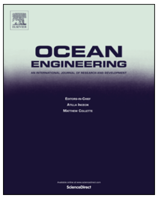
Ocean Engineering 116 (2016) 273–285

Contents lists available at ScienceDirect

Ocean Engineering

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



Ultimate strength of hull structural plate with pitting corrosion damnification under combined loading

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ARTICLE INFO

Article history:
Received 30 April 2015
Accepted 27 February 2016
Available online 18 March 2016

Keywords:
Ultimate strength
Corroded volume loss
Pitting corrosion
Hull structural plate

ABSTRACT

The ultimate strength of the hull structural plates is degraded due to pitting corrosion on the surface of the plates. This report aims at development of an assessing formula for ultimate strength of hull plate with pitting corrosion damage under combined loading. Firstly, the qualitative expression was deduced in theory. Secondly, the effects of a few factors (such as the shape, the distribution status and the depth of corrosion pits and the element type for finite element method analysis) on the ultimate strength with respect to the corroded volume loss were investigated. The influences of some parameters (such as the plate slenderness ratio, the plate aspect ratio, the linear load factors at the edges, the ratio between the transverse and longitudinal in-plane stresses, the ratio between the shear and longitudinal in-plane stresses and the maximum deflection of the initial geometric imperfection) on the ultimate strength reduction with respect to the corroded volume loss were also discussed. Lastly, the ultimate strength assessment formula based on the corroded volume loss was obtained from the data by non-linear FEM analyses for series of corroded plate models that were in accord with the actual hull plates with pitting corrosion damage.

1. Introduction

The hull structure is a typical thin-walled composed structure. The local structure under the environment loads easily buckles. The buckling effect is similar to the domino effect, so the whole structure will finally destroy. Furthermore, it is inevitable that the hull structural plates are corroded to induce the plate thickness reduction, so the local structural buckling more easily happens. In addition, the rate of corrosion of ship's plating may increase with long periods of exposure when combined with plate flexure (Melchers and Paik, 2010). It is considered that the ultimate strength assessment of the hull structural plates with the corrosion damage is an important part of the hull safety assessment. Pitting corrosion is one important kind of common corrosion not only in hull structure, but also in the other marine structures such as subsea gas pipelines (Mohd et al., 2014). The thickness loss of the whole plate with pitting corrosion is not uniform and the ultimate strength analysis involves the geometric and material nonlinearities, so it is hard to assess the ultimate strength of the plate with pitting corrosion.

Early the research concentrated on the effective thickness of the corroded plate and the typical achievements were mainly developed in the past decade. Paik et al. (2003) proposed a new parameter, i.e. the smallest cross-sectional area, to represent the ultimate strength reduction characteristics due to pitting corrosion by a series of non-linear FEM (Finite Element Method) analyses for steel plate elements under axial compressive loads. They also proposed closed-form design formulae for the ultimate compressive strength of pitted plates by regression analysis of the experimental and numerical results obtained. The further study indicated (Paik et al., 2004) that the ultimate strength of a plate element with pit corrosion and under edge shear was governed by the degree of pit corrosion intensity and the ultimate shear strength reduction factor due to pit corrosion was empirically derived by regression analysis of the computed results as a function of the degree of pit corrosion intensity. Nakai et al. (2004, 2006a, 2006b) carried out a series of compressive buckling tests and the FEM analysis. The uniform thickness loss was defined as average thickness loss. They found that ultimate compression load or bending moment of pitted plates and ultimate strength of the web plates with pitting under patch loading were both smaller than or equal to that of members with uniform thickness loss. Furthermore a series of non-linear FE-analyses (i.e. Finite Element Analyses) were conducted with steel plates with a variety of random pit distributions under various loading conditions such as

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http://dx.doi.org/10.1016/j.oceaneng.2016.02.039
0029-8018/

uni-axial compression, bi-axial compression, shear and combination of these (Nakai et al., 2007). Based on these research, a method for the estimation of equivalent thickness loss of pitted plates was discussed using the thickness diminution-DOP relationship, where DOP (Degree of Pitting Intensity) was defined as the ratio of the pitted surface area to the total surface area. Ok, Pu and Incecik used the multi-variable regression method (Ok et al., 2007a) and artificial neural network method (Ok et al., 2007b) to predict ultimate strength of unstiffened plates with localized corrosion, which concentrated at one or several possibly large area on the unstiffened plates, under uniaxial in-plane compression, and over 256 nonlinear FEM analyses of panels with various locations and sizes of pitting corrosion were carried out in these research. Zhang et al. (2008) proposed an ultimate strength assessing model for a plate under uniaxial in-plane compression loading through theoretical deduction and a series of finite element analyses, and in which the corroded volume loss parameter was employed to describe the pitting corrosion damage. Huang et al. (2010) proposed the ultimate strength assessment formula based on the corroded volume loss for the hull plates with pitting corrosion under biaxial compression. Jiang and Soares (2009) carried out a series of nonlinear FEM analysis of pitted mild steel square plate subjected to in-plane compression. They found that the intensity of pits denoted by DOP (the ratio percentage of the corroded surface area to the original plate surface area) had significant and direct impact on degradation of ultimate capacity of plates among other factors, i.e., size, depth of pits, slenderness ratio of plate, etc. Moreover thickness effect seemed negligible with increasing slenderness ratio to 3 or so. Jiang et al. (2009) proposed that under severe immersed corrosion, it was not enough to occupy DOP exclusively to represent the extent of damage caused by pits, "thin-plate effect" should be given a consideration. Khedmati et al. (2011) performed a series of nonlinear elastic–plastic finite element analyses on the plates in different conditions of uncorroded and randomly corroded and subjected to in-plane compression load. The results indicated that the ultimate strength of the pitted plate differed from that of the plate suffering random general corrosion and the amount of difference in the strength values depends mainly on the pitting corrosion parameters.

In these existing research, only a kind of loading (such as uniaxial loading and shear loading) was applied in the models and these parameters that were used in ultimate strength were mostly hard to be obtained in engineering. The aim of the present paper is to develop an ultimate strength assessment method of hull plates with pitting corrosion under combined loading. The qualitative expression was deduced theoretically, the effects of some factors on the ultimate strength with respect to the corroded volume loss were investigated and the ultimate strength assessment formula was obtained from the data by non-linear FEM analyses for series of corroded plate models.

2. Ultimate strength assessment of pitted plates based on corroded volume loss in theory

The ultimate strength analysis involves the material and geometric nonlinearities, so the accurate analytical solution can not be obtained. Some parameters that may affect the ultimate strength of the plates subject to the combined loading have been proposed, and the main parameters include the plate aspect ratio (α), the plate slenderness ratio (β), the linear factors at the plate edges (ψ_x and ψ_y), the ratio between the transverse and longitudinal in-plane stresses (λ_y), the ratio between the shear and longitudinal in-plane stresses (λ_τ) and the maximum deflection of the initial geometric imperfection (ω). Thus the longitudinal in-plane stress that is the most important stress for the hull structural plates can be expressed as follows.

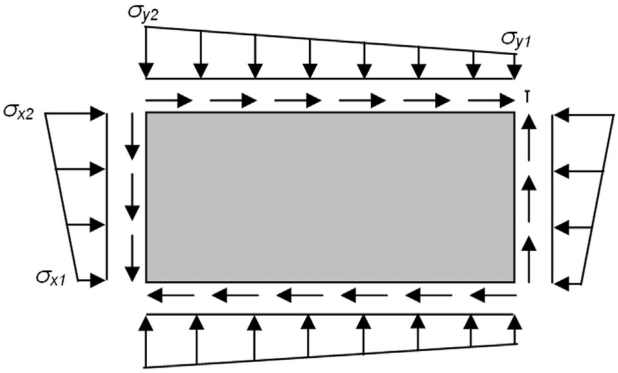

Fig. 1. Combined loading of the plate.

$$\sigma_{xu} \sim (\alpha, \beta, \psi_x, \psi_y, \lambda_y, \lambda_\tau, \omega) \tag{1}$$

where

$$\alpha = a/b \tag{2}$$

a is the plate length and b is the plate width.

$$\beta = \frac{b}{t_e}\sqrt{\frac{\sigma_s}{E}} \tag{3}$$

t_e is the effective thickness, σ_s is the yield stress and E is Young's modulus.

$$\psi_x = \sigma_{x1}/\sigma_{x2} \tag{4}$$

σ_{x1} is the maximum compressive stress in the longitudinal direction and σ_{x2} is the minimum compressive stress in the longitudinal direction when the loads at the plate edge are equivalent to the linear loads as shown in Fig. 1.

$$\psi_y = \sigma_{y1}/\sigma_{y2} \tag{5}$$

σ_{y1} is the maximum compressive stress in the transverse direction and σ_{y2} is the minimum compressive stress in the transverse direction when the loads at the plate edge are equivalent to the linear loads as shown in Fig. 1.

In the present study, it is assumed that corrosion does not happen on the plate edges and the ultimate strength is the average stress on the plate edge. Generally, the reduction factor that is the ratio of the ultimate strength of the corroded plate to that of the initial plate σ_{XU}/σ_{XU0} is applied in the ultimate strength assessment of the corroded plate. After the plate is corroded, the effective thickness is changed. In Eq. (1), only the parameter β is correlative with the thickness. The initial plate slenderness ratio β_0 is defined as Eq. (6),

$$\beta_0 = \frac{b}{t_0}\sqrt{\frac{\sigma_s}{E}} \tag{6}$$

where t_0 is the initial plate thickness.

Thus the reduction factor can be shown as Eq. (7).

$$\frac{\sigma_{xu}}{\sigma_{xu0}} \sim \left(\alpha, \frac{\beta}{\beta_0}, \psi_x, \psi_y, \lambda_y, \lambda_\tau, \omega\right) \tag{7}$$

If Eqs. (3) and (6) are substituted into Eq. (7), the following Eq. (8) can be obtained.

$$\frac{\sigma_{xu}}{\sigma_{xu0}} \sim \left(\alpha, \frac{t_e}{t_0}, \psi_x, \psi_y, \lambda_y, \lambda_\tau, \omega\right) \tag{8}$$

The effective thickness of the hull structural plate is difficult to be calculated in fact, but Zhang et al. (2008) proposed that the effective thickness is correlated with the corroded volume loss as shown in Eq. (9). Moreover, the corroded volume loss can be