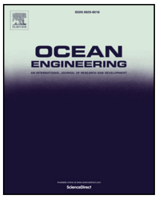
Ocean Engineering 162 (2018) 161–175

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Empirical formula for predicting ultimate strength of stiffened panel of ship structure under combined longitudinal compression and lateral loads

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ARTICLE INFO

Keywords:
Stiffened panel
Ship
Collapse
Buckling
Finite element method

ABSTRACT

The influence of lateral pressure and stiffener type on the collapse behaviours of steel stiffened panels are investigated in the FE (finite element) analysis. Based on the numerical results, the empirical expressions are derived for the ultimate strength assessment of stiffened panels under combined in-plane axial compression and different levels of lateral pressure. The regression formulae only include the plate slenderness ratio and column (stiffener) slenderness ratio. Hence, to consider the influence of stiffener type, the databases of sample points are separately grouped for various cross sections in the regression process. At the same time, for the convenient of utilizing the regression model, the coefficients are expressed as water head in meters. To investigate the approximating accuracy of regression model, the statistical measurement analyses are conducted by comparing with FE analysis, simplified analytical method and experiments.

1. Introduction

Stiffened panels are generally adopted in the ship and offshore structures, which would be subjected to the compressive load and water pressure. Ultimate limit state method has been widely used in the ship design (ISSC, 2000; IACS, 2014). For the safety of ship structure, it is vital to predict the load carrying capacity of this kind of member. There exist several methods to estimate the collapse behaviour of ship structure including experiment, numerical analysis and analytical method and so on.

Many tests had been conducted in the past decades, which could help the understanding of the collapse behaviour of stiffened panel, e.g. Tanaka&Endo (1988), Ghavami (1994), Ghavami&Khedmati (2006), Chen et al. (1997). With the development of calculation capacity of computer, numerical simulation is often used to estimate the collapse behaviour of stiffened panel under various load conditions, e.g. Guedes Soares&Soreide (1983), Fujikubo et al. (1997), Ozguc et al. (2007), and Cho et al. (2013). Using numerical simulations, Wang&Moan (1996) and Paik&Seo (2009) investigated the collapse behaviour of stiffened panels under combined loads. The influences of boundary conditions, geometrical range (Xu et al., 2013), dimensions and number of stiffeners (Tanaka et al., 2014) also have been investigated on the collapse strength of stiffened panels under in-plane compressive load. Using FE analysis, Yang et al. (2018) investigated the influence of initial imperfections, lateral pressure and strain rate on the ultimate strength of stiffened panels under in-plane dynamic compression.

Since the numerical simulation is time consuming and the estimated result significantly depends on the researcher who perform the FE modelling, it is necessary to use empirical formula for the assessment of load carrying capacity of stiffened panel, which would be more useful for the design (Guedes Soares& Gordo, 1997; Yao&Fujikubo, 2005) and for the reliability analysis of ship structure (Mansour et al., 1997), although the factors of safety in association with uncertainties and deviations should be considered carefully. China Classification Society (Wang et al., 2009) developed common structural rule computation software CSR2SDP to calculate the ultimate strength of stiffened panel and hull girder, which could improve the efficiency of ship design. Paik & Thayamballi (1997), Paik et al. (2001), Fujikubo et al. (2005a) and Harada et al. (2007) had proposed serial formulae for predicting the ultimate strength of stiffened panel under the combination of in-plane compression and lateral loads. For the application in the design of ship structure, PULS (2005) and IACS-HCSR requirement (2014) also give the formulations and computational procedure for predicting the ultimate strength of unstiffened plate, stiffened panel and hull girder.

The external bottom plating and the lower parts of side shell are mainly subjected to the uniaxial and biaxial compressive loads, and moreover to the relatively high external lateral pressure. The effect of lateral pressure on plate collapse strength depends on the interaction of

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https://doi.org/10.1016/j.oceaneng.2018.05.015
Received 6 November 2017; Received in revised form 7 May 2018; Accepted 8 May 2018

Notations

t_p	thickness of plate
β	plate slenderness
s	breadth of local plate panels
l	length of local plate panels
t_w	web thickness of longitudinal stiffener
λ	column slenderness
t_f	flange thickness of longitudinal stiffener
h_w	web height of longitudinal stiffener
h	water head (pressure) in meters
b_f	flange breadth of longitudinal stiffener
r	gyration radius of stiffener with attached plate
I	moment of inertia of a stiffener with attached plate
σ_y	yield stress of material
B	width of stiffened panel
w_{0pl}	initial imperfection of local plate
E	Young's modulus of material
v_{0s}	side-way initial deflection of stiffener
w_{0s}	column-type initial imperfection of stiffener
$\sigma_{u,f}\sigma_{u,FEM}\sigma_{u,s}$	ultimate strength of stiffened panel assessed by regression formulae, FE analysis and simplified analytical method
σ_{xav}	average stress of stiffened panel

axial compression and lateral pressure (Wang&Moan, 1996) and is usually accounted for by including an additional term in the interaction equations used for biaxial loads, such as Davidson et al. (1992) and Guedes Soares&Gordo (1996). Based on the results of nonlinear finite element analysis, Kim et al. (2017) and Ozdemir et al. (2018) also proposed approximate formulas to predict the ultimate strength of stiffened panels under longitudinal compression.

The combination interaction of lateral pressure and constraint on plate edges would induce tensile stress, which affects the collapse strength of stiffened panel under combined loads (Xu et al., 2017). However, this state of tensile stress is still not well considered in IACS-HCSR requirements (IACS, 2014) for predicting the ultimate strength. The existing data is used as the starting point for the formulation, and more specimens are also simulated in the FE analysis as supplementation data in order for the regression of formula to be applicable to a desired wide geometrical range of stiffened panel for bulk carrier and VLCC (very large crude carrier). Based on the numerical databases, the regression analysis is used to derive the closed-form empirical expressions for predicting the ultimate strength of stiffened panels used for marine applications.

2. Numerical analysis

In order to derive the formulae for assessing the ultimate strength of stiffened panels, the databases of numerical analysis are required. Thus, a series of elastic-plastic large deflection analyses are performed applying the nonlinear finite element method. Although there are part of numerical database in (Xu et al., 2017), more specimens are also simulated to provide different geometrical dimensions.

2.1. Geometrical characteristics of the analysed stiffened panels

Since the accuracy of the regression formula significantly depend on the design sample point, the dimensional range of plate and stiffener, and their combinations should include most of the realistic member of ship structures. It was found that the length, width and thickness of the local plate are between 2.5 and 6.0 m, 0.7–1.0 m, and 12–36 mm from the statistical analyses of 46 ships by Zhang (2016). Considering the geometrical characteristics of bulk carrier and VLCC (very large crude carrier), the dimensions of the plate and stiffener are showed in Table 1, Table 2 and Fig. 2, which are given by ISO (International Organization for Standardization) as benchmark and also had been used in the numerical analysis by Tanaka et al. (2014). Parts of numerical results were presented in Ref. (Xu et al., 2017) to investigate the influence of initial imperfection, boundary conditions, and lateral pressure on the collapse behaviours of stiffened panels. The design sample used to regression is very important for the accuracy of developed formulae for predicting the ultimate strength of stiffened panels, and thus more specimens covering wider dimensional range are also simulated at the present study. These data are used in the regression of formulae at the present paper.

The spacing between the adjacent transverse frames and longitudinal girders are denoted as *l* and *s* in Fig. 1. The aspect ratios of local plate are taken as 3.0 and 4.0 for bulk carrier and 5.0 for VLCC, respectively. To consider the effect of the geometrical combinations, the designed sample points in the numerical analysis include three types of stiffeners (i.e. flat-bar, angle-bar and tee-bar) with four sizes and six thicknesses of the plates; the lateral pressures (0, 0.1 MPa and 0.2 MPa) caused by water head are also considered; There are totally 1296 designed sample points that are used in the regression analysis.

2.2. Finite element modelling

Shell element (181) with eight nodes in the FE program ANSYS are used for both stiffener and plate to simulate the load carrying capacity of the stiffener panels under the combination of uniaxial compression and lateral loads. The perfect elastoplastic model of material is adopted in the FE analysis, with which yield stress, Young's modulus and Poisson's ratio are 313.6 MPa, 205.8 GPa, and 0.3, respectively. The mesh density of element in the FE model should be appropriate for capturing the collapse behavious and then give enough accuracy results, at the same time the computational time should be acceptable, since many sample data points would be simulated that used in the regression analysis. According to the analysis of element sensitive for obtaining the balance between required accuracy and computation time (Xu et al., 2013), the element number on the flange and web of stiffeners are set as six, and the element size on the plate is 85 mm (Fig. 3).

2.3. Range of FE model, loading and boundary conditions

The geometrical range of FE model of the stiffened panels and external loads are showed in Fig. 1. The deformation of stiffened panel is not symmetric, when the cross-section of the stiffener is not symmetric (e.g. for angle bar), or there exists lateral load. Hence, two bays/spans model (abcd in Fig. 1.) with periodical boundary condition are adopted in the longitudinal and transversal edges in the numerical analysis. More discussions about the setting of boundary conditions and geometrical range of FE model can be found in Ref. (Xu et al., 2013). The lateral displacement is constrained but the rotation is free at the strong longitudinal girders and transversal frames (denoted as dash line in Fig. 1), since which are not explicitly included in the FE model. The setting of the boundary conditions is given by.

Table 1
Dimensions of the plating.

Bulk carrier model	VLCC model
$l \times s$: 2550 × 850 mm/3400 × 850 mm t_p: 33, 22,16, 13, 11, 9.5 mm β: 1.01, 1.51, 2.07, 2.55, 3.02, 3.49	$l \times s$: 4750 × 950 mm t_p: 37, 25,18.5, 15, 12.5, 11 mm β: 1.00, 1.48, 2.00, 2.47, 2.97, 3.37