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Residual ultimate strength of large opening box girder with crack damage under torsion and bending loads

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ABSTRACT

This paper numerically investigated the residual ultimate strength of large opening box girders with crack damage under individually or jointly applied torsion and bending loads. Series of nonlinear finite element analyses were carried out with varying the crack length, location, and orientation angle to assess their effects on the residual ultimate strength of large opening box girders. Three types of cracks, namely longitudinal crack, transverse crack and inclined crack, are considered in this paper. The residual ultimate strength are obtained and discussed for the three types of cracks under torsional or bending moment loading condition. Based on the numerical results under individually applied torsion or bending moment, two of the most dangerous crack damage situations are adopted for analyzing the residual ultimate strength of large opening box girders with crack damage under combined loads. An interaction equation is proposed for predicting the residual ultimate strength of large opening box girders with crack damage under combined loads. The validity of this simple equation is verified by some crack damage cases of varying crack length.

1. Introduction

The ultimate strength analysis of ship hull structures has been regarded as a necessary safety index in ship design and safety assessment. For common vessels, vertical bending moment is frequently evaluated as one primary component of the hull girder loads. However, it has been recognized that torsional moment is also very important for some types of ships such as container ships or large bulk carriers. These ship types with a lower torsional rigidity are much more vulnerable to the torsional moment due to the large opening deck. On the other hand, ship hull structures are inevitable to suffer various kinds of damages during their lifetime in service. One of the most fatal damage is cracks, which is known to have a significant effect on the buckling and ultimate strength behaviors of thin-walled structures. So it is necessary to take combined loads into consideration when making assessment on the residual ultimate strength of ship hull structures with crack damage.

In this respect, many experimental and theoretical investigations have been carried out to study the post-buckling behavior and residual ultimate capacity of ship hull structures with crack damage under combined loads. Paik et al. (Paik et al., 2005; Paik, 2008, 2009) numerically and experimentally investigated the ultimate strength characteristics of plates with transverse and longitudinal cracks under axial compression or tension. Major crack parameters including crack direction, crack location, crack size, plate thickness, and plate aspect ratio are considered. Later, a similar study on cracked panels under shear loading had been conducted by Alinia et al. (2007). Bayatfar et al. (2014) numerically discussed the effect of transverse cracks on the ultimate compressive strength of unstiffened and stiffened plate. Margaritis et al. (Margaritis and Toulios, 2012) conducted series of nonlinear finite element analyses to investigate the post-buckling behavior and residual ultimate capacity of stiffened plates with straight cracks. Wang et al. (Wang et al., 2015; Wang et al., 2009) carried out the ultimate shear strength analyses of intact and cracked stiffened panels with single or multiple crack damage. Multiple crack damage consists of one 'lead crack' and several 'disturbing cracks'. The effects of the location and size of the disturbing cracks on the ultimate strength of central cracked stiffened panels were investigated. Xu et al. (2014) investigated the ultimate strength characteristic of stiffened panels with locked cracks. In their research, the orientation angle and the length of cracks are varied to examine their effect on the failure modes and equivalent stress distributions of cracked stiffened panels. It had been concluded that projected length of the crack should be regarded as an important index for the effect of crack.

More recently, more attentions have been paid to large-scale ship

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hull structures. Ao and Wang (2012) numerically investigated the post torsional buckling behavior and residual ultimate torsional strength of stiffened box girders with large deck opening and made a comparison with the torsional experiment conducted by Sun (Saad-Eldeen et al., 2016a). Then, Shi and Wang, 2012a, 2012b made some explorations on residual ultimate strength of the similar box girder model under different loading conditions. Three types of cracks in regard to crack locations, namely central crack, edge crack and double edge crack were considered. Shi and Gao et al. (2012) carried out investigations about the collapse behavior of box-girders and hull structures with cracks and corrosion damage. Soares et al. (Saad-Eldeen et al., 2016a, 2016b) conducted numerous studies on the ultimate bending moment capacity of a single hull structure with multiple large openings or locked cracks, and provided specific emergency repairs for locked crack damage. Tekgoz et al. (2015) carried out series of nonlinear finite element analyses to investigate ultimate load carrying capacity of ship shaped structures subjected to asymmetrical longitudinal bending moments. Other contributions about residual ultimate strength assessment of ship hull structures with crack damage can refer to (Sun and Soares, 2003; ISSC Committee III.1, 2000; ISSC Committee III.1, 2012; Paik et al., 2004; Cui et al., 2016; Cui et al., 2017; Nishihara, 1983; MSC, 2010; Paik and Thayamballi, 2003; Rahbar-Ranji and Zarookian, 2014; Harada et al., 2007; Shi et al., 2017; Gannon et al., 2012; Smith et al., 1987; Saad-Eldeen et al., 2016c; Yao et al., 1998).

From all the literature mentioned above, it can be known that most of studies (Paik et al., 2005; Paik, 2008, 2009; Bayatfar et al., 2014; Margaritis and Toulios, 2012; Wang et al., 2009, 2015; Ao and Wang, 2012; Shi and Wang, 2012a, 2012b; Gao et al., 2012; Saad-Eldeen et al., 2016a, 2016b) assumed crack type as longitudinal or transverse cracks. However, few investigations have been conducted for inclined cracks that are common in aging ship structures. Furthermore, there are fewer researches on the crack location and combined loads. In this paper, special attentions are paid to the impact of these respects.

For the status and problems about the residual ultimate strength of large opening box girders with crack damage, series of analyses for ship hull structures with crack damage have been carried out by using the nonlinear finite element method to evaluate the effect of crack damages. The aim of the present study is to gain insights into the residual ultimate strength behavior of large opening box girder with crack damage under individually applied load (torsion or bending only) and combined loads (torsion and bending together). Based on the numerical results under individually applied torsion or bending moment, two of the most dangerous crack damage situations are adopted for analyzing the residual ultimate strength of large opening box girders with crack damage under combined loads. An interaction equation is proposed for predicting the residual ultimate strength of large opening box girders with crack damage under combined loads. The validity of this simple equation is verified by some crack damage cases of varying crack length.

2. Finite element analysis models

2.1. Geometric and material properties

A simplified large opening box girder which is similar to the literature (Shi and Wang, 2012a, 2012b) is designed based on the torsional experiment conducted by Sun (Sun and Soares, 2003). Fig. 1 shows the schematic diagram of the large opening box girder and the cross section. As shown in Fig. 1, the large opening box girder model consists of 1/2 + 1+1/2 bays in the longitudinal direction for the consideration of the influence of boundary condition and two transverse frames support at the two ends of large opening. Table 1 gives the main dimensions of the model. The thickness of model plates is 5 mm. The size of two transverse frames is 60mm × 10mm.

The cracks discussed in the paper are located in the side of the box girder. Three types of cracks are taken into consideration, namely transverse crack, longitudinal crack and inclined crack. Fig. 2 presented the configuration of three types of cracks. The crack size is expressed as $2c \times w$, and s and h are the distances from the crack center to the transverse frame and deck side line, respectively. A semi-circle with small diameter at the two crack tips is adopted as the reference (Xu et al., 2014). In practice, cracks in relatively thin plate, used in ship and offshore structures, are generally considered as through-thickness (Paik and Thayamballi, 2003). The premised cracks can propagate as the torsion and bending loads are applied, and subsequently structural responses can significantly differ from those where the premised cracks are constant in size and geometry. However, the unstable cracks can cause unstable propagation at a certain stress level, which means the crack propagation path and the increased crack length due to crack growth are indefinite. It is the fact that the crack propagation is another issue mainly focusing on the proposition of reasonable crack propagation criteria based on fracture mechanics or damage mechanics. In such case, the cracks are considered as a variable model and their evolvement rules are defined accurately for the time-variant reliability assessment. This issue is much more different from that discussed in this paper. Meanwhile, the torsional buckling usually occurs prior to the crack propagation due to the thin thickness of the plates (Ao and Wang, 2012). In order to simplify the analysis, the cracks are presumed to be through thickness, having no friction between their edges and no propagation is allowed in the present study (Shi and Wang, 2012a).

The material used in this paper is a high tensile strength steel. In general, steel material has strain-hardening tangent modulus (E_t) typically in the range of 5–15% of the Young's modulus. Some authors, such as Paik (Paik and Thayamballi, 2003), have indicated that due to the strain-hardening effect the ultimate strength of steel plate is larger than that obtained without considering it. For pessimistic assessment of ultimate strength of steel thin-walled structures, an elastic-perfectly plastic steel material model is considered sufficient and adequate. In this respect, the behavior of the material used in this paper is assumed to follow elastic-perfectly plastic manner without considering strain-hardening effect. The detailed material properties are the same as the vessel steel plate in the ISSC 2012 (ISSC Committee III.1, 2012), listed in Table 2.

2.2. Boundary and loading conditions

Two independent reference nodes are built at the torsional center of front end and back end of box girder, respectively. The other nodes of end face and reference node are coupled in six degrees of freedom by using multipoint constraints (MPC) in Marc software. Simply-supported constraint is applied to two independent reference nodes as: front end, $U_x = U_y = U_z = 0$; and back end, $U_y = U_z = 0$. In the subsequent nonlinear finite element analysis, the external loads, such as vertical bending moment and torsion, are also applied on the two independent reference nodes in the form of enforced moment or displacement. The boundary and loading conditions of large opening box girder with crack damage are illustrated in Fig. 3.

2.3. Initial imperfection

During welding in fabrication, initial imperfection is inevitable. It has been shown that initial imperfection can reduce the ultimate bearing capacity to a certain extent, so the initial imperfection must be taken into account in ultimate strength assessment of ship structures. Paik et al. (2004) and Yao et al. (1998) investigated the effect of initial imperfections on the ultimate strength behavior of welded steel plate. In their research, it was found that the effect of welding residual stress on the ultimate strength is less importance compared to the welding-induced residual deformation, so for simplicity the welding residual stress is not accounted for in the present study. As for the initial deformation, The most accurate data comes from the actual measurement data, but the more commonly used way in the finite element simulation