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Numerical assessment of experiments on the ultimate strength of stiffened panels with pitting corrosion under compression

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ABSTRACT

The ultimate strength of stiffened panels under compressive loads is assessed by numerical simulations, in order to compare with tests made to investigate the influence on the ultimate strength of varying pit location, pit diameter and pit depth. The validated model is them used for a numerical study on the influence of pitting on the residual ultimate strength of stiffened panels by a series of non-linear finite element analysis. The parameters of pit position, diameter, number, depth, and corroded volume loss will be investigated for the stiffened panels subjected to axial compressive load with initial deformations. It is found that the pits will induce the buckling failure of stiffened panels. All parameters discussed in this paper have significant influence on the residual ultimate strength of the pitting corroded stiffened panel. A formula was derived by introducing the reduction of plate slenderness and column slenderness.

1. Introduction

Corrosion is an unavoidable aged-related phenomenon in ship and offshore structure after commissioning and problems of corrosion are significant for maintaining the safety of hull structures [1]. Corrosion in ship steel plates is normally evenly spread over the surface of the metal in corrosive environment bringing a reduction of plate thickness [2,3], which is one of the primary causes reduction of the strength of the stiffened panels. General corrosion, which is the most common form of corrosion, takes place over the entire surface of the metal and affects the global ship hull reliability [4,5]. Pitting corrosion is one form of localized corrosion that can lead to accelerated failure of structural components by perforation or by acting as an initiation site of cracking. The extreme value of pit size is the relevant parameter that govern this type of damage [6,7]. It is well recognised the Ultimate strength analysis can give a real safety margin, more useful than the traditional allowable stress approach [8]. The ultimate strength of pit corroded stiffened panels will be investigated in the present study.

Corrosion wastage in structures can reduce their ultimate strength in different ways for different corrosion types. Many studies on the influence of corrosion on plate elements and local hull structural members are found in the literature. For general (uniform) corrosion, which reduces structures' thickness uniformly the ultimate strength calculations are typically carried out by excluding the thickness loss [9–11]. Mateus and Witz [12] investigated the effect of general corrosion on the post buckling of plates using the uniform thickness reduction approach and a quasi random thickness surface model. The ultimate strength with uniform corrosion is calculated by some empirical formulas, IACS rules and finite element method. The characteristic values of the ultimate strength for corroded plate are investigated by a reliability analysis, including the randomness of the material properties, geometric size, corrosion depth and initial imperfections [13,14]. An expression for average stress-strain was derived for a randomly corroded steel plate, using elastic large deformation theory and rigid-perfectly plastic mechanism. The thickness of corroded plate is simplified as the equivalent thickness, defined as the uncorroded thickness minus the mean and standard deviation corrosion depth [15].

Localized corrosion such as pitting, is found all over aged marine structures. The basic characteristics of residual ultimate strength of pitted plate elements under tensile and compressive loads have been considered in previous studies. Nakai et al. [16,17] carried out a series of investigations regarding actual pitting corrosion observed in hold frames of bulk carriers. Paik et al. [18] studied the ultimate strength behavior and Sumi [19] estimated tensile strength and deformability of corroded steel plates.

Ultimate strength and collapse of stiffened panels and plates with localized corrosion was analyzed by the finite element method (FEM) including the geometric imperfections and residual stress [20,21]. The

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local corrosion is the simplified model of the pit corrosion, as described in Dunbar et al. [20], the plate subjected to corrosion is divided into some sub-sections as rectangular shape. The uniform corrosion is assumed to happen in each sub-section. Based on this localized corrosion, Ok et al. [22] proposed an expression of artificial neural networks to predict the ultimate strength of plates with pit corrosion. Localized corrosion has also been studied by Teixeira et al. [23] and Gaspar et al. [24].

Pitting corrosion is a localized corrosion that occurs in marine structures contacted with water, such as bottom and side structures for ships and ship-shaped offshore structures, as well as for liquid tank or ballast. This type corrosion does not occur in the structures that are not immersed in water [25]. If the pits are left or unchecked, they cause severe problems on the structures in the form of loss of strength for plate elements, even loss of hull girder integrity resulting in structure collapse and oil leakage even pollutions.

Nakai et al. [26] has studied the strength of a web plate subjected to pit corrosion under patch loading by experiments and numerical simulation. By comparing with the uniform corrosion, the results shows that the ultimate load for web plate with pitting corrosion under patch loading is almost the same as or a little smaller than the one with general corrosion in terms of average thickness loss, and the shear buckling failure mode and strength for the pit corroded web plate is estimated in [27].

Huang et al. [28] investigated the ultimate strength of plate with pit corrosion under compression is studied by the FEM. The cylindrical, semi-spherical and conical pit shapes are investigated and compared and they concluded that different pit shapes have little influence on the ultimate strength in the same corroded volume loss. It was found that the volume loss is the most important factor that reduces the ultimate strength of corroded plates. Some other parameters that will have influence on the ultimate strength for corroded plate and stiffened plate are investigated, as the extent of corrosion and plate slenderness [29].

The compressive strength of plates and stiffened panels are also studied to discuss random distributed pit corrosion [29,30]. However, it has not been discussed that the effect of randomness of local pit location, geometric size and other parameters on the deviation of ultimate strength of the plate and panel. DOP and corroded volume were investigated. It is found that the ultimate strength of the pitted stiffened panels were almost the same with the same corroded volume [31]. However, with the same corroded volume, the difference of ultimate strength are almost 1.5% compared the random distributed model and the uniformly distributed one. The collapse mechanics of the pitted structure (plate or stiffened panel) are not revealed clearly, the aim of this paper is to investigate the collapse of the stiffened panel with pits. The bending ultimate strength of a hull girder with non-uniform corrosion was studied by Saad et al. [32], which was placed in the real sea environment. And the residual ultimate strength of the plate cut from the corroded hull girder was also studied [33], including the material properties, degree of degradation, equivalent thickness. Jiang and Guedes Soares [34–36], investigated the ultimate strength of rectangular plates with pit corrosion subjected to uniaxial and biaxial loading. The effects of random nonlinear and non-uniform time dependent corrosion on the ultimate compressive strength of an unstiffened rectangular steel plate are analyzed by Silva, Garbatov and Guedes Soares [37], who used it then to a reliability assessment [38].

In view of the relatively large number of numerical results available, the present authors have conducted experimental programs on damaged stiffened plates, both with cracks [39] and with pits [40], so that they can be used to validate numerical methods. This paper follows up that work in [40] and starts by validating a FE model that analyses the ultimate strength of the pitted panels that have been tested. It then uses the same type of model to explore different aspects of the ultimate strength of plates with pits.

2. Modelling of stiffened panels with PITS

2.1. Modelling of PITS

Bhandari et al. [41] reviewed the mechanisms of pitting corrosion and all possible factors investigated by the researchers during last years, and the different modelling techniques of the pitting corrosion are also summarized. Work has also been done on the probability and uncertainties in maximum depth of pits [42], extreme value and long term distribution of the pitting corrosion loss [5,6,43,44], the corrosion rate increased by the plate loading condition [45]. Paik et al. [46,47] introduced a probability evaluation model of corrosion for bulk longitudinal and ballast tank including local corrosions. Melchers [48,49] analyzed field data of models with pitting corrosion based on the traditional coupon experiments, and introduced a pitting probability model using the probability method combination with experimental observations.

A large number of real ship check record data reveals that the maximum diameter of pits is usually less than 80 mm [25]. The diameter d_c and depth t_c of pits are randomly distributed as lognormal distribution. In addition, the pit corrosion must be treated usually as filling the pits with epoxy, as long as the depth of pits is not greater than 50% of the plate thickness [25].

In the inspection of hulls when the allowable maximum average thickness is 50% of the original thickness t_0 and the allowable maximum area of pitting corrosion is over 30% of original area, the plate must be replaced or repaired in time [50]. However, the depth of pitting corrosion in some models will exceed half of original thickness in this paper so as to ensure the corroded volume loss of models identical while discussing the influence loss volume of pitting corrosion on ultimate strength of stiffened panel. According to these characteristics, the size of pits in this paper is listed in Table 1.

The pits are assumed to be uniformly distributed on one side surface of the plate [18], because of the same corrosion environment, as seawater and air. For ultimate strength analysis, different shapes of pits as conical, hemispherical and cylindrical may have little influence on the results if they have the same volume loss [28]. Cylindrical shape pits are adopted in this paper.

2.2. Model of stiffened panels with pits

Fig. 1 and Table 2 show the one-bay stiffened plate model considered in the present study. Six series of experiments were carried out in [40] with specimens that have the same plate slenderness and column slenderness and the corresponding FE analyses are conducted here. The plate length, width and thickness are denoted by a, b and t respectively. The web height and thickness are denoted by h_w and t_w. The material of the stiffened plate is hot-rolled structural steels Q345. The yielding stress σ_y is 345 MPa. The Young's modulus E is 205.8 GPa. The plate slenderness ratio is denoted by

$$\beta = \frac{b}{t}\sqrt{\frac{\sigma_Y}{E}} \tag{1}$$

In addition to the slenderness ratio, another important geometric property for a stiffened plate model is the column slenderness, denoted by

$$\lambda = \frac{a}{\pi r}\sqrt{\frac{\sigma_y}{E}} \tag{2}$$

Table 1
Size of pitting corrosion.

Diameter of pits d_c/mm	Depth of pits t_c/mm
20–60	0–0.5t_0