

A closed form formula to predict the ultimate capacity of pitted mild steel plate under biaxial compression

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ABSTRACT

The aim of the present paper is to investigate the effects of pitting corrosion on the ultimate capacity of mild steel rectangular plates under biaxial compression, extending earlier results of uniaxially loaded plates. A series of non-linear FEM analysis of plates with partial depth corrosion pits are carried out, changing geometrical attributes of both pits and plates, i.e., the radius, depth and location of pits and the slenderness of plates. Simulation results show that volume loss dominates the degradation of the compressive capacity of pitted mild steel plates as well as loading ratio. Plate slenderness has considerable effect on biaxial interaction curve shape. A regression analysis of FEM results is conducted leading to a closed form formula able to predict the remaining strength of pitting corroded plates, where both volume loss and plate slenderness are taken into account. The proposed formula will facilitate a quick estimation of the remaining strength of pitting corroded plates during lifetime ship design phase which is relevant to maintenance decision-making of aging ship structures and components.

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1. Introduction

The overall failure of a ship hull girder is normally governed by buckling and plastic collapse of the deck, bottom, or sometimes the side shell stiffened panels. Therefore the accurate calculation of buckling and plastic collapse strength of stiffened plating in deck, bottom, and side shells is a basic requirement for the safety assessment of ship structures. Since the collapse loads of plates is an indicator of the ultimate strength of the whole stiffened panel in ship structures, the ultimate capacity of plates is important from the design and safety viewpoints.

Over the past decades there have been many losses of merchant ships due to either due to accidents or to various deteriorating environmental forces. Typically ship hull structural members are subjected to a highly corrosive environment after commissioning and with aging a reduction of plate thickness due to corrosion will unavoidably be present. Statistics reveal that corrosion is the number one cause for marine casualties in old ships [1]. Structural deterioration over time due to corrosion causes the variability in structural capability to increase with time. Therefore, it is very important to understand the corrosion processes involved and the effect of corrosion wastage on

effective plate thickness from viewpoint of inspection and maintenance policy making decision.

The objective of this paper is to investigate the effect of pitting corrosion on the ultimate capacity of mild steel plate under biaxial compression. A series of nonlinear finite element analysis has been undertaken with changing geometrical attributes of both plate and pits in order to systematically study the effects of pitting corrosion, which illustrates the close internal relationship between ultimate strength of intact plate and that of pitting corroded plates. Finally a closed form formula is proposed to predict the remaining strength of the corrosion damaged plates. The formula can provide guidance during the process of ship structural maintenance decision-making and strength reassessment.

2. Ultimate strength of plates under biaxial compression

When predominantly in-plane compressive loads are applied on a continuous plated structure supported by stiffer beam members, the buckling pattern of the plate elements is expected to be unsymmetrical, thus rotational restraints along the plate edges can be considered to be small. Therefore, the normal assumption is that stiffeners and support members have been properly designed so that their local instability will not occur prior to the failure of plating. Thus, to assess the collapse of stiffened panels it is very important to evaluate the buckling and

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collapse strength interactions of plate elements under combined loads [2].

The buckling behavior of intact plates under biaxial compression has been studied for many decades. Based on elastic critical strength interaction, Timoshenko and Gere [3] proposed that the biaxial interaction curve will be governed by a set of three straight lines corresponding to $m=1, 2$ and 3 longitudinal half-waves at collapse. Faulkner et al. [4] suggested a parabolic interaction curve stemming from a series of experiment data as follows:

$$R_x + R_y^2 = 1 \quad (1)$$

where,

$$R_x = \sigma_{mx}/\sigma_{mux}, \quad R_y = \sigma_{my}/\sigma_{muy} \quad (2)$$

σ_{mx} and σ_{my} are mean longitudinal and transverse compression stress under biaxial compression respectively. σ_{mux} and σ_{muy} are mean longitudinal and transverse compression stress under uniaxial loading respectively. It has been shown that slenderness was the main parameter governing the plate's compressive strength [5].

Valsgard [6] developed design formulas for the ultimate load capacity of rectangular plates with varying aspect ratios in biaxial in-plane compression, using a generalization of von Mises yield ellipse,

$$R_x^\alpha + \eta R_x R_y + R_y^2 = 1 \quad (3)$$

Compared with Eq. (1), two parameters α and η are introduced herein, which are the plate aspect ratio and the slenderness ratio. The biaxial interaction for square plates is shown in Fig. 1. It is noted that if α and η are become unit and zero respectively, Eq. (3) will be simplified to Eq. (1).

Ueda et al. [7] investigated theoretically the nonlinear behavior of flat plates and stiffened panels subjected to in plane biaxial and shearing forces. They found that the loading ratio and plate aspect ratio have considerable effect on behavior of plates and they proposed interaction relationships of buckling, ultimate and fully plastic strength for both bare plate and stiffened plate in

explicit forms. Considering biaxial compression without shear forces along edges, the form for plate could be expressed as

$$R_x^{e1} + R_y^{e2} = 1 \quad (4)$$

where $e1$ and $e2$ are two aspect ratio related parameters.

Guedes Soares and Gordo [8] have derived an interaction formula for biaxial loading which fits within the general format of Eq. (1), but they extended it to account explicitly for the effect of initial imperfections and residual stresses. They also extended it to account for the simultaneous effect of lateral pressure and have calibrated it with experimental data.

Paik et al. [9] proposed other ultimate strength formulations for plate under combined biaxial compression/tension, shear force and lateral pressure loads, and discussed effect of initial deflection on ultimate strength of plates under biaxial [10]. The formulation for plates under biaxial compression is in the form of

$$R_x^2 + R_y^2 = 1 \quad (5)$$

Compared with relatively long term and wide range research on ultimate strength of intact plate under combined loadings, the research on remaining strength of the corroded plates has been booming just in recent years.

Daidola et al. [11] developed a mathematical model to estimate the residual thickness of pitted plates using the average and maximum values of pitting data, and presented a method to assess the effect of thickness reduction due to pitting on local yielding and plate buckling based on a probabilistic approach.

Paik et al. [12–13] studied the ultimate strength characteristics of pitted plate elements under axial compressive loads and in-plane shear loads, and derived closed-form formulae for predicting the ultimate strength of pitted plates using the strength reduction (knock-down) factor as follows:

$$R_{xr} = \frac{\sigma_{xu}}{\sigma_{xuo}} = \left(\frac{A_0 - A_r}{A_0} \right)^{0.73} \quad (6)$$

where R_{xr} is a factor of ultimate compressive strength reduction due to pitting corrosion, σ_{xu} and σ_{xuo} are ultimate compressive strength of pitting corroded and intact plate respectively. A_0 and A_r are original cross section area and reduced area at the smallest cross section.

Nakai et al. [14–16] have performed a series of experimental studies on the effects of pitting corrosion on the strength of steel panels, focusing on web plates of hold frames. It was noticed that the shape of corrosion pits in the hold frame is a circular cone, and the ratio of pit diameter to depth is in the range between 8:1 and 10:1. Meanwhile, a series of nonlinear FEM analysis of web plate under tension, compression and bending has been carried out to investigate effects of pitting corrosion on ultimate strength of plates.

Dunbar et al. [17] investigated the effect of localized corrosion in square plate and stiffened panels. A stiffened plate was divided into four main sections, each of which was further divided into uniformly distributed sub-sections. Different levels, say, 10%, 50% and 75% of volume loss over local sub-sections were applied and it was found that corrosion at higher levels (50% and 75% volume) caused local buckling at the corroded region, which affected the global collapse mode of the stiffened panel and the ultimate load was decreased as the corrosion location was closer to the center of the panel span.

Amlashi and Moan [18] studied the strength reduction of pitted stiffened plates under biaxial compression using a series of FEA with different corrosion intensity DOP , pit depth and the location of the densest pitted zone. They found that the ultimate strength of pitted stiffened plates is governed not only by the level of DOP , but also by the smallest sectional area and the location of densest pitted zone.

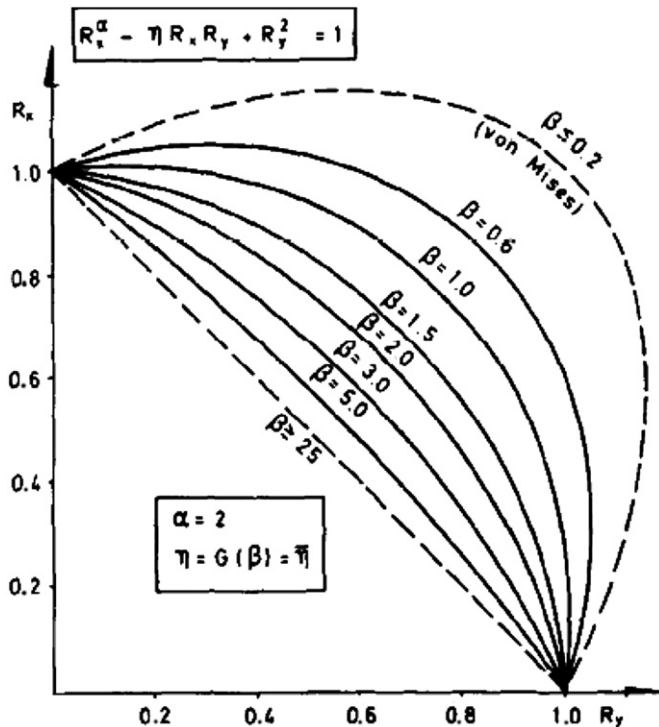


Fig. 1. Biaxial interaction for square plates Valsgard (1980).

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