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Effect of corrosion severity on the ultimate strength of a steel box girder

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ABSTRACT

The objective of this paper is to analyse the ultimate strength of ageing ship structures based on experimental and numerical assessments. Three experimental ultimate strength tests have been carried out on box girders under vertical bending moment and several effects have been detected due to corrosion. Extensive nonlinear finite element analyses have been performed to compare the numerical and experimental results. The ultimate bending moment of corroded box girders has been compared with existing formulas. A relationship to calculate the equivalent tangent modulus as a function of the total reduction of the cross-sectional area due to corrosion degradation has been proposed. A new stress–strain relationship has been developed, taking into account the residual stresses and the corrosion effect, which may be directly used as a master stress–strain curve for a non-linear finite element analysis.

1. Introduction

Marine structures are predominantly made of carbon and low alloyed steels. In seawater environment, they are affected by corrosion, which is one of the most important factors reducing the structural capacity during its service life. During the design of the ship structures, a corrosion thickness allowance is added to compensate the potential thickness reduction due to corrosion along the ship's service life.

An important feature for ship design is the ability to describe the structural behaviour of the hull and to accurately predict its ultimate strength. Therefore, the assessment of longitudinal strength involves the evaluation of the structural capacity of the hull girder under longitudinal bending and the estimation of the maximum bending moment that may act on it. The first analysis of ultimate strength of ship's hull strength was performed by Caldwell [1], who derived a formula for calculating the ultimate bending moment of a hull girder. After that, the method was made more realistic by Smith [2] including the effect of buckling collapse of compressed members.

In order to understand the collapse behaviour of ship structures, experimental results provide the first-hand information. Intensive work has been carried out to simulate the behaviour of box girders loaded up to its ultimate strength limit, as representative of the behaviour of the midship region of ship's hull. The typical elements of the box girder are plates with bar stiffeners, which have been proved to be representative of the midship structure of the ship's hull.

During the last decades, various ultimate strength experimental tests for intact box girders have been performed. For example, Reckling [3] carried out collapse tests on seven box girder models under pure bending. Dow [4] performed a collapse test on 1/3-scale welded steel hull girder model of a frigate under sagging bending moment. Ostapenko [5] performed a test on three box girders subjected to combined bending, shear and torque.

Nishihara [6] tested eight box girder models representing conventional ship types of tanker, bulk carrier and container ship. All the specimens were subjected to pure bending. Mansour et al. [7] carried out experimental tests of two large-scale models, which represented two types of ships. Yao [8] reported two groups of collapse tests on hull girder models. The first group was fore-body hull sections of a bulk carrier, a container ship and an ore carrier. Shear force and bending moment were applied simultaneously simulating a slamming load. The second group is of wood chip carriers, which were tested under sagging condition.

Gordo and Guedes Soares [9] conducted an experimental test on the ultimate bending strength of a box girder. Four-points bending was applied to obtain pure bending throughout the whole specimen. Gordo and Guedes Soares [10] performed a study on the behaviour of two box girders made of different material but with the same configurations in order to have a good basis of comparison and to establish experimentally the effect of material properties on the collapse strength.

A continuation of the previous work is the one presented in [11], where three box girders subjected to pure bending moment were tested. The specimens were made of very high-tensile steel. The tests consist of a four-point bending of a beam like box girder.

Qi et al. [12] reported an ultimate hogging strength test of a box-girder model simulating a large surface ship.

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The step forward with respect to the already reported analyses of ultimate strength of intact box girders is the study of aged box girders. Saad-Eldeen et al. [13] carried out a test of a slightly corroded multispan stiffened box girder representing a midship of ship hull. The box girder was subjected to a uniform bending moment along the specimen. A continuation of the previous study is the one conducted in [14], where a box girder made of mild steel subjected to moderate corrosion was tested. The experimental results and the collapse modes have been analysed and confirmed the expected global deformation shape and strength capacity as a result of corrosion deterioration and the reduction of the residual stresses.

An extension of the corroded box girder test was presented in [15], where a severely corroded box girder was also tested under the same conditions. Thickness measurements have been performed to evaluate the residual thickness and the corrosion wastage data has been fitted to a non-linear time-variant degradation model. A corrosion-dependent analysis of the ultimate strength analysis of the corroded steel box girders based on experimental results has been performed in [16]. Two corrosion-dependent formulas for assessing the ultimate strength as well as the ultimate bending moment of corroded structures were proposed. Using a time-dependent corrosion growth model, equivalent time-dependent formulations were developed. The effect of corrosion degradation on the residual stresses during the service life was also analysed, and a regression equation for predicting the remaining residual stresses along the service life was proposed. Finally, a corrosion-dependent moment–curvature relationship had been developed accounting for the changes in geometrical characteristics and material properties of the tested box girders.

Saad-Eldeen et al. [17] investigated 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. A significant reduction in the stiffness, stress–strain relationship and elastic modulus was observed.

Extensive finite element analysis has been performed by the authors, in order to find out the best configuration of the finite element model by varying the initial imperfection (shape and amplitude) and mesh size that affect the ultimate strength and post-collapse behaviour as reported in [18]. The behaviour of the corroded box girders was investigated numerically by conducting a series of nonlinear collapse analyses using different material models and also different weld toe shapes as presented in [19,20]. 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.

The aim of this paper is to present the results of the research work on the strength assessment of aged box girders subjected to different corrosion degradation levels experimentally and numerically. The box girder is not representing a scale model of an existing ship. It was designed, built and tested to analyse a behaviour that could be similar to that of the midship section of a tanker or FPSO ship type subjected to vertical bending moment and corrosion deterioration. The objective of the study is to validate existing approaches and eventually to support the development of new ones for ultimate strength assessment of box girder type structures accounting for the deterioration effect along the service life. Additional work is needed, including experimental tests and numerical verifications, before the achieved results may be directly applied for the design of new ships.

1.1. Corrosion deterioration test

Corrosion tests were performed for three box girders in order to simulate different corrosion levels of the ship's hull. The specimens were exposed to Baltic seawater. The box girders (specimens) were placed in a large tank where seawater was pumped into the tanks continuously. The corrosion test conditions for each box girder are shown in Fig. 1. As may be seen in Fig. 1, the initially corroded box, has been tested in hot water without anodic polarisation, the temperature of seawater was increased and additionally oxygen depolarisation sub process rate was increased by the agitation of seawater, which resulted in corrosion rate increase. The test duration was 90 days for the test performed without polarisation and the total weight loss observed 37 kg (13% of initial weight).

To model corrosion rate acceleration, anodic polarisation of the metal surface was used. Anodic electric current was supplied by an external source. The test durations were 30 days for experiments with the application of external electrical current. The total weight loss observed in the case of anodically polarised tests was 56 kg (23% of initial weight). More detailed information about the corrosion setup are given in [21].

The present type of corrosion is general corrosion with different degradation levels and it tends to occur over extended areas of plating and results in a roughly uniform thickness reduction. A survey of thickness measurement has been performed to find out the remaining thicknesses of the box girders structural elements. The plating thicknesses have been measured using an ultrasonic thickness measurement device (T-Mike EZ Ultrasonic Thickness Gauge). The place at which the thickness measured was cleaned with sandpaper, pressured air tools to remove any accumulated rust particles, and then cleaned with a detergent. During the measurement, Vaseline was used on the steel surface to ensure good conductivity between the measurement tool and the corroded surface. The measured plate thickness distribution for the deck panels of the three corroded box girder is shown in Fig. 2.

The corrosion data consists of 212 thickness measurements collected in each box girder. The as built thickness of plates and stiffeners are 4.5 mm.

The mean values of measured corrosion depth of deck plates (0.41, 2.31, and 2.62 mm) of the three boxes reveal that the initially moderately and severely corroded box girder matches the 0.2, 17.9 and 23.3 years of deterioration, respectively, using the corrosion wastage model of [22,23], without accounting for the coating as shown in Fig. 3. Based on the thickness measurement survey, the average thicknesses of the structural elements of the three corroded box girders are shown in Table 1.

2. Ultimate strength tests

Three ultimate strength tests have been carried out for three corroded stiffened box girders with length, breadth, and depth of 1400 mm, 800 mm, and 600 mm, respectively. The box girders consisted of 3 bays as may be seen in Fig. 4. The structural configurations of the box girders are as follow: the deck panel was stiffened with five longitudinal flat bars with a spacing of 150 mm; the side panels were stiffened with two stiffeners on a distance of 300 and 500 mm measured from the bottom, respectively. The bottom panel was stiffened with one stiffener in the middle.

During the manufacturing process, when stiffeners are welded to plate elements some deformations were induced as angular distortion of the welded structural components. The presence of welding residual stresses promotes initial imperfections.

Extensive measurements of plating imperfections were taken along the deck panel between the stiffeners and the web frames. The recorded data were analysed and fitted to a lognormal distribution with a mean value and standard deviation of 3.13 and 2.05 mm, respectively, as shown in Fig. 6.

According to the measurements, the initial imperfection amplitudes are 1.72 mm, 3.94 mm and 3.92 mm for initially, moderately and severely corroded box girders, respectively.