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Ductile fracture prediction for welded steel connections under monotonic loading based on micromechanical fracture criteria

Fangfang Liao [a,b], Wei Wang [b,c,*], Yiyi Chen [b,c]

[a] School of Civil Engineering, Chang'an University, Xi'an 710061, China
[b] State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
[c] Department of Structural Engineering, Tongji University, Shanghai 200092, China

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A B S T R A C T

Micromechanics-based fracture criteria for structural steels can be used to predict ductile fracture initiation with large-scale yielding and no initial flaws. High-fidelity finite-element analyses were carried out on ten welded connection specimens between the square steel tube column and H-beam flange under monotonic tensile loading. The calibrated micromechanics-based fracture criteria, including the Stress Modified Critical Strain (SMCS) model and the Void Growth Model (VGM), were used to predict fracture initiation for each specimen. The predicted results demonstrated high accuracy compared to test results. Sensitivity analyses of fracture toughness parameters in the SMCS model and VGM to the predicted fracture results were conducted. The results show that, when the fracture toughness parameters were increased or reduced by twenty percent, fluctuations in the predicted fracture results were within the acceptable range. Therefore, calibrated micromechanics-based fracture criteria can be used to predict ductile fracture initiation of connections under monotonic loading. Subsequently, the user subroutine VUMAT, from ABAQUS software edited by the authors, was employed. Using the SMCS model and VGM as fracture criteria, the post-fracture load–displacement curves of eighteen notched round bar specimens and two welded connection specimens (between the square steel tube column and H-beam flange) that fractured at different locations were traced by deleting the failure elements one by one. The predicted results agree well with the test results. Consequently, these calibrated micromechanics-based fracture criteria and associated simulating techniques can be used for collapse analysis of steel structures during extreme events.

1. Introduction

Fracture constitutes a significant failure mode in building structures. Recently, collapse of whole building structures caused by connection fracture occurred occasionally. These events not only resulted in casualties, but also caused large economic losses, thus much attention has been paid into this field. To study the mechanisms of connection fracture behavior has become a very important and urgent subject [1,2]. Current research regarding the fracture performance of steel structures mainly use conventional fracture mechanics methods, such as the stress intensity factor based on linear elastic fracture mechanics, the crack tip opening displacement (CTOD) and the *J*-integral based on elastic–plastic fracture mechanics. Because all these methods assume that a crack already exists and that there is a high strain constraint on the initial crack tip, they are suitable for studying brittle fractures or pseudo brittle fractures with limited plasticity [3]. However, these methods are not appropriate for investigating ductile fractures with large-scale yielding regions and no initial flaws during strong earthquakes [4]. In addition, the conventional fracture mechanics methods do not take triaxiality into consideration, so they are not applicable to predicting fractures in connections controlled by triaxial stress conditions [5].

In contrast to these conventional fracture mechanics, micromechanical models that are based on plastic damage mechanisms of materials can describe the influences of stress and strain on the microstructure characteristics of materials. The latter methods can, therefore, be used as physically significant fracture criteria to predict ductile fracture initiation in steel connections [6,7]. Micromechanical models applicable to ductile fracture prediction under monotonic loading include the Stress Modified Critical Strain (SMCS) model proposed by Hancock and Mackenzie [8], the Void Growth Model (VGM) proposed by Rice and Tracey [9]

* Corresponding author at: State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China. Tel.: +86 13917324286; fax: +86 21 65984976.

E-mail address: weiwang@tongji.edu.cn (W. Wang).

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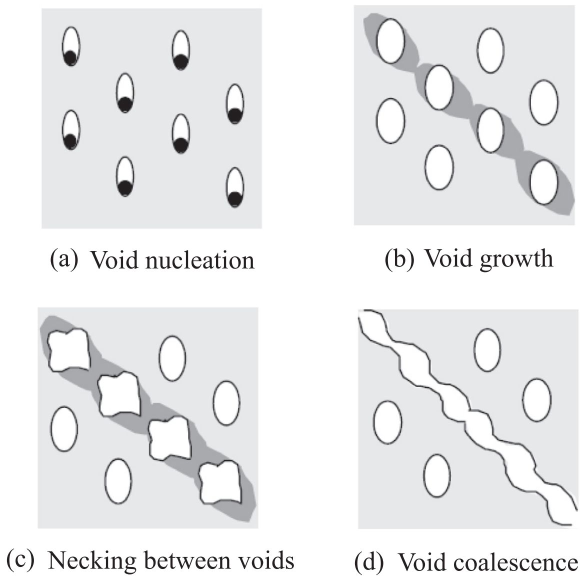

Fig. 1. Mechanisms of void nucleation, growth and coalescence.

Table 1
Parameters of the micromechanical fracture criteria for Q345 steel.

Material	α	η	Characteristic length (mm)		
			Lower bound	Mean value	Upper bound
Base metal	2.44	2.55	0.087	0.201	0.473
Deposit metal	2.49	2.63	0.062	0.202	0.311
Heat-affected zone	2.43	2.53	0.072	0.329	0.671

Table 2
Dimension parameters of specimens.

Serial number	B_c (mm)	t_c (mm)	L_c (mm)	B_b (mm)	t_f (mm)	B_f (mm)	g
BP	250	8	750	200	10	–	–
RP1	250	8	750	200	10	–	–
RP1_R	250	8	750	200	10	–	–
RP2	250	16	750	150	8	–	–
RP3	250	16	750	150	30	–	–
RP5	250	8	750	200	10	–	–
RPh1_1	250	8	750	180	10	200	1
RPh1_2	250	8	750	180	10	200	2
RPh1_4	250	8	750	180	10	200	4
RPh2_2	250	16	750	135	8	150	2

and the Gurson model [10]. Kanvinde and Deierlein [11–13] verified the accuracy of SMCS model and VGM in predicting ductile fractures in steel structures through twelve pull-plate tests that represent reduced section conditions in bolted and reduced beam section connections. Using SMCS model as fracture criterion, Chi et al. [14] conducted finite-element analyses to relate the fracture behavior between a pull-plate weldment test with a full-scale welded beam–column connection, which demonstrated the application of the SMCS criterion to ductile fracture prediction. Kanvinde et al. [15] conducted tensile tests on twenty-four fillet welded cruciform specimens and then used conventional fracture mechanics method *J*-integral and micromechanics-based method SMCS to predict fracture deformation of each specimen, respectively. The results indicated that the SMCS model can predict fracture in the structural fillet welds with good accuracy, while the *J*-integral based methods resulted in somewhat conservative and inaccurate predictions of fracture. The inaccuracy was higher, especially for the tougher fillet welds where extensive yielding prior to fracture invalidated the *J*-integral as a measure of fracture toughness. Wang et al. [16] applied conventional *J*-integral based fracture mechanics and micromechanics-based fracture models (VGM and SMCS) to predict fracture in seven local connections representing beam-to-column connections through refined three-dimensional finite-element models. The results indicated that the VGM and SMCS model were able to predict fracture of welded connection with good accuracy, while the *J*-integral based approach resulted in quite conservative fracture prediction. Kang et al. [17] conducted tests and finite element (FE) analyses of smooth flat bar, U-notch and V-notch specimens to demonstrate the application and validation of proposed three-stage and two-parameter ductile fracture model for evaluating the ductile fracture in steel welded joints under monotonic loading.

However, research regarding ductile fracture mechanisms in steel building structures has been quite insufficient. The post-fracture path of welded steel connections has not been studied yet. This paper predicts the fracture behavior of welded connection specimens between a square steel tube column and an H-beam flange under monotonic tensile loading using micromechanical models calibrated through fracture performance tests of Q345 steel. The predicted results are verified by the test results, using the VUMAT subroutine based on ABAQUS software edited by the authors. Using the SMCS model and VGM as fracture criteria, the ductile fracture initiations and post-fracture paths of eighteen notched round bar specimens and two welded connection specimens are simulated and verified by test results. This study

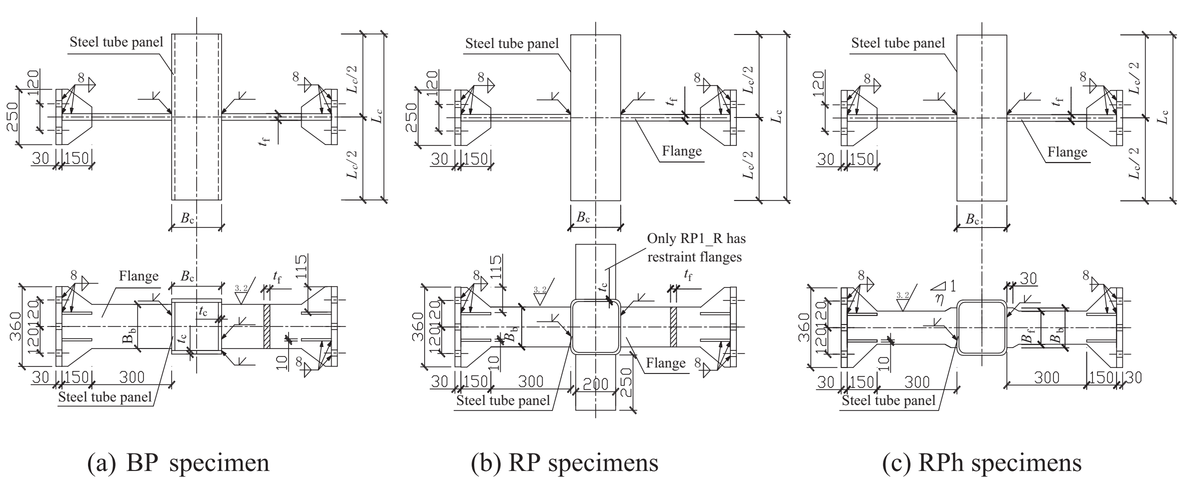

Fig. 2. Constitutions of the connection specimens.