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A new method to estimate ultimate strength of stiffened panels under longitudinal thrust based on analytical formulas

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ABSTRACT

In this paper, a new approximate method based on analytical formulas is proposed to estimate the ultimate strength of stiffened panels by investigating collapse mechanisms of the stiffened panels. In this respect, firstly, a series of detailed elastoplastic large deflection Finite Element Analysis (FEA) is performed to investigate the collapse behavior and the ultimate strength of the stiffened panels. In the analysis, the initial deflections are considered in the form of thin-horse mode plus overall buckling mode for the plates, and flexural buckling mode plus tripping mode for the stiffeners. On the basis of the observed FEA results, an efficient method is proposed to estimate the ultimate strength of stiffened panels based on Elastic Large Deflection Analysis (ELDA) with the initial yielding concept. In the ELDA, the deflection modes are defined as the sum of overall buckling mode plus local plate buckling mode. The welding residual stresses are not taken into account in this study. The ultimate strength is predicted by examining yielding at several critical points. The calculated results by the proposed method and the nonlinear FEA are compared, and a very good agreement is obtained for all collapse scenarios investigated.

1. Introduction

Stiffened panels are main structural components of ship hulls. The ship hull is subjected to overall and local bending during operation, and it has to resist the forces and bending moments caused by self-weights, cargo loads, buoyancy forces, wave forces *etc.* [1–4]. Therefore, the ultimate bending moment capacity of the ship hull girder has been studied by many researchers, *e.g.* Refs. [5–8]. Due to the overall bending of the hull girder, the stiffened panels on the deck and bottom structures are subjected to longitudinal thrust loads, respectively, under sagging and hogging conditions. Hence, many research works have also been performed on the ultimate strength assessment of the stiffened panels by nonlinear FEA [9–15], simplified methods [16–32], and Idealized Structural Unit Method (ISUM) [33–37].

The FEA is one of the most powerful tools to evaluate the ultimate strength as well as to simulate the collapse behavior. Owing to the development of computer and software technologies, it has become possible to perform analysis for large-scale structures by considering the nonlinearities arising from large deflection and plasticity. The recent works on the ultimate strength analysis of stiffened panels by Finite Element Method (FEM) mainly focus on the effects of imperfections, modeling extent and boundary

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conditions [9–13]. Despite the popularity of FEM, the ultimate strength analysis by FEM may not be economical for large-scale structures.

Simple formulas have been proposed, in the open literature, to estimate the ultimate strength of stiffened panels. For instance, two of the authors [16,17] proposed a simplified method for stiffened panels, with many attached stiffeners, under longitudinal thrust. In these studies, the stiffened panels are idealized as a stiffener and attached plating combination, and the axial stress is computed at several locations of the plate-stiffener structure. The initial yielding is assumed as the ultimate strength state of the structure. It is also assumed that the local plate buckling takes place first. This method was then extended for the stiffened panels under combined biaxial thrust and lateral loads [38–42].

Semi-analytical methods are also available in the open literature to obtain the ultimate strength of stiffened panels. For instance, Paik et al. [18] proposed a simple analytical method for calculating the ultimate strength of the stiffened panels by considering initial deflections and welding residual stresses. Three collapse modes, namely plate induced, stiffener induced and local buckling of the stiffener web, are considered. A plate-stiffener combination model is used as a representative of the stiffened panel. Paik et al. [19] introduced a large deflection orthotropic plate approach for estimation of the ultimate strength of stiffened panels considering overall grillage buckling. In the study, axial compression/tension and lateral loading, as well as initial imperfections, are considered. In the last decade, PULS code [20] was released by DNV for the ultimate strength analysis of stiffened panels. The fundamental theory behind the code was presented in Refs. [21–23]. Byklum et al. [21] proposed a new computational semi-analytical method for calculating the ultimate strength of stiffened panels. In the proposed method, the membrane stresses at certain critical locations are examined using the Von Mises yield criterion, and the onset of yielding at those points is assumed as the ultimate strength state of the structure. In-plane compression-tension, shear loading, and lateral load effects are also taken into consideration. Later, Byklum et al. [22] improved the previous concept, allowing one-way interaction between global and local mode deflections. It was assumed that the overall deflections do not influence the local mode of deflections. This is to say that local plate buckling is the primary buckling, and the overall buckling of the stiffened panel takes place as secondary buckling. Zhang and Khan [30] performed nonlinear FE computations and they defined the yielding modes at the ultimate state. A simple semi-analytical formula to estimate the ultimate strength of stiffened panels under axial compression was also proposed in Ref. [30]. The application limits of this formula was then revised in Ref. [31]. In 2006, Common Structural Rules were released for bulk carriers (CSR-B) [43] and double hull oil tankers (CSR-T) [44], respectively, as the structural design standards. The possible failure modes for the stiffened panels are defined as local plate buckling, overall panel buckling, and torsional stiffener buckling. The lowest failure strength of the possible failure modes is assumed as the ultimate strength of the stiffened panel. In 2015, Harmonized Common Structural Rules [45] came into effect to supersede the CSR-B and CSR-T. Recently, Kim et al. [32] proposed a simple empirical formula to obtain the ultimate strength of stiffened panels by curve fitting based on the results of nonlinear FE computations.

In the present study, a detailed elastoplastic large deflection FEA is performed to investigate the collapse behavior and the ultimate strength of stiffened panels. In the analysis, the initial deflections are considered in the form of thin-horse mode plus overall buckling mode for the plates, and flexural buckling mode plus tripping mode for the stiffeners. Observing the FE simulations, a new efficient and simple method, based on ELDA with the initial yielding concept, is proposed to estimate the ultimate strength of stiffened panels under longitudinal thrust load. The initial and the total deflections for ELDA are assumed as the sum of deflections of an overall stiffened panel buckling mode and a local plate buckling mode. The welding residual stresses are not taken into account in this study.

Rest of the present paper is organized as follows: In Chapter 2, FEA is performed to evaluate the ultimate strength, as well as to examine the collapse behavior of stiffened panels, then formulation and verification for ELDA and concept for ultimate strength estimation are presented in Chapter 3. The estimated ultimate strength results and discussions are documented in Chapter 4. Main conclusions are drawn in Chapter 5.

2. Finite element analysis of stiffened panels

2.1. Stiffened panels for analysis

In the nonlinear FEA, two different panels, namely bottom panel of a Bulk Carrier (BC) and deck panel of a Very Large Crude oil Carrier (VLCC) in Ref. [1], are considered. The aspect ratios of the local plates are taken as $a/b = 3.0$ for the BC panel, and as $a/b = 5.0$ for the VLCC panel. The local plate ($a \times b$) is considered with six different thicknesses in the analysis. In Fig. 1, a is the distance between two successive transverse frames, while b denotes the longitudinal stiffener spacing.

The properties of the stiffened panels, which are adopted from Ref. [1] and used in the FEA, are given as follows.

- BC model:
  $a \times b = 2{,}550 \times 850$ mm $(a/b = 3.0)$
  $t_p = 33, 22, 16, 13, 11, 9.5$ mm
  $\beta = 1.01, 1.51, 2.07, 2.55, 3.02, 3.49,$
- VLCC model:
  $a \times b = 4{,}750 \times 950$ mm $(a/b = 5.0)$
  $t_p = 37, 25, 18.5, 15, 12.5, 11$ mm
  $\beta = 1.00, 1.48, 2.00, 2.47, 2.97, 3.37,$