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Designed-Oriented Methods of Ultimate Hull Girder Strength

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Abstract

Based on long-time theoretical and experimental work in authors group, assessment methods of ultimate strength of ship hulls are analyzed and improved. Nonlinear finite element analysis method (FEM), idealized structural unit method (ISUM), simplified method (SM) and analytical method (AM) are integrated into a software system of direct calculations of large tankers. Using this software system, a comparative calculation is performed on ultimate hull girder strength of a 300,000dwt double hull tanker and the calculation results are also compared with the single step procedure of Common Structural Rules for double hull tankers (JTP CSR).

Key words: double hull tankers; ultimate strength; analytical method; simplified method; elastic-plastic method.

1 Introduction

Ship structures are exposed to many types of loads and most often overloading is related to extreme environmental actions due to wind, waves and current and accidental events due to collision, grounding and explosion. Moreover, damage and corrosion may reduce ship hull strength expected in intact condition. In the past more than one decade, there has been a major worldwide concern about the continuous loss of some large tankers. A major contributing factor to the cause of these losses is considered to be catastrophic structural failure. The industry cost of such disasters is not only counted in terms of loss of human life, the ship and its cargo, but also in terms of environmental damages, increases in insurance premiums and loss of business due to bad publicity. The hull girder ultimate capacity is an explicit control of the most critical failure mode for large double hull tankers. In order to gain safe and economic design of ship structures, it is necessary to accurately evaluate the ultimate hull girder strength of large double hull tankers.

Ultimate hull girder strength is defined as the maximum bending capacity of the hull girder beyond which the hull will collapse. Caldwell (1965) firstly proposed a rational method considering both buckling and yielding effects. Since then, there has been continuous effort worldwide with regard to the study of ultimate hull girder strength and many researches have been carried out. The existing methods of ultimate hull girder strength can be classified into three categories [1]:

- ship accident investigation and model test,
- direct methods, such as linear method, empirical formulas and analytical method (AM), along with
- progressive collapse analysis, such as simplified method (SM), idealized structural unit method (ISUM) and nonlinear finite element method (FEM).

In the above methods, AM and SM (in which average stress-strain relationship is derived using empirical formulas or beam-column theory) are design-oriented methods which should be verified by test or more precise method.

Some achievements have been applied in ship design, such as single step procedure and rule criteria of ultimate hull girder strength in CSR for oil tankers developed by ABS, DNV and LR. In recent years, many benchmark calculations on ultimate strength of ship hulls and members have been organized by ISSC. However, calculation results are scattering and have distinct differences with test results since ship hulls are large thin-walled welded structures and their ultimate strengths are sensitive to many factors. Hence, reasonable and reliable method of ultimate hull girder strength urgently needs to be developed and structural reliability and rational life cycle cost method should be used to make rules.

With regard to above facts, this paper analyzes and improves assessment methods of ultimate strength of ship hulls based on long-time theoretical and experimental work in authors group. FEM, ISUM, SM and AM are integrated into a software system of direct calculations of large tankers. Using this software system, a comparative calculation is performed on ultimate hull girder strength of a 300,000dwt double hull tanker and the calculation results are also compared with the single step procedure of JTP CSR.

2 Assessment methods

General finite element system plays a more and more important role in structural nonlinear analysis with development of computer technology and numerical calculation method. Based on general finite element system and coupled with ship hull damage and initial imperfections treatments, an integrated framework of finite element analysis of ultimate strength of intact and damaged ship hulls wasestablished where damage model, initial deflection and residual stress analysis modules are user-defined program [1-2]. Fig.1 shows the framework of ultimate strength analysis of intact and damaged hulls based on general finite element system, where damage model, initial deflection and residual stress analysis modules are user-defined program. Special program needs to be developed to analyze damage and initial imperfections and put them on model on account of their complexity. When the above framework is used to analyze the ultimate hull girder strength, the following critical problems usually occur

- ● mesh dimension,
- ● boundary condition, and
- ● solution method.

Hence, the integrated framework of finite element analysis should be verified by model tests before it can be used as benchmark of comparative study of ultimate hull girder strength. This paper uses the verified integrated framework to perform comparative study.

Considering the similarity of ship structural unit and the scale of nonlinear finite element calculation, many researchers developed semi-empirical and semi-analytic method to improve unit behavior and tried to reduce unit scale and calculation complexity. Ueda & Rashed (1974) proposed the concept of idealized structural unit. In this method, large structure member is regarded as one unit and thus calculation time is reduced. The key of the method is to develop effective and simple unit considering buckling and yielding. Paik et al (1996) developed a program of nonlinear analysis of large plated structure using ISUM, which employs the following five types of the ISUM units:

- ● beam-column unit,
- ● unstiffened plate unit,
- ● stiffened plate unit,
- ● hard unit, and
- ● virtual unit.

These units (except for the hard and virtual units) take into account either singly or in combination: buckling in compression, yielding in tension, strain-hardening, necking, rupture due to excessive tension-deformation, interaction effects between local and global system failure of structure, combined bi-axial loading and shearing force, lateral pressure and initial imperfection. The above ISUM program was

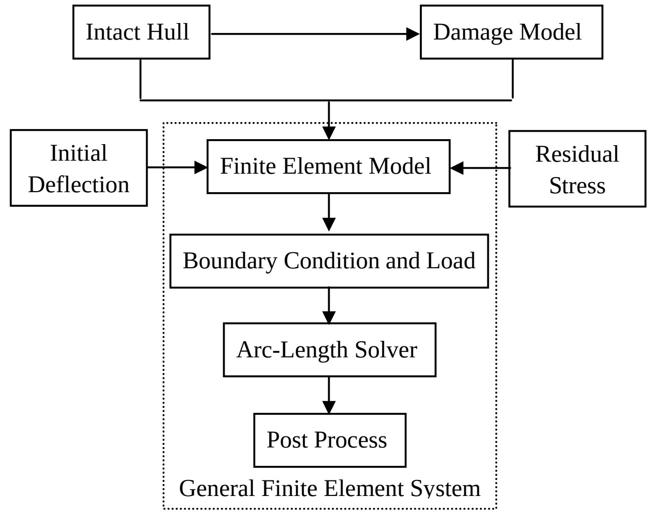

Fig.1 Framework of nonlinear FEM

digested and improved locally [3]. This paper uses the improved ISUM to perform comparative study.

Smith (1977) proposed a simplified method of progressive collapse analysis of ship hull girder on the basis of plane section assumption. The key of simplified method is to define the average stress-average strain relationships of the individual elements. The existing methods of the average stress-average strain relationships can be classified into three categories:

- ● finite element method,
- ● elastic-plastic method or beam-column theory, along with
- ● empirical formulas.

Rigo et al (2001) performed a sensitivity analysis on ultimate hull bending moment. The results show that the most important factor is ultimate strength of stiffened plate elements, but the influence of the shape of the average stress-average strain curve cannot be neglected, especially the length of the plateau. For fast and reliable calculation, the simplified method in which average stress-average strain relationship is derived using beam-column theory should be paid close attention [4]. This paper uses this simplified method to perform comparative study.

Analytical method is based on an assumed stress distribution over hull section at limit state, from which ultimate hull girder strength is approximately calculated taking into account buckling in compression flange and yielding in tension flange. Caldwell was the first who tried to theoretically evaluate the ultimate hull girder strength of a ship subjected to longitudinal bending. He introduced a so-called Plastic Design considering the influence of buckling and yielding of structural members composing a ship hull and idealized a stiffened cross-section of a ship's hull to an unstiffened cross-section with equivalent thickness. Fully yielding was assumed for the material in tension at limit state, while the entire material in compression was assumed to have reached its ultimate buckling strength which is calculated by a stress reduction factor. The calculation formulation of ultimate hull girder strength was then derived by integration of the moment resulting from stresses with respect to the neutral axis. Maestro and Marino (1989) extended the Caldwell's formulation to the case of bi-axial bending, and modified the method to estimate the influence of damage due to grounding and/or collision on the ultimate hull girder strength. Paik & Mansour (1995) developed Caldwell's method. The material in the vicinity of the neutral axis was assumed to remain in the elastic state and the height of the elastic range was determined by assuming that the elastic range was partial to tensile flange. Analytical method is very simple and suitable for design and reliability analysis.

Although AM does not explicitly take into account of strength reduction in the members beyond their ultimate strength, accurate results can be obtained provided that the stress distribution assumption of the cross-section is reasonable. The results of model test and finite element analysis of real ship verify Paik's assumption that the material in the vicinity of the neutral axis was assumed to remain in the elastic state, but query Paik's assumption that the elastic range was partial to tensile flange. Furthermore, Paik's analytical method cannot be used for biaxial bending and non-symmetric structures of damaged ship hulls. Hence, the key of analytical method is to determine the elastic range and include the effects of biaxial bending and non-symmetric structures of damaged ship hulls.Based on model tests and finite element analyses, Qi and Cui (2005) [5] proposed an advanced analytical method that is design-oriented and suitable for biaxial bending and non-symmetric structures of damaged ship hulls. The basic procedure of the advanced analytical method is:

- The cross-section of the hull is divided into stiffened panels, the ultimate buckling strength of the stiffened panels is calculated using the elastic-plastic method,
- At limit state, the material in tension flange is assumed to reach its yielding strength, the material in compression flange is assumed to reach its ultimate buckling strength, while the material in the vicinity of the neutral axis is assumed to remain in the elastic state,
- The elastic range is determined by the distance between tensile and compressive force center perpendicular to the neutral axis in Caldwell's ultimate strength model,
- The ultimate neutral axis is determined by equilibrium condition in the elastic-plastic ultimate strength model,
- The ultimate bending moment can be expressed as multiplication of tensile force and the distance between tensile and compressive force center in elasto-plastic model.

One of the key problems of analytical method is to calculate ultimate buckling strength of stiffened panels. Cui et al (2000) [6] considered four types of failure modes:

- Mode A – gross buckling of cross-stiffened panel,
- Mode B – overall buckling of longitudinal stiffened panel,
- Mode C – yielding or buckling of longitudinal stiffener, and
- Mode D – tripping of longitudinal stiffener.

An elastic-plastic method (EPM) for ultimate buckling strength analysis of stiffened panels considering initial imperfections and combined loads of biaxial compression and later pressure was given based on large deflection theory and rigid plastic analysis. Qi and Cui (2005) [5] improved EPM by adding the work done by lateral pressure into the energy function and modifying the treatment of initial imperfections, and thus some parameters are different from those of [6].

3 Verification by Model Tests

Using EPM1 of [6], EPM2 of [5] and FEM (Smith 1992), comparative calculation of ultimate buckling strength is performed on cross-stiffened panels of Simth test (Smith 1976). The detailed data of test panels can be found in [1]. The results of comparative calculation are shown in Table 1. The model uncertainties of FEM1 with average initial imperfections on the basis of test is mean = 0.900 and COV = 0.144. The model uncertainties of FEM2 with actual initial imperfections on the basis of test is mean = 0.887 and COV = 0.083. The model uncertainties of EPM1 on the basis of test is mean = 0.894 and COV = 0.118. The model uncertainties of EPM2 on the basis of test is mean = 0.898 and COV = 0.109. The results calculated by EPM2 of [5] coincide well with that of test.

Table 1 Comparative calculation of panels of Smith test

No.	p (MPa)	FEM1	σ FEM2	σ EPM1	EPM2
1a	–	0.855	0.908	1.013	1.013
1b	0.103	0.781	0.781	0.795	0.767
2a	0.048	0.890	0.890	0.824	0.813
2b	–	0.988	0.988	1.060	1.012
3a	0.021	1.000	0.913	0.710	0.710
3b	–	1.164	0.984	0.852	0.902
4a	–	0.976	0.915	–	1.012
4b	0.055	0.880	0.916	–	0.855
5	–	0.708	0.764	0.889	0.903
6	–	–	–	0.980	0.918
7	–	0.754	0.815	0.923	0.969
Mean		0.900	0.887	0.894	0.898
COV		0.144	0.083	0.118	0.109

Table 2 Comparative calculation of ship hulls of series tests

Model	Condition	$(M_u)_{Cal.}/(M_u)_{Exp.}$ FEM[a] or ISUM[b]	SM	AM
D2	Hogging	1.057[b]	0.991	1.056
D4	Hogging	1.014[b]	–	1.026
D10	Hogging	1.026[b]	–	1.091
NST	Sagging	1.000[a]	–	1.008
NDT	Sagging	1.011[a]	–	1.045
	Hogging	1.006[a]		0.922
MII	Hogging	0.978[b]	–	0.946
DF	Sagging	1.012[b]	0.980	0.975
AF	Sagging	1.014[a]	–	1.008
SAC	Hogging	0.955[a]	–	1.021
VLCC	Hogging	1.010[b]	1.059	1.033
Mean		1.008	–	1.012
COV		0.024	–	0.046

Using AM, FEM and ISUM, comparative calculation of ultimate hull girder strength is performed on three box girder models of Dowling (1976) (D2, D4 and D10), single and double hull tanker models of Nishihara (1983) (NST and NDT), tanker model of Mansour (1990) (MII), 1/3-scale frigate model of Dow (1991) (DF), frigate model of Akhras et al (1998) (AF), Large surface warship model of Sun et al (2000) (SAC) and VLCC *Energy Concentration*. The detailed data of test models can be found in [1]. The results of comparative calculation are shown in Table 2. The model uncertainties of FEM and ISUM on the basis of test is mean = 1.008 and COV = 0.024, FEM and ISUM can be used as benchmark of comparative study of ultimate hull girder strength. SM is only used to calculate ultimate strength of D2,DF and VLCC and the results of these three examples coinside well with that of test. The model uncertainties of AM on the basis of test is mean = 1.012, COV = 0.046, the results calculated by AM coincide very well with that of test.

4 Integrated system

The above verified FEM, ISUM, SM and AM are integrated into a software system of direct calculations of large tankers as shown in Fig.2. This software system is designed to perform direct calculation and analsis of extrenal load, fatigue strength, ultimate strength and strucutral optimization of large tankers. It inludes 11 functional modules, such as file management, general data, still water load, wave load, ship hull strength, fatigue strength, buckling and ultimate strength, cargo tank anlysis and strucutral optimization.

Fig.2 Integrated system

This software system is used to perform a comparative calculation on ultimate hull girder strength of a 300,000dwt double hull tanker [7]. Using FEM, ultimate hogging strength analysis of the large double hull tanker is performed. Half midship section is selected as analysis object and is attached with an extended section on which linear distributed load is applied to simulate pure bending moment. Elastic-plastic plate and beam-column element is used to establish finite element model while initial imperfections are neglected in order to reduce the calculation scale of nonlinear finite element. Fig.3 shows the equivalent stress distribution of the cross section at limit state under hogging condition. The material in deck and upper side reaches its yielding strength, the material in bottom and lower side reaches its ultimate buckling strength, while the material in the vicinity of the neutral axis remains in the elastic state. Ultimate hogging strength calculated by FEM is M_{uhf} = 31,669MNm.

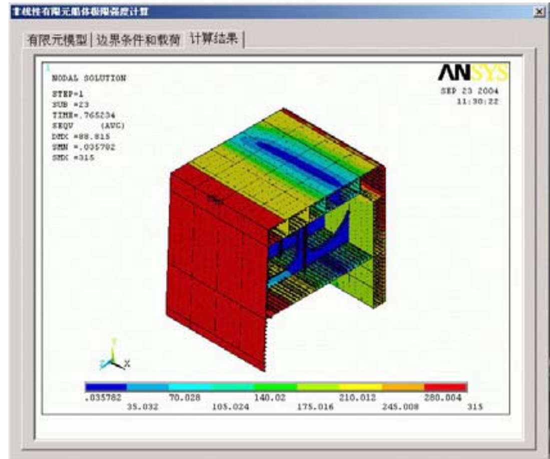

Fig.3 Equivalent stress distribution by FEM

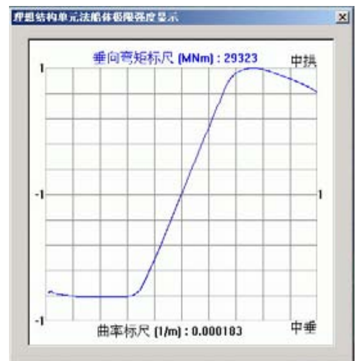

Fig.4 Bending moment and curvature relationship by ISUM

Using ISUM, ultimate hogging and sagging strength analysis of the large double hull tanker is performed. A single-span midship section is selected as analysis object of which heavy longitudinal and transverse supporting members are modeled as the idealized beam-column unit, unstiffened or stiffened panels are modeled as the idealized unstiffened or stiffened plate unit, corner members are modeled as hard unit and transverse stiffness is simulated by virtual unit. The progressive collapse course of ship hull is analyzed by incremental curvature on the basis of plane section assumption. In ISUM calculation, residual stress is taken as ξ = 0.1 ($\xi = \sigma_{rcx} / \sigma_{op}$) and initial deflection is taken as A_{om} = 0.01t. The bending moment and curvature relationship calculated by ISUM is shown in Fig.4. Ultimate hogging strength calculated by ISUM is M_{uhi} = 29,323MNm, ultimate sagging strength calculated by ISUM is M_{usi} = 23,827MNm.

Using SM, ultimate hogging and sagging strength analysis of the large double hull tanker is performed. Midship section is divided into stiffened plate and hard corner elements of which the average stress-average strain relationship is derived using elasto-plastic beam-column theory. The progressive collapse course of ship hull is analyzed by incremental curvature on the basis of plane section assumption. In SM calculation, residual stress is taken as ξ = 0.1 and initial deflection of beam column is taken as $\Delta = a / 750$. The bending moment and curvature relationship calculated by SM is shown in Fig.5. Ultimate hogging strength calculated by SM is M_{uhs} = 29,423MNm, ultimate sagging strength calculated by SM is M_{uss} =

24,108MNm. Although the elastic stiffness calculated by SM is on the low side on account of the introduction of A / A_e considering panel collapse due to plate compression, ultimate strength and its curvature calculated by SM coinsides well with that by ISUM.

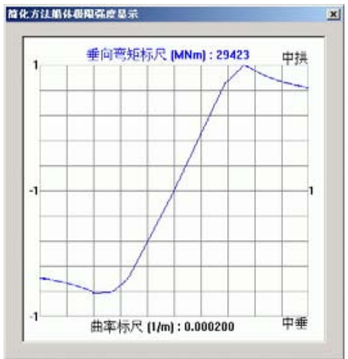

Fig.5 Bending moment and curvature relationship by SM

Using AM of this paper, ultimate hogging and sagging strength analysis of the large double hull tanker is performed. Midship section is divided into stiffened panels of which ultimate buckling strength is calculated by EPM. The ultimate hull girder strength is theoretically calculated by stress distribution assumption of the cross section at limit state. In AM calculation, residual stress of plating is taken as ξ = 0.1, initial deflection of plating is taken as A_{om} = 0.01t, residual stress of stiffener is taken as ξ_s = 0.1 and initial deflection of stiffener is taken as W_{os} = a / 750. Ultimate hogging strength calculated by AM is M_{uha} = 29,252MNm, ultimate sagging strength calculated by ISUM is M_{usa} = 23,962MNm. Ultimate strength calculated by AM coincides well with that by ISUM and SM.

Table 3 Comparative calculation of double hull tanker (MNm)

Condition		CSR	FEM	ISUM	SM	AM
H	Strength	—	31,669	29,323	29,423	29,252
	Mean	—	—		29,333	
	S / M	—	1.080	1.000	1.003	0.997
S	Strength	19,830	—	23,827	24,108	23,962
	Mean	—	—		23,966	
	S / M	0.827	—	0.994	1.006	1.000

The results of comparative calculation of the large double hull tanker using FEM, ISUM, SM and AM are shown in Table 3. Ultimate hogging and sagging strength calculated by ISUM, SM and AM agree well with each other. Ultimate hogging strength calculated by FEM is on the high side on account of no initial imperfections are considered. Ultimate sagging strength calculated by the single step procedure of CSR is also given in Table 2. Instead of using PULS, the verified EPM of [5] is used to calculate the buckling strength of tanker deck. Although the single step procedure considers deck buckling, it remains a linear method based on reduced section modulus. Ultimate sagging strength calculated by CSR is conservative and is 0.827 of the mean value by ISUM, SM and AM.

Based on the theoretical analysis of FEM, ISUM, SM and AM, along with verifications by model tests and accident investigation, comparative analysis of calculation methods of ultimate hull girder strength from many aspects of basic assumptions, loading type, key points, calculation time and applicability are given in [7]. For general analysis of ultimate hull girder strength, reasonable results can be obtained using these methods provided that the basic assumptions are reasonable and the key points are solved. FEM and ISUM are suitable for comparative study while SM and AM are suitable for design and assessment.

5 Summary and Conclusions

Assessment methods of ultimate strength of ship hulls are analyzed and improved. FEM, ISUM, SM and AM are integrated into a software system of direct calculations of large tankers. FEM and ISUM are suitable for comparative study while SM and AM are suitable for design and assessment.

Ultimate sagging strength of a large double hull tanker calculated by the single step procedure of CSR is also given in this paper. Since the single step procedure remains a linear method based on reduced section modulus, the ultimate sagging strength calculated by CSR is conservative. Furthermore, the single step procedure is only suitable for sagging condition and more study should be given to hogging and damage condition.

Combined with EPM, an advanced analytical method for ultimate strength analysis of ship hull girder is proposed on the basis of model tests and finite element analysis. Comparative study of ultimate strength of intact and damaged ship hull shows that the advanced analytical method has good precision, is suitable for structural non-symmetry of damaged ship hull and biaxial bending and can include detailed structural information of ship hull.

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