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Ultimate strength assessment of steel stiffened plate structures with grooving corrosion damage

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ABSTRACT

An approach to simulate the behaviour of steel stiffened plates subjected to weld-induced grooving corrosion using nonlinear finite element modelling is proposed. The model includes the effects of different initial geometric imperfections and weld-induced residual stresses. The influence of corrosion damage on the load shortening curves and ultimate strength is investigated. It is shown that grooving corrosion depth has a greater influence on structural performance as compared with corrosion width for the same volume loss. Such corrosion damage could cause a significant reduction in the ultimate strength of a plate panel. Considerations of weld-induced deflection and residual stresses further enhance the corrosion influence on the strength capacity.

1. Introduction

Marine platforms, including ships and offshore structures are at high risk of corrosion particularly after 15–20 years in service. Aging also often leads to corrosion induced deterioration of steel bridges especially those on the coast (or from exposure to de-icing salts, high humidity and moisture [1]). Such corrosion induced failure is considered to be financially costly, a waste of natural resources and life-threatening. For shipping alone, in 2011 the total global cost of corrosion was estimated to be $7.5 billion per year for new construction and $5.4 billion per year for repair and maintenance [2]. Although ship surveys and repair strategies have been implemented, due to the size variance and structural complexity of vessels, difficulties often occur in corrosion protection, inspection and maintenance. Therefore, it is vital to evaluate the strength capacity of these corroded steel structures based on a comprehensive understanding of the corrosion mechanism, in order to improve the survey efficiencies and facilitate economical maintenance decisions.

General corrosion, where there is a uniform loss of material over an entire surface, has been systematically studied for steels. Results from survey data sets and numerous empirical corrosion models are extensively reviewed recently in Refs. [3–4]. Additionally, for large engineered marine structures grooving corrosion can also occur. Grooving corrosion is referred to as preferential weld line corrosion, knife-line or trench-like corrosion, with a localised line of material deterioration normally adjacent to welding joints along abutting stiffeners and at stiffener or plate butts or seams [5–6]. In 2008, a 5 m long vertical crack was found on the side of a 26-year-old bulk carrier, resulting in severe leakage (300 $m^3\ h^{-1}$ water ingress) [7]. The probable cause of this incident was reported to be the grooving corrosion at the joint of the stiffener and the plate (Fig. 1), which had been left unattended over years and ultimately led to a crack to propagate. Severe localised attack has also been observed on the bearing stiffeners of steel bridges [9].

Considerable effort has been made to assess the strength capacity or ultimate strength degradation caused by general corrosion for steel plated structures. Both experimental and finite element methods (FEM) have been utilised by varying structural properties and loading conditions. While the influence of pitting corrosion (typically in the order tens of millimetres in diameter for hull structures) has been extensively studied [10–12], to date there is no detailed analysis of the grooving corrosion influence on the strength capacity. Therefore, this paper investigates the influence of such corrosion damage considering various initial imperfections and welding methods.

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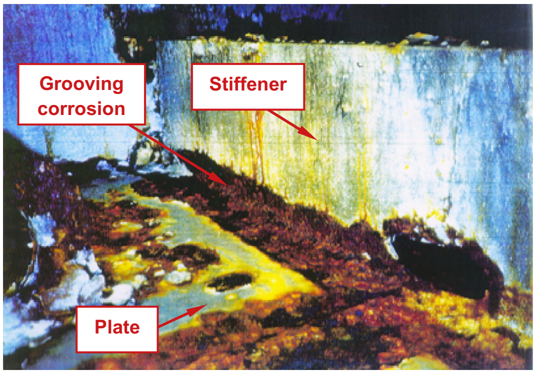

Fig. 1. An example of grooving corrosion observed for a steel structure [8] (typical height of the stiffener: 138–580 mm).

2. Modelling structures with grooving corrosion for ultimate strength

2.1. Ultimate strength modelling

The ultimate limit state is of significant importance at both the design and operational stages of ships. Traditional ultimate limit design simply estimates the elastic buckling strength corrected by a plasticity factor [13]. The accuracy of the prediction requires proper consideration of the material and geometric nonlinearities, i.e., plasticity and large deflection. In addition, due to the effects of fabrication processes, geometric distortions and weld-induced residual stresses are inevitable and should also be considered. Usually, to simplify the problem, initial deflection is assumed to follow a Fourier function. Regarding residual stresses, based on experimental observations, an idealised stress distribution has been widely used assuming yield stress of the material at the heat-affected zone (HAZ) and three level of compressive stress on the remainder area [13].

2.2. Background of grooving corrosion for modelling

During welding, the HAZ has its microstructure and properties altered; the base metal is likely to expand and be restrained by the adjacent metal. On cooling, local shrinkage induces high residual tensile stresses. In addition to the mechanical effects, corrosion may be caused by galvanic effects generated from the difference of the metallographic structure between the HAZ and the base metal. For example, manganese sulphide (MnS) inclusions were reported to develop preferentially within the weld due to rapid heating and cooling of carbon steel [6]. The surrounding sulphide-enriched portion is anodic to MnS and metal dissolution at these microscale initiation sites eventually leads to macroscale grooving corrosion [6]. Grooving corrosion has also been found in the base material where coating has been scratched or the metal itself has been mechanically damaged. In addition, the corrosion damage may be accelerated by poor maintenance of the protective coating and/or sacrificial anodes [14]. The weld imperfections (spatter) subsequently mean that an applied protective coating will have an uneven thickness, which will be detrimental to corrosion performance. When marine structures experience repeated loading and unloading, a shakedown effect may result in continuously changing residual stress patterns and consequently heighten the corrosion complexity. When grooves occur, this may create a higher deformation (flexibility) of the stiffener and stress concentrations, resulting in an accelerated corrosion rate of the groove.

2.3. Model construction

To focus on the corrosion feature effects, this study intends to examine a simplified plate–stiffener model instead of a large stiffened panel. According to benchmark studies reported in Ref. [15], a stiffened plate model comprising a stiffener and plate flange could provide good accuracy in both pre- and post-collapse phases. Therefore, this model will be used for further analysis under such loading conditions.

ANSYS 14.0 [16] was chosen to conduct a static analysis using its parametric design language. Since this study has focused on the buckling strength of the structures, instabilities were observed for some situations due to large displacements for small load increments, resulting in convergence difficulties. To tackle this issue, an artificial damper element was introduced in each node based on an energy dissipation ratio, which ranged from 0 to 1. A high ratio could result in a better convergence, in expense of a stiffer structure and hence affect the accuracy. Throughout the numerical studies, the energy dissipation ratio was kept at around 0.01%, below the suggested 1% [16]. The widely used shell element SHELL181 was one option to construct the model assuming perfect connection between the stiffener and the plating by sharing nodes and degrees of freedom without considering the modelling of the welds. However, it was realised that modelling of the welds and detailed through-thickness stress data are essential for weld-induced corrosion analysis. Although shell elements are computationally economical, due to the 2D nature of representing the mid-plane of a cross section, it was decided that solid element SOLID185 was more appropriate for modelling the weld connections, corrosion features and the weld-induced residual stresses. SOLID185 is an 8-node element with three translation DOFs at each node. To achieve a simply supported boundary condition, the cross-section of short edges where longitudinal girders lie was fully constrained in the y-direction: refer to the coordinate system in Fig. 2(a). Symmetric boundaries along the edges in the longitudinal (z-) direction are achieved at the mid-thickness nodes. The compressive load was also applied on the mid-thickness nodes by controlling the displacement.

Numerical studies of welding effects on stiffened plates have recently been carried out using solid elements [17–20], where the interface between the stiffener and the plating has always been modelled with shared nodes/elements. However, in reality this is not the actual condition for fillet welds since it is the weld metal which joins the stiffener and the plating together (Fig. 2(d)). Therefore, unlike the previous studies, contact surfaces TARGE170 coupled with CONTA175 were adopted in this investigation to represent the fillet weld connections. CONTA175 associated with TARGE170 represent contact and sliding between two surfaces in 2D or 3D [16]. The width of the fillet weld cross section is 6 mm. Fig. 2(c) shows the cross-section of the model and contact surface locations. For the interface between the stiffener and the plating, Coulomb's friction model was used with the static coefficient of friction of 0.78 and a dynamic value of 0.42 for a high-tensile steel contact [21].

Initial geometric imperfections were applied based on the frequently observed deflection shapes for all models as well as to initiate the buckling phenomenon. For the application of weld-induced residual stresses, the representative residual stress distribution suggested in Ref. [22] was applied explicitly in the longitudinal direction. The residual stress matrix was formed consisting of stress records for every integration point in every element depending on the location of the element centroid. Through the application of an initial deflection, the initial stress matrix was read and the resulting equilibrium equations solved with all DOFs constrained in order to obtain the reaction force records for all elements. Next, the constraints needed to be