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Experimental and numerical investigations on extremely-low-cycle fatigue fracture behavior of steel welded joints

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ABSTRACT

Beam-to-column welded joints in moment-resisting steel frames may undergo extremely low cycle fatigue in earthquake action. The aim of this paper is to investigate the fatigue failure behavior by means of experimental study and finite element analysis. Experiments were conducted on the six full scale beam-to-column welded joints. The seismic performance of welded joints with different weld access hole geometries was compared among them and the effect of crack initiation and growth on the load carrying capacity of welded joints was discussed. In addition, a continuum damage mechanics model used previously for monotonic loading was reformulated in order to account for the extremely low cycle loading condition. The model was implemented in a commercial nonlinear finite element software of ABAQUS, which was adopted to predict the fracture of beam-to-column welded joints subjected to monotonic loading and extremely low cycle loading. The predicted load displacement response agrees well with the test results. The distribution and evolution of damage in the welded joints were calculated during crack initiation and propagation. It is found that the methodology based on continuum damage mechanics proposed in the paper can successfully predict fracture behavior of beam-to-column welded joint with reasonable accuracy.

1. Introduction

Moment resisting steel frames, widely used in intense seismic zones, are considered to be able to provide the strength and ductility required to resist strong seismic loading as steel is ductile. However, the 1994 Northridge earthquake and 1995 Kobe earthquake have caused seriously damage in steel structure [1,2], where various fractures were observed at beam-to-column welded joints and the fractures occurred in welded joints could cause the progressive collapse of the whole structure. This fracture resulting from seismic events can be categorized into extremely (or ultra) low cycle fatigue (ELCF) [3–6], which is characterized by a few reverse loading cycles (in general less than 20) with large strain amplitude. The ELCF failure process includes crack initiation and crack growth at the welded joints, and steel has large plastic deformation, therefore the phenomenon is very different from conventional high or low cycle fatigue failure. Numerous experiments have been carried out to investigate the hysteretic behavior of beam-to-column welded joints [7–9], however, these studies often focus on the ductility and energy dissipation capability of the welded joints and ignore the cracking behavior during ELCF fracture process.

Accurate prediction of earthquake induced fracture may be critical to evaluate the seismic performance of structural and develop fracture-resistant design provisions for steel structures. The prediction approach based on traditional fracture mechanics (e.g. stress intensity factor K, J integral and crack tip opening displacement), although widely used and effective under many conditions, has several limitations when applied to building structures subjected to seismic loading. The stress intensity factor range ΔK and J integral range ΔJ type approaches assume that an infinitely sharp crack or initial flaw already exists, which might be absent in many structural. Moreover, ELCF failure is often associated with large scale plasticity, which may invalidate the methods based on ΔK and ΔJ [10]. Since failure under earthquake type loading is characterized by cyclic loading, many fatigue research methods were applied to investigate ELCF behavior in steel structure. For example, the S–N curve usually used in design codes was introduced to predict the ELCF life, where displacement amplitude or rotation amplitude was used instead of stress amplitude [11–13].

Recently, the micromechanical approach, as a suitable alternative to more traditional methods, has already been used for the fracture prediction in welded joints. An example of micromechanical models involves void growth model (VGM) [14,15] and cyclic void growth model (CVGM) [3], which were proposed to predict crack initiation under monotonic loading and ELCF loading, respectively. Their application to the pull-plate specimens [16] and the welded joints [17,18] had shown ability of the VGM model and the CVMG model to predict crack initiation in steel structures. The CVMG model had been simplified to degraded significant plastic strain (DSPD) model with the assumption

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Nomenclature

D	continuum damage
E	elastic modulus of the damaged material
E_0	elastic modulus of the undamaged material
c	material parameter in the continuum damage model
D_0	initial damage of material
D_{cr}	critical damage at failure of material
ε_{th}	uniaxial damage strain threshold
ε_f	uniaxial fracture strain
$\bar{\varepsilon}^p$	accumulated plastic strain
ε_{ij}^p	matrix plastic strain tensor
σ_m	hydrostatic stress
σ_{eq}	equivalent von Mises stress
σ_m/σ_{eq}	stress triaxiality
ν	Poisson's ratio
$\bar{\varepsilon}_{th}^p$	plastic strain threshold under multiaxial stress
$\bar{\varepsilon}_f^p$	fracture accumulated plastic strain
$\bar{\varepsilon}^{p+}$	active accumulated plastic strain
δ_y	yield displacement of welded joint
P_y	yield load of welded joint
δ_i	crack initiation displacement of welded joint
δ_f	fracture displacement of welded joint
N_i	fatigue life corresponding to cracking in welded joint
N_f	fatigue life corresponding to fracture failure of welded joint
θ	rotation of welded joint
θ_p	plastic rotation of welded joint
M	beam moment at column face
K_θ	elastic rotational stiffness of welded joint
P_u	ultimate load of welded joint
δ_u	ultimate displacement of welded joint
$\theta_{\max}$	maximum rotation of welded joint
$\theta_{p\max}$	maximum plastic rotation of welded joint
$\theta_{pa\max}$	maximum accumulated plastic rotation of welded joint
W	maximum accumulated dissipated energy of welded joint
θ_{pa}	accumulated plastic rotation of welded joint
θ_{pai}	accumulated plastic rotation when crack initiation
θ_{pat}	accumulated plastic rotation when crack extended through the thickness of flange
P_{iN}	load corresponding to cracking in welded joint
P_{iN+1}	load corresponding to crack displacement in the next cycle after crack initiation
$\overline{\sigma}$	yield surface size
σ_y	initial yield stress
Q_∞	material parameter in Lemaitre–Chaboche hardening model
b	material parameter in Lemaitre–Chaboche hardening model
α_i	bace stress tensor
d_0	initial diameter of standard coupon specimen
d_f	minimum diameter of standard coupon specimen at failure
δ_f'	fracture displacement of notched coupon specimen

that the triaxiality was treated as constant during loading [19,20]. For this type model, the material damage is independent variable and it has no direct effect on the constitutive model. Another example of these models is micromechanics damage model. The damage effects are accounted for into the constitutive model by the internal variables, which are usually related to voids in the material. The classical yield function was developed by Gurson [21] and later extended to the cyclic loading [22,23]. This type of model had been verified to simulate crack growth in pipe structures under monotonic loading [24] and ELCF fracture of beam-to-column welded joint [6].

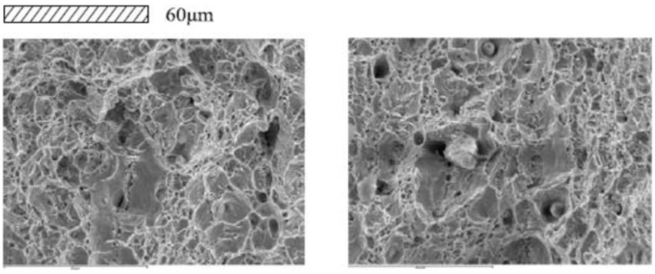
Continuum damage mechanics (CDM) model, as another typical example of micromechanical models, describes the macroscopic material behavior based on the irreversible mechanisms that occur in the microstructure during the deformation process. The damage is considered to be one of the internal constitutive variables that accounts for the effects on the material constitutive response. Starting from the early work by Lemaitre [25] and Chaboche [26], many CDM-based models have been proposed, some of which were introduced into the field of steel structure for the fracture prediction due to monotonic loading [27] and high or low cycle fatigue loading [28]. However, the discussion about continuum damage evolution under ELCF loading condition is still an open question, in addition, there isn't much study on the application of CDM model into ELCF fracture prediction of welded joints.

In this paper, experiments and numerical simulation based on CDM model were carried out to investigate the fracture behavior of beam-to-column welded joint. The ELCF fracture mechanism and CDM model for ELCF loading were briefly introduced. Experimental investigation on six full scale beam-to-column welded joints was presented. Furthermore, these experiments provided data to validate the CDM model to predict earthquake induced ELCF in steel structures. The CDM model, when validated by test data, provides deep insights into the complicated fracture behavior.

2. Mechanism and theoretical model for extremely low cycle fatigue of structural steel

2.1. Fracture mechanisms of extremely low cycle fatigue of structural steel

Most steel structures undergo large scale plasticity before fracturing. Failure usually takes place in a ductile manner, which is known as ductile fracture. The initiation of ductile fracture in structural steel during monotonic loading is typically controlled by the growth and coalescence of microvoids that nucleate around secondary particles, such as carbides or sulfides in the steel matrix. Evidenced by dimples on the fracture surface, this mechanism has been extensively documented by various researchers. For fatigue failure in structural steel, the slip and decohesion are widely applied to reveal the mechanism of fatigue crack initiation. Since ELCF involves both large scale inelastic strain and cyclic loading, the damage mechanism during ELCF is a combination of ductile fracture process and fatigue mechanism, where the main controlling factor is the ductile fracture. This has been previously pointed out by Kuwamura and Yamamoto [29] and is evident from the dimpled fracture surfaces in Fig. 1, where the fracture surface are



(a) Monotonic loading (b) ELCF loading

Fig. 1. Micro-failure structures of Q345B (Shi et al. [30]) (a) Monotonic loading (b) ELCF loading.