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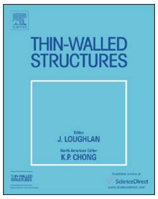

Full length article

Ultimate strength characteristics of cracked stiffened plates subjected to uniaxial compression

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ABSTRACT

Cracking damage in a stiffened plate affects its ultimate strength and collapse behavior. To examine this problem, this paper presents a nonlinear finite element study on the ultimate strength of cracked stiffened plates subjected to uniaxial compression. The cracks in transverse direction are presumed to be through-thickness, and crack propagation is not considered. The crack damage is assumed to exist on plate only or on both plate and stiffener and the relevant four types of cracked models are accounted for in this paper. The effects of crack length and crack location as well as plate thickness on the ultimate strength characteristics of cracked stiffened plates are analyzed. A series of nonlinear finite element analyses is carried out for the analyses where the crack damage effect is treated as a main parameter. It is concluded that the presence of crack may change the collapse mode and stress distributions of stiffened plate, and will decrease its ultimate strength. The reduction of ultimate strength increases as the crack length increases, while the longitudinal location of crack has little influence on the ultimate strength reduction of cracked stiffened plate.

1. Introduction

Many thin-walled structures, such as ship structures, are typically stiffened with longitudinal girders and transverse frames as well as equal-spaced stiffeners. The structural member between the longitudinal girders and transverse frames is usually termed stiffened panel which is a basic structural element of ship hulls. In ship design practice, it is well recognized that the ultimate limit state (ULS) approach is better than traditional allowable stress approach [1], because the former can truly determine the safety margin of the structure. Already, the assessment of ultimate limit state or ultimate strength for ship hull girders, including the ultimate strength of stiffened plates has been stipulated in the Common Structural Rules (CSR) [2,3]. The main loaded components of the ship hull, such as deck and bottom stiffened plates, are mainly axial compressed by sagging or hugging bending moment on the ship. Therefore, in the ULS design, a primary task is to estimate the maximum load carrying capacity or the ultimate strength of these stiffened plates for the safe and economic design of ships.

On the other hand, thin-walled structures such as ships made of metals are inevitable to suffer various types of damages in ship's service life. One of the most important damages is fatigue cracks which have significant effect on the collapse behavior of structural members. In hull structures cracking damages are typically initiated in welded or stress-concentration regions, such as the intersection line between plate and stiffener. These cracks may grow under different loading conditions during ship's service life resulting in various sizes and locations. Although cracking is usually treated as a fracture mechanism problem under cyclic loading, it is also of crucial importance to study and better understand the ultimate strength characteristics of cracked stiffened plates.

Many efforts have been made concerning the effect of cracking damage on the strength behavior of structures. The buckling behavior of cracked plate under tension was analyzed by Riks et al. [4] by using finite element method. Brighenti et al. [5,6] investigated the effect of crack damage on buckling of cracked rectangular plate under tension, compression and shear loading, in which the crack length and crack orientation as well as Poisson's ratio of material was varied. The results indicated that the crack orientation $\theta = 0^\circ$ (i.e. the direction of crack is normal to the tension or compression loading direction) is to be the most dangerous situation. A comprehensive study of finite element modeling techniques of shear panels with crack was conducted by Alinia et al. [7]. They suggested that the refined meshing must be generated near the crack tip in order to accurately capture the buckling behavior of cracked shear panels. Later Alinia et al. [8] numerically investigated the influence of central cracks on buckling and post-

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Nomenclature

a	plate length
A	sectional area of stiffened plate
b	plate breadth
c_p	crack length in plate
c_s	crack length in stiffener
E	elastic modulus
E_t	tangent modulus
h_w	web height
m	buckling half wave number
R_i	reaction force on each node
s	longitudinal position of crack
t	plate thickness
t_w	web thickness
w_{oc}	column-type initial deflection function
w_{opl}	plating initial deflection function
w_{os}	side-ways initial deflection function
β	plate slenderness ratio
γ	radius of gyration
δ_x	uniform compressive displacement
ε_y	yield strain
λ	column slenderness ratio
ν	Poisson's ratio
σ_u	ultimate strength of cracked stiffened plate
σ_{u0}	ultimate strength of intact stiffened plate
σ_y	yield stress

buckling behavior of shear panels. Khedmati et al. [9] carried out sensitivity analysis of the elastic buckling of cracked plate under axial compression using an in-house FE program.

The prime concern of the above literature is an estimation of elastic buckling strength of structural members with cracks. The ultimate strength of cracked structures has received attention in recent years. Paik et al. [10–12] made experimental and numerical investigations on the residual ultimate strength of steel plates with transverse or longitudinal cracks under axial compression, and proposed a formula to predict the ultimate strength of steel plates with transverse cracks under longitudinal tension or compression and with longitudinal cracks under longitudinal compression. Margaritis Y et al. [13] studied the ultimate and collapse response of cracked stiffened plate. In their research, the role of crack closure on the structural response is carefully examined. More recently, Fang Wang et al. [14] carried out numerical study on the ultimate shear strength of intact and cracked stiffened panels, and the formula for predicting the ultimate shear strength of cracked stiffened panels was developed on the basis of the formula for intact stiffened panels. Saad-Eldeen et al. [15] conducted experimental investigation on the residual strength of thin steel plates with a central elliptic opening and locked cracks. The specimens were taken from real structural members during the service life, rather than newly-built specimens. Besides, other contributions have been made on ultimate strength assessment of cracked stiffened plates or cracked box girders and some of them are reported in [16–20].

From all the literatures mentioned above, it can be seen that the early investigations are mainly focused on the behavior of cracked structures under predominantly tensile loading or on the estimation of elastic buckling strength. The residual ultimate strength of cracked structures under axial compression has received attentions in recent years, but the contributions about this topic are limited and still not enough. Therefore, further studies are needed to give deeper insights into the collapse characteristics of structural members with cracking defects.

The objective of this paper is to obtain insights into the ultimate strength behavior of stiffened plates with cracking damage under monotonic axial compression. The cracks in transverse direction of the plate are presumed to be located at the plate-stiffener intersection, either in plate only or in both plate and stiffener. It should be noted that crack propagation and fracture related critical crack length are not included in the present study.

Stiffener with flat-bar profile is adopted in this study and the steel material is in the category of high tensile steel. In order to reach our goals, a series of non-linear elastic-plastic large deflection analyses for cracked stiffened plates with varying crack sizes and crack locations has been carried out under loading of monotonic uniaxial compression. In the investigation more than 80 cracked stiffened plates are modeled and analyzed.

2. Nonlinear finite element analysis

2.1. Geometry and material

In literature [21], Shengming Zhang et al. conducted a review on contemporary design of large ships and found out that to bulk carriers the aspect ratios a/b of bottom plates in the mid-ship region are in the range of 3.0–4.5 and the plate slenderness ratio β are in the range of 1.0–4.5. These ratios ranges have adopted for the geometrical dimension selection of stiffened plates to be analyzed in this paper. A combination of single flat-bar stiffener (having a symmetric cross section) with associated plate has been taken as the analyzed model in this paper, as shown by the shaded area in Fig. 1. In Fig. 1, the plate dimension is denoted by $a \times b \times t$ while the geometry of flat-bar stiffener is characterized by $h_w \times t_w$. The detailed dimensions of local plate and flat-bar stiffener are given in Table 1.

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 [25], have indicated that due to the strain-hardening effect the steel plate ultimate strength 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 regard, 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 listed in Table 2, and a schematic of the stress-strain behavior of adopted material is illustrated in Fig. 2. Two important parameters governing the buckling/collapse behavior of stiffened plates are β and λ [22,23], defined as follows:

$$\text{Plate slenderness ratio: } \beta = \frac{b}{t_p}\sqrt{\frac{\sigma_y}{E}} \tag{1}$$

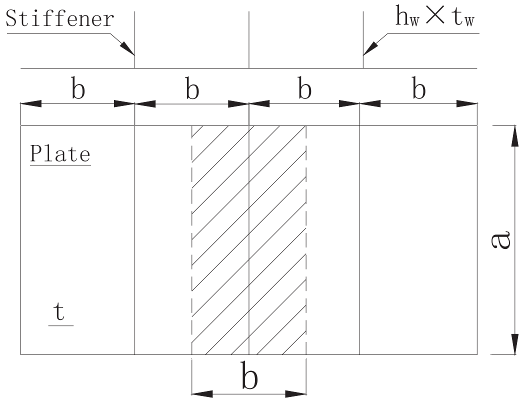

Fig. 1. Model extent of stiffened plate.