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Influence of corrosion on the ultimate compressive strength of steel plates and stiffened panels

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ABSTRACT

This study concentrates on a comparison between steel plate and stiffened panels subject to localised corrosion. A finite element analysis is used to investigate the effect of random corrosion on the compressive strength capacity of marine structural units. Variables include the extent of corrosion; slenderness ratio and aspect ratio. A corrosion prediction model is incorporated to determine the thickness reduction with time. Corrosion-induced volume loss results in a greater reduction of ultimate strength for slender plates compared to stiffened panels, up to 45%, showing the structural element selection can strongly influence the accuracy of the estimated corrosion damage effect.

1. Introduction

Corrosion is a problem for a large number of steel structures. The ability to model this corrosion is vital to understand the behaviour of a structure though its life, rather than just after deployment. Corrosion damage is especially prevalent in marine structures due to the constant exposure to the harsh environment and to the highly corrosive cargo transported by ships such as crude oil, iron ore and coal. Empirical evidence shows that corrosion is one of the main five damage causes which lead to loss of ships [1]. Corrosion mechanisms lead to thinning of the structural material, a change in its mechanical properties and ultimately a decrease in its strength capacity [2]. Major oil spill accidents such as the Erika (1999), Castor (2000) and Prestige (2002) [3] have highlighted the importance of the corrosion assessment on the strength of structures.

A review on corrosion predictions in the marine environment and the corrosion effects on the structural strength capacity can be found in Wang et al. [4]. Various corrosion prediction models have been proposed in the literature, including mathematical models based on mechanistic principles [5] and statistical models based on actual corrosion data [6–9], where Ref. [6] analysed the statistical scatter of corrosion damage using a Weibull function at any time point and which has been proven to work well by further studies [7,8], even for subsea environments. When comparing these approaches Jiang and Guedes Suares [10] propose that statistical models based on data from different ages and locations is more versatile and can be used to analyse a wide range of marine structures. A number of nonlinear finite element analysis (FEA) has been carried out to investigate the influence of these models on the strength capacity of structures. Saad-Eldeen et al. [11] modelled a box girder, representing the large structural scale, and this showed that corrosion can affect the compartment level ultimate strength but, due to the computational time, often makes systematic studies difficult. Studies at the smaller structural scale [12–17] allow for a large quantity of data to be analysed. However, despite the ever improving modelling techniques, there are still challenging issues including the realisation of one-side localised corrosion using shell elements, rough surface on the corroded area and cracking associated with pits. In addition, small scaled models with detailed corrosion features may not accurately reflect the global behaviour of a corroded structure. The transmission of the corrosion effect from large to small scale has yet to be fully understood. The present work explores the comparison between plate and larger structural units. Following on from the authors' previous work [16], which focused on the corrosion location and microbial attack on plate elements, this study investigates the effects of a number of geometrical parameters and considers a newly developed stiffened panel model. This allows the examination of the ultimate strength of different structural configurations and provides insights in the structural element selection when

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assessing the corrosion influence. Based on a review of the literature [6–10], a statistical corrosion prediction model is used to inform the temporal damage extent for different locations in a ship hull.

2. Modelling structures subjected to pitting corrosion

2.1. Ultimate strength modelling

Structural failure is normally associated with material and geometric nonlinearities. The former is related to yielding or plastic deformation, whilst the latter is due to buckling or large deflections [18]. To incorporate such features, structural strength assessment is undertaken through a nonlinear FEA procedure in ANSYS 14.5. An elastic perfectly plastic material model is used for the material nonlinear properties. For all the models, the large deflection static analysis is used to achieve the geometric nonlinearities, with full Newton–Raphson method and automatic time stepping. The structural models are generated using a shell element SHELL181 (a 4-node element representing the mid-plane of a structure), which is typically used for thin-walled structures [4]. The resulting stress and deflection values for each corrosion case are then analysed to understand how the structure responds to a range of parameters.

2.2. Application of corrosion model

Based on the corrosion data collected from different locations in bulk carriers [19], the present study makes use of the nonlinear time-dependant corrosion model proposed by Qin and Cui [9] to predict the depth of the random corrosion pitting after a number of years in service, see Eq. (1)

$$d(t) = d_{\infty}\left\{1 - \exp\left[-\left(\left(\frac{t - T_{st}}{\eta}\right)^{\beta}\right)\right]\right\}, \tag{1}$$

where $d(t)$ is the thickness reduction due to corrosion, mm, at various time point t, y; $d\infty$ is the long-term corrosion wastage, mm;T_{st} is the pitting corrosion initiation time point, y and β and η are parameters determined by collected data. In the present research the corrosion data for different plate locations of bulk carriers gathered by Paik et al. are used to deduce d_{∞}, T_{st}, β and η. One of the benefits of this model is that it takes into consideration the time when pitting corrosion initiates unlike most existing models. Moreover, parameters can be quickly determined based on the survey data compared to the first principle model proposed by Melchers et al. [5].

Paik et al. [19] gathered a total of 7503 thickness measurements from 16 different structural locations on 44 bulk carriers (up to 20 years in service). Six structural locations are studied here, including bottom plates (BP), inner bottom plates (IBP), lower slopping plates (LSP), lower wing tank side shells (LWTSS), side shells (SS) and upper wing tank side shells (UWTSS). A schematic of the location of these plate components is represented in Fig. 1 [19]. Using the least-square method, the long term corrosion wastage thickness d_{∞} is assumed to be different for different locations. The value of the time at which corrosion initiates T_{st} is assumed to be equivalent to 7 years for all cases. Due to the high uncertainties in the corrosion database, all parameters are assumed to be random rather than deterministic. The Qin and Cui [9] model may not be representative of all marine corrosion conditions and the characteristics of corrosion may differ with environment and operating conditions. However, this study does not intend to investigate the adaptability of such corrosion prediction models, and those available in the literature can be used for other conditions.

The results of the corrosion model application together with the measured data are shown in Fig. 2, which shows that the behaviour of the model varies depending on the structural location. The BP and LWTSS thickness reductions follow a nearly linear trend, while nonlinear changes were obtained for the other locations. However, the highly scattered data points are probably due to the data collected from the renewed plates at around 15 years old.

2.3. Model construction

The results shown in Fig. 2 are used to determine the thickness reduction for the simulated structural members. Circular shaped pits are distributed randomly on the structural surface with the degree of pitting (DOP, percentage of pitted area to the entire surface area) ranging between 10, 20 and 30%. Fig. 3 shows plate models for each DOP with simply supported boundary condition. The simulated corrosion pattern is similar to that observed during ship surveys [20]. The upper limit of DOP is based on the current classification regulations on the allowable wastage [21]. The lower limit is chosen to align with Daidola et al.'s findings [22], who reported that pitting corrosion only becomes effective when the intensity is above 10–20%. The pit depths for 10, 15, 20 and 25

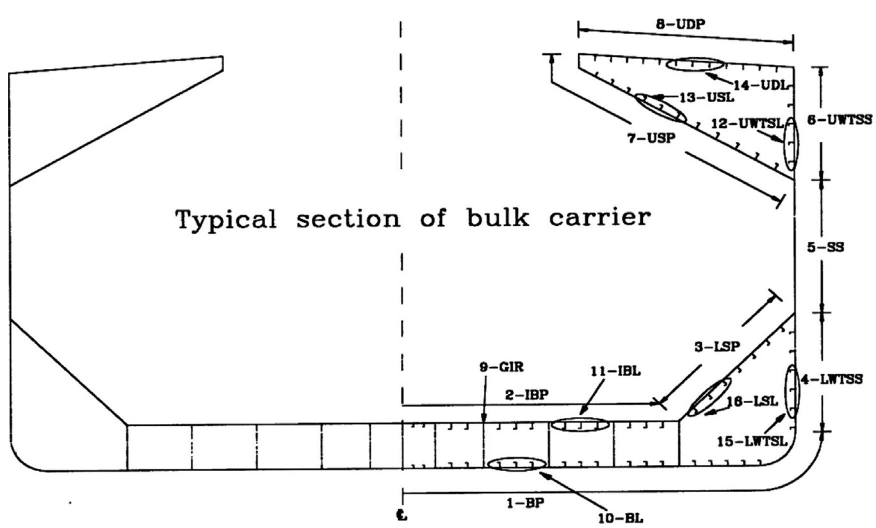

Fig. 1. Longitudinal primary members of bulk carrier [19].