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An improved ductile fracture model for structural steels considering effect of high stress triaxiality

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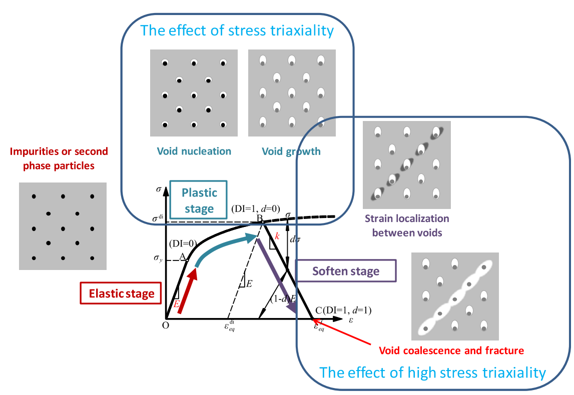
HIGHLIGHTS

- Effect of high stress triaxiality on ductile fracture behavior of steels is investigated.
- 10 fracture tests of steel specimens with U- and V-notches are conducted.
- Three-stage and two-parameter ductile fracture model is improved and its application is validated.
- Mesh size dependency of U- and V-notch specimens is studied.

GRAPHICAL ABSTRACT



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ABSTRACT

This study presents results of experimental investigation and ductile fracture model for ductile crack initiation, propagation and final failure in structural steels subjected to high stress triaxiality. To this end, uniaxial tension tests on smooth flat bars, U-notched specimens and V-notched specimens are conducted. Nonlinear finite element analysis of the notched specimens is carried out to obtain the stress triaxiality distributions and histories of notch tip and center of specimens. Based on the previous three-stage and two-parameter ductile fracture model proposed by the authors, the equivalent plastic displacement at element failure during simulations is obtained by notched specimen tests, and an improved ductile fracture model is presented considering the effect of high stress triaxiality during both the plastic stage and the softening stage. The relationship between the equivalent plastic displacement at element failure and nonuniform ratio (nonuniform ratio is the ratio of the average value of stress triaxiality of notch tip and center) is determined by a series of tests and analyses. Detailed finite element analyses that employ the improved ductile fracture model are shown to predict ductile fracture behavior under high stress triaxiality with good accuracy across the mesh sizes, notch radii, and notch degree in terms of ductile crack initiation point, ultimate load point and load-displacement curve.

1. Introduction

Ductile fracture is one of the common failure modes for thick-walled steel structures subjected to tensile loading [1–14]. "Thick-walled steel structures" means "compact sectional steel

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structures", herein "compact" means that local buckling is not easy to occur. For thick-walled steel structures, ductile crack initiation and propagation often occurs before local buckling and the crack initiation point is selected to be the ultimate point [15,16]. Ductile fracture due to crack initiation and propagation governs the ultimate strength of steel structure in a variety of situations where discontinuities lead to the concentration of inelastic strain and triaxial stresses, such as net-sections of bolted connections, welded connections, regions of localized yielding in steel members [17–22]. Ductile fracture in metallic materials occurs through progressive nucleation, growth and eventual coalescence of void. Among these processes, void nucleation and coalescence events are both highly stochastic, resulting in a lack of quantitative experimental data [23]. Assuming the void growth to be the defining step for ductile crack initiation, models that aim to predict ductile fracture need to capture the combined effects of the triaxiality and plastic strain [2]. Several researchers conducted uniaxial tensile tests on smooth samples [24–29]. However, ductile crack initiation and propagation are found to be sensitive to stress triaxiality (η), and comprehensive studies on the microvoid evolution under high stress triaxiality is lacking from civil engineering application aspects.

Microvoid dilation and elongation are the important microscopic damage mechanisms that ultimately lead to ductile fracture in metals. The influence of stress triaxiality on these microscopic damage mechanisms is investigated from material perspective by several researchers [8,11,14,21–23,30–42]. Void growth and linkage of an artificial void array embedded in a notched model material was studied by X-ray computed tomography, coupled within situ tensile deformation, as shown in Fig. 1 [23], in which ε is the local strain estimated from a principal radii measurement. We can find out that the location of ductile fracture initiation correlates well with the location of notch, where the stress triaxiality is high for most of the loading history. To investigate the effect of stress triaxiality on void evolution, tensile tests up to fracture were conducted on a sample with a rather smooth geometry (R = 6 mm), and also on samples with sharper notches of radius R = 2.5 mm and R = 1 mm, respectively, by Revil-Baudard et al. [35]. It is concluded that the higher the triaxiality (notch radius) the higher is the rate of void growth. Tests for high stress triaxialities (0.4–0.95) were carried out on smooth bar, and the fracture ductility was found strongly dependent on the stress triaxiality [30]. Uniaxial tension testing on various notched axisymmetric specimens was carried out to obtain different initial stress triaxiality in the range of (0.33–1.05) to calibrate and validate the proposed model by Kiran and Khandelwal [11]. It is observed by Khandelwal et al. [8,32] that at high stress triaxiality (0.7–1.6), the void growth is typically volumetric, and in this range, the ductility decreases with increase in triaxiality. The influence of stress triaxiality (0.75–2.5) on microvoid growth phase of ductile fracture under cyclic loading is investigated using micro-mechanical analyses [14]. The sensitivity of large stress triaxiality (larger than 1.5–2.0) in a variational porous plasticity model on the crack tip problems was studied by Mora et al. [38].

In the past, some coupled constitutive models were used for predicting ductile fracture in steels [12,43–49]. Coupled constitutive models directly account for change in the microstructure of material during the fracture process [8]. The coupled models have some internal damage variables along with the plastic internal variables to describe the evolution of microstructure. For example, the damage is coupled with the stress triaxiality and equivalent plastic strain in the three-stage and two-parameter ductile fracture model [46]. The microvoids in the coupled model employed in this paper grow in the plastically deforming metal matrix under the influence of the existing strain and stress states. The strain state is measured in terms of the equivalent plastic strain, and the stress state is measured in terms of the stress triaxiality. The two internal damage variables in this ductile fracture model include the damage initiation parameter DI and the damage evolution parameter d, which are related to the stress triaxiality and equivalent plastic strain. The authors discussed the applications of this model in smooth flat bars, welded U-notched flat bars and V-notched flat bars, three types of materials used in welded structures including base metal, weld metal and HAZ were investigated, and the capability and feasibility of the proposed ductile fracture model to predict ductile fracture under monotonic loading was demonstrated. Compared with stress-based models in previous studies [50,51], which are affected by the void shape and distribution, the model employed in this study is a strain-based model, which is a great convenience for researchers and engineers to employ. However, crack initiation and propagation is sensitive to notch shape of specimens. Experimental studies with U-notched and V-notched specimens show that the high triaxiality significantly reduces the ductility of structural steels. Distributions of equivalent plastic strain and stress triaxiality of critical fracture sections (such as section 1-1 in Fig. 2(a)) in smooth, U-notched and V-notched flat bars in reference [46] are illustrated in Fig. 2, in which P_1: ductile crack initiation point, P_2: ultimate load point, and P_3: fracture load point; the more detailed geometries of these specimens can refer to the reference [46]. The relatively flat notch leads to stable crack growth, and unstable crack growth may result from the relatively sharp notch. Uniform distributions of equivalent plastic strain and stress triaxiality lead to rapid propagation of ductile crack, and on the contrary uneven distributions result in slow propagation of ductile crack. Sharp cracks such as ductile crack due to V-notch give rise to singularities in stress, strain fields, meaning that the stress and strain at the crack tip rise to infinity. This precludes the use of three-stage and two-parameter model.

In this study, the ductile fracture mechanism is investigated for SM490 structural steels. Tension tests on U-notched and V-notched steel specimens with different detailed geometries are carried out to investigate fracture mechanisms of the steel material at

(a) ε= 0 (b) ε= 0.68 (c) ε= 0.80

Fig. 1. Reconstructed images for the Hexagonal material [23].