Engineering Structures 100 (2015) 742–750

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Hull girder ultimate strength assessment based on experimental results and the dimensional theory

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ARTICLE INFO

Article history:
Received 11 January 2015
Revised 28 May 2015
Accepted 1 June 2015
Available online 14 July 2015

Keywords:
Experimental analysis
Ultimate strength
Hull girder
Dimensional theory

ABSTRACT

The objective of this work is to perform a hull girder ultimate strength verification according to the Class Society rules based on experimental results and the dimensional theory. The results of the ultimate strength test of three box girders, that may represent the behaviour of a mid-ship section of a ship, deteriorated in a real corrosive seawater environment representing different levels of corrosion degradation of ageing ship structures, is used to evaluate the ultimate strength. The analysis is based on a structural model, used in the experimental test, which maintains the first-order similarity between the model and real structures. The present analysis may be used to validate the global ultimate strength of ship hull structures in the phase of the new structural design or during the service life and to calibrate the new developed codes.

1. Introduction

Many research works have been carried for analysing the ultimate strength of ship hull structures. One of the first works in this field was performed by Caldwell [1], after that a method for ultimate strength assessment was developed in [2] including the effect of buckling collapse of compressed members. The method is based on the assumption that the framing is assumed to be longitudinal. The collapse of a girder section is assumed to occur between two adjacent frames, being induced either by the interframe flexural beam–column collapse of panels under compression or by the interframe yielding of panels under tension. This theory is based on two assumptions, namely: the overall grillage instability where stress is higher than the interframe beam–column collapse stress, which needs enough rigidity of the transverse frames to provide supports to the longitudinal stiffeners; and the tripping stress of stiffeners is also higher than the interframe collapse stress. Both can be achieved during design, satisfying suitable design constraints on the relative sizes of the transverse frames and the longitudinal structure.

To assess the ultimate strength various simplified approaches have been developed in the last decades. By taking into account systematic errors associated with the yield strength, ultimate compressive strength and section effects, Faulkner and Sadden [3] suggested an empirical formula for calculating the ultimate bending moment. Viner [4] proposed an expression for calculating the ultimate bending moment assuming that the elastic behaviour is maintained up to the point where the longitudinals of the compression flange reach the collapse state resulting in immediate hull collapse. Frieze and Lin [5] expressed a normalised ultimate bending moment capacity of the hull as a function of a normalised ultimate strength of the compression flange. A new expression for predicting the ultimate strength of single and double-hull ships under vertical bending moments was derived by Paik and Mansour [6]. To calculate the ultimate compressive strength, Paik and Thayamballi [7] derived an empirical formula for the ultimate compressive strength of a stiffened panel as a function of the plate and column slenderness based on existing collapse test results for stiffened panels. The governing factors in all approaches were formulated for intact, non-degraded structures are the plate and column slenderness.

Very recently, a further development of new ultimate strength approaches has been presented in [8–10].

Saad-Eldeen et al. [11] verified the applicability of some of the simplified approaches to assess the ultimate strength of the initially corroded box girder, used in the present analysis here, and noted that the Caldwell modified method gives almost the same results compared to the experimental results. The Viner [4] equation and Paik and Mansour [6] showed a good agreement with the experimental result. On the other hand, for the moderately

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http://dx.doi.org/10.1016/j.engstruct.2015.06.003
0141-0296/

corroded box girder the only expression that demonstrates a good prediction of the ultimate strength is the one proposed by Faulkner and Sadden [3].

An alternative method to perform progressive collapse analysis may be the idealised structural unit method (ISUM), which was originally proposed in [12] to perform progressive collapse analysis on the transverse frame of a ship structure. Then, new elements have been developed to perform progressive collapse analysis of a hull girder under longitudinal bending. This could improve the accuracy of the method when it is applied to evaluate the strength of double-bottom of ships. The existing ISUM plate element has been extended to consider combined uniaxial, biaxial compression and lateral load.

The finite element method (FEM) has been applied often to predict the ultimate strength of unstiffened and stiffened plates where both geometric and material nonlinearities are considered. It may be said that it is straightforward to use FEM for ultimate strength prediction of plates and stiffened plates. The FEM can also be a powerful method to perform progressive collapse analysis on a hull girder. However, the hull girder is too large to perform progressive collapse analysis by the ordinary FEM, and some simplified methods are required [13].

Large experience has been accumulated during the last three decades about the behaviour of plates, stiffened plates and panels. Many empirical formulas, based on experimental or numerical results, have been proposed for the ultimate strength assessment of plates, stiffened plates and panels in [14–16].

Experimental results provide first-hand information for understanding the collapse behaviour of structures; therefore, intensive works have been carried out to simulate the behaviour of ship hull by a box girder specimen loaded up to its ultimate strength limit. The box girder specimen has been designed to reproduce the mid-ship section of ship's hull subjected to a pure bending moment. Typical elements of the box girder are plates, stiffeners and transfer frames.

Various box girders have been tested during the last decades [17–21]. Recently an ultimate strength test of a multispan stiffened box girder representing a mid-ship section was carried out and reported in [22], which is the one of the series of the three corroded box girders to be used here. The box girder was subjected to a four-point bending moment. A continuation of the previous study is the one reported in [11], where the analysed box girder was subjected to moderate corrosion deterioration level and an extension of the corroded box girder test was presented in [22], where a severely corroded box girder was tested under the same conditions.

A corrosion-dependent analysis of the ultimate strength of the corroded steel box girders, based on experimental results, has been performed in [23]. Two corrosion-dependent formulas for assessing the ultimate strength as well as the ultimate bending moment of corroded structures were proposed. A corrosion-dependent moment–curvature relationship has been developed accounting for the changes in the geometrical characteristics and material properties of the tested box girders.

The work presented in [24] analysed the effect of corrosion deterioration on coupons subjected to tensile loading. The corroded test specimens were cut from a box girder that was initially corroded in real sea water conditions. It was observed that for the corroded steel specimens with more than 20% of the degree of degradation, the reduction in strength is significant. There is a difference between reductions in yield stress and tensile strength. The reduction in yield strength is nonlinear but in the case of tensile strength is linear. An equivalent stress–strain curve of corroded steel plates as a function of the corrosion degree of degradation was developed based on the regression equations, which identify the relation of the experimental true stress–strain curve with the Young's modulus, yield stress, toughness, and hardening parameter.

The effect of corrosion degradation on the ultimate strength, dissipated energy, compliance, ductility and elastic limit of the corroded steel box girders are verified and discussed in [25]. A significant reduction in the stiffness, stress–strain relationship and elastic modulus was observed.

The work presented in [26], analysed specimens made of the same material that corroded box girders were built and demonstrated that the severe corrosion degradation of a stiffened panel may reduce the fatigue strength from FAT 100 to 65 MPa as a result of the crack propagation starting from corrosion pits and due to changes in mechanical properties of the corroded steel.

The behaviour of the corroded box girders was investigated numerically by conducting a series of nonlinear collapse analyses using different elasto-plastic material stress–strain models in [27]. Different elasto-plastic material models have been developed accounting for the residual stresses effect and post-buckling behaviour and the effect of corrosion degradation of the material mechanical properties. Comparisons between numerical and experimental results have been performed and a very good agreement was observed. Moreover, a series of nonlinear FEA have been conducted for the severe corroded box girder as given in [28], where two models of corrosion degradation have been adopted, one for an average general corrosion thickness reduction, and the other for the real thickness distribution of the corroded plates. The new stress–strain relations have been developed to account for the effect of corrosion on the flexural rigidity.

The objective of this work is to check the hull girder ultimate bending moment, according to the Class Society rules [29] based on the experimental results scaled on the basis of the dimensional theory. The results of the ultimate strength test of three box girders that simulate the behaviour of a mid-ship section of the ship, deteriorated in a corrosive seawater environment to simulate different levels of corrosion degradation of ageing ship structures are used. The analysis is based on a structural model using the first-order similarity and accounting for the nonlinear structural response.

2. Structural modelling

A structural model may be defined as a physical representation of a structure or a portion of a structure. A definition of a model given in [30] is that the structural model is any structural element or assembly of structural elements built to a reduced scale, which is to be tested, and for which laws of similitude must be employed to interpret test results.

Any structural model must be designed, loaded, and interpreted according to a set of similitude requirements that relate the structural model to the real structure. These similitude requirements are based on the theory of modelling, which can be derived from a dimensional analysis of the physical phenomena involved in the behaviour of the structure.

Using of dimension data is to specify and measure physical quantities, which have qualitative and quantitative characteristics. The qualitative characteristics enable physical phenomena to be stated in certain fundamental measures of nature. These fundamental measures are commonly referred to as dimensions [31].

Dimensional analysis is of substantial benefit in any study of structural behaviour because it permits to combine the variables into convenient groups of π terms with a subsequent reduction of unknown quantities.

The problem of experimentally estimating the maximum stress at a section of a simply supported beam subjected to two known forces, P, creating so-called four point bending moment is analysed here (see Fig. 1).