Ocean Engineering 169 (2018) 70–86

Contents lists available at ScienceDirect

Ocean Engineering

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

Towards a unified formulation for the ultimate strength assessment of uncorroded and pitted platings under uniaxial compression

V. Piscopo*, A. Scamardella

The University of Naples "Parthenope", Department of Science and Technology, Centro Direzionale Isola C4, 80143, Naples, Italy

ARTICLE INFO

Keywords:
Plating ultimate strength
Uniaxial compression
Initial geometrical imperfections
Welding residual stresses
Pitting corrosion wastage

ABSTRACT

A benchmark study, devoted to systematically investigate the ultimate strength of simply supported platings under uniaxial compression, is performed to develop unified design formulas, accounting for geometrical imperfections, welding residual stresses and pitting corrosion wastage. Particularly, two boundary conditions for the in-plane motion of longitudinal edges, namely free and fully restrained, are considered as they significantly affect the plating behaviour in the post-buckling regime. Several practical design equations for uncorroded platings are derived to account for different levels of initial deflections and residual stresses, based on a wide and systematic series of elasto-plastic large deflection analyses performed by Ansys Mechanical APDL. Subsequently, proposed formulas are extended to platings affected by pitting corrosion wastage, on the basis of a new series of FE analysis, where the pitting intensity and corrosion degrees are systematically varied based on random distribution of the corrosion wastage on the plate panel. Finally, the goodness of proposed formulas is checked against current Rule equations, as well as several experimental collapse tests and FE results available in literature.

1. Introduction

The longitudinal strength of large sea-going ships is one of the key issues to be accounted in the design process, focusing on both permissible and ultimate limit state design conditions. In the last century, buckling and ultimate strength analysis of steel-plated structures was widely investigated by a variety of researchers throughout the world, by means of analytical methods, experimental tests, empirical approaches and non-linear FE analysis (Cui et al., 2002). Starting from the first pioneering works by von Kármán (1924) and Schnadel (1930), several formulations for the elastic and ultimate strength assessment of platings under uniaxial compression were proposed by Frankland (1940), Faulkner (1975), Paik et al. (1997), Guedes Soares and Gordo (1997), Piscopo (2010a,b), among others. Besides, many efforts were undertaken to investigate the incidence of initial geometrical deflections (Antoniou, 1980; Antoniou et al., 1984; Kmiecik et al., 1995) and welding residual stresses (Dwight and Moxham, 1969; Faulkner et al., 1973; Carlsen and Czujko, 1978) on the ultimate strength of platings and hull girder structures (Campanile et al., 2014, 2016a; b). In this respect, several approximate formulations were developed to separately and jointly account for fabrication related imperfections.

Besides, following the endorsement by the Classification Societies of new Rules and Guidelines for the risk and reliability analysis of aged structures, it became essential to provide rational standards for the assessment of the ship structural integrity in presence of corrosion wastage. In this respect, even if the incidence of pitting corrosion on the plating ultimate strength was studies since the 60s (Chapkis, 1967), this topic became popular in the last two decades only. Particularly, Paik et al. (2003a, 2004b,c) carried out several experimental and numerical studies on steel-plated structures affected by pitting corrosion wastage under uniaxial or edge shear loads and concluded that the ultimate strength reduction mainly depends on pitting and corrosion intensity degrees. Recently, Khedmati et al. (2012), Jiang and Guedes Soares (2012) and Zhang et al. (2017a) performed a series of non-linear FE analyses. They investigated the plating ultimate strength reduction in presence of pitting corrosion wastage and provided some practical design formulas to predict the strength degradation.

Based on actual state-of-art, there is still need to investigate the ultimate strength of platings under uniaxial compression. Particularly, a wide and systematic benchmark study needs to be performed, in order to investigate the incidence of corrosion wastage and fabrication related imperfections, due to geometrical distortions and welding residual stresses, on the plating ultimate strength. Hence, in current analysis more than 1000 non-linear FE simulations of isolated plate panels under uniaxial compression are performed by Ansys Mechanical APDL (Ansys, 2017). In this respect, the incidence of the above mentioned

* Corresponding author.
E-mail addresses: vincenzo.piscopo@uniparthenope.it (V. Piscopo), antonio.scamardella@uniparthenope.it (A. Scamardella).

https://doi.org/10.1016/j.oceaneng.2018.08.042
Received 10 March 2018; Received in revised form 5 July 2018; Accepted 23 August 2018

parameters is separately and jointly investigated, based on different combinations of initial deflection amplitudes, welding residual stresses and pitting corrosion wastage. Furthermore, the incidence of in-plane boundary conditions is further investigated. In fact, the ultimate strength of uniaxially loaded platings is mainly affected by the in-plane motions of longitudinal edges in the post-buckling regime, that can be free or restrained (Paik and Thayamballi, 2006). Hence, the following main topics are fully investigated and discussed:

(i) A systematic benchmark study, devoted to the ultimate strength assessment of simply supported platings, is carried out. Different levels of initial imperfections and welding residual stresses are investigated, assuming that longitudinal edges are free to move or fully restrained in the horizontal plane. Particularly, 32 design equations are provided, as a function of the in-plane boundary conditions of longitudinal edges and the assumed level of fabrication related imperfections.
(ii) A systematic benchmark study, focusing on platings affected by pitting corrosion wastage, is performed, with the main aim of investigating the incidence of pitting and corrosion degrees on the plating ultimate strength. Hence, a practical design equation is provided to accurately assess the ultimate strength degradation of corroded platings, combined with different levels of fabrication related imperfections and free/restrained in-plane motions of longitudinal edges.
(iii) A comparative analysis is performed between the proposed formulas and the design equations embodied by the Rules, as well as with the results of several experimental tests and non-linear FE analyses available in literature.

Firstly, a brief theoretical background is provided, recalling some basic points about the ultimate strength assessment of uncorroded and pitted platings.

2. Theoretical background

2.1. Ultimate strength of uncorroded platings

The first pioneering works on the ultimate strength assessment of platings under uniaxial compression go back to the last decades of the 19th century (Box, 1883). Nevertheless, the first formulations that resemble the currently embodied ones, at least with reference to the equation format, were provided quite later by von Kármán (1924) and Schnadel (1930), who introduced the concept of plating slenderness ratio. In the same years, a wide experimental campaign was carried out at the David Taylor Model Basin. Following the results of the collapse tests, the well-known equation, formerly attributed to Frankland (1940), was derived:

$$\phi_u = \begin{cases} 1 \; if \; \beta \le 1.25 \\ \frac{2.25}{\beta} - \frac{1.25}{\beta^2} \; if \; \beta > 1.25 \end{cases} \quad (1)$$

where $\phi_u = \sigma_u/\sigma_y$ and $\beta = (b/t)\sqrt{(\sigma_y/E)}$ are the ultimate to yield strength and the plating slenderness ratios respectively, while b (t) is the plating width (thickness) and σ_y (E) is the material yield strength (Young modulus). In the following decades, the American Bureau of Shipping requested to upgrade the ultimate strength formulation. Hence, a new wide experimental campaign was carried out in the late 50s and early 60s at the Structural Mechanics Laboratory of the David Taylor Model Basin (Conley et al., 1963), where 50 collapse tests on simply supported isolated plate panels, made of steel or aluminium alloy, were carried out. Based on the results of this new experimental campaign, it was found that Frankland equation overestimates the ultimate strength of simply supported platings up to 25%. Really, as stressed by Faulkner (1975), the main reason of this discrepancy was due to the presence of stiff supporting members, making the edge constraints of the tested platings nearer to the clamped rather than the simply supported condition. In this respect, Conley et al. (1963) developed a new ultimate strength formulation that was partly modified some years later by Faulkner, who proposed for the first time in the discussion session of a paper by Caldwell (1965), the following well-known equation:

$$\phi_u = \begin{cases} 1 \; if \; \beta \le 1 \\ \frac{2}{\beta} - \frac{1}{\beta^2} \; if \; \beta > 1 \end{cases} \quad (2)$$

Faulkner formula was subsequently re-checked against a series of experimental collapse tests, confirming that it provides a reasonable ultimate strength assessment for simply supported platings, with longitudinal edges free to move in the horizontal plane, in conjunction with slight/average levels of initial deflection amplitudes. Nevertheless, it must be pointed out that eq. (2) provides the mean value of the plating ultimate strength, based on experimental results, with the following coefficient of variation (Faulkner, 1975):

$$COV_{\phi_u} = \begin{cases} 0.05 \quad if \; \beta \le 2.5 \\ 0.02\beta \; if \; \beta > 2.5 \end{cases} \quad (3)$$

In the following years, even if a variety of modified formulations was proposed by several authors (Cui et al., 2002; Masaoka and Mansour, 2004; Paik et al., 2004a), Frankland (1940) and Faulkner (1975) equations were widely applied. Nowadays they are still embodied by the Rules, due to the good reliability for the practical assessment of plating ultimate strength.

2.2. Ultimate strength of pitted platings

It is well-known that corrosion wastage reduces the ultimate strength of platings under uniaxial compression, depending on the extent of thickness loss. In this respect, while the ultimate strength of uniformly corroded platings is generally assessed by excluding the thickness loss due to corrosion, in case of localized corrosion, such as pitting or grooving, the strength calculation procedure becomes more complex (Paik et al., 2004b). Following the first works by Chapkis (1967) and Flaks (1978), in the last two decades a variety of theoretical and experimental works have been carried out to derive simplified formulations for the practical assessment of the ultimate strength of platings with pitting corrosion wastage (Melchers, 2004; Wang et al., 2008). In this respect, Ok et al. (2007) performed over 256 non-linear FE analyses of panels affected by pitting corrosion wastage, with various locations and size, and applied the multi-variable regression method to derive practical design formulas for the ultimate strength assessment of unstiffened plates with localized corrosion. Jakubowski (2011) investigated the incidence of pitting corrosion on the mechanical properties of mild and low alloy steels, as well as on the strength of steel structures under static and quasi-static loads. Nouri et al. (2012) investigated the post-buckling behaviour and the ultimate strength of imperfect pitted platings. Particularly, they performed a series of elasto-plastic large deflection FE analyses, systematically varying the pitting corrosion intensity, with the main aim of reaching an effective thickness proposal for pitted platings. Khedmati et al. (2012) performed some non-linear elasto-plastic large deflection analyses of corroded steel platings, assuming that pitting wastage was randomly distributed on either one or both surfaces of the analysed platings. Following the main