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Assessment of residual ultimate strength of cracked steel plates under longitudinal compression

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ABSTRACT

This paper numerically deals with the ultimate strength reduction characteristics of steel plate due to crack damage under longitudinal compression. A series of nonlinear finite element analyses was carried out with varying the length, location, and orientation angle of cracks to examine their effects on the ultimate strength of cracked steel plates. Three types of cracks, namely transverse crack, longitudinal crack and inclined crack, are considered in the present study. It was assumed that the cracks are through-thickness, having no contact between their faces and propagation of cracks is not considered in the present study. It is found that the minimum and the maximum ultimate strength values are obtained for the transverse crack and longitudinal crack cases respectively when the crack length is constant. The projected length of the crack normal to loading direction is an influential parameter to the ultimate compressive strength of plate with central inclined crack. Based on the numerical results, simple empirical formula as a function of crack projected length are proposed to predict the ultimate strength of plate with central inclined crack under longitudinal compression.

1. Introduction

In ship structural design, it is essential to accurately evaluate the maximum loading carrying capacity of ship structures in rough sea. The basic components of ships and offshore structures are steel plates and the overall failure of ship structure is governed by the collapse behaviors of its structural components. Therefore, a primary task is to predict the ultimate strength of ship plates.

On the other hand, thin-walled structures including ships are inevitable to suffer various kinds of damages during their lifetime in service. One of the most important damage is cracks, which is considered to have a significant effect on the buckling and ultimate strength behaviors of plates. Cracks are prone to occur in welded joints and local stress concentration areas in inappropriate fabrication process. And also under the action of repeated loading in ship's service life, the fatigue cracks may be initiated in the stress concentration areas and pitting corrosion areas. These cracks may grow under different loading conditions, resulting in various sizes, locations and orientations. Although fatigue cracks is usually treated as a fracture mechanics problem, from the viewpoint of ultimate strength it is also crucial to understand the effect of crack on the collapse response of structural components. In addition, it is well recognized that cracking damages can reduce ultimate strength of plates to some extent. Therefore, it is of great importance to understand thoroughly the ultimate strength behaviors of cracked structural members, including ship plates, to avoid catastrophic failure of structures in lifetime cycle.

In this regard, a number of efforts on the strength behavior of cracked unstiffened and stiffened plates have been previously carried out in the literature. Paik et al. (2005) experimentally and numerically investigated the ultimate strength behavior of plates with transverse cracks under axial compression or tension. They proposed a simple formula for predicting the ultimate strength of plates with transverse cracks on the basis of the reduced cross-sectional area due to the cracking damage. Later, (Paik, 2008 ,2009) continued to study residual ultimate strength of steel plates with longitudinal cracks under axial compression varying crack size and locations. He found that the formula developed for predicting the ultimate strength of plates with transverse cracks under axial tension can estimate that of plates with longitudinal cracks at a very conservative side. A comprehensive study of finite element model of cracked panels under shear loading had been conducted by Alinia et al. (2007). In order to simulate accurately the strength behavior of cracked panels, the refined meshing should be allocated around the crack tips. Wang et al. (2009) conducted numerical study on the residual ultimate strength of structural members with multiple crack damage. Multiple crack damage was consisted of a ‘lead crack’ and several ‘disturbing

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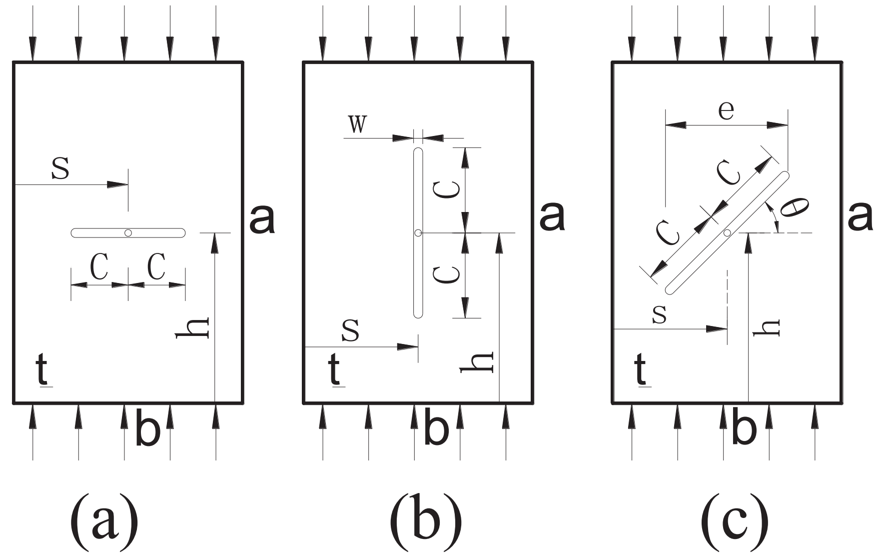

Fig. 1. Unstiffened plate with crack. (a) Transverse crack ($\theta=0°$), (b) Longitudinal crack ($\theta=90°$), (c) Inclined crack.

cracks'. The effects of the location and size of the disturbing cracks on the ultimate strength of initially central cracked structural members were investigated.

Margaritis and Toulios (2012) performed a series of nonlinear finite element analysis to investigate the collapse behavior of stiffened plates having straight cracks. In the research, two element types, namely shell element and brick element, were adopted to simulate the cracked panels for comparing their effect on the ultimate strength behavior of stiffened plates.

More recently, Bayatfar et al. (2014) numerically dealt with the influence of transverse cracks on the ultimate compressive strength characteristics of unstiffened and stiffened plate elements. (Ming Cai Xu et al. 2014) presented residual ultimate strength assessment of stiffened panels with fixed cracks. In his research, the length and the orientation angle of cracks are varied to check their effect on collapse behavior of cracked stiffened panels. It was concluded that the projected length of the crack could be regarded as an important index for the influence of crack. (Rahbar-Ranji and Zarookian, 2014) analysed ultimate strength of stiffened plates with a transverse crack under uniaxial compression. The influence of various geometrical properties of stiffened plates, accounting for different crack sizes and locations was investigated.

For large scale ship structures, Shi and Wang (2012a, 2012b) explored the residual ultimate strength of closed/open box girders with crack damage under different loading conditions. Three types of cracks with respect to crack location, namely center crack, double edge crack and edge crack were considered. They proposed a simple model to predict the residual ultimate strength of box girders with cracks.

From all the literatures mentioned above, it can be seen that most of studies (Paik et al., 2005; Paik, 2008, 2009; Margaritis and Toulios, 2012; Bayatfar et al., 2014; Rahbar-Ranji and Zarookian, 2014; Shi and Wang, 2012a, 2012b) assume crack damage as transverse or longitudinal cracks, which are parallel to one edge of the relevant structures. However, there are few investigations conducted for inclined cracks that are more common in aging structures. In the present study, special attentions are paid to ultimate strength of plates with central inclined cracks.

According to the literature review, the study on the collapse behavior of cracked plates has been undertaken. This paper presents the numerical results of ultimate strength of cracked plates under uniaxial compression, which is a primary load component in ships and offshore structures when they are in the sea environment. Three types of cracks, namely transverse crack, longitudinal crack and inclined crack, are considered in the present study. It is assumed that the cracks are through-thickness, and the contact between their faces and crack propagation are not accounted for in the finite element modeling. Effects of fabrication related initial deflections are taken into account in the study. A series of elastic–plastic large deflection analyses of cracked plates with varying crack sizes and orientation angles as well as locations under uniaxial compression are performed by using the FE code ANSYS. Based on the numerical results, simple empirical formula as a function of crack projected length are proposed to predict the ultimate strength of plate with inclined crack under longitudinal compression.

2. Finite element modeling

2.1. Geometric and material properties

The geometrical dimensions of unstiffened steel plate discussed in this paper are taken from the report of Ultimate Strength Committee of ISSC2012 (ISSC Committee III, 2012). In the present series of analysis, the plate dimension length × breadth × thickness is $a\times b\times t=2550\times 850\times 11$ mm. Three types of cracks are taken into account, namely transverse crack, longitudinal crack and inclined crack. The configuration of the three types of cracks is presented in Fig. 1. The crack size is $2c\times w$, and s and h are the distance from the crack center to the longitudinal edges and the transverse edges of the plate, respectively. A semi-circle with small diameter at the every crack tip is adopted to prevent crack's propagation, as the reference (Ming Cai Xu, 2014). The crack orientation is described by the angle θ, while $e=2c\times\cos\theta$ represents the projected length of the crack normal to the longitudinal loading direction.

The material property used in this study is also taken from the reference (Ming Cai Xu, 2014). The stress–strain relationship of the material is assumed to follow elastic-perfectly plastic model with yield stress $\sigma_y=313.6$ MPa. The elastic modulus $E=205800$ MPa and Poisson's ratio $\nu=0.3$ are employed.

2.2. Boundary and loading conditions

The cracked plates are extracted from a continuous ship plated