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Influence of geometric imperfections on the ultimate strength of the double bottom of a Suezmax tanker

Segen F. Estefen [a,*], John H. Chujutalli [a], C. Guedes Soares [a,b]

[a] Ocean Engineering Department, COPPE, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil
[b] Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

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ABSTRACT

In this work, the influence of initial geometric imperfection modes on the ultimate strength of a ship's hull is studied, with a focus on the buckling behavior of stiffened panels that initiates the structural hull failure. A numerical model of a cargo compartment at the midship of a Suezmax tanker is developed by using the finite element method and by considering both geometric and material nonlinearities. Analyses are conducted under hogging conditions to evaluate the double bottom stiffened panels experiencing axial compression by hull girder bending. Different imperfection modes on the bottom and inner bottom plates are considered in the model. Two cases are studied. In the first one, a half-wave imperfection mode is employed in the longitudinal and transversal directions. In the second case, the imperfection mode coincides with the main natural buckling mode of the plate between the stiffeners. Experimental tests were performed using small-scale models that are representative of the bottom panels, and the results are correlated with those from numerical simulations to define a proper mesh refinement to reproduce the buckling phenomenon. The ultimate strength of the ship hull, in full-scale, employed the same mesh refinement for the bottom panels, assuming the two proposed initial imperfections. The results from the ultimate strength are compared with the reference values for the design bending moment recommended by a classification society.

1. Introduction

In a large ship the evaluation of the ultimate strength of the hull structure under a bending moment is an important parameter for the structural design. A ship hull is much longer than it is wide or deep. An analogy of this is a beam, which is associated with a denomination hull girder. The initial procedure for hull girder structural design assumes that it is positioned over a wave with a length and height associated with the region where the ship will be operated. Although the ship's weight in waves does not vary, the buoyancy distribution varies along the length due to the geometric variation of the hull transversal sections, causing vertical bending in the midship region subjected to the greatest stresses when the hull bends under sagging and hogging conditions.

The structural design of ships, as specified by the classification societies, has been based for many years on the elastic modulus of the midship section. However, advances in the assessment methods have allowed design limit state equations to be based on the ultimate strength, as proposed by Guedes Soares et al. [1], which was adopted in 2006 into the Common Structural Rules of Classification Societies, leading to changes in the evaluation of strength and reliability [2].

An important step in the methodology of a realistic assessment of the ultimate strength for ships was performed by Smith [3] and followed by others, including Gordo et al. [4] and Yao et al. [5]. The nonlinear finite element method (NFEM) allows detailed modeling of the structure and has been recognized for a long time [6]. However, processing power available then did not allow this method to be widely used. More recently, this method has become more widespread and various studies are now available, including those by Amlashi and Moan [7], Paik et al. [8], and Khedmati and Rashedi [9]. Methods of intermediate computational efficiency have also became available, including the Idealized Structural Unit Method (ISUM) [10,11], as well as mixed structural models where the collapsing part is simulated by ISUM elements and the remaining parts are simulated using elastic FEM elements [12].

Ship structural arrangements consist of longitudinally stiffened panels. The panels are characterized by structural components made of thin-walled elements with a high strength to weight ratio. Because the overall failure of a ship's hull is governed by buckling and the subsequent plastic collapse of the deck and bottom

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* Corresponding author.
E-mail address: segen@lts.coppe.ufrj.br (S.F. Estefen).

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structures, it is of crucial importance to understand the behavior of the structural members under extreme loading conditions to ensure that there is an adequate safety margin during the ship's life cycle.

Nonlinear finite element models have also been adopted to study the ultimate strength of plates and stiffened panels by looking at the influence of various factors, including initial imperfections [13], residual stresses [14–16], boundary conditions [17,18], aspect ratios and combined loading [19,20], as well as corrosion [21] and mechanical damage [22], with most of the work performed in steel but also in aluminum [23].

The detailed modeling of the plate characteristics that affect strength has started to be incorporated into the hull girder ultimate strength assessment. Recently, Khedmati and Rashedi [9] evaluated the ultimate hull girder strength and the progressive collapse of a product carrier subjected to pure bending using a nonlinear finite element analysis. Different configurations of geometric imperfections were included in the model. The pattern of initial deflections in the plate and stiffener elements was described via the "hungry horse mode", the same adopted by Rigo et al. [23]. The results showed that any configuration that adopted the initial geometric imperfections do not have significant effect on the moment–curvature relationship for the hull girder and its ultimate capacity, assuming that this may be because the progressive collapse behavior is dominated by the overall buckling of the deck or bottom plating, which is treated as a stiffened panel.

Most studies of tanker ultimate strength have examined the behavior under a sagging moment, as often the ultimate strength of deck structures is the critical condition [24]. However, under hogging moments, the compressive strength of the bottom is the critical element. This is the primary objective of this paper, where an ultimate strength analysis of a Suezmax tanker is performed, considering different plate imperfection modes. Experiments are performed on a typical plate from the double bottom, and finite element convergence studies are performed to validate the finite element model using experimental results before incorporating them into the global double bottom model. The obtained ultimate longitudinal strength is compared with that recommended by the classification society DNV for design purposes to allow an estimate of the safety reserve.

2. Experimental and numerical analysis of small-scale stiffened panels

To validate the numerical model used to study the full midship section, the approach adopted was to validate the model using the ultimate collapse of a stiffened panel. Many results are available on the ultimate strength of stiffened panels, since the classical experiments from Smith [25] to the more recent ones from Xu and Guedes Soares [26]. However, the configuration of the plate and stiffener combination is relevant to other types of structures and although they could be used to validate the numerical model, it was found preferable to conduct experiments using a scaled model of a panel that has dimensions that are typical for a double bottom from a ship under consideration; thus, conducting a specific experimental program.

When designing scaled models of a full-scale structure, scaling laws are required as discussed by Garbatov et al. [27]. The scaling considers the geometric dimensions but has difficulty in scaling

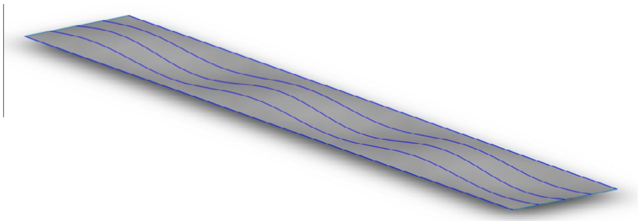

Fig. 1. Plate with geometric imperfection generated by Solidworks.

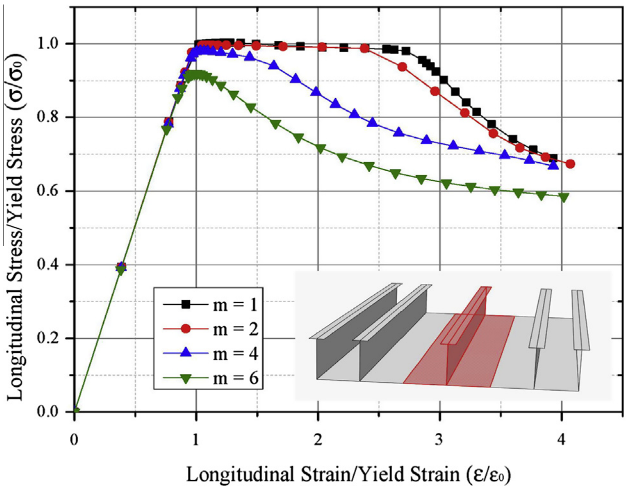

Fig. 3. Stress versus strain curves for different half-wave number (m) representing the plate geometric imperfection mode.

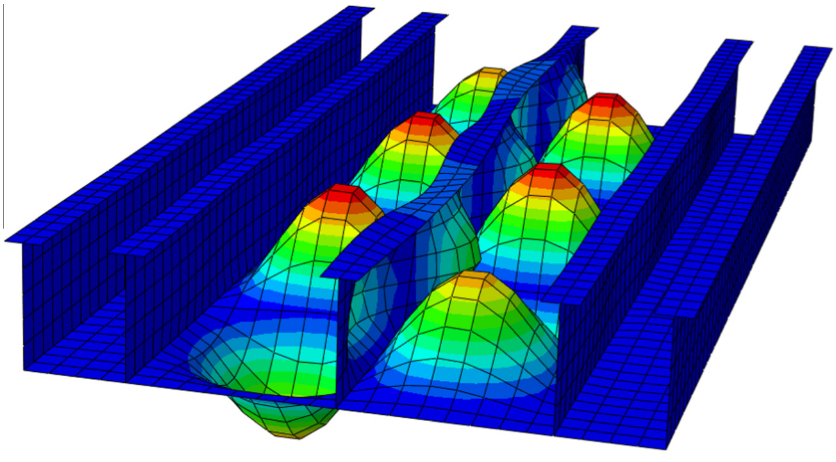

Fig. 2. First elastic buckling mode of the panel.