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# Buckling and ultimate capability of plates and stiffened panels in axial compression

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This paper presents extensive non-linear finite element (FE) analysis and formulation development work carried out on the ultimate compressive strength of plates and stiffened panels of ship structures. A review of contemporary designs for large ships was carried out. The existing formulae for plate ultimate compressive strength were reviewed and compared with non-linear FE analysis results. A semi-analytical formula for ultimate compressive strength assessments of stiffened panels was proposed and is described. The developed formula was verified against results using ABAQUS non-linear FE software for a series of 61 stiffened panels and a good agreement between the proposed formula and FE results were achieved. The method was verified against a large number of published FE results and was also compared with 58 experimental results. The developed method was also applied to the deck and bottom structures for a range of various sizes oil tankers and bulk carriers.



## 1. Introduction

The longitudinal strength of a ship's hull girder has been, and will always remain, one of the key parameters for consideration in the design of large sea-going ships. The traditional ship classification society rules, e.g. Lloyd's Register [1], adopt a permissible stress approach for hull girder bending strength. This method does not predict the maximum capability of the hull girder. Alternatively, an ultimate strength approach can be used to assess the hull girder's ultimate capacity.

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Buckling and the ultimate strength of ship structures have been widely investigated over the years by employing analytical methods, experimental tests, empirical approaches and non-linear finite element (FE) simulations. Analytical methods employ first principles and are more mathematically sound, and a number of studies were carried out by e.g. Fujita et al. [2], Ueda et al. [3], Paik et al. [4] and Cui et al. [5]. Due to the complexity of the issue, analytical methods deal mainly with simplified cases. Model tests provide first hand materials to understand the collapse behaviours of structures. A large number of experiments on plates and stiffened panels were carried out in the past, e.g. Dwight et al. [6], Dowling et al. [7], Smith [8], Faulkner [9], Horne et al. [10,11], Tanaka et al. [12], Chen et al. [13] and Gordo et al. [14,15]. Empirical formulae, which are based on a large number of experimental or numerical data, were proposed for the ultimate strength assessment by many investigators, e.g. Frankland [16], Faulkner [17], Lin [18], Paik et al. [19] and Guedes Soares et al. [20]. With the rapid development of computing technology, non-linear finite element analyses have become a powerful tool for the numerical simulation of ultimate strength analyses. Many investigators have carried out numerical studies, e.g. Fujikubo et al. [21], Yao et al. [22], Ozguc et al. [23] and Paik et al. [24,25]. By applications of various analysis approaches, the longitudinal strength assessments of hull girders were carried out by Caldwell [26], Smith [27], Rutherford et al. [28], Frieze et al. [29] and Gordo et al. [30]. Some of the results were compared with data obtained from ships' incidents or model tests.

Over the last decades, significant progress on the prediction of ultimate strength has been achieved. Comprehensive summaries can be found in ISSC Ultimate Strength Committee reports [31–33] and Paik et al. [34]. However, the concept of "ultimate strength" for ship designs was introduced first only recently in 2006, with the release of IACS Common Structural Rules [35] for double hull oil tankers and bulk carriers. This can be considered as one step forward in ship design philosophy.

To assess the ultimate strength of a hull girder, reliable approaches for the buckling and ultimate capability assessments of plates and stiffened panels are essential. The primary objective of the present study is to establish simple but robust methods for assessing ultimate compressive strength of plates and stiffened panels for practical applications, through extensive non-linear FE simulations and analytical investigations.

The ultimate strength of plates was analyzed using ABAQUS non-linear FE software [36] and the results were compared with Faulkner's formula. A method for assessing ultimate strength of stiffened panels was developed based on analyses and FE simulations. The method was verified against results using ABAQUS software for a series of 61 stiffened panels. It was compared with a large number of published non-linear FE analyses, 132 stiffened panels in total. The method was also checked against experimental results of 58 model tests. Finally, the developed method was applied to the deck and bottom structures of contemporary designs for 12 double hull oil tankers and 10 bulk carriers between 150 m and 400 m in length.

## 2. A review on contemporary design of large ships

The midship region of a ship, e.g. an oil tanker or bulk carrier, can be considered as a rectangular box enveloped by stiffened panels, which are composed of closely spaced longitudinal stiffeners and relatively widely spaced transverse frames. A typical stiffened deck panel under axial loads and its geometric parameters are illustrated in Fig. 1.

A review on the structural designs of 12 contemporary double hull oil tankers and 10 bulk carriers between 150 m and 400 m in length has been performed. The aspect ratio $a/b$ of plates in the midship region was found to be 3.5 to 6.7 for tanker decks and bottoms, and 4.6 to 6.3 for bulk carrier decks and 3.0 to 4.5 for bulk carrier bottoms. It is noted that the decks and bottoms of oil tankers usually have the same transverse frame spacing, while the decks of bulk carriers have larger transverse frame spacing than its bottom. Buckling and ultimate strength of plates and stiffened panels are strongly related to two parameters. These are defined as:

$$\text{The plate slenderness ratio}: \ \beta = (b/t)\sqrt{\sigma_y/E} \tag{1}$$

$$\text{The stiffener slenderness ratio}: \ \lambda = (a/\pi r)\sqrt{\sigma_y/E} \tag{2}$$