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An empirical formulation for predicting the ultimate strength of stiffened panels subjected to longitudinal compression

D.K. Kim[a,b], H.L. Lim[a], M.S. Kim[b], O.J. Hwang[a,c], K.S. Park[d,*]

[a] Ocean and Ship Technology Research Group, Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Bandar, Seri Iskandar, Perak, Malaysia
[b] Graduate School of Engineering Mastership, Pohang University of Science and Technology, Pohang, South Korea
[c] Technip Asia Pacific, Kuala Lumpur, Malaysia
[d] Steel Structure Research Group, Steel Solution Marketing Department, Steel Business Division, POSCO Global R & D Center, POSCO, Incheon, South Korea

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ABSTRACT

There are several methods such as experimental, numerical, and analytical methods which are the mostly adopted in the verification of proposed design code or guidelines to calculate the ultimate strength performance of stiffened panel structures. This study proposes an advanced empirical formula shape, which is a function of plate slenderness ratio and column slenderness ratio with two (2) correction coefficients (C_1 and C_2), used to predict the ultimate strength performance of stiffened panel structures in ships. In addition, the two aforementioned correction coefficients were decided and verified by obtaining the result of an ANSYS nonlinear finite element analysis. An average level of initial imperfection and 2 bay – 2 span (1/2 – 1 – 1/2) model were adopted in the proposed empirical formula. The effects of residual strength were not considered in this study. A total of 124 stiffened panels with four different plate slenderness ratios (β) and changing column slenderness ratio (λ) were selected for the simulation scenarios. To confirm the accuracy of the obtained formula, a statistical analysis was also conducted on the ANSYS results and other existing formulas. The proposed method and its details were documented.

1. Introduction

Stiffened panels are one of the important structural components in ships and offshore structures with plate elements. The global and local strength of panels' performance should be carefully checked by designer, especially when used in ships and ship-shaped offshore structures. In this context, global strength represents hull girder strength, while buckling check for plates and stiffened panels are considered as local strength.

A number of studies were conducted to investigate the ultimate strength performance of stiffened panels. The renowned International Ship and Offshore Structures Congress (ISSC) has conducted a wide range of benchmark studies for stiffened panels, especially in terms of comparison in analysis methods used (ISSC, 2012, 2015).

Initially, Caldwell (1965) calculated the ultimate strength of a ship hull using his original formula, but the formula did not consider the strength reduction of individual members which represent the local ultimate strength. Thus, Smith (1977) proposed a simplified beam-column method considering the elasto-plastic behaviour of panels and local buckling. The simplified beam-column method used in design provided acceptable results where the stiffener's characteristics proved to be dominant for plate behaviour. Subsequently, Ueda and Rashed (1984) proposed an idealised structure unit method (ISUM) to decrease the degree of freedom and node on the system structure for reducing the computational time of ultimate strength analysis. This progressive collapse method took into account load shedding.

Paik et al. (2001) proposed a large deflection orthotropic plate approach to estimate the ultimate strength of stiffened panels (one-

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Abbreviations: CSR-BC, Common Structural Rule for Bulk Carrier; CSR-OT, Common Structural Rule for Double Hull Oil Tanker; CSR-H, Harmonised Common Structural Rule; GBS, Goal Based Standard; CFM, Closed Form Method; IACS, International Association of Classification Societies; M1, Buckling assessment method in CSR-OT that buckling capacity with allowance for redistribution of load unless otherwise specified; M2, Buckling assessment method in CSR-OT that buckling capacity with no allowance for redistribution of load unless otherwise specified; Method A, Buckling assessment method in CSR-H that all the edges of the elementary plate panel are forced to remain straight (but free to move in the in-plane directions) due to the surrounding structure/neighbouring plates; Method B, Buckling assessment method in CSR-H that the edges of the elementary plate panel are not forced to remain straight due to low in-plane stiffness at the edges and/or no surrounding structure/neighbouring plates; PULS, Panel Ultimate Limit State (= a computerized semi-analytical model proposed by DNV and used for CSR-OT); UP-A, Unstiffened panels with method A in CSR-H; UP-B, Unstiffened panels with method B in CSR-H; SP-A, Stiffened panels with method A in CSR-H; SP-B, Stiffened panels with method B in CSR-H; SP-M1, Stiffened panels with M1 in CSR-OT; SP-M2, Stiffened panels with M2 in CSR-OT

[*] Corresponding author.

E-mail address: kyusik.park@posco.com (K.S. Park).

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sided small stiffeners) under biaxial compression/thrust and lateral pressure. Chen (2003) used both the simplified and beam-column methods to investigate the ultimate strength of several panels. Fujikubo et al. (2005) ran a series of elastic/elasto-plastic large deflection finite element analysis to investigate the ultimate strength of continuous plating under combined transverse thrust and lateral pressure. They formularized simple equations for the computation of the ultimate strength of ordinary ships. The elasto-plastic large deflection behaviour is governed by geometric and material non-linearities. The effect of strain hardening is neglected as is normally assumed for the elastic-perfectly plastic material. Lately, benchmark studies for ultimate strength assessment under various methods by Paik et al. (2008) and ISSC (2012) have been conducted.

Lin (1985) proposed an empirical formula which has a reasonably more accurate solution for stiffened panels with relatively large dimensions of stiffeners. However, it showed underestimation in ultimate strength when the column slenderness ratio (λ) was increased. In addition, initial imperfection was not considered. Following that, Paik and Thayamballi (1997) proposed a modified formula which encompassed a wider range of stiffened panels dimensions as compared to Lin's formula. Their formula was proposed based on experimental data obtained by Horne and Narayanan (1976), Horne et al. (1977), Faulkner (1977), Niho (1978), Yao (1980) and Tanaka and Endo (1988), which means that boundary conditions could be hard to set as the simply supported conditions assumed in numerical simulation. This was the reason why Paik and Thayamballi's formula overestimates the ultimate strength of stiffened panels. Johnson-Ostenfeld formula and Perry-Robertson formula (developed based on Euler's formula) are mostly used in the ship industry. However, these are not considered as a purely empirical formula. In addition, these formulas do not consider local buckling effects. As time went by, modified Perry-Robertson formulas were also proposed by Murray (1975), especially the effective width concept which is one of the powerful approaches used to predict ultimate strength in the last two to three decades. Paik and Duran (2004) also proposed an empirical formula for aluminium stiffened panels based on the finite element method (FEM) with λ in the 0.23–2.24 range. Recently, Khedmati et al. (2010) had also proposed an empirical formula for the estimation of the ultimate strength of aluminium stiffened panels subjected to combined axial compression and lateral pressure.

For the buckling assessment of ship plate and stiffened panel, the International Association of Class Societies (IACS) which is considered as most important ship design rule has adopted PULS for oil tanker (IACS, 2006a) and DIN software for bulk carrier (IACS, 2006b) before they had proposed Harmonised Common Structural Rule (CSR-H) which was issued in its January 2014 edition and entered into force on 1st July 2015 (IACS, 2015). For the buckling assessment method in CSR-H, the harmonisation of two (2) rules, i.e., Common Structural Rule for Double Hull Oil Tanker (CSR-OT), and Common Structural Rule for Bulk Carrier (CSR-BC) was the result after they performed several benchmark studies with different buckling assessment methods to revise their design rule. In the CSR-H technical background, they have compared two (2) different edge conditions (Method A and B), and two (2) allowances for redistribution of load (M1 and M2). From their investigation, they decided that PULS, which was used for CSR-OT can be eliminated since the results show that it overestimates buckling performance, while DIN which was used for CSR-BC can be modified for the preparation of an unified Closed Form Method (CFM) based on advanced buckling theory with some modification based on nonlinear finite element analysis (NLFEA) calibration. The IMO GBS requirement for structural redundancy was also considered. The difference of unified CFM used in CSR-H (called new CFM or revised DIN) for buckling assessment and other methods used previously (CSR-OT and CSR-BC) are summarised in Section 3.

However, the calculation for the ultimate strength performance of stiffened panels using the above mentioned CFM can still be simplified, especially in considering applied loading conditions in CSR-H (IACS, 2015). In this regards, it is targeted to propose simple empirical formula as a function of plate slenderness and column slenderness ratios for the estimation of ultimate strength performance of stiffened panels subjected to longitudinal compression. The empirical formula is posited based on the ANSYS nonlinear FEA results and will be compared with other existing formulas.

2. Ultimate strength analysis of stiffened panel

Continuous efforts to develop methodologies for the prediction of ultimate strength of stiffened panels subjected to axial compression was made by several researchers (Moolani and Dowling, 1976; Guedes Soares and Soreide, 1983; Bonello et al., 1993). Recently, several methodologies for the determination of the ultimate strength of stiffened panels were compared by Zhang and Khan (2009), Paik and Seo (2009), Paik et al. (2011), Frieze et al. (2011), ISSC (2012) and Hughes and Paik (2013). Some application studies, including the corrosion effect has on stiffened panels have also been performed by Kim et al. (2012, 2014, 2015). The adopted FE modelling technique under selected stiffened panel scenario cases used in this study is summarised in this section.

2.1. Modelling technique

Basically, finite element (FE) modelling in this study is based on ISSC (2012) report. In ISSC (2012), they have formulated a working group for the benchmark study of ultimate strength analysis of stiffened panels by adopting six (6) different simulation methods/tools as shown in Table 1.

It is mentioned in the ISSC (2012) that several factors should be clearly defined and carefully considered to compute ultimate strength of stiffened panels such as boundary conditions, extent of model, element size (mesh size), and many others. Fig. 1(a)–(c) represent explanations of FE modelling with sample analysis results. In ISSC (2012) report, the effect of model size by adopting both one bay/one span model and two bay/two span models was investigated. It was found that the one bay/one span model where the sideways distortions of stiffener at the edge location is not allowed, so that the ultimate strength of stiffened panels may be overestimated. In this regards, 2 span (1/2 – 1 – 1/2 in longitudinal direction) and 2 bay (1/2 – 1 – 1/2 in transverse direction) model is considered as the extent of analysis shown in Fig. 1(a) for the ANSYS FE simulation in the present study.

With regards to initial imperfection, welding-induced residual stresses are not considered in this study. The effect of initial deflection for plate and distortion for stiffeners is only considered as follows. For the modelling of ship's stiffened panel, in general, three (3) types of initial distortions were considered, namely plate initial deflection (w_{opl}), column type initial distortion of the stiffener (w_{oc}), and sideways initial

Table 1
Adopted methods/tools for stiffened panels (ISSC, 2012).

Method/Tool	Working organisation
ALPS/ULSAP	– Pusan National University
Abaqus	– National Technical University of Athens – Det Norske Veritas
ANSYS	– Indian Register of Shipping – Pusan National University – University of Liege
BV Advanced Buckling	– Bureau Veritas
DNV/PULS (IACS CSR-OT)	– Det Norske Veritas
MSC/MARC	– Osaka University