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Experimental and ductile fracture model study of single-groove welded joints under monotonic loading

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ABSTRACT

Tests and finite element (FE) analyses of smooth flat bar, U-notch and V-notch specimens are presented to demonstrate the application and validation of proposed three-stage and two-parameter ductile fracture model for evaluating the ductile crack initiation, propagation and final failure in steel welded joints under monotonic loading. Modeling concepts and procedures for characterizing the material parameters of ductile fracture model using smooth flat bar and U-notch tests are described. Accuracy of the model is validated through a series of tensile tests of U-notch, V-notch and welded smooth flat bar specimens. Three types of materials used in welded structures including base metal, weld metal and HAZ are investigated. Furthermore, the effect of notch position on ductile fracture behavior of HAZ specimens and the effect of mesh size on ductile fracture behavior of U-notch and V-notch specimens are studied. Detailed finite element analyses that employ the ductile fracture model are shown to predict ductile fracture behavior with good accuracy across the specimen geometries and material types in terms of ductile crack initiation point, ultimate load point and load–displacement curve.

1. Introduction

As one of the features of steel bridge structures, the steel member is of comparatively thin-walled section, and local buckling occurs in the steel member. However, for thick-walled welded steel members or concrete-filled steel piers, ductile cracks may occur in the welding or the base metal due to extreme load before occurrence of local buckling [1–6]. Despite the importance of welded structures in civil engineering construction, rigorous computational methods to evaluate their fracture resistance are not well developed, due to the challenges of simulating fracture in these weld details [7]. Accordingly, ductile fracture becomes one of important failure modes in steel structures for developing fracture-resistant design provisions and for evaluating structural performance under extreme loads such as strong earthquakes, especially for the thick-walled welded steel structures, and needs to be investigated deeply [8].

Fracture 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 in net-sections of bolted connections, welded connections, regions of localized yielding in steel members [9]. 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 [7]. In McClintock's model [10,11], ductile failure initiation strain was first related with stress triaxiality. Rice's and Tracey's model [12] and Chi's model [13] showed that the extension rate of void growth size is dependent on the triaxiality ratio and plastic strain rate of the material. Kanvinde and Deierlein [9] employed two models (void growth model indicated as VGM and stress modified critical strain model indicated as SMCS) based on this theory. The VGM involves an explicit integration of the stress and strain histories, whereas the SMCS is a simpler approach that is based only on the instantaneous values of the stress–strain quantities at fracture initiation [7,14–16]. Lemaitre's model [17], which is based on continuum damage mechanics (CDM), showed that triaxial stresses contribute to damage leading to ductile fracture. Some researchers employed CDM to evaluate damage initiation and evolution in structural steels [18,19]. The above mentioned models can be classified into micromechanics-based fracture model because they predict fracture based on combinations of local stresses and strains (at the crack tip or in a continuum) determined through finite element (FE) analysis [7]. Some researchers employed similar micromechanics-based fracture model to evaluate structural steels or steel members subjected to static tension [20–26]. However, those studies concentrated on

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Nomenclature

DI	damage initiation parameter
d	damage evolution parameter
ε_{eq}	equivalent plastic strain
σ^{di}	yield stress at the onset of damage
$\varepsilon_{eq}^{\mathrm{di}}$	equivalent plastic strain at the onset of damage
ε_{eq}^{f}	equivalent plastic strain at element failure
η	stress triaxiality
$\mathrm{d}\varepsilon_{eq}$	incremental equivalent plastic strain
$\dot{\varepsilon}_{eq}$	equivalent plastic strain rate
DI_c	critical value of damage initiation parameter
α	material toughness parameter
$F(\eta)$	stress modification function
D_{cr}	material constant
M	material constant
ε_R	material constant
ε_D	material constant
p	material constant
ν	Poisson's ratio
$\boldsymbol{\sigma}$	damaged stress tensor
E'	damaged elastic modulus
E	undamaged elastic modulus
$\bar{\boldsymbol{\sigma}}$	undamaged stress tensor
u_{eq}	equivalent plastic displacement
$D(u_{eq})$	damage evolution function of equivalent plastic displacement
L_e	characteristic length of the element
u_{eq}^{f}	plastic displacement at element failure
α_{bs}	material toughness parameter of base metal
α_{wm}	material toughness parameter of weld metal
α_{haz}	material toughness parameter of HAZ
COV	coefficient of variation
K_e	elastic stiffness
K_s	degradation stiffness
σ_y	yield stress
ε_y	yield strain
E_{st}	initial strain-hardening modulus

structural steels, not weld metal and heat-affected zone (HAZ), where ductile crack easily initiates during earthquake because of their material discontinuousness. The ductile fracture performance of welded structures under extreme load still is a puzzle, yet not to be effectively resolved.

Modeling of the crack distribution and extension of cracking in three dimensions can be difficult and requires an enormous amount of computational effort and time [27] because a real structure often has welded connection components with a complicated geometry. Due to the complexity of simulating fracture in structural weld details, there has been limited research in the application and modern fracture predictive techniques to weldments [7,27]. Some previous studies focused on the ductile fracture strength of welded members [5,28,29]. These studies focused on the global fracture behavior of welded members, the local fracture behavior (such as the ductile crack initiation and propagation) cannot be simulated effectively. Besides, detailed FE analyses are employed to study fracture toughness requirements in welded beam–column connections by Chi et al. [30]. The ductile plastic damage behavior of weld HAZ was studied based on CDM theory by Wang [31]. A ductile failure model proposed by Peñuelas et al. [32] based on the Gurson model for integrating the constitutive equations that describe the ductile failure process of a metallic material in a welded joint, and Gurson model is a basic damage model recommended for use in the analysis of emergency condition for building structures according to the current European standards [33]. Kanvinde et al. [7] employed SMCS model to evaluate its effectiveness in predicting fracture deformation capacity of structural fillet welds. Fracture behavior of beam-to-column welded joints was predicted by Huang et al. [34] using micromechanics damage model. Qian et al. [35] present a new fracture formulation to describe the ductile tearing and unstable fracture failure for circular hollow section joints under monotonically increasing brace tension. Although these approaches have been applied to welded steels in steel coupons or mechanical components, and the toughness and ductility of steel material are prescribed in European standard [33], they are relatively new to civil engineering applications because few studies (including experimental and analytical research) have been done in both qualitative and quantitative senses to structural engineering details.

In severe earthquake, the structural steel members usually have to resist enormous extreme load which show a short load duration with large plastic deformation. It mainly depends on the mechanical properties of materials themselves to resist such loads, which is described as the reaction of large strain in material level [36] including ductile crack initiation, propagation and final failure. A multiscale approach (as shown in Fig. 1), which has been employed in other research areas [37], should be employed to the complete analysis and design of a steel structure that involves the material property characterization (material level), verification (member level) and its applications on structure analysis subjected to extreme load (structure level). Therefore, ductile fracture model of welded steel structures under extreme load plays a quite important role in structural seismic design and analysis. This study applies micromechanics-based fracture model based on Rice's and Tracey's theory [12] to the compact tension tests for fracture characterization of welded steels described in this paper. The model is selected due to its accuracy and simplicity for prediction of fracture in base metals during previous research [7,9,12,13,15,16]. The investigation involves a range of compact tension experiments and complementary FE analyses, including U-notch fracture test, V-notch fracture test, and smooth flat-bar fracture test. The ductile fracture parameters of different materials (including base metal, weld metal and HAZ), which are widely applied to civil engineering, are obtained. The paper then presents results of FE simulations conducted to examine the fracture modeling technique. The effect of notch position on ductile fracture behavior of HAZ specimens and mesh size sensitivity are investigated. Finally, commentary is provided on the results and limitations of the approach.

2. Three-stage and two-parameter ductile fracture model

The ductile fracture model of structural steel in this paper is described using three stages and two parameters, as shown in Fig. 2(a). The damage initiation parameter DI is the variable which judges whether the corresponding damage initiation criterion has been reached. The damage evolution parameter d is the accumulated damage once the damage initiation criterion is met. The 1st stage – elastic stage (O → A): the material is in elastic state, at the end of this stage (point A), a metal or other material ceases to behave elastically. The 2nd stage – plastic stage (A → B): the material is in plastic state. At point A, the parameter DI = 0 because the equivalent plastic strain $\varepsilon_{eq}^{\mathrm{A}} = 0$, and point A is the onset of