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Combined effect of imperfections on ultimate strength of cracked plates under uniaxial compression

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ABSTRACT

A series of nonlinear finite element analyses were carried out for varying levels of initial deflections, welding residual stresses as well as the length and location of cracks to investigate their combined effects on the ultimate strength of intact and cracked steel plates. The effects of plate slenderness are also considered. Based on numerical results, it is found out that when the three factors are included in the plate together, they will have combined effect on the ultimate strength of the plate rather than a simple superposition of their influences. The meaningful phenomenon is revealed that cracks will change the effect of residual stress on the ultimate strength, depending on the crack's location and length. The crack's breaking effect on residual stress are discussed for three typical crack locations and different crack lengths in the paper. The breaking effect will reduce the effect of residual stress where crack is located.

1. Introduction

Marine structures are inevitable to suffer various kinds of imperfections and damages from fabrication and service. As the basic components of ships and offshore structures, steel plates are certain to obtain initial deflections and welding residual stresses when they are manufactured and assembled into stiffened plates. Furthermore, crack and corrosion damages may appear in plates when marine structures are in service. Various imperfections and damages will have significant influences on the ultimate strength of plates. So it is necessary to take their combined effect into consideration when making assessment on the ultimate strength of plates.

Many efforts have been made in dealing with the effect of imperfections and damages on the ultimate strength of thin-walled structures. Experiment study has been made by Paik et al. (Paik, 2008) to investigate strength behaviors of steel plates with cracks. The specimens are square columns made of four cracked plates. Saad-Eldeen et al. (2012, 2016) analyzed plate deflections during ultimate strength experiments of corroded box girder. The effect of initial imperfections and corrosion degradation on the final post-collapse deformation shape has been investigated and a relationship between different loading responses, shape of initial imperfections and plate slenderness has been obtained. They also carried out a series of experimental tests for plate specimen having a central elliptical opening with and without different locked crack lengths. The force–displacement relationships, dissipated energies, strength–strain relationships, resilience, toughness and collapse modes have been presented and analyzed.

A large amount of numerical investigations have also been done by researchers. Paik et al. (Paik et al., 2005; Paik, 2009, 2012) conducted nonlinear finite element analysis on the residual ultimate strength of steel plates with transverse and longitudinal cracks varying their length and locations under axial tension or compression. In their studies initial deflection and welding residual stresses are taken into consideration as an average level. They further studied the effect of the welding residual stresses on ultimate strength of high tensile steel plate to calculate its individual effect. Xu et al. (2014) changed the orientation angle of cracks to examine its influence on the strength behavior of plates. Wang et al. (Paik et al., 2015; Wang et al., 2012) studied the ultimate shear strength of cracked stiffened panel and strength behaviors of steel plates with multiple crack damage. Shi and Gao et al. (Shi and Wang, 2012a, 2012b; Gao et al., 2012) carried out investigations about the collapse behavior of box-girders and hull structures with cracks and corrosion damage. Teixeira et al. (2013) made an assessment on characteristic values of the ultimate strength of corroded steel plates with initial imperfections. In their study, the initial deflection was taken as a stochastic model described by a lognormal distribution. Tekgoz et al. (2015) performed a sensitivity analysis accounting for the plate thickness, heat source, speed and level of residual stresses to assess their effects on ultimate strength of

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Table 1
Ultimate strength of the plate σ_u with average level of initial deflection and residual stress and the same crack projected length e/b.

θ(°)	$2c/b$	e/b	σ_u(MPa)	Difference (%)
0	0.200	0.2	162.20	–
30	0.231	0.2	162.36	0.10%
45	0.283	0.2	162.51	0.19%
60	0.400	0.2	162.67	0.29%
75	0.773	0.2	163.33	0.70%

welded stiffened plates. Cui et al. (Cui and Mansour Alaa, 1998) conduct a series of theoretical analysis on effects of welding distortions and residual stresses on the ultimate strength of long rectangular plates under uniaxial compression.

In the authors' previous researches (Cui et al., 2016, 2017), the effects of various crack defects on the collapse behavior and ultimate strength have been studied. Steel plates and stiffened plates in the researches are under uniaxial compression. The initial deflection amplitude is kept constant as an average level and the welding residual stresses are ignored. Other contributions about ultimate strength assessment of steel plates, stiffened plates or box girders with imperfections and damages are reported in (Alinia et al., 2007; Margaritis and Toulios, 2012; Bayatfar et al., 2014; Yao et al., 1992, 1998a; Paik et al., 2004; Rahbar-Ranji and Zarookian, 2014; Abbas and KhedmatiRigo, 2014; Yao et al., 1998b; Fujikubo et al., 2005; Guedes Soares, 1988; Segen et al., 2016; Shi et al., 2017; Gannon et al., 2012; Ao and Wang, 2016).

Investigations on the strength behavior of thin-walled structures with imperfection and damages have been adequate, but most of them are focused on the individual influence of single kind of imperfections or damages while others are left out or kept as a constant. Researches about combined effect of imperfections and damages on the ultimate strength of structures are limited and not enough. This paper aims at making an investigation on the combined effect of initial deflection, welding residual stresses and crack damage on the strength behavior of steel plates under uniaxial compression.

2. Finite element models

2.1. Geometric and material properties

The geometrical dimensions of steel plates adopted in this paper are the same with the authors' previous studies (Cui et al., 2016, 2017). The length and breadth of the plates are set as $a \times b = 2\,550 \times 850$ mm.Three thicknesses (11, 16, and 22) mm are adopted. These sizes of the plates have been used in the report of Ultimate Strength Committee of ISSC2012 (ISSC Committee III.1, 2012). In previous studies, it was concluded that the crack projected length to the transverse direction is a main parameter to predict the ultimate strength of cracked plates. It is recognized that transverse crack is the most dangerous case for the strength behavior of plates when the crack length is constant. The effect of oblique cracks on the ultimate strength of plates is equivalent to that of transverse cracks provided the projected lengths of oblique cracks have the same length with that of transverse cracks. That fact is also verified when combined effect of imperfections and crack damages are both considered as shown in Table 1. The level of the initial deflection and residual stress in Table 1 are both average levels mentioned in Section 2.3 and the projected lengths of oblique cracks here are all 0.2b. θ is the inclined angle between oblique cracks and the transverse direction. Hence, at the present paper, only the transverse crack is considered for conservative ultimate strength assessment. It is also found out by the authors (Cui et al., 2016) that the transverse location of the transverse crack has significantly influence on the ultimate strength of cracked plate under uniaxial compression while the effect of longitudinal location is slight. So three typical crack locations are discussed in present paper named as central crack, one-edge crack and double-edge crack. They are all set at the mid-span in the longitudinal direction of the plates as shown in Fig. 1. A semi-circle is adopted as the shape of the crack tip. The length and breadth of the crack are expressed as $2c$ and w. The effect of crack width has been discussed by the authors (Cui et al., 2016), and from the conclusion the Crack width w = 3 mm is adopted to catch the membrane stress distribution precisely without affecting the ultimate strength of cracked plates. It was assumed that the cracks are all through-thickness.

An elastic-perfectly plastic model is adopted for material properties. The material is high tensile strength steel with its yield stress $\sigma_Y = 313.6$ MPa, Young's modulus $E = 205800$ MPa, and Poisson's ratio $\nu = 0.3$.

2.2. Boundary and loading conditions

At the present study, the boundary and loading conditions used in the authors' previous studies (Cui et al., 2016) are adopted, i.e. exerting uniform displacement on the two opposite loading edges to apply longitudinal compression actions with the two nodes at the mid-span of the longitudinal edge fixed in the x-direction, and the two nodes at the mid-span of the transverse edges are fixed in the y-direction to prevent rigid body movement. The four edges of the plates are all simply supported "Coupled" boundary condition is applied on the unloaded edges to ensure y-displacements of its nodes are the same. "Rigid zones" are set at the loaded edges `to guarantee the nodes can move together with the same value in the x-direction. The boundary and loading conditions are illustrated in Fig. 2.

2.3. Initial imperfections

During welding in fabrication, initial deformation and residual stress will take place in steel plates. They are two of the most common initial imperfections in plates. For the reason that initial imperfections have effects on the ultimate strength behavior of thin-walled structures, many investigations have been made to consider their influence.

Yao et al. (1992, 1998a) and Paik et al. (2004) have studied the effects of initial deflection on the buckling and collapse behavior of plates. A double Fourier series is widely adopted in their researches. In present paper, the lowest buckling mode is used to simulate the initial deflection shape. It is in fact a simplest case of the double Fourier series expressed as the following function:

$$w = A_0 \sin\frac{m\pi x}{a}\sin\frac{\pi y}{b} \tag{1}$$

where a and b are the length and width of the plate; m is an integer equal

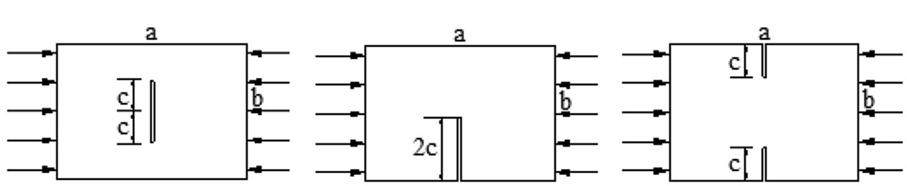

Fig. 1. Plates with cracks.