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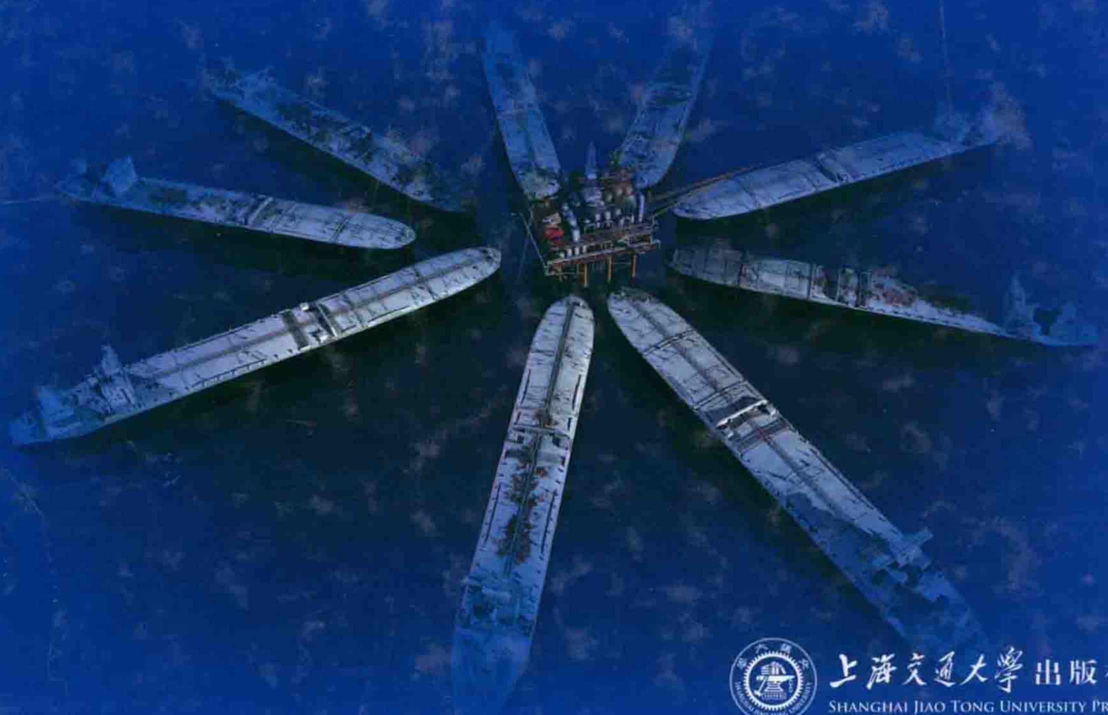
MARINE STRUCTURAL ANALYSIS AND DESIGN

王迎光 编



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PREFACE

The material in this book has been continuously developed since the author started to teach《Modern Ship Structural Design》in the Department of Naval Architecture and Ocean Engineering of Shanghai Jiao Tong University in 2004. The subject of marine structural analysis and design is so broad that it is not possible to incorporate every aspect of this subject into one textbook. No attempt has been made to make the presentation complete in this book. However, the topics included in the book have been made as complete as possible so that they can be studied in their entirety without reference to other works. Most of the basic ideas of the subjects covered have been included. The book is intended to have at least two applications. It is expected that the book may be used as a textbook in both the undergraduate and graduate studies for students majoring in the area of Naval Architecture and Ocean Engineering. On the other hand, the final results including handy tables and illustrations, may be referenced directly without going through detailed derivation. Therefore, the book should also be useful to the marine structural engineers and naval architects, as well as civil engineers and mechanical engineers who work on structural design.

Briefly, the organization of this book is as follows: Chapter 1 is an introduction to marine structural design including explanation of both the traditional design method and the modern design method. Chapter 2 outlines some marine structural design fundamentals including structural arrangements, structural materials, welding and some basic knowledge on classification societies and their rules. Chapter 3 and Chapter 4 consider loads and loads combinations in the process of marine structural design and how to calculate initial scantlings for a specific marine structure. Chapter 5 deals with the total strength assessment of an initially designed marine structure. Yielding, buckling and fatigue criteria are outlined in this chapter. Detailed explanations regarding spectral fatigue analysis of ship structures are also given in this chapter. Finally, Chapter 6 presents some fundamental knowledge about marine structural design optimization and several calculation examples. A knowledge of calculus, principles of naval architecture, strength of materials, solid mechanics and numerical optimization is the prerequisite for the complete use of this book.

It is a pleasure to acknowledge the help I received during the preparation of the manuscript. Among my colleagues at the Naval Architecture and Ocean Engineering Department of Shanghai Jiao Tong University, I am deeply indebted to Professor Zhang Weijing, deputy head of the Department, for giving me warm and constant encouragement to finish writing this book. I am grateful for those who have reviewed my application proposal for publishing this book. Among my students, my special thanks are due to Shi Yongpeng and He Yong, who ably assisted in a number of computations, and Zhang Youwen, who unfailingly assisted in putting the manuscript in proper order. While it has been a joy to write this book, only the enjoyment and benefits realized by the readers will make my labor fruitful.

Contents

Chapter 1 Introduction to marine structural design

1.1 The traditional design method

1.1.1 The evolutionary process

The way that ships were designed and built until the 1970s was essentially an evolutionary process, without dramatic changes in configuration and size. Most importantly, mild steel was predominant in ship construction through that period. It was therefore relatively easy for classification societies to develop their strength criteria. These were based on practical experience gained over the years and were typically presented in a semi-empirical type[1]. In the next sub-section, we give an example of a ship structural design based on this kind of semi-empirical rules.

1.1.2 A ship structural design example

The ship we consider is a 77.7m dredging barge. It has the main particulars as listed in Table 1.1.

Table 1.1 Main particulars of the dredging barge

Length overall (L_{OA})	77.7m
Length waterline (L_{WL})	77.7m
Molded breadth (B)	18.2m
Molded depth (D)	5.2m
Design draft (T_d)	3.50m
Frame spacing (S)	0.7m
Block coefficient (C_b)	0.883

The ship has a single deck and is not self-propelled. The main hull of the ship has a longitudinal framing system and the deck house of the ship also has a longitudinal framing system. There are two longitudinal bulkheads and six transverse bulkheads inside the main hull of the ship. The ship's structural design is according to *Building and Classing Rules for Steel Ocean ships* issued by China Classification society (CCS). The ordinary CCS-A class steel (mild steel) was used for the hull structure members. An example of calculating the scantlings of the hull structural members according the semi-empirical CCS rules is given as follows: The thickness of a bottom shell plate in the midship 0.4L region should not be less than the values calculated according to the following two formulae:

$$t_1 = 0.043s(L_{WL} + 230) \text{ (mm)} \quad (1.1)$$

$$t_2 = 5.6s\sqrt{(T_d + 0.26 \times [(0.0412L_{WL}) + 4])} \text{ (mm)} \quad (1.2)$$

After calculation and adding an empirical margin value, $t = 12$mm is finally selected for the bottom shell plate. The scantlings of the other hull structural members are calculated and decided in the same way. After the scantling of all the hull structural members are selected, the static moment and vertical moment of inertia of the midship section can then be calculated. The calculation processes are listed in Table 1.2 and Table 1.3, respectively.

Table 1.2 Midship section static moment calculation

Structural members	Specification/mm	A/cm^2	From $B.L.$/cm	S/cm^3	I_s/cm^4
Main deck plate	18	1,503	520	781,560	405.8
Main deck longitudinal	$L160\times100\times14$	344	510	175,440	8,921
Side shell plate	24	1,056	410	432,960	4,259,200
Side shell plate	12	720	150	108,000	5,400,000
Side shell longitudinal	$L160\times100\times14$	68.8	47	3,233.6	1,784
Side shell longitudinal	$L160\times100\times12$	119	135	16,065	3,120
Side shell longitudinal	$L150\times100\times10$	96	275	26,400	2,222
Side shell longitudinal	$L125\times80\times10$	78	415	32,370	1,240
Bottom plate	14	224	0	0	36
Bottom plate	12	1,992	0	0	238
Bottom longitudinal	$L160\times100\times14$	206	10	2,060	5,352
Bottom longitudinal	$L100\times63\times10$	214	8	1,712	2,142

(continuous)

Structural members	Specification/mm	A/cm^2	From *B. L.* /cm	S/cm^3	I_s/cm^4
Inner bottom plate	10	360	100	36,000	30
Inner bottom longitudinal	*L*100×63×8	62	92	5,704	632. 5
Center girder	12	120	50	6,000	100,000
Side girder	10	100	50	5,000	83,332
Iongitudinal bulkhead	10	1,040	260	270,400	23,434,666
Bulkhead longitudinal	*L*125×80×10	156	345	53,820	2,482
Bulkhead longitudinal	*L*125×80×12	92	100	9,200	1,448
Total		8,550. 8	229. 9	1,965,924. 6	33,307,251. 3

In Table 1. 2 and Table 1. 3, A means the area of the respective structural members, *B. L.* means the baseline of the ship, *S* means the static moment , *N. A.* means the neutral axis of the midship section, *I* means the moment of the inertia, and I_s means the moment of the inertia of each hull structural member to its own neutral axis. Based on the information in Table 1. 2 and Table 1. 3, we can obtain that the moment of inertia of the whole midship section is 388,433,657. 1cm^4, the section modulus of the midship section at the main deck is 1,338,964. 7 cm^3 and the section modulus of the midship section at the bottom is 1,689,576. 59cm^3. The CCS rule requirement for the value of the section modulus of the midship section is:

$$W_0=0.95(0.041\,2L_{WL}+4)\ L_{WL}^2 B\ (C_b+0.7) \qquad (1.3)$$

We can find that $W_0=1,189,901\text{cm}^3$, which is smaller than both the real ship section modulus at the main deck and at the bottom. This demonstrates that the strength of the hull girder of this ship is enough.

Table 1. 3 Midship section moment of inertia calculation

Structural members	Specification/mm	A/cm^2	From *N. A.* /cm	I/cm^3	I_s/cm^4
Main deck plate	18	1,503	290. 1	126,489,489	405. 8
Main deck longitudinal	*L*160×100×14	344	280. 1	2,6988,867. 44	8,921
Side shell plate	24	1,056	180. 1	34,252,426. 56	4,259,200

(continuous)

Structural members	Specification/mm	A/cm^2	From *N. A.* /cm	I/cm^3	I_s/cm^4
Side shell plate	12	720	−79.9	4,596,487.2	5,400,000
Side shell longitudinal	*L*160×100×14	68.8	−182.9	2,301,525.808	1,784
Side shell longitudinal	*L*160×100×12	119	−94.9	1,071,715.19	3,120
Side shell longitudinal	*L*150×100×10	96	45.1	195,264.96	2,222
Side shell longitudinal	*L*125×80×10	78	185.1	2,672,436.78	1,240
Bottom plate	14	224	−229.9	11,839,298.24	36
Bottom plate	12	1,992	−229.9	105,285,187.9	238
Bottom longitudinal	*L*160×100×14	206	−219.9	9,961,338.06	5,352
Bottom longitudinal	*L*100×63×10	214	−221.9	10,537,276.54	2,142
Inner bottom plate	10	360	−129.9	6,074,643.6	30
Inner bottom longitudinal	*L*100×63×8	62	−137.9	1,179,017.42	632.5
Center girder	12	120	−179.9	3,883,681.2	100,000
Side girder	10	100	−179.9	3,236,401	83,332
longitudinal bulkhead	10	1,040	30.1	942,250.4	23,434,666
Bulkhead longitudinal	*L*125×80×10	156	115.1	2,066,689.56	2,482
Bulkhead longitudinal	*L*125×80×12	92	−129.9	1,552,408.92	1,448
Total		8,550.8		355,126,405.8	33,307,251.3

1.1.3 The changes to the traditional design method

The evolutionary approach to rule development changed in the 1970s. At that time a significant change in ship design took place, driven primarily by the tanker market. The most noticeable change was the dramatic increase in the size of ships with the introduction of Very Large Crude Carriers (VLCCs), Ultra Large Crude Carriers (ULCCs), large container ships and large bulk carriers. More recently, Liquefied Natural Gas (LNG) carriers have followed this same pattern. Structural configurations changed. Also significant was the increasing use of higher strength steels that, with reduced scantlings facilitated by computer-aided-design, had a noticeable impact on ship durability and structural problems in service [1].

In addition, the requirements of the International Conferences on Marine Pollution (MARPOL 1973) and on Tanker Safety and Pollution Prevention (1978), had a significant impact on the design of tankers. One result was deeper ships, allowing thinner deck and bottom scantlings, while maintaining the required hull girder section modulus. With the MARPOL and OPA 90 requirements for double hull structures, tanker design is continuously undergoing change. This means that using prescriptive rules based on service experience is difficult, bearing in mind that such experience does not exist[1].

The critical nature of bulk carrier structures has been dramatically demonstrated over the last three decade by the number of serious casualties that these ships have suffered. Large containership structural performance has, in general, been very positive. However, the trends of ever increasing size, capacity, speed and innovative design require detailed design criteria that are not available using traditional rules[1].

An important ramification of these changes in ship design is the effect they have had on the failure modes of hull structures and the impact on safety. Many modern design features fall outside the experience base of existing strength criteria. As a result, the traditional primary structural design criteria based on yield strength needed to be augmented by criteria for buckling and fatigue, which influences, and possibly controls the design. Buckling and fatigue can no longer be assumed to be accounted for through implied safety margins of the existing criteria [1].

As there was no consistent and rational basis for extending the existing criteria into these new areas, a new basis had to be established. All these developments meant that a scientific approach was required to determine appropriate levels of strength in ship structures, accounting for various failure modes in a comprehensive and realistic manner. The modern structural design method has been developed in response to this need[1].

1.2 The modern design method

1.2.1 The first-principles-based approach

The fundamental objective of a first principles based approach is to determine if a structure has sufficient capability (strength) to satisfactorily withstand the demands (loads) placed on it for its intended service. To obtain this "fitness for purpose" of any structural component, or the entire ship, it is necessary to take the following steps [1]:

- determine suitable realistic environmental conditions appropriate to the nominal lifetime operation of the ship;
- accurately establish the realistic loads (static and dynamic) acting on the ship, as well as the expected interaction and combination of those loads. All loads which are likely to be imposed on the structure by the natural environment in all loading scenarios, throughout the ship's life, must be considered;
- model the strength of the global and local structures to resist all relevant failure modes in response to the realistic loads imposed on that structure; and
- establish criteria to obtain required factors of safety for the failure modes, in response to the loads on the structure. The criteria must take into account the deterioration that is expected due to wastage and corrosion.

This scientific approach is not feasible using simple empirical rule formulations. Therefore, the world leading classification societies have restated the traditional prescriptive Rules in a first principles based format. An essential theme in these principles is an accurate representation of the dynamic loads. One of the most important tasks in the design of the hull structure using the modern method is to predict dynamic loads, the maximum loads, load ranges, and the appropriate combination of all these loads[1].

1.2.2 The design procedure

The modern design process begins with the identification of the initial scantlings (Phase Ⅰ), where the designer enters the structural data into an interactive system for generating the hull configuration. The designer then calculates strength requirements for the design, using dynamic design load criteria, and reports compliance or non-compliance with Rule and Guide criteria. The designer need only modify that data which does not comply, to arrive at a design that fully meets all basic Rule and Guide criteria. This can be as elementary as changing a structural component or material, or as complicated as moving a bulkhead, but the designer need only re-specify those elements that are being changed[1].

Fatigue evaluation is included in the development of the initial scantlings. Using the fatigue assessment procedures specified in the class rules, stiffeners in fatigue sensitive areas are analyzed and the results are checked against Rule and Guide fatigue criteria. By including a fatigue assessment in the initial scantlings design, the designer can adjust scantlings to meet fatigue requirements without having to do a separate fatigue analysis, or a detailed Finite Element Analysis (FEA) assessment (Phase Ⅱ). Many designers find that the scantlings resulting from Phase Ⅰ are adequate for carrying out feasibility and economic studies[1].

Following the development of the initial scantlings in Phase Ⅰ, the designer creates finite element models (global 3-D and fine mesh 2-D and 3-D) for the strength assessment portion in Phase Ⅱ. In this phase, FEM pre-processors are used to automate the generation of the models. Then, the global and local loads are calculated, considering the dynamic nature of the expected environmental and operational conditions [1].

In the following, the detailed procedures in Phase Ⅰ and Phase Ⅱ are listed:

Phase Ⅰ — Initial scantlings calculation

This phase of the design determines basic hull structural scantlings that satisfy the load, strength and fatigue requirements. In general, the scantlings from Phase Ⅰ are considered as a minimum, and must also comply with the strength assessment of Phase Ⅱ. The Phase Ⅰ analysis comprises the following steps[1].

Modeling of hull geometry and definition of tanks and holds

The geometric model of the ship is generated and the boundaries of the cargo holds and ballast tanks are defined using a graphical user interface.

Generation of dynamic loads

After the hull envelope and internal spaces are defined, the loading for the required cases is calculated.

Development of scantlings for longitudinal strength

Scantlings of individual plates and stiffeners are entered by the designer based either on experience, or as a first iteration estimate to be checked using the criteria.

Assignment of scantlings for main supporting members

The definition of the scantlings for the main supporting members, such as deck, side, cross deck, double bottom structures and transverse bulkheads, is carried out.

Determination of initial minimum scantlings

The section modulus and overall properties of the structural members are calculated in this step of the analysis. The midship section modulus is assessed for compliance with the hull girder strength criteria. The individual longitudinal and transverse structural members are evaluated against the strength criteria, based on the nominal loads acting at each location. This step of the process is repeated until the initial scantlings fully comply with the class strength criteria for both local and hull girder strength.

Fatigue strength assessment of structural details

The fatigue life characteristics of the structural details are calculated. Should any of the fatigue results be below the required values, the designer can iterate from the appropriate point in Phase Ⅰ, to take the most effective corrective action.

Warping and torsional effects

Due to large deck openings, the torsional response of containerships is extremely important. The designer should calculate the warping stress along the entire length of the ship. The designer considers the magnitude and distribution of the torsional moment, the variation of torsional properties, and the rigidity between the open and closed decks. These warping stresses are added to other hull girder stresses in proper phasing, to determine the total stress at any hull girder section. A minimum hull girder torsional stiffness should be specified to prevent excessive hull girder distortion.

Phase Ⅱ — Total strength assessment

The Phase Ⅱ procedure is structured to perform the detailed FEM analyses required for the strength assessment of the scantlings obtained from Phase Ⅰ. The designer checks the structure with respect to the failure modes of yielding, buckling and ultimate strength. The Phase Ⅱ strength assessment uses FEA to determine the structural response of the ship to the imposed loads. This requires developing idealized finite element models of the ship structure and loads to determine the deflections and stresses. The solved model results are then evaluated against the failure criteria in class rules [1].

Loading

The FEA is performed for the standard loading patterns specified by classification rules, appropriate to the ship type, with corresponding hull girder responses and external pressures acting on the ship as formulated in the class criteria. Internal pressure loads, representing various combinations of full, empty and partially loaded cargo and ballast tanks, together with associated external pressures representing full and light drafts, are imposed on the global 3-D finite element model. These cases represent full and ballast loading conditions that typically occur in service. The model loading process uses a graphical interface, where the designer may point and click on the model to define input data[1].

Analysis results

Typical stress results obtained from the structural analysis are produced in both tabular and colored stress contour formats. The numerical results are normally printed for high stress areas where detailed yielding and buckling evaluations are to be carried out. These stress results are assessed against the yielding and buckling criteria of class rules.

1.2.3 Benefits of the modern approach

In assessing the value of applying the modern design method to ships, there are a number of significant benefits to consider. The modern design method can benefit designers, owners, operators, charterers, builders, and underwriters [1].

More thorough investigation of design

The modern design method reduces the time needed for developing the basic hull scantlings and streamlines some of the time consuming calculations for classification purposes. This gives designers the capability to evaluate more innovative designs, or to better develop a particular design. Evaluation of design alternatives can now be performed in significantly less time [1].

Increased confidence of compliance with class requirements

The modern design method is also seen as benefiting the classification process, particularly in the area of plan review. By using the modern design method throughout the design process, a designer will have a much better understanding of how the proposed design compares with the class strength criteria, before submittal to class for approval. Using the same tools during the development of the structural design that class will use in its approval evaluation will result in reduced cycle time in the classification review [1].

Enhanced safety through more effective use of materials

The modern design method can make much more effective use of steel, while complying with class scantling requirements. As an example, the steel weight of a tanker designed by using the modern method has generally been found to be within plus or minus one percent of what would have been expected in applying the traditional design method. A bigger difference can be expected, however, in local structure scantlings. Some local scantlings may vary by as much as plus or minus ten percent from the traditional Rule requirements. By using the modern