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Study on influence of nonlinear finite element method models on ultimate bending moment for hull girder

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ABSTRACT

The various assessment methods of ultimate strength for hull girder of ships or offshore structures might lead to different results and computation time. The nonlinear finite element (FE) analyses include the implicit static analysis and explicit dynamic analysis, which both can consider the large deflection and material nonlinearity during the process of progressive collapse. Comparing with the implicit static analysis, the explicit dynamic analysis can consider the transient influence of time and avoid the convergence issue in iterative procedure. The object of the present paper is to figure out a reliable and suitable FE modelling in the explicit dynamic method, which could keep the balance of the acceptable accurate results and computation resources. Several influential factors on the collapse behaviours of hull girder are discussed including boundary conditions, geometric ranges of finite element model, element types, loading methods and loading time. The results of a Suezmax oil tanker and Reckling models assessed by the explicit dynamic method are compared with that by the other analytical methods or in the experiment.

1. Introduction

Ship structures might be damaged under occasionally extreme loads, such as winds, waves and currents. The longitudinal strength of hull girder is the basic fundamental aspect to ensure the safety of ships and offshore structures, human life and property. It is vital to assess the ultimate strength of ship hull girder. So far, various assessment methods of the vertical bending capacity of hull girder have been developed, which generally include five types as follows:

(a) Simple “closed-form” formulations, which were firstly adopted by Caldwell [1] and improved by Paik et al. [2] using more reasonable presumption of bending stress distribution across the cross-section to calculate the ultimate strength of hull girder.
(b) Incremental-iterative method (namely Smith's method) was initially proposed by Smith [3], which based on Navier's hypothesis and average stress-average strain relationship of individual stiffened and unstiffened plates. Ozguc et al. [4] and Vhanmane and Bhattacharya [5] studied on the accuracy improvement of the load-end shortening relationship of stiffened panels by considering the initial geometric deflections and welding residual stresses. Xu and Duan [6] and Tanaka et al. [7] applied this method to discuss the ultimate strength of hull girder under bending moment or combination of vertical moment and torsion.
(c) Simplified finite element methods. For example idealized structural unit method (ISUM), which was developed by Ueda and Rashed [8], and was used by Paik et al. [9] to investigate the progressive hull girder collapse of ships. Zhang et al. [10] utilized the intelligent supersize finite element method (ISFEM) to assess the shakedown limit state of hull girder with breakage.
(d) Experimental method. For instance, Nishihara [11] performed the tests for eight box-girder models, which were attended to represent the real ships of single hull tanker, double hull tanker, bulk carrier and container ship. Furthermore, Iijima et al. [12] utilized a scale box-shape models to design a series of experiments in order to investigate the post collapse behaviours of hull girder under whipping loads.
(e) Finite element (FE) method, introduced by Turner [13] for the analysis of elastic behaviours of structures, and was employed by increasing researchers, such as Xu et al. [14] used the FE analysis to simulate the behaviours of stiffened panels under uniaxial compression until collapse and beyond, and then compared with the results in the tests.

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Nomenclature

β	plate slenderness
b	width of plate
t_p	thickness of plate
h_w	web height of stiffener
σ_y	yield stress of material
M_u	ultimate bending moment
w_{opl}	initial deflection of local plate panel
v_{os}	side-way initial deflection of stiffeners
a	length of plate
B	width of stiffened panel
t_w, t_f	thickness of web and flange on stiffener
b_f	flange width of stiffener
E	Young's modulus of material
H	height of the hull girder
w_{os}	column-type initial deflection of stiffeners
m	buckling half-wave number

The incremental-iterative method and some alternative methods including the nonlinear FE analysis have been introduced in Common Structural Rules for Buck Carriers and Oil Tankers (called as CSR-H) [15]. However, for the nonlinear FE analyses, CSR-H specified by the International Association of Classification Societies (IACS) only provides some principle requirements for the assessment of ultimate strength of ship hull girder, including inelastic material behaviour, geometric imperfections and so on. Many other aspects would also influence the simulation results and are still not clear for the setting in the numerical modelling, and thus the configurations of numerical simulations need to be studied for obtaining reliable results.

In numerical simulations, many researchers used the implicit static analysis to assess the ultimate strength of hull girder or stiffened panels of ships and offshore structures. Qi et al. [16] and Paik et al. [17] performed some comparative studies by different methods to assess the ultimate strength of hull girder, such as the incremental-iterative method and the implicit static analysis method. Shu and Moan [18] adopted the implicit static analysis method by FE code ABAQUS to investigate the ultimate strength for a Capesize bulk carrier with three cargo holds under hogging and alternate hold loading condition. However, the implicit static analysis method sometimes might be instable and is difficult to converge due to the local geometric and material nonlinearity, e.g. buckling and yielding of hull structure during the process of progressive collapse. The volumetric damping can be employed to solve part of the converge issue, but the optimal value for damping factor is a little difficult to be obtained by trial and error tests in ABAQUS [18]. Besides, some benchmarks have been studied for a Capesize bulk carrier in ISSC 2015 Committee III.1 [19], and it was found that sometimes both buckling and post collapse could not be obtained by the implicit static analysis method due to the converge issue, especially for sagging condition. Moreover, this method does not consider the inertial effect of structures that more or less influences the results.

Relative to the implicit static analysis method, the explicit dynamic analysis method could avoid the convergence problem in iterative solution and account for the transient influence. Benson et al. [20] compared the results in the implicit static analysis and explicit dynamic analysis with that in the incremental-iterative method for the intact specimens used in the tests of Gordo and Guedes Soares [21], in which the imposed moments were applied and the loading time was set as 1 s in the explicit dynamic analysis. Yamada [22] investigated the ultimate bending moment for a bulk carrier under intact and damaged conditions by using LS-DYNA. The bending moment was imposed at the end section of hull girder, and the geometric range of the FE model was one cargo hold for intact condition. The difference of the ultimate bending moment with loading time between 0.3 s and 2.0 s was analysed, whose results had distinct difference between the two cases. These investigations showed that there were some differences of the load carrying capacity and collapse behaviours when different configurations of FE modelling were adopted. Many aspects could influence on the simulation results in the explicit dynamic analysis, including the loading time, loading methods, boundary conditions, element types and geometric ranges of FE model. Hence, it is very important to investigate the effects of these influential factors on the ultimate strength and collapse behaviours of hull girder. The object of the present paper is to figure out reasonable FE modelling configurations for obtaining reliable results in the explicit dynamic analysis, and at the same time saving computation time. Moreover, relative to previous versions, IACS CSR-H [15] includes the requirements for the both bulk carriers and oil tankers, and the formulae of average stress-average strain relationships of individual stiffened panels were also revised recently. To further verify the results in the numerical simulation, the comparative studies are also conducted, including the explicit dynamic analysis, implicit static analysis, incremental-iterative method in IACS CSR-H [15] and experiment.

2. Nonlinear finite element analysis

2.1. FE models

In the explicit dynamic analysis, FE software package LS-DYNA is adopted to evaluate the ultimate strength of hull girder for a Suezmax oil tanker [23] and Reckling No. 23 [24] under sagging load, which represent full and small scale models to consider the size effect of different models. The middle transverse cross-sections for the two models are shown in Fig. 1. The main particulars and dimensions of the longitudinal stiffeners for the Suezmax oil tanker and Reckling No. 23 are shown in Tables 1–3, respectively.

For the Suezmax oil tanker, the plate thicknesses of hull girder range from 11 mm to 21.5 mm. The hull structures including middle longitudinal bulkhead, double bottom and side frames are supported on the longitudinally stiffeners. The transverse frame spacing is 2205 mm, and the longitudinal stiffener spacings range from 550 mm to 860 mm. The material of the plates and stiffeners used in this vessel are normal and high-strength steel with yield stress of $\sigma_y = 269$ MPa and 348 MPa, respectively, Young's modulus $E = 206,000$ MPa and Possion's ratio $\nu = 0.3$. For Reckling No. 23, the thickness of the plates is 2.5 mm. The longitudinal length of the model is 500 mm. The material of the plates and stiffeners are normal steel with yield stress of $\sigma_y = 246$ MPa, Young's modulus $E = 210,000$ MPa and Possion's ratio $\nu = 0.3$. The elastic-perfectly plastic material is adopted in the nonlinear FE analyses.

For evaluating reliable load carrying capacity of hull girder, several influential factors on solution accuracy and time are also systematically investigated, including loading methods, loading time, boundary conditions, geometric ranges and element types of the FE models. The element types and element size of the FE models should have priority to be considered. In the explicit dynamic analysis, there are two kinds of available shell elements, including reduced and full integration elements in the explicit method. For full integration elements using four sampling points, there may exist shear-locking problem causing excessive stiffness. Hence, the reduced integration four-node quadrilateral element (shell 163) with Belytschko-Wong-Chiang formulation and beam 161 is adopted [25], which can efficiently avoid the shortcoming in warping configuration.

Finer mesh generally can capture the collapse shape and give more accurate prediction, but would cost longer solution time relative to coarse mesh. A balance between required accuracy and computation resources is needed. According to the benchmark of modelling