also be strongly influenced by the structural design in such areas as:

1. Durability—by which is meant the ability of the structure to maintain its original level of structural efficiency. The design of a structure has an important influence on its resistance to damage, which in turn helps to avoid both lost revenue and the costs of repair.
2. Maintenance—the minimization of corrosion, which is of particular importance for marine structures, requires the provision of good access for inspection, painting, and so on and this must be considered at the design stage.

3. Habitability—noise and vibration levels are directly influenced by structural design.

(B) NAVAL VESSELS

For naval ships the objective is to obtain the maximum possible mission capability over the life of the ship, subject to budget limitations. Thus cost is here a constraint instead of an objective. The two aspects of a structural design which have the greatest influence on mission capability are the weight of the structure and its vertical center of gravity (VCG):

1. Weight savings permits either a higher speed or more mission-related equipment (weapons, sensors, etc.) or increased range and endurance, or some combination of these.
2. A low VCG of the hull structure is of great benefit since most of the important weapons and sensor systems involve large topside weight. In fact, the provision of adequate stability is often the limiting factor on the number or size of such systems, particularly as a vessel gets older and it becomes necessary to fit more modern systems.

These objectives tend to produce a structure that is more intricate and involves less material. Hence for naval vessels the structural cost (i.e., the cost that is attributable to structure and is a function of the structural design variables) is mainly fabrication cost; the material cost is much smaller and, for a given material, it has little influence in determining the final optimum design.* Thus naval design involves a trade-off between weight, VCG, and fabrication cost. The designer seeks to determine the number, arrangement, and size of structural members which will give the lowest possible weight and VCG, subject to cost limitations and to a variety of other constraints requiring satisfactory strength, reliability, endurance, and functioning of the vessel. The constraint on cost is somewhat different from the other constraints. Rather than being an absolute limit it is a somewhat elastic barrier in which the rigidity of the resistance to further increase in cost depends on the cost : benefit ratio, that is, how much benefit the increase in cost will yield. Nevertheless, besides the cost/benefit type of constraint, there can also be an explicit upper limit on total cost.

*The possibility of using a very expensive material such as titanium would be investigated by making a separate optimum design using that material and then judging whether the weight/VCG savings is worth the extra cost.

The situation is illustrated in Fig. 1.7 in which the coordinates are the three main aspects: weight, VCG, and fabrication cost. The curved surface represents the combined and net effect of all of the constraints. It is actually an irregular surface—it is the outer envelope of all of the many individual constraints, each of which is itself a surface consisting of the lowest possible combinations of weight, VCG, and cost which just satisfy the requirements of that particular constraint. In different regions of the design space different constraints are the outermost or "active" constraints. Any point in the design space that does not penetrate below this surface is a feasible design, and any point actually on the surface is an optimum design. The surface indicates what sort of trade-offs are available to the designer.

For example, by raising the height of the strength deck or increasing its thickness the designer may achieve a lower overall weight at no extra fabrication cost, but incur a higher VCG. Alternatively, if he is willing to pay more for a more sophisticated and intricate structural arrangement (more stiffeners and thinner plating) he can achieve a lower weight, or a lower VCG, or both. The choice of which tradeoff to make and the selection of the final optimum combination must be left to the designer because this depends entirely on the particular mission requirements, cost limitations, and other design requirements and priorities.

The objective function U is a combination of weight W and VCG in the form

$$U = \nu \frac{VCG}{VCG_0} + (1 - \nu) \frac{W}{W_0} \quad (1.2.7)$$

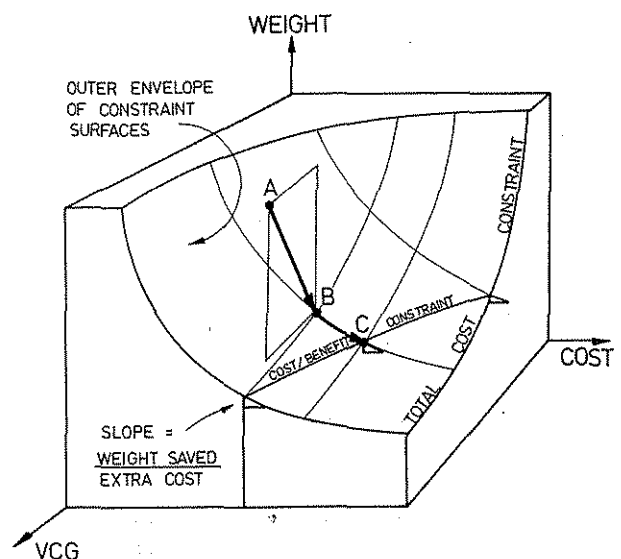


Figure 1.7 Design space.

where W_0 and VCG_0 are the weight and VCG of a previous design of approximately the same size, in which the VCG is at a satisfactory height. The value of the parameter ν is then determined by making a few trial optimizations, starting with $\nu = 0.5$ and adjusting ν until the resulting optimal design has a satisfactory VCG. If the previous design was smaller or if it is desired to achieve a lower VCG ν should be increased.

For purposes of explanation the benefits of using a rationally-based optimization approach in the design of naval ship structures may be grouped into three categories. First there is a savings in weight and VCG simply because of the greater accuracy of the rationally-based method. In current practice design both the load effects and the limit values of the load effects are only known approximately, and therefore so also are the margins between them. To help prevent the actual margin from becoming less than the required margin (which allows for genuine and unavoidable uncertainties such as wave loads) the design margin is made larger than is actually required. But in rationally-based design the actual margin is known and so it can be set to the required value rather than an inflated value. The result is illustrated in Figure 1.8 which is an enlargement of Fig. 1.7. Point A represents a current practice design. The calculation and use of actual margins gives an immediate savings in structural

weight, and the improved (in fact, optimal) distribution of material gives a reduction in VCG (point B in the figure). Both savings can be achieved with no additional fabrication cost. As indicated earlier, the proportion between the two can be altered to any desired figure by modifying the value of the parameter ν in the objective function.

But these savings are just the start; the designer can also investigate the question of cost. He can ease some or all of the cost constraints, which would then allow more intricate and efficient (but costlier) structural arrangements and proportions (point C in Fig. 1.8). The most common example is an increase in the number of stiffeners and a decrease in plate thickness. And finally, since rationally-based implies computer-based it gives the designer a far greater ability to examine other design alternatives and perform parametric studies, thereby achieving still further savings in weight and VCG. For example he can investigate the use of an improved steel or other material, with a higher ultimate strength or an improved fatigue resistance. These changes would have the effect of moving the corresponding constraint surfaces in Fig. 1.7 closer to the origin, and if one of them had been an active (outermost) constraint for the current optimum design, then the optimal design surface in that region of the design space also moves closer to the origin, and an immediate savings in weight and/or VCG is gained.

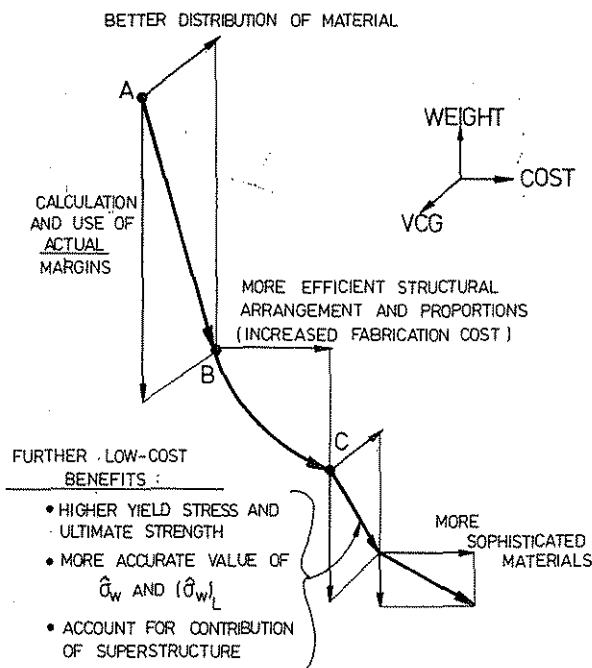


Figure 1.8 Benefits of rationally-based design.

Overall Procedure for Ship Structural Optimization

The final basic aspect of the rationally-based design procedure shown in Fig. 1.1 is the structural optimization process. This aspect consists of a mathematical method which utilizes the information provided by the other aspects and generates the design (i.e., the set of scantlings for all of the principal members) which maximizes the objective and which satisfies all of the constraints. The aim of the present section is twofold: to give an overview of structural optimization and also, now that we have discussed all of the aspects of the overall design procedure of Fig. 1.1, to explain briefly how that procedure works. For this it is not necessary to have a comprehensive or detailed knowledge of mathematical optimization theory. It is sufficient to know the basic features. Therefore, since the primary aim of this text is to present and explain the methodology—both theory and practice—of rationally-based structural design, there is no attempt to cover mathematical optimization theory, or even to give a complete coverage of structural opti-

mization, but rather only those aspects which are needed by a designer. The coverage is in three parts:

1. In this section, a brief summary of the basic features of structural optimization, presented as part of a simple example of the overall design process of Fig. 1.1.
2. In the next section, a brief summary of the broad classes of optimization methods, some comments on these in relation to the requirements of preliminary ship structural design, and references where more detailed information on these methods may be found.
3. In Section 2.7 a summary of a "dual level" optimization strategy which permits the efficient optimization of large structures in which some constraints apply to the structure as a whole.

The second book, which is planned as a companion to this one, will provide further information on practical and design-oriented aspects of optimization, such as computer implementation, postoptimal design studies, and other aids for decision-making in structural design.

SAMPLE APPLICATION OF THE PROCEDURE FOR RATIONALLY-BASED PRELIMINARY STRUCTURAL DESIGN

We now present a simple example of the rationally-based design procedure of Fig. 1.1, illustrating the various steps of the procedure and showing how the structural optimization step brings together and utilizes the results of the other steps. The procedure is intended for the structural design of an entire ship, but in order to have a simple example we will here apply it to just one small part of the structure—a stiffened panel in the strength deck of a vessel, as shown in Fig. 1.9. We will also make many simplifying assumptions, none of which are made in the actual procedure. For example, let us say that the panel has only two design variables: the plate thickness t_p and the stiffener height h_s . In reality the panel would have several more design variables: the number of stiffeners (or their spacing) and the web thickness and flange area of the stiffeners. But for this example let us say that the number and type of stiffeners have already been selected, perhaps because of a need to match some existing structure.

CALCULATION OF ENVIRONMENTAL LOADS

The first step in structural design is to investigate the maximum or extreme value of each load so as to deter-

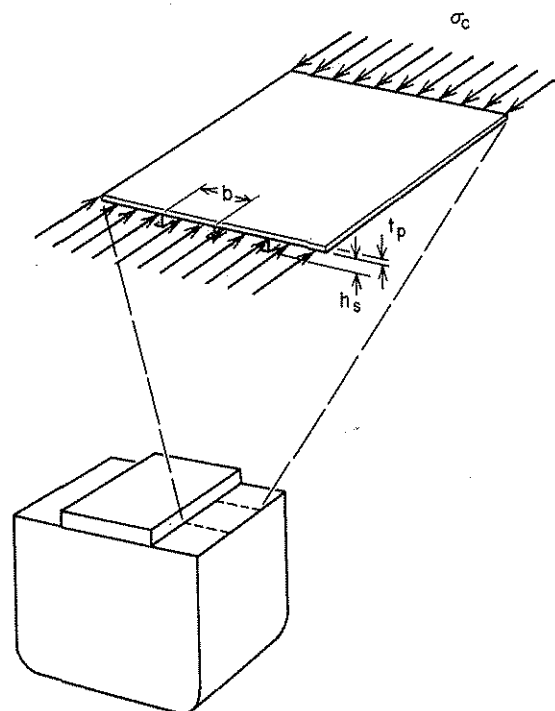


Figure 1.9 Stiffened panel example.

mine a suitable extreme value to be used for design, that is, the *characteristic load* Q_c . For simplicity let us say that the only significant load is hull girder bending moment M and that the only significant load at the panel level is the hull girder bending stress σ . In reality, of course, there would also be other loads acting on the panel (lateral pressure, shear stress, etc.) and the magnitude of these loads could only be obtained by a hull girder analysis, followed by a hull module analysis.

As will be discussed in Chapter 4 the wave-induced portion of the hull girder bending moment M_w is probabilistic and therefore statistical methods must be used to establish a *characteristic extreme value* for it, denoted as $\bar{M}_{w,c}$. For standard types of ships, a value for $\bar{M}_{w,c}$ is available from the classification societies, having been determined by research and by at-sea measurements for that type of vessel (Section 3.5).

HULL GIRDER ANALYSIS

The next step is the hull girder analysis which consists of the calculation of:

1. The section properties of the hull girder (location of the neutral axis, value of the moment of inertia, etc.).
2. The stillwater bending moment M_s .

3. The combined total hull girder bending stress $\sigma_c = (\hat{M}_{w,c} + M_s)/Z$.

Since there are two values of wave bending moment (hogging and sagging) and several values of still water bending moment (corresponding to different cargo and/or ballast configurations) it is necessary to perform the hull girder analysis for several loadcases.

We note that in order to perform the hull girder analysis it is necessary to have some initial or starting value for the scantlings of all of the longitudinally oriented structure in the hull girder. For the design variables of the panel let us denote the initial values as t_{p1} and h_{s1} , or in vector form, $\mathbf{x}_1$. These initial values are arbitrary; they are required simply because any computer calculation or analysis (such as steps 2, 3, and 4) requires specific numerical values for all quantities. These values do not require any calculation by the designer: he can either select standard values, or arbitrary values, or values from some other design. This will be discussed further when considering the structural optimization step.

HULL MODULE ANALYSIS

The next step is to perform the hull module analysis, for the current scantlings, $\mathbf{x}_1$. As shown in Fig. 1.1 this step and all of the subsequent steps constitute a cycle (the hull module design cycle) which must be performed repeatedly, because at the end of each cycle the values of the design variables (which comprise all of the scantlings of the hull module) are altered by the optimization process. This alteration makes it necessary to repeat the hull module analysis and the subsequent steps, using the new values of $\mathbf{x}$. The hull girder analysis does not need to be included in this cycle because the bending moment and shear force do not change. All that is required is a recalculation of the section properties of the hull girder, whereupon all of the new hull girder bending stresses can be calculated from the basic beam equation $\sigma_c = M/Z$.

For reference we will denote the current values of $\mathbf{x}$ as $\mathbf{x}_i$ (or t_{pi} and h_{si}); that is, $\mathbf{x}_i$ represents the scantlings which are used during the i th hull module design cycle.

The purpose of the hull module analysis is to obtain all of the values of the individual load effects in each of the principal members, for each loadcase. In this example we are examining only one principal member—a deck panel—and we are saying, purely for simplicity, that the only load effect is the hull girder stress. Thus we are, in effect, ignoring the hull module analysis.

LIMIT STATE ANALYSIS

To illustrate this step let us assume that there are five limit states for the panel: three types of compressive collapse, with collapse being initiated by (1) plate buckling, (2) torsional buckling of the stiffeners, or (3) flexural buckling of plating and stiffeners acting together; and also (4) large plastic deformation under tensile load and (5) fracture due to fatigue. Hence the five limit values are the three buckling stresses denoted by $\sigma_{bj}(\mathbf{x})$ with $j = 1, 2$, and 3, the yield stress σ_Y , and the fatigue-derived limit on wave-induced stress, $(\hat{\sigma}_{w,c})_L$ corresponding to the expected number of hogging and sagging cycles in the life of the ship (which is about 10^8 for a 25-year life).

The purpose of the limit state analysis is to calculate the limit values for the current values of $\mathbf{x}$. In this example two of the limit values are material properties and do not depend on $\mathbf{x}_i$, and so the limit analysis here consists of the calculation of the three buckling stresses, $\sigma_{bj}(\mathbf{x}_i)$. The theory for this is presented in Chapters 13 and 14.

FORMULATION OF CONSTRAINTS

The next step is to formulate the constraints for the optimization problem. The general form of a constraint was given in (1.2.4). Applying that here gives the following equations for the five panel constraints

$$\begin{aligned}\gamma_0 \sigma_c &\leq \sigma_{b1}(\mathbf{x}) & \gamma_0 \sigma_c &\leq \sigma_Y \\ \gamma_0 \sigma_c &\leq \sigma_{b2}(\mathbf{x}) & \gamma_0 \hat{\sigma}_{w,c} &\leq (\hat{\sigma}_{w,c})_L \\ \gamma_0 \sigma_c &\leq \sigma_{b3}(\mathbf{x})\end{aligned}$$

As mentioned before, an actual design involves several loadcases, which here would mean several different values of σ_c . Hence for each constraint it is necessary to use whichever value of σ_c is the worst for that type of limit state. Moreover, in reality, each loadcase usually involves several loads acting on the member, in various different combinations, and so the search for the worst combination must be very systematic and thorough.

As explained in Section 1.5 the total factor of safety, γ_0 , is made up of several partial safety factors which are chosen in accordance with: (1) the degree of (nonstatistical) uncertainty which exists in regard to both the load and the limit value, and (2) the degree of seriousness of the limit state. For this example the degree of seriousness is about the same for all constraints since they all refer to collapse rather than un-serviceability. Although there would be differing degrees of uncertainty in σ_{bj} , σ_Y , and $(\hat{\sigma}_{w,c})_L$ let us say,

again purely for simplicity, that γ_0 is the same for all five constraints.

Since the three limit values for buckling are functions of the design variables t_p and h_s , the three buckling constraints are equations in these two variables and can be plotted as curves on a diagram of t_p versus h_s , as shown in Fig. 1.10. In this type of diagram any specific combination of t_p and h_s —that is, any specific panel design—is a particular point on the diagram. For example, point A represents the initial or starting design, corresponding to t_{p1} and h_{s1} . The plane of the diagram represents all possible designs and is referred to as the *design space* (or hyperspace; the concept is extended to any number of design variables). The constraint equations are inequalities and therefore each curve is the boundary between all designs that satisfy that constraint and all that do not. In the figure the permissible side of each constraint is indicated by shading the unpermissible side.

The two constraints corresponding to tensile yield of the panel and fatigue fracture cannot be drawn in the figure because the limit values are material properties and therefore the limit states are essentially independent of the design variables. The only way in which the design variables x are involved is through σ_c , because σ_c is inversely proportional to the hull girder section modulus Z . But the plate thickness of a single panel has only a small influence on Z , and h_s has even less influence. That is, even a large change in t_p would cause only a small increase in the section modulus, and hence only a small decrease in σ_c . If either of these constraints was not satisfied, such that it was necessary to reduce σ_c , then this would require increasing the plate thickness of *all* of the deck panels and probably also all of the bottom panels. In other words, these two constraints relate to the overall structure, via section modulus, and not just to this panel. Constraints of this type are discussed in Section 2.5. Also, the determination of the *optimum* combination of thickness changes requires that all of the panels be redesigned together, in a coordinated manner.

We have already seen that a principal member cannot be analyzed in isolation, but only in conjunction with the other principal members, through the medium of the hull module analysis. We now see that in optimization the situation is similar—a principal member cannot be designed in isolation, but only in conjunction with the other principal members. For the present example let us assume that the current values of deck and bottom thicknesses are already sufficient to give a reasonable value of σ_c , such that these two constraints are not violated. In that case they will not become

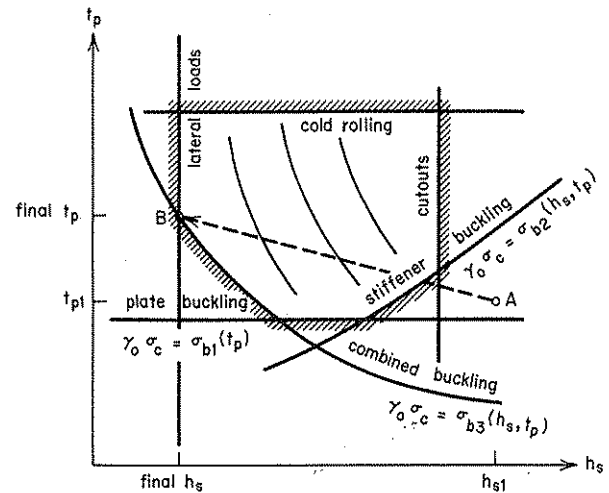


Figure 1.10 Design space for optimum design of a stiffened panel.

violated due to a reduction in thickness of just this one panel, and so we will not consider them further in this example.

Besides the strength constraints there are other constraints on the structural design arising from operational requirements and fabrication considerations. For the deck panel, for example, there might be a maximum plate thickness for cold rolling, a minimum stiffener height (for a given stiffener spacing b) to support lateral loads, and a maximum stiffener height (for a given height of the transverse deck beams h_f) so that the cutout for the stiffener leaves sufficient web area in the beam.

We note that in a more realistic example the stiffener spacing and the frame height would also be design variables, and hence the latter two constraints would only restrict the ratios h_s/b and h_s/h_f ; not the absolute value of h_s .

These additional constraints are also drawn on Fig. 1.10. Taken as a group the constraints define a region of the design space in which none of the constraints is violated. This region is known as the *feasible* design space, and corresponds to the shaded outline in the figure.

OBJECTIVE FUNCTION

In this example let us assume that least initial cost has been chosen as the objective for this design. The cost of a panel would depend mainly on the amount of steel used and the cost of fabrication. In the present example t_p and h_s are the only variables and the amount of

steel is linearly proportional to each of them, but in general the amount of steel is the product of two design variables; for example, in a stiffener web it is $h_s t_w$, where t_w is the web thickness. The fabrication cost is related to the design variables in a completely different way from the material cost, and therefore the sum of the two costs will be even more nonlinear. Thus the cost function $C(\mathbf{X})$ is, like many of the constraints, a nonlinear function of the design variables. In Fig. 1.10 a typical cost function for the panel is indicated by means of contour lines of constant cost.

STRUCTURAL OPTIMIZATION

The figure also shows two particular combinations of t_p and h_s ; that is, two specific panel designs. Design A represents the initial design, that is, the starting point for the optimization process. It may correspond to an actual panel in some existing ship, or it may be purely arbitrary. For any good optimization process the latter is sufficient. Thus the starting design need not be feasible (and often will not be, even if it does correspond to an actual design, since the loads and/or limit values for the current design are different). Design A is not only infeasible (it violates the maximum h_s and the stiffener torsional buckling constraint) but also expensive. Design B is the optimum design; it is the point within the feasible region which has the least cost. The task of the mathematical optimization process is to find this optimum point, from any starting point, and to do so with as little computation as possible.

POSTOPTIMALITY INFORMATION

In Fig. 1.10 the optimum design is governed by two constraints: combined buckling of stiffener and plating and the minimum height of stiffeners to support lateral loads. Another feature of a good optimization method is that, if requested, it can inform the designer as to all the circumstances relating to the optimum design, such as what are the governing constraints. Other useful information which should be available includes: how steep or flat is the optimum; that is, how much extra cost would be incurred in moving away from the optimum design point in various directions; what would be the effect on the cost of relaxing or tightening any of the active constraints; and if relaxation were possible, which direction would give the greatest further decrease in cost.

Optimization Methods for Large Structures

Mathematical optimization is purely a mathematical process and therefore it can and should be a fully automated process. That is, in the overall design process of Fig. 1.1 the optimization step is simply a "black box," which performs a specific task: it accepts as input an objective function and a set of constraints, and it returns as output the specific optimal values of the design variables, that is, the values that maximize the objective while satisfying all of the constraints. Since there is only one optimum point in the design space the optimization task is straightforward and unambiguous; there is no need or reason for any intervention by the designer. The only requirement is that the method must find the optimum rapidly and efficiently. The particular manner in which it does this is not important, and any optimization method that meets the requirement can be used in the overall design process of Fig. 1.1, without any need for the designer to have a detailed knowledge of it or of mathematical optimization theory. Therefore in this section we merely describe the broad classes of optimization methods, identify those methods which have been proven to be capable of meeting the requirements of ship structural optimization, and provide references from which detailed information about these methods may be obtained.

TYPES OF NONLINEAR OPTIMIZATION METHODS

During the past two or three decades many optimization methods have been developed which have at least some nonlinear capability. The majority may be grouped into three categories.

Fully nonlinear methods, such as mathematical programming methods and various algorithms for unconstrained minimization.

Special purpose methods, such as fully stressed design, the optimality criteria methods, and geometric programming.

Methods based on sequential application of linear programming.

In all there are many different optimization methods and nearly all of them can be used for structural optimization in some application or other. However, most of them tend to be suitable only for a particular type of problem. Reference 5 gives a basic explanation of all of the principal methods and demonstrates their appli-

cations. A brief review of various methods with particular reference to their application in ship structural optimization is given in [6].

In general, it may be said that the majority of the methods are suitable either for nonlinear problems which are small (i.e., which have only a few design variables) or for large problems which are only slightly nonlinear. As far as the author is aware, only the third type of method—sequential linear programming—has been shown to be capable of solving the large nonlinear problem which is involved in ship structural optimization with sufficient speed, computational efficiency, and generality. The fully nonlinear methods perform satisfactorily for small problems (say five or six design variables) but the amount of computation increases sharply with problem size, and for a structure as large and complex as a hull module these methods are simply not feasible. The special purpose methods are rapid and efficient but they are too restricted; they cannot handle constraints that are highly nonlinear and/or involve many design variables, and the first two (fully stressed design and optimality criteria) cannot handle an arbitrary (user-specified) nonlinear objective.

METHODS BASED ON SEQUENTIAL LINEAR PROGRAMMING

In this type of method all of the nonlinear functions [the objective function and the limit values $Q_L = f(\mathbf{x})$] are replaced by linear approximations and the linearized problem is solved very rapidly by the well-known method of linear programming, using the Simplex algorithm. This process is repeated sequentially, with the linear approximations being recalculated at each new design point. The original version of sequential linear programming was developed around 1960 by Kellogg [7] and by Griffith and Stewart [8]. In this first version the linearized form of each function f was simply the linear terms of its Taylor Series expansion, which involves the various first derivatives of f with respect to each design variable: $\partial f / \partial x_i$. It was found that unless all of the functions were only slightly nonlinear the linearized problem was too different from the actual nonlinear problem and the process would not converge. Hence for many years the method was limited to problems which were only moderately nonlinear. But it was subsequently shown that this limitation can be overcome by using some second-derivative terms in formulating the linearizations. Various second-order methods have been developed. In 1976 Hughes and Mistree presented the SLIP2

method [9], which uses the second derivatives of the nonlinear functions (but only terms of the form $\partial^2 f / \partial x_i^2$; mixed derivatives $\partial^2 f / \partial x_i \partial x_j$ are not required) to obtain a more accurate linearization of both the objective function and the constraints. This method was developed specifically to meet the requirements of rationally-based ship structural design, and it is this method which is used in the MAESTRO computer program. As shown in the examples and references given in Section 1.3, SLIP2 is able to solve problems involving a large number of constraints of various types (linear and nonlinear, equality and inequality) and in which the objective may be any user-specified nonlinear function of the design variables. Most importantly the method is very rapid and cost-effective. The SLIP2 method is not limited to structures; it is a general purpose method which can be used for commercial, industrial, or other optimization applications. The complete mathematical algorithm and logic structure for SLIP2 are given in Ref. 10.

Another second-order version of Sequential Linear Programming was developed by Murtagh and Saunders [11]. In Ref. 12 this method is demonstrated for several large-scale optimization problems in commerce and industry. Although these examples do not include structural optimization it is clear that the method is also suitable for this application.

Pedersen [13] has presented a systematic method for using "move limits" in Sequential Linear Programming which overcome most of the convergence problems referred to earlier.

Coverage and Plan of this Text

Having now had an introductory look at all of the basic aspects of rationally-based design, we can now give a more precise summary of the scope of the book and the organization of topics. The rest of Chapter 1 is devoted to some further basic aspects of structural safety, probabilistic design, and the use of partial safety factors. The specification of safety factors is primarily the responsibility of the classification societies, and therefore this text does not seek to determine or recommend any specific combination of safety factors or any specific values for them. Instead, these are described in general terms, and the combinations and values given are purely for illustration.

Chapter 2 summarizes the four major analysis tasks in rationally-based ship structural design: calculation of loads, of the structure's response to the loads, of the various limit values of each response, and optimiza-

tion. Thus chapters 1 and 2 give the overall methodology of rationally-based structural design.

Chapters 3 to 8 deal with the structural response of the ship. Chapter 3 presents the hull girder response analysis. This is the oldest and best established aspect of preliminary structural design, and was developed in conjunction with rule-based design. Therefore this text does not cover all of the traditional topics, but only those which continue to be relevant for rationally-based design. Chapter 4 summarizes the theory and techniques for obtaining a more precise estimate of wave bending moment, when account is taken of the probabilistic, dynamic, and nonlinear aspects of wave loads.

Chapters 5 through 8 present the various aspects of hull module analysis, which was earlier shown to be one of the most important and most distinctive features of rationally-based structural design. In the hull module analysis the method of structural modeling is very similar to frame analysis. Moreover much of the development of the finite element method came about as a generalization and extension of frame analysis. For this reason frame analysis provides a good introduction and foundation for the finite element method, particularly for the design-oriented finite element method which is used for the hull module analysis. Therefore the explanation of the hull module analysis is presented in a sequence of four chapters. Chapter 5 presents a summary of frame analysis, which serves mainly to introduce all of the basic concepts. Chapter 6 presents a special beam element which is the basis for a more accurate and more versatile type of hull girder analysis, permitting the analysis of a non-prismatic hull girder and the calculation of torsional response. Chapter 7 presents the basic features of the finite element method and introduces some basic two-dimensional elements which are of use in hull module analysis. Finally, Chapter 8 presents various aspects of the modeling strategy for the hull module analysis and some further finite elements that are useful for this analysis.

Chapters 9 to 14 represent the largest part of the book and deal with the limit analysis of the principal members: plates, columns, beam-columns, and stiffened panels. In each case the elastic aspects are covered first and then the inelastic. The former consists mainly of material culled from many different sources and augmented or generalized in whatever way was necessary to make it suitable for computer-based analysis. For example, for all of the various types of elastic buckling it is necessary to have either explicit expressions or numerical procedures for calculating the val-

ues of the buckling coefficients. In many cases these coefficients were only available in charts or tables, and so suitable expressions were developed. Some methods are new, such as that for clamped beam-columns in Section 11.3, and the generalized orthotropic plate theory which allows for shear distortion, presented in Section 10.2.

For inelastic limit analysis there were only a few cases in which a suitable method was available, that is, a method which had the required combination of computational economy, accuracy, and generality of application. In some cases a suitable method was obtained by combining and adapting existing methods e.g., the ultimate compressive strength of plates in Section 12.6. In other cases a new method was developed, for example, the estimation of the permanent set of plating (Section 9.4) and the ultimate compressive strength of stiffened panels (Chapter 14).

In regard to the limit analysis of ship panels and girders, mention should be made of the *Ships' Load and Strength Manual*, published by the Norwegian classification society Det norske Veritas [14]. This manual contains a comprehensive set of approximate explicit formulas for the strength of girders and stiffened panels, that is, formulas for the limit values of the forces and stresses in these members corresponding to various types of failure. In general these formulas have been obtained by making suitable engineering approximations to the underlying theory. Formulas of this type are an essential part of any practical method of rationally-based structural design, and the manual provides them in a systematic and concise manner. It is not aimed at giving theory or derivations and it does not consider the hull module, either in regard to response analysis or limit analysis, since neither of these analyses can be achieved by or put in terms of explicit formulas. Therefore the author considers the manual to be a very useful adjunct and complement to this text, both in purpose and in scope.

Chapters 15 to 17 deal with the limit state analysis of the hull module. Because of the structural complexity of a hull module and the complex interaction which often occurs between instability and plastic deformation, this analysis requires an *incremental load-deflection* approach, which traces the history of the collapse. Elastic instability is examined in Chapter 15, which introduces nonlinear (incremental) frame and finite element analysis and shows that for a complex three-dimensional structure, in which the members carry both lateral and axial loads, an incremental approach is essential; the classical bifurcation buckling analysis is not sufficient. Chapter 16 deals with failure

by large plastic deformation. It presents a new incremental method of plastic frame analysis and shows that here also the classical method of plastic frame analysis is not adequate for the limit analysis of a hull module, principally because of the interaction between instability and plastic deformation. Finally, in Chapter 17 these two incremental methods for the limit analysis of large structures—one for failure by instability and the other for failure by large plastic deformation—are combined to give a comprehensive method for the limit analysis of a hull module.

1.3 PRACTICALITY AND PERFORMANCE OF THE METHOD

As explained earlier, the aims of this text are to present a method for rationally-based design and to explain all of the basic theory and analysis methods which are required for that method. But the first requirement of a design method is that it be practical, and a method which lacks this characteristic is of no real value, no matter how "rational" it may be. Thus when a method is proposed which has a much larger theoretical content and is entirely computer-based, the questions which immediately arise are: what stage has it reached regarding implementation, availability, and actual use; what are its benefits and its performance characteristics; what does it require; in short: how practical is it? Therefore before proceeding any further with the theory and methodology it is necessary to demonstrate that the method of rationally-based design which is presented herein is truly as powerful, practical, and beneficial as implied in the previous section, and to provide factual information that will answer all of the questions just raised.

This can readily be done because the method has been developed over a long period of time (since 1972) and throughout all of this period the practical aspects have been given just as much attention as the theoretical aspects. As each portion of the method was developed it was computer-implemented and tested before being accepted, and each portion received many further tests as other portions were added or modified. If at any stage some portion was found to be impractical it was promptly discarded and work was begun on a replacement. In the first six years or so there were many discards.

Two milestones in the overall development were the completion of a first version of the method in 1975, for which the computer program was called AUSTRO-SHIP, and a second version in 1978, for which the

program was called SHIPOPT. This was followed by a series of validation tests; the finite element portion was validated against DAISY, a large general purpose finite element program owned by the American Bureau of Shipping, and the structural optimization portion was validated by a series of formal, full-scale design studies involving four ship types: a 14,000 dwt general purpose cargo vessel [15], a 96,000 dwt segregated ballast tanker and a 140,000 dwt bulk carrier [16], and a destroyer [17]. Finally, in 1981 and 1982 the complete method was implemented in the computer program known as MAESTRO.

The practicality and performance of the method, and also of MAESTRO, may be judged from the results of the validation tests and design studies. All of them showed a similar performance, and since Ref. 16 is the most comprehensive study most of the results quoted here are from that reference.*

Since this section deals mainly with the features and performance of a particular computer program—MAESTRO—it is perhaps appropriate to emphasize that the subject matter of the book is not a computer program but rather the underlying theory of, and a general methodology for rationally-based structural design, which is necessarily computer based. The theory and methodology presented in this book can serve as the foundation for various computer programs, some more general and some more specific. It is not limited to one particular program.

Use of MAESTRO for Structural Evaluation

Being a program for rationally-based design, MAESTRO is organized along the lines of the design process of Fig. 1.1. Thus, corresponding to steps 3, 4, and 5 it contains:

1. A special high-speed design-oriented finite element method which calculates the load effects Q (deflections and stresses) in all of the principal members for all loadcases.

*Only published studies are quoted so that, if desired, full details may be readily obtained. These studies were all performed using the predecessor program, SHIPOPT; the author has repeated all of them using MAESTRO and found that the computing costs remain the same, in spite of the many new features and capabilities of the latter. For example, MAESTRO accommodates non-prismatic ship sections such as bows and sterns and changes in frame spacing, and it includes overall limit states as well as those of principal members. These and other features will be demonstrated in further design studies.

2. A set of coordinated subroutines which perform limit state analysis, examining all relevant types of failure and calculating Q_L , the limit values of the load effects, for each different principal member and for all loadcases.

3. Other subroutines which formulate the constraints against each type of limit state for each different principal member. This involves searching the values of Q and Q_L to find and use the currently worst combinations of these two quantities. The program then makes a note of the corresponding lowest value of the margin of safety for each limit state, and the location and loadcase where each lowest value occurs. If requested it prints all of this information in structured easy-to-read tables (in several optional levels of detail).

These three features make the program a powerful tool for a variety of structural analysis and evaluation purposes, in addition to optimum design. When used in this mode the program executes only one cycle and stops just short of the optimization step. Because the finite element portion is extremely rapid and because a given set of input data is easily modified, the designer can quickly determine the effect of a design change which he has in mind. Moreover, the structural evaluation portions of the program have many valuable applications outside of, or immediately following, the design of a ship. Some examples are:

1. To check the structural adequacy of a proposed design.
2. To investigate proposed structural modifications.
3. To assess the seriousness of structural damage and the degree of urgency of repair.
4. To assess the structure after an actual or a projected corrosion wastage.

A common example of the first application is the checking of a proposed design prior to or as part of the classification approval process. For large and/or non-standard ships classification societies usually require that a finite element analysis be made of the hull structure in order to check whether the general stress levels are satisfactory and whether there are any particular locations of overstressing. The analysis is usually performed in two stages: a three-dimensional "coarse mesh" analysis of a hull module (much the same as MAESTRO) followed by a series of two-dimensional "fine mesh" analyses of selected areas. MAESTRO uses a level of modeling similar to the "coarse mesh" analysis used with other finite element programs, together with an internal logic developed specifically for

high computational speed. As shown in the bulk carrier example, MAESTRO is approximately 12 to 15 times faster than conventional finite element programs. Also, MAESTRO uses more sophisticated finite elements and therefore, in spite of the coarse mesh, it gives all of the important stress values in all of the principal structural members of the ship. Moreover, besides calculating the stresses, MAESTRO also performs the complete limit state analysis just described and produces a series of tables giving a complete assessment of the vessel's structural adequacy, in various optional levels of detail: first, overall adequacy—are there any problems and if so which regions of the ship. Then for each region it gives the location and loadcase of the lowest value of safety margin for each type of limit state. Finally, if desired, it gives a complete report on each principal member in each region: its lowest value of safety margin for each relevant limit state, together with the corresponding loadcase, and the various stresses in each principal member for all of the loadcases.

These features, together with a simple, user-oriented data input, make MAESTRO ideal for obtaining a rapid and yet thorough evaluation of the adequacy of a proposed design. This is useful for two purposes:

1. To assess a design in which there are some non-standard aspects, but not sufficiently unusual to warrant a detailed (fine mesh) finite element analysis.
2. For designs that are nonstandard, to determine whether there are any regions which require a two-dimensional fine mesh analysis and if so, where and for which loadcase. These detailed analyses can then be performed immediately because MAESTRO provides all the required boundary conditions.

Selection of Design Objective

MAESTRO allows the designer to achieve an optimum ship structure and leaves him free to specify how the optimality is to be measured. For commercial vessels the usual objective is maximum profitability over the ship's lifetime. The factors which most affect profitability are initial cost and operating revenue. Initial cost is a combination of material cost and fabrication cost, and to a first approximation these two may be expressed in terms of the volume (or weight) of material and the combined lengths of all of the girders, frames, and stiffeners. These are the parameters which were used in Ref. 16, but the program can accept any

cost algorithm defined by the user. The specific algorithm contained four factors:*

1. Cost per unit volume for stiffened panels.
2. Cost per unit length of stiffening for stiffened panels.
3. Cost per unit volume for web frames and girders.
4. Cost per unit length for web frames and girders.

The other principal aspect of profitability—operating revenue—is determined mainly by cargo capacity. In bulk carriers a savings in hull steel weight gives a corresponding increase in cargo deadweight, and hence revenue. The additional revenue due to weight savings (or, on a cost basis, the lost revenue due to weight increase) can be allowed for by increasing the volumetric cost factors.

The four cost factors are part of the data input and if desired can be different for different regions of the hull module. The lineal (cost per unit length) factors would reflect such items as welding costs and would influence the optimum number of stiffeners in each strake of plating. These factors might vary according to which shipyard is building the ship. For example, one shipyard might have more automatic welding machines so that its cost per unit length of stiffener weld might be cheaper. In this case, the optimum design would probably have more stiffeners and less steel than at another shipyard with higher welding costs. The type of ship could also influence the cost function. In a double bottom bulk carrier, one would want to penalize increased double bottom height since this reduces cargo capacity. In this way, the program would automatically look first at other structural changes before increasing the double bottom height.

Example 1—Segregated Ballast Tanker

The first example from Ref. 16 is a segregated ballast tanker. Since one of the main purposes of this study was to assess the economic benefits of rationally-based design, all of the design specifications (principal dimensions, geometry, loads, etc.) were the same as for an actual, rule-based, manually produced design. As explained in Ref. 16 special steps were taken to avoid any bias in favor of MAESTRO and to remove the rather uncertain question of corrosion allowance from the comparison. In rationally-based design there is a

*As shown there, the costs are not, and do not need to be, actual dollar costs, but rather cost indicators, or indices, which portray the correct relative proportions of the various costs.

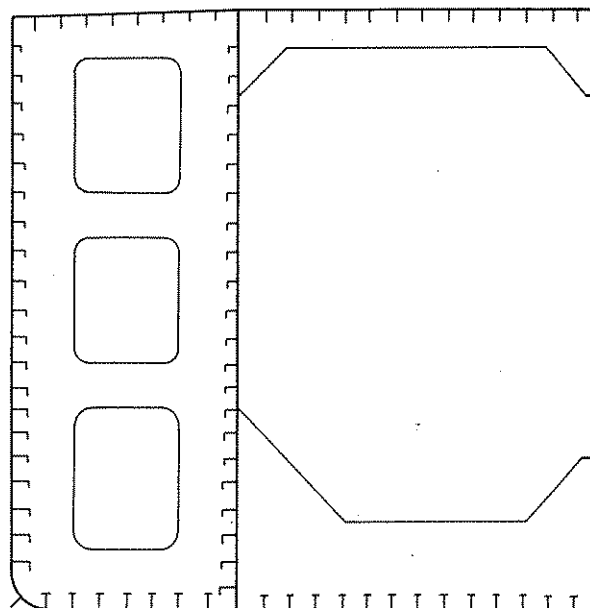


Figure 1.11 Basis ship: 96,000 dwt tanker.

clear distinction between steel that is required for adequate strength and steel that is provided in order to allow for corrosion. MAESTRO provides only the former; the latter must be added on after the optimization.

The transverse section of the basis ship is shown in Fig. 1.11. For the three cargo tank lengths which comprised the MAESTRO structural model the cost of the basis design was 9708 cost units, and the structural weight (which is automatically calculated by MAESTRO) was 8050 tons. As mentioned earlier, the initial scantlings for MAESTRO are completely arbitrary and so in this case, in order to provide a direct and graphic comparison between the rule-based design and the MAESTRO design, the scantlings of the former were used as the initial scantlings for MAESTRO. The performance of MAESTRO is shown in Fig. 1.12.[†] The solution for the optimum design required 11 design cycles, which took about 12 minutes of computer time on an IBM 370/158. The total computing cost was about \$130. The resulting optimum design had a total life-cycle cost (in which increased revenue from weight savings is converted to and subtracted from initial cost) of 8477 cost units, which is a 13% improvement on the basis or current practice design. The savings in initial cost was 6%, which for a tanker of this size represents a savings of the order of one million dollars.

[†]Including solutions with two other quite different sets of initial scantlings.

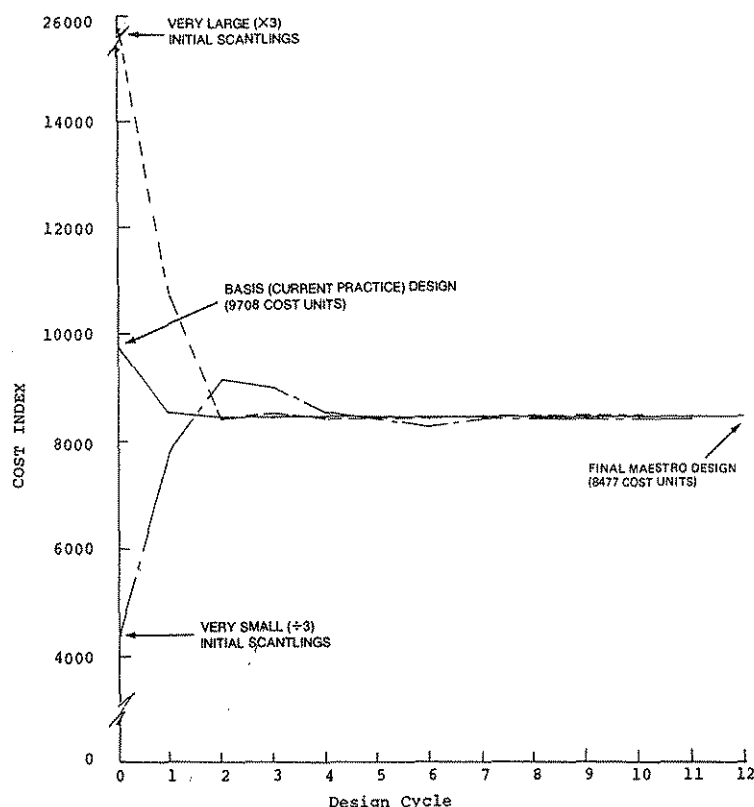


Figure 1.12

EFFECT OF USING STANDARD SECTIONS

The foregoing savings will be decreased slightly by the need to use standard plate thicknesses and standard rolled sections for the stiffeners. MAESTRO initially treats these design variables, and also the stiffener spacing, as continuous variables in order to avoid the enormous computation and complexity of discrete variable optimization. Then, in the final design cycle it converts to standard sizes, based on a list of standard sections and available thicknesses that the designer specifies in the input data. The designer can also specify the location and extent of whatever inter-strake (see Fig. 2.15) uniformity he wishes to impose, in order to limit the total number of different sections and thicknesses. Moreover, he can make these choices *after* seeing the idealized optimum, which provides a great deal of insight and guidance. In the final design cycle the program does not merely round off all scantlings to the next larger standard size, but rather looks for trade-offs between rounding up and rounding down, subject to the overriding requirement that all constraints (safety, fabrication, etc.) must remain satisfied. But because this requirement is essentially "one way," it is unavoidable that the standardized design will be a few percent-

age points away from the "ideal" (but impractical) optimum of the non-standard design. In this example the final design was 8670 cost units, and so the savings over the rule-based design decreased from 13% to 11%, and the savings in initial costs became 5%. But the latter is still of the order of one million dollars, since the hull construction cost for such a tanker is at least \$20 million. Moreover, this savings can be regarded as realistic because the design itself is both realistic and "production-friendly": standard sizes and a limited number of different sections and thicknesses.

ABILITY TO REPEAT A PRELIMINARY DESIGN

Since the preliminary structural design, by definition, does not examine local effects, it often happens that in the detail design it is necessary to increase some of the scantlings because of local loads, cutouts, and so on. This will happen more frequently when the preliminary design is an optimum design, since there is no excess steel in such a design. In most cases the cost increase is small. However if there are many such loads or other influences, such that the subsequent cost increase is found to be large, then these are not really local effects; they are general effects and the pre-

liminary design should be redone with these effects included. With manual design this is a large and time-consuming task; in many cases the more expensive locally adjusted design would have to be accepted. With MAESTRO it is a relatively easy matter to add the loads or make an approximate modeling of the local geometry, and rerun the program. In that case the extra design requirement will be satisfied in the optimal way, and so the cost increase (over the previous preliminary design) will be much less than the cost increase associated with making local adjustments. It will also be less than that obtained by redoing a manual preliminary design.

A similar situation arises when an important design requirement is changed after a preliminary design has been completed, and to fulfil the new requirement properly would mean repeating the design. A designer using standard manual methods must choose between making another costly and time-consuming design or only partially fulfilling the requirement by making local changes.

EXAMINATION OF ALTERNATIVE STRUCTURAL CONFIGURATIONS

Another principal benefit of the program is that it allows the designer to compare the optimum designs for alternative structural configurations. In order to demonstrate this a study was made of an alternative tanker design having three longitudinal girders in the center tank; that is, three parallel "ring frames" around the inside of the tank in a vertical longitudinal plane, instead of only one ring frame in the ship's centerplane. The data for this alternative configuration took about one man day to prepare. The results showed that the optimum design based on this configuration was slightly more costly than that of the single-girder model, and hence that there was no point in adding the extra girders. To have performed such a study without a program like MAESTRO would have constituted a major research project, occupying several manweeks and requiring a large amount of computer time.

Example 2—Bulk Carrier

The other ship type which is investigated in Ref. 16 is a 140,000 dwt bulk carrier. This also was an actual current practice design, but in this case the design chosen was not the final design but an earlier version in which a coarse mesh finite element stress check (by DAISY, a general-purpose finite element program) had found stresses exceeding yield in the bottom and

inner bottom plating. The yielding was caused by a combination of stresses from the local cargo bending moment and the overall hull girder bending moment (see Figs. 1.13 and 2.3). This early version of the design was chosen to illustrate how MAESTRO can be used to check a tentative design and also, if desired, to produce optimal corrections. For this model it was necessary to analyze five hold lengths because of the ballast tank arrangement. Since the model was structurally symmetric longitudinally, it was only necessary to model $2\frac{1}{2}$ hold lengths of the structure.

STRUCTURAL EVALUATION

At first MAESTRO was used in the "evaluation mode" to compare its results with those obtained earlier in the DAISY three-dimensional coarse mesh analysis. To analyze seven loadcases DAISY had required more than 50 minutes of computer time. To analyze five loadcases (and also to perform a complete limit state analysis, and to evaluate the adequacy of the entire structure) MAESTRO took about three minutes, using the same computer and modeling the same portion of the ship ($2\frac{1}{2}$ cargo holds). All of the deflections and all of the stresses given by the MAESTRO analysis were in good agreement with those given by DAISY. Figure 1.13 is an example of a deflection plot produced by MAESTRO. In these plots the deflection is greatly exaggerated for clarity.

OPTIMIZATION

After the structural evaluation of the existing design MAESTRO was used to produce an optimum (least cost) design while also correcting the deficiencies. The cost factors were basically the same as those used in Ref. 15.

With the height of the double bottom fixed at its original value of 2.3 meters, the optimum design produced by MAESTRO had thicker plating but smaller longitudinals. The resulting cost was 7.5% and the weight 6.4% less than the starting design. Next, the double bottom height was allowed to vary. This produced a design that had a lower double bottom height (1.9 m) and thicker bottom plating (24 mm). Compared to the original design, the cost was reduced 8.8%. These results indicate that the design having a smaller double bottom height is of slightly lower cost. In addition, this design is able to carry more cargo. Because the hull module in this example included more cargo holds than the segregated ballast tank model ($2\frac{1}{2}$ cargo holds versus $1\frac{1}{2}$ cargo holds), the

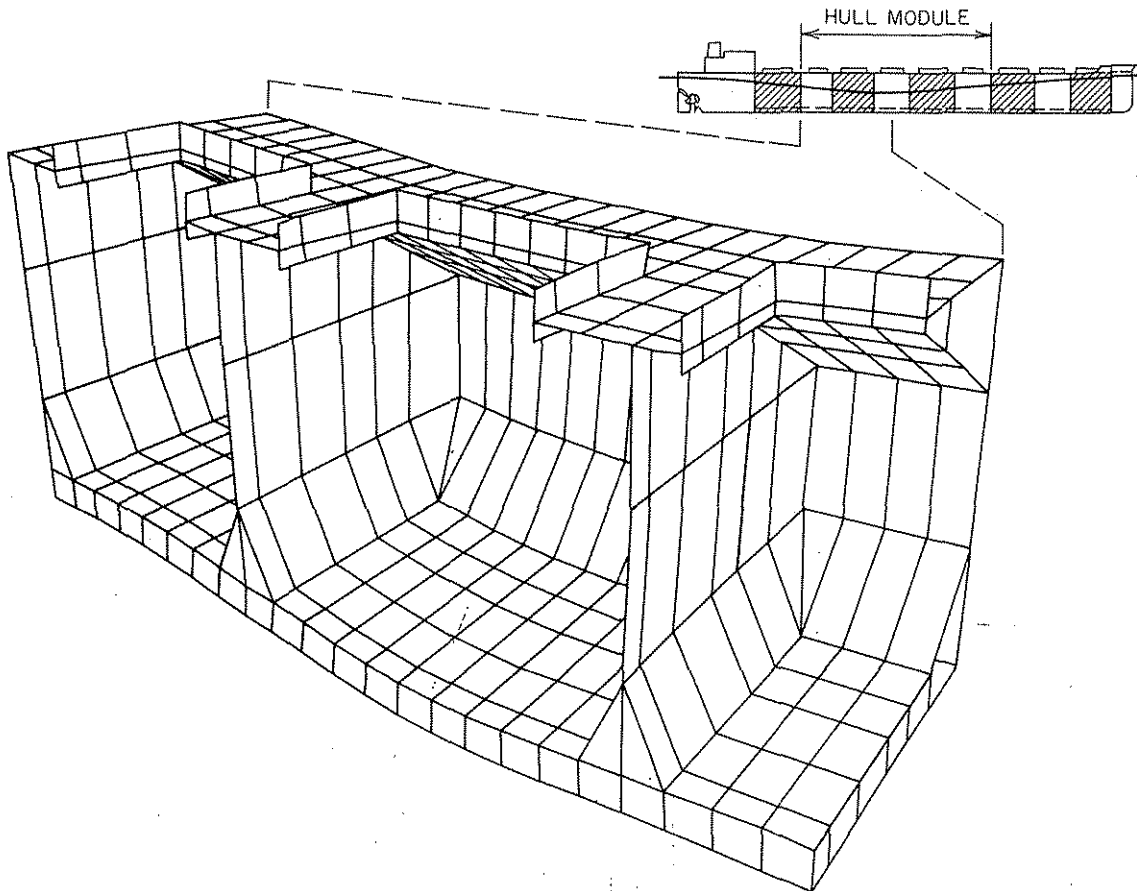


Figure 1.13 MAESTRO deflection plot—full load sagging condition; heavy ore cargo.

computer cost per design cycle was higher. An eight-design-cycle run in this case used 12 minutes of computer time and cost about \$150.

The effect of varying the double bottom floor spacing in the bulk carrier was also examined. The original design had a floor spacing of 2.4 m (23 bays in the MAESTRO model). From this original model two others were developed: one with a spacing of 2.208 m (25 bays) and one with a spacing of 2.76 m (20 bays). The overall lengths of all three designs were identical. The length of the cargo holds however did vary due to the differing floor spacing, with the variation not more than 14%. One man-day was required to generate these two additional models.

Running MAESTRO for these three floor spacings without restricting the double bottom height produced the results shown in Fig. 1.14. Because there were no restrictions on double bottom height, each floor spacing resulted in a different double bottom height. From the cost index curve, it appears that the original spacing of 2.4 m was a reasonable choice. To determine the minimum value of the curve, it would be necessary

to make additional runs with larger frame spacings. Notice that the weight is lowest at the original frame spacing.

To eliminate the variation in double bottom height as a factor in determining the optimum frame spacing,

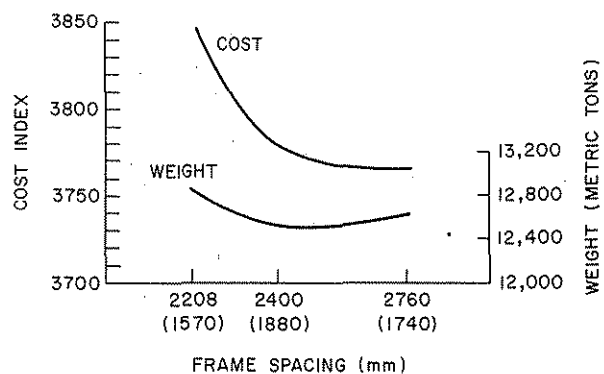


Figure 1.14 Cost and weight versus frame spacing—variable double bottom height. Note: Numbers in parentheses are the double bottom height (mm).

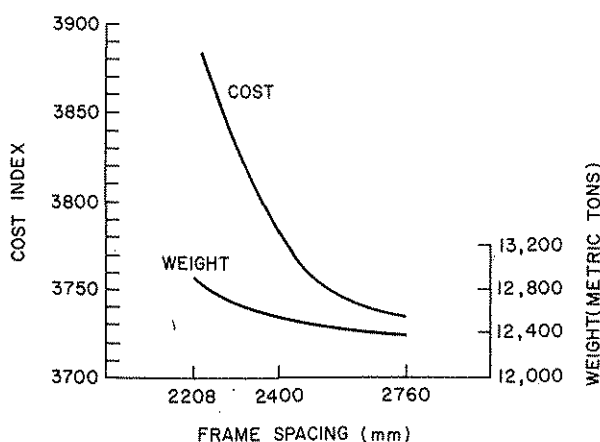


Figure 1.15 Cost and weight versus frame spacing—1880 double bottom height.

the three models were run with the double bottom height fixed at 1.9 m. The weight and cost index curves for these runs are shown in Fig. 1.15. In this case it appears that of the three spacings, a frame spacing of 2.76 m is still the optimum.

Use of MAESTRO in Teaching and Research

Since rationally-based design deals with the actual characteristics of a structure, including the complex and interrelated response of all of its members and the calculation of the various limit values of these responses, and since the program is a mathematical model of these characteristics, it is very helpful in teaching both the theory and the practice of ship structural design. First, because of its structural analysis and structural evaluation features, the program assists in gaining a deeper understanding of the complex and interrelated characteristics of a ship structure, and in learning what types of structural arrangement are more efficient. Second, because it also has an optimization capability the program is in effect a "ship design simulator," in which a designer can try out various ideas and possibilities, and can increase his knowledge in many aspects of structural design, such as the relative cost efficiency of various structural arrangements and the optimum proportions of structural members for various structural arrangements.

The program also has many useful applications in ship structural research. For example it may be used to examine the effect of corrosion on the strength of the hull girder and to develop improved corrosion criteria (initial allowance, permissible wastage—both thickness and extent, etc.). The program may also be used

to perform a series of "hindcasting" analyses of various types of ships in order to determine the approximate magnitude of the safety factors that are inherent in current design practice, and to see how the factors compare for various locations in the ship, types of principal structural members, types and modes of failure, and types of ship.

Other Practical Aspects

MAESTRO includes several features that make it versatile and easy to use, such as a graphical interface and menu system, an interactive modeler for rapid structural modeling, and color graphics that display complete information about the structural model and the various results of a MAESTRO job: stresses, mode shapes, structural adequacy parameters and optimum scantlings. Special methods of color coding allow the designer to quickly review, quantify and comprehend the wealth of information that is obtained. Thus the designer always remains in control of the overall process.

The use of the program does not require any specialist knowledge about computing or about optimization theory. The program is fully documented, with a Modeler Tutorial, Users' and Reference Manuals, an Operating Guide and an Example Manual. In addition, this book itself serves as a very complete type of Theoretical Manual for the program. MAESTRO can be run on virtually all major operating systems: DOS, Windows/NT, Windows 95, UNIX, VMS, etc. It requires a minimum of 8 MB of RAM and 200 MB of available disk space. As of 1995 it has been adopted by nine navies, various structural safety authorities (Coast Guard agencies, classification societies, etc.) and by over fifty structural designers and shipyards in Europe, North America, Asia and Australia. Distribution and technical support is done through Proteus Engineering, Stevensville MD, USA, Design Systems Europe, Antibes, France, and Delteq Pte., Singapore.

1.4 STRUCTURAL SAFETY

Uncertainty, Risk, and Safety

In the design of ocean structures there are many uncertainties which must be dealt with. First there is the uncertainty of the loads, especially those arising from

waves. The ocean environment is severe, complex, and continuously varying. Ocean waves are essentially probabilistic and can be adequately defined only by means of statistics. Second, there are uncertainties regarding material properties such as yield stress, fatigue strength, notch toughness, and corrosion rate. For example, in ordinary steel which has not had special quality control the yield stress can vary by as much as 10%, and it is also dependent on the rate of loading and on the effects of welding. Third, there is inevitably some degree of uncertainty in the analysis of a structure as complex as a ship. Both the response analysis and the limit state analysis necessarily involve assumptions, approximations, and idealizations in formulating mathematical models of the physical environment and of the structure's response to that environment. Fourth, there can be variations and hence uncertainties in the quality of construction, and this factor has a particularly strong influence on the strength of a structure. Finally, there are uncertainties of operation, such as operating errors (improper loading, mishandling, etc.) or a change of service.

Wherever there are uncertainties there is risk of failure. For a structure, the risk of failure is the probability of a load reaching or exceeding its limit value. That is, for each limit state

$$\text{risk} = P_f = \text{prob}(Q \geq Q_L) \quad (1.4.1)$$

in which, for simplicity, we are here considering a limit state which involves only one load. The safety of a structure is the converse—the probability that it will not fail. Hence

$$\text{safety} = \text{prob}(Q < Q_L) = 1 - P_f \quad (1.4.2)$$

Since there are always some uncertainties, and hence some risk of failure, it is impossible to make a structure absolutely safe. Instead it can only be made "sufficiently safe," which means that the probability of failure can be brought down to a level that is considered by society to be acceptable for that type of structure. Therefore, if a structural design process is to be rationally based, the whole question of safety must be dealt with on a probabilistic basis, and the process must provide the means whereby the designer can ensure that the degree of safety meets or exceeds the required level. The calculation of the probability of a particular type of failure involves the probability density functions of the relevant load and of the limit value of that load. If these probability density functions are denoted by $p_Q(\cdot)$ and $p_{Q_L}(\cdot)$ respectively, then the

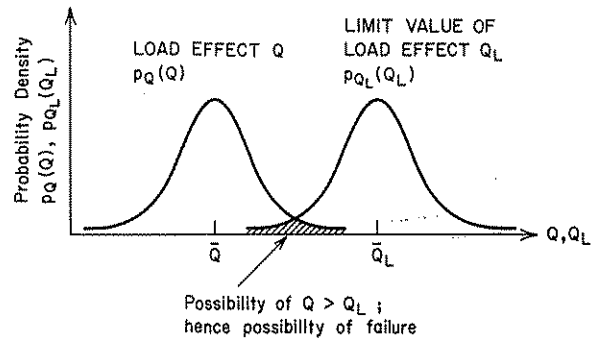


Figure 1.16 Probability distributions of load effect and of limit value of load effect.

probability of this particular type of failure occurring is

$$P_f = \int_0^{\infty} \left[\int_0^{\eta} p_{Q_L}(\xi) d\xi \right] p_Q(\eta) d\eta \quad (1.4.3)^*$$

This is illustrated in Fig. 1.16 which shows that even though $\bar{Q}_L$, the mean of the limit value, is well above the mean load there is still some overlap of the curves and hence some possibility of failure. (Note: The probability of failure is *not* equal to the area of the overlap, but this area nevertheless provides a useful visual and qualitative indication of P_f .) The figure also shows that the important regions of the distribution curves are the tails, because this is where the overlap occurs. Unfortunately it is this portion of a distribution curve which is most difficult to obtain with any precision, mainly because one is dealing with rare events. However it will be shown that there are ways of obtaining satisfactory estimates and upper limits of P_f , even though the tail portions of the distribution curves are not known precisely.

Levels of Safety

The required level of safety varies according to the type of failure and the seriousness of its consequences. Because these levels are ultimately determined by society there are no precise values or exact rules for determining them, but they can be estimated by surveys and by examining the statistics regarding failures, particularly those types in which the failure rate is considered by the public to be generally satisfactory, in the sense that the costs and resource usages that

*This equation assumes that Q and Q_L are independent random variables.

TABLE 1.1 COMPARATIVE ANNUAL PROBABILITY OF DEATH PER 10,000 PERSONS

Activity	Annual Exposure (hr)	Annual Risk per 10 ⁴
Offshore operations (including diving and vessels)		65
Mountaineering (international)	100	27
Distant water trawling (1958-1972)	2900	17
Offshore operations (other than construction, diving, or vessels)		11
Air travel (crew)	1000	12
Coal mining	1600	3.3
Car travel	400	2.2
Construction site	2200	1.7
Air travel (passenger)	100	1.2
Home accidents (all persons)	5500	1.1
Home accidents (able bodied)	5500	0.4
Manufacturing	2000	0.4
Structural failure (land-based structures)	5500	0.001
All causes (England and Wales, 1960-1962)		
Male, age 30	8700	13
Female, age 30	8700	11
Male, age 50	8700	73
Female, age 50	8700	44
Male, age 53	8700	100

would be required to further reduce the failure rate are considered to be unwarranted when balanced against other needs. For example, in regard to occupational risk Ref. 18 reviewed a range of activities and obtained the results shown in Table 1.1. From the results of a study of merchant ship losses the authors of Ref. 19 estimated a value of between 0.003 and 0.006 as the lifetime probability of overall structural failure that has been tacitly accepted over the past 20 years for large ocean-going ships. From studies of this type it would appear that the value of P_{FT} , the total annual failure probability per structure (ship, aircraft, drill rig, etc.) ranges from 10^{-3} or less for failures that have moderately serious consequences (substantial economic loss but no fatalities) to 10^{-5} or less for catastrophic failures, such as the crash of a passenger aircraft.

A different approach to the question of required level of safety is the use of economic criteria [20]. This is particularly appropriate for cases in which loss of life is not involved. For a large number of similar structures the total annual cost C_T of each of them can be formulated as:

$$C_T = C_i + P_f [C_f]_{EQ} \quad (1.4.4)$$

where C_i = initial cost, converted to an annual depreciation cost

P_f = annual probability of failure

$[C_f]_{EQ}$ = equivalent failure cost in present worth.

The equivalent failure cost involves a discounting of future damage costs to present worth by appropriate interest rates. Failure costs should include all costs involved such as salvage operation, pollution abatement, cleanup, and lost production. It could also include loss of reputation and public confidence. In Fig. 1.17 a typical relationship between annual cost and annual probability of failure is demonstrated. The figure shows that the most important parameter is the ratio ρ between failure cost and initial cost.

Many structures are comprised of, or can be divided into, a set of members each of which is sufficiently important that failure of any one member is regarded as failure of the structure. If the failure modes of the members are independent the total failure probability is

$$P_{FT} = \sum P_{fj} \quad (1.4.5)$$

where P_{fj} is the failure probability of the j^{th} member. Since the total probability of failure consists of several components there is an opportunity to optimize the way in which this total required level is obtained. Under some simplified assumptions the optimal design

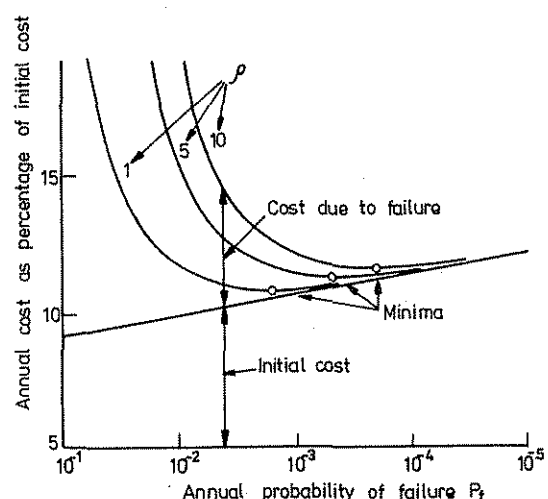


Figure 1.17 Typical relationship between cost and total probability of failure.