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Experimental and numerical investigation of material failure criterion with high-strength hull steel under biaxial stress

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ABSTRACT

The loads, stress and strain state of the ship structures are quite complicated under the condition of collision and grounding. The failure criteria which are commonly used in numerical simulations of ship collision have limitations in evaluating the failure characteristics of hull steel under complicated stress. Based on the shell theory, complex stress in plate is simplified as plane stress. In experiments, six different shapes of specimens were designed to study the failure characteristics of high-strength hull steel under biaxial stress. The specimens were pressed with a hemispherical indenter until destruction under quasi-static loading. The displacement of specimens' midpoint and loading force were recorded. The simulation models which considering the mesh size sensitivity and the failure criteria combined with the damage evolution model have been studied. A new reasonable formula is proposed to calculate the average failure strain of different mesh size. With the application of the average failure strain, a bilinear damage evolution model for high strength hull steel in biaxial tension stress is established. Based on a plastic instable criterion, a modified BWH (m-BWH) criterion is proposed. The comparison of Constant strain (CS) criterion combined with linear damage evolution model, the BWH and m-BWH failure criteria which are combined with the bilinear damage evolution model has been performed in the simulations by Abaqus user material subroutine (VUMAT). Although the BWH criterion is more precise than the constant strain criterion in comparison with the experiment results, its errors will increase with rising of strain ratio. The m-BWH criterion improves the accuracy of the simulations when the strain ratio is high.

1. Introduction

Ship collision and grounding accidents will cause damage to hull structures, leakage of oil, environmental pollution and other serious consequences. Research on failure mode and failure criterion of hull structures and materials is meaningful for ship design.

The most commonly used failure criterion in the ship collision simulation is the equivalent plastic strain which is usually decided by uniaxial tension experiment, namely the constant strain criterion. The equivalent plastic strain ranges from 0.1 to 0.7 in most finite simulation models (Calle and Alves, 2015). Although the constant strain criterion application is convenient, the simulation results are sensitive to the selected failure strain. The failure strain is an important parameter for the prediction of structural failure and absorbed energy of the collision. Many scholars (Wang et al., 2000; Glykas et al., 2001; Kitamura, 2002) found that the failure strain has strong influence on ship collision simulation. However, they chose the failure strain by experience. Based on Barba's law, Yamada et al. (2005) proposed an approximate formula related to mesh size to calculate the true failure strain. Hogström et al. (2009) confirmed that Barba's relation is valid for handling stress–strain dependence on the length scale used for strain evaluation after necking. Some similar formulas related to mesh size, strain hardening exponent and other parameters are proposed by researchers (Ehlers et al., 2008; Alsos et al., 2009). Ehlers (2010) chose an element length-dependent constant-strain failure criterion to simulate rupture and proved it to be sufficiently accurate. These formulas work well under uniaxial tension stress states. Some of the recent findings suggest that mesh size has strong influence on failure strain only under uniaxial tension. However, under plane strain and equi-biaxial tension the mesh size dependence is considerably weaker (Kõrgesaar and Romanoff, 2014; Kõrgesaar et al., 2014a and Walters, 2014). Failure strain represents the damage initiation of a material. After that, the behavior of the material is described by

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damage evolution. Simulation models considering the damage evolution of material can avoid abrupt failure and produce better results (Hogström et al., 2009).

It is well known that the constant strain criterion has limited precision when the stress states of structures or materials are different from uniaxial tension, such as biaxial tension or pure shear (Wierzbicki et al., 2005). Ship plates are mainly subject to biaxial tension in collision events and failure takes place mostly between plane strain and equi-biaxial tension (Kõrgesaar and Romanoff, 2014; Kõrgesaar et al., 2014b and Werner et al., 2015). Before failure, ductile sheet metals often generate necking area. In the necking area, narrow band of material starts to deform at a significantly higher strain rate than the surrounding material. Forming limit diagram (FLD) is widely used to predict the onset of local necking in sheet metal forming process (Graf and Hosford, 1994; Brunet and Morestin, 2001). However, FLD is affected by changing strain path which appears in structural collision processes (Graf and Hosford, 1994). A stress based criterion called BWH criterion was proposed by Alsos et al. (2008). The BWH criterion combines the shear stress criterion of Bressan and Williams (1983) (BW criterion) with the local necking criterion of Hill (1952). It is insensitive to changing stain path and mesh size. Alsos and Amdahl (2009) also calibrated the BWH criterion with a series of indentation experiments of unstiffened panel and different kinds of stiffened panels. The discrepancy between simulation and experiment of unstiffened panel was relatively greater than different kinds of stiffened panels. The BWH criterion was used to predict the material failure of ship structures and reasonable results were produced (Hogström et al., 2009; Ringsberg, 2010).

In this paper, uniaxial tension experiments and a series of biaxial tension experiments were conducted to study the failure characteristics of high-strength hull steel under biaxial stress. Simulation results of the uniaxial and biaxial tension experiments have been studied. The simulation models which consider the mesh size sensitivity, the failure criteria and the damage evolution model have been studied.

2. Experiments

2.1. Uniaxial tension experiments

The uniaxial tension experiments were conducted in accordance with ISO 6892–1:2009. A kind of high-strength hull steel (AH40) was used in these experiments. Two groups of specimens were processed which are parallel and perpendicular to the rolling direction respectively. Each group of uniaxial tension experiment was done three times. The thickness of the specimens was 4 mm. They were fractured by the material stretch test machine at a speed of 3 mm/min. The average maximum loading force of the experiments is 36.3 kN. The engineering stress-strain curves were obtained from the experiments. Then the true stress-strain curves can be obtained by Eq. (1).

$$\begin{aligned}\sigma_{true} &= \sigma_{eng}\left(1+\varepsilon_{eng}\right)\\ \varepsilon_{true} &= \ln\left(1+\varepsilon_{eng}\right)\end{aligned} \tag{1}$$

The true stress-strain curves (average of three specimens) are illustrated in Fig. 1. Because of rapid section reduction, the data of true stress and strain may be inaccurate after the onset of necking. That means the decreasing stage of the true stress-strain curves can't accurately denote the material behavior. This paper adopts power-law model to represent the material hardening behavior, which is expressed as follows

$$\overline{\sigma} = K\overline{\varepsilon}^{n} \tag{2}$$

(K, n) are the material strength coefficient and hardening exponent, respectively.

The material constants $K = 884$ and $n = 0.133$ are obtained by the least square method, using the hardening stage data of true stress and strain. Then the true stress-strain can be described as

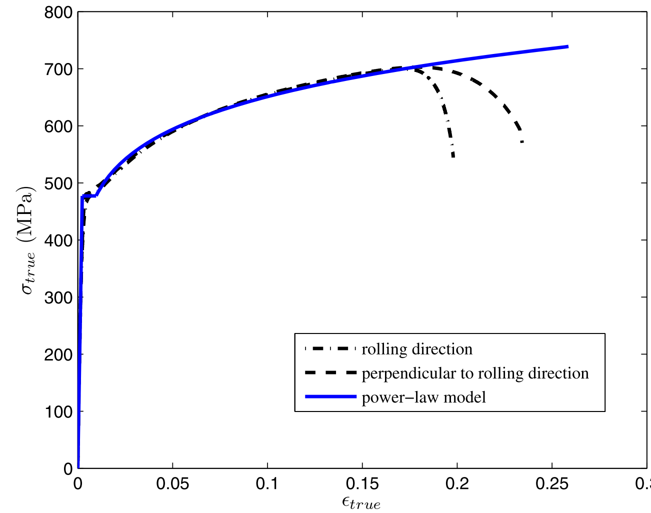

Fig. 1. True stress-strain curve of the uniaxial experiments and fitting curve by power-law model.

$$\sigma = \begin{cases} E\overline{\varepsilon} & \sigma < \sigma_s \\ \sigma_s & \overline{\varepsilon} < \overline{\varepsilon}_h \\ K\overline{\varepsilon}^{n} & \text{otherwise} \end{cases} \tag{3}$$

Where, $E = 202$GPa, $\sigma_s = 477$MPa. $\overline{\varepsilon}_h = 0.0097$ is the equivalent strain when the material starts to harden.

The strain at the onset of necking is also obtained, $\varepsilon_n = 0.176$. The curve obtained by power-law model in Fig. 1 has good agreement with uniaxial tension experiments.

Fig. 1 shows that the specimens perpendicular to the rolling direction (PD) have greater fracture strain than the rolling direction (RD) specimens. However, the onset of necking point, yield stress and elastic modulus are almost the same. The discrepancy of fracture strain may be caused by different fracture positions of the two groups, see Fig. 2. In the experiments, two specimens of the RD group fracture near the clamping end. However, all specimens of the other group fracture in the middle area. The extensometer was installed in the middle area of the specimens. A fracture near the clamping end may cause large error because of the disadvantage of extensometer.

Failure strain is an important parameter to evaluate the ductile failure mechanism by numerical simulation. Because of the limitations of experimental conditions, the failure strain of uniaxial tension experiment is hard to be obtained. Therefore, an approximate method is applied. Based on the assumption of plastic incompressibility, the failure strain is indirectly calculated by the necking width of specimens after fracture. The calculated failure strain is usually less than the true value, because of the release of the elastic strain. However, the elastic strain is very small with respect to the plastic strain. Though it is not precise enough, the conservative results will be obtained. The approximate method is to calculate the strain of width direction by $\varepsilon_w = \ln(w/w_0)$ first, and then

Fig. 2. Photo of specimens fractures at different position. The upper half is specimen of the RD group, and the lower half is specimen of the other group.

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