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Strength assessment of a severely corroded box girder subjected to bending moment

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ABSTRACT

This work deals with the evaluation of the ultimate bending moment of a severely corroded box girder subjected to uniform vertical bending moment through a series of nonlinear finite element analysis. Two models of corrosion degradation have been adopted, one is an average general corrosion thickness reduction, and the other is the real thickness of the corroded plates. New stress–strain relations have been developed to account for the effect of corrosion on the flexural rigidity. To validate the new developed stress–strain relationships, a comparison between the finite element analysis results using the existing stress–strain models, the newly developed ones and the experimental test results of a severely corroded box girder have been conducted. The comparison showed a good agreement and supported the choice of the newly developed stress–strain relationships of corroded structures.

1. Introduction

A ship hull girder is a structure built up of unstiffened, stiffened plates, frames and other components subjected to complex loading. The ultimate hull girder strength is the maximum bending capacity that a ship hull girder can sustain under longitudinal bending.

The linear elastic theory has been employed to predict the longitudinal strength of the ship hull for years. According to this theory, the maximum bending moment that the hull cross-section can withstand is equal to the bending moment corresponding to the first yield, that is, the bending moment when the maximum stress on the hull cross-section reaches the yield stress of the material. In design practise, an allowable stress is used instead of the yield stress, which corresponds to a safety factor against yielding.

However, in the last decades, it has been established that ship hulls have considerable additional strength beyond the first yield and thus the ultimate strength is the appropriate criterion to determine the ship hull strength and to be used in codified design as proposed by Guedes Soares et al. [1], which finished up being introduced in the design codes several years later [2,3].

To estimate the longitudinal strength of the ship hull several factors have to be accounted for: (1) various possible failure modes including buckling, (2) progressive and interactive behaviour of the failure of structural members, (3) redistribution of stresses on the hull cross-section and (4) residual strength of structural members after buckling and even after the collapse. By considering these factors, the maximum bending moment that the hull cross-section can withstand is designated by the ultimate longitudinal strength, which represents the maximum load-carrying capacity of the ship hull under longitudinal bending.

The ultimate longitudinal strength assessment is a nonlinear problem in which both the nonlinearity related to material behaviour and geometry are involved [4]. There are three main methods to calculate the ultimate longitudinal strength of the ship hull. The first one is the simplified method (SM), where the first attempt to assess a ship's hull strength was made by Caldwell [5] who derived a formula for calculating the ultimate longitudinal bending moment of the hull girder in a sagging condition. This formula was derived from the stress distribution along the cross-section corresponding to a fully plastic collapse.

Later, the method was extended by Smith [6], who proposed a simplified method that is now commonly called the Smith's method. This method enables to perform progressive collapse analysis on the cross-section of a hull girder subjected to longitudinal bending. The cross-section is divided into small elements composed of a stiffener with attached plating. At the beginning, the average stress–average strain relationships of individual elements are derived under the axial load considering the influences of yielding and buckling. Then, a progressive collapse analysis is performed assuming that a plane cross-section remains plane and each element behaves according to its average stress–average strain relationship.

Many other methods have been also proposed to simulate the progressive collapse behaviour of the hull girder. Billingsley [7] used an engineering approach, which considered a very simplified model for each individual beam column element. The strength of the hull girder was obtained by the linear superposition of the individual contributions of each element.

Dow et al. [8] developed an incremental curvature procedure, which allows the derivation of a moment–curvature relationship for a

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complete hull. This procedure was correlated with experimental data derived from the collapse tests of three box girders and ultimate longitudinal strength test carried out on the destroyer ALBUERA, which was a riveted ship. Based on the flexural buckling formulations, Adamchak [9] developed an approximate method to obtain the moment–curvature relationship and to calculate the ultimate strength of stiffened panels.

Yao and Nikolov [10] developed a progressive collapse method taking into account the flexural torsional behaviour of angle bar stiffeners welded to continuous plating. A series of elasto-plastic large deflection analysis have been done. A large-scale frigate model was analysed using the developed code.

Hughes [11] proposed a method for estimating the ultimate longitudinal bending moment of the ship's hull, suggesting discrete steps from one element collapse to the next, instead of applying regular small increments of the curvature. In this method, the contribution of the post-collapse resistance of compressed panels was ignored to simplify and speed up the calculations.

Gordo and Guedes Soares [12] have developed an approximate method of determining the load shortening curve of one stiffened with an associated plate, which became the building block of a method to assess the ultimate strength of hull girders [13] in an approach inspired by Smith [6]. This method was validated against data from a full scale accident [14] where the loading conditions could be well established.

Rahman and Chowdhury [15] developed a computing methodology for calculating the ultimate longitudinal bending moment at any cross section of a ship or a box girder. The cross section was modelled as one stiffener with its associate effective plating. The overall layout of the algorithm is similar to the one presented in [6], with different post-collapse behaviour definition of the compressed elements as defined in [9], with some modifications of the stress–strain relationship from the elastic range to the post-collapse region. The programme was validated by comparing the output with some experimental results of a tested box girder and real very large crude carrier, showing a good agreement.

The second method used to calculate the ultimate strength is the nonlinear finite element method (NFEM), the applications of this method to the collapse analysis of ship's hull are very few; the earlier attempt was done by Chen et al. [16] who take into account elasto-plastic properties of the material, nonlinear geometric behaviour of the elements and their buckling and post-buckling strength.

Valsgaard and Steen [17] used a nonlinear super element approach within the framework of a general nonlinear shell programme. A comparison between the numerical strength predictions obtained, the test results of a large scale box girder and a VLCC has been carried out.

A series of finite element analyses were conducted to simulate the behaviour of tested box girders. Hansen [18] performed four finite element analyses (FEA) with different considerations for a cross-section selected from the models tested by Nishihara [19]. The finite element model used in the analyses was built up by a 4-node shell element with 5 layers in thickness. The model was loaded incrementally with force vector at the end of the load section in order to ensure the overall bending.

Qi et al. [20] performed a series of nonlinear FEA for the ultimate strength of tested box girders simulating a large surface ship, frigate and double hull tanker. A good agreement with the test results has been obtained. Harada and Shigemi [21] have performed a series of nonlinear FEA for a double hull VLCC and a cape size bulk carrier to obtain the ultimate longitudinal strength in hogging and sagging conditions.

Amlashi and Moan [22] investigated the ultimate strength of a Capsize bulk carrier by carrying out extensive nonlinear FE strength analyses under alternate hold loading (AHL) in hogging condition, by modelling of $1/2 + 1 + 1/2$ hold tanks. An extension of this work has been performed in [23] where an extended model which covers 3 cargo holds and four transverse bulkhead in the midship region is set up to investigate the ultimate strength of the same bulk carrier. The nonlinear FEA is carried out using the finite element code ABAQUS. The ultimate strengths in a hogging condition are evaluated and compared with results from simplified methods, and concluded that, the FEA can provide more information about the ultimate strength and collapse mode beyond the ultimate strength, also, the difference of ultimate strength of the hull girder in hogging is very small with or without consideration of the geometric imperfections. However the ultimate strength based on gross scantlings are about 15% higher than those based on net scantlings.

Nikolov [24] performed a comparison between the experimental results and different simplified methods of five different box girders used for the ultimate strength test. The stress–strain and moment–curvature relationships were obtained, and the comparison showed that there is a significant difference between the numerical and some experimental results.

The third method is the idealised structural unit method (ISUM), the most obvious way to reduce modelling effort and computing time is to reduce the number of degrees of freedom, so that, the number of unknowns in the finite element stiffness equation decreases, and this concept is the base of the ISUM that has been proposed in [25]. In the

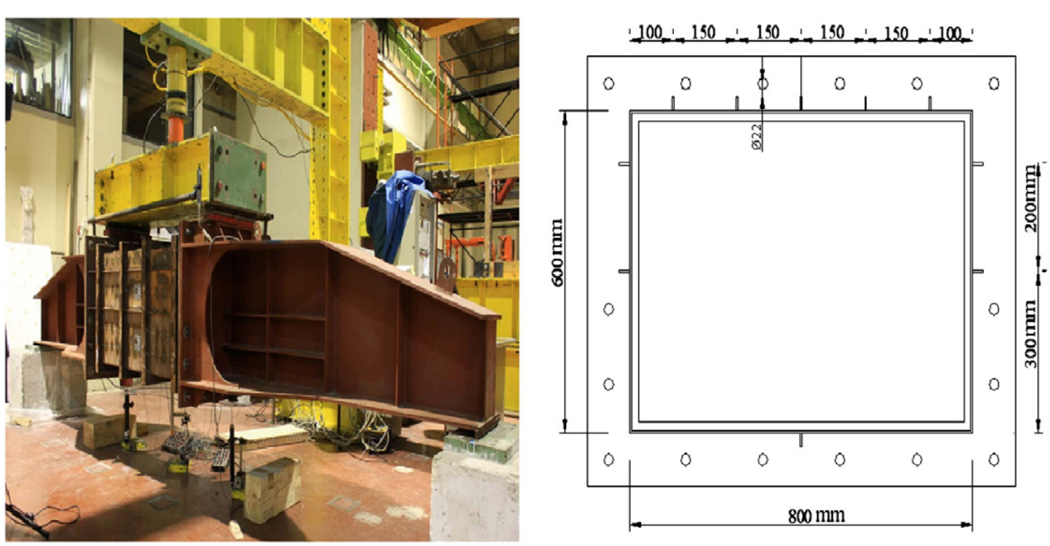

Fig. 1. Experimental set up (left), cross-section view (right).