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Ductile fracture model for structural steel under cyclic large strain loading

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ABSTRACT

This paper aims to predict ductile fracture of mild steel under cyclic large strain loading (CLSL) using only tensile coupon test results. A micromechanics-based fracture model which adopts void growth model and Miner's rule in incremental form is proposed, where fracture is assumed to occur when a damage index reaches unit. Damage is postulated not to accumulate when stress triaxiality is less than a threshold. To calibrate the fracture model, cyclic experimental and numerical studies on hourglass-type coupons are conducted under various loading histories. Since cyclic plasticity models play an important role on the simulation results, two cyclic plasticity models are employed to carry out the simulation, in which the proposed fracture model is employed. The predicted fracture displacements using either of the plasticity models compare with the experimental results with acceptable accuracy.

1. Introduction

Ductile fracture of structural steel members has been observed in buildings that experienced strong earthquakes, e.g., Northridge earthquake in 1994 [1] and Kobe earthquake in 1995 [2,3]. Moreover, ductile fracture of structural members and connections has also been observed in laboratory tests, e.g., [4–8]. Ductile fracture under seismic loading is often mistaken as low cycle fatigue, since the two fracture modes both occur under cyclic loading within a small number of cycles. Kuwamura [9] found that there is a transition of fracture modes from low cycle fatigue to ductile fracture depending on the size of strain amplitude based on cyclic test results of hourglass-type notched coupons. During an earthquake event, structures commonly experience dozens of large plastic loading cycles, and most of the fracture modes should be classified as ductile fracture but not low cycle fatigue. The aforementioned findings are of great importance for the study of fracture of steel structures under seismic loading, since the mechanisms and evaluation approaches of the two fracture modes are distinguished. Ductile fracture has a typical dimple fracture surface under fractographic observations with scanning electron microscope (SEM), and it is possible to predict ductile fracture with only small-scale monotonic tensile coupon tests. However, a typical SEM fractography of low cycle fatigue is striations. It may be impossible to predict low cycle fatigue life from a monotonic tensile coupon test. To distinguish the loading history of ductile fracture from that of low cycle fatigue which is concerned with relative small strain amplitudes, the loading history concerned with ductile fracture under seismic loading is termed as cyclic large strain loading (CLSL) in this study.

Research on ductile fracture of metals under CLSL is limited. A fracture model based on a concept of effective damage is proposed by Ohata and Toyoda [10], and effective plastic strain was defined as the equivalent plastic strain when back stress exceeds the maximum back stress during the preceding loading cycle. Ductile fracture was postulated to occur when the accumulated effective plastic strain reaches a two-parameter critical condition defined by the accumulated effective plastic strain as a function of the stress triaxiality. The model was also applied to ductile fracture prediction of circular tubes under cyclic incremental bending [4] and beam-to-column connections of steel piers under CLSL [11]. A cyclic void growth model (CVGM) based on the Rice–Tracey void growth model [12] was proposed [13] to predict ductile fracture of structural steels under CLSL, and the model was also applied to ductile fracture prediction of bluntly-notched and dog-bone steel coupons [14].

A ductile fracture model with only one parameter for monotonic tension, which employs the void growth model [15–17] and Miner's rule [18] in incremental form, has been proposed [19]. As an extension of the previous study, this paper aims to predict ductile fracture of structural steel under cyclic compression and tension. The prediction of ductile fracture under CLSL is more complicated than that of monotonic tension. The difficulties may involve three aspects, i.e., a fracture model for cyclic compression and tension; a proper cyclic plasticity model to accurately evaluate cyclic stress–strain behaviors; and straightforward

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methods to calibrate the corresponding model parameters of the fracture and plasticity models.

In this study, a modification of the single-parameter fracture model for structural steel under monotonic tension is first conducted to extend the application of the model from monotonic tension to cyclic compression and tension, where damage is postulated not to accumulate when the stress triaxiality is less than −1/3 [20]. A method to calibrate the single fracture parameter only using a smooth coupon under monotonic tension is also given. Then, two validated plasticity models, i.e., Chaboche model with isotropic hardening (IH) and modified Yoshida–Uemori (Y–U) model, as well as the calibration method of the model parameters are briefly introduced. Finally, the proposed cyclic fracture model is validated by both cyclic experiments on hourglass-type coupons under various loading histories, and corresponding numerical simulations using the two plasticity models, where the cyclic fracture model is incorporated. The numerical simulation results are compared with the experimental results, from which the rationality of the cyclic fracture model for structural steel under CLSL is proved.

The fracture model proposed by Ohata and Toyoda [10] is relatively convenient for engineers compared with the CVGM [13], since the fracture parameters can be obtained from a monotonic test and numerical simulation. However, a smoothly-notched coupon under monotonic tension is still required. Meanwhile, the Ohata–Toyoda model will fail to predict ductile fracture under constant-amplitude loading histories, since the accumulated effective plastic strain in subsequent loading cycles will not increase under the loading condition according to its definition. The CVGM model [13] has several fracture parameters, and the values of the fracture parameters in the CVGM are different for monotonic and cyclic loadings. Cyclic tests on smoothly-notched coupons are also required to obtain the fracture parameters, which makes it difficult to apply from the viewpoint of structural engineers. Compared with the two ductile fracture models, the newly proposed one in this study has only a single fracture parameter, which can be obtained easily from a smooth tensile coupon. Moreover, the values of the newly proposed fracture parameter under monotonic and cyclic loadings are the same, which keeps the consistency of the ductile fracture model under different loading histories. The proposed fracture model is also applicable to both constant-amplitude loading and other loading histories.

2. Damage model of structural steels under cyclic large strain loading

2.1. Fracture model for monotonic tension

Rice and Tracey [12] analyzed the relationship between the radius of a void and stress triaxiality based on a simplified model of a spherical void in a remote simple tension strain rate field as illustrated in Fig. 1. The void growth rate could be given by the following formula for Mises materials.

$$\frac{dR}{R} = 0.283 \cdot e^{\frac{3}{2}\frac{\sigma_h}{\sigma_{eq}}} d\varepsilon_{eq} = 0.283 \cdot e^{\frac{3}{2}T} d\varepsilon_{eq} \quad (1)$$

where R is the average radius of the void, and σ_h and σ_{eq} are hydrostatic stress and equivalent stress respectively; T is stress triaxiality and $d\varepsilon_{eq}$ is incremental equivalent strain.

The Rice–Tracey model can be applied to describe void growth, while no criterion for void coalescence is given. Integrating Eq. (1), one can obtain

$$\ln\frac{R}{R_0} = 0.283 \int_0^{\varepsilon_{eq}} e^{\frac{3}{2}T} d\varepsilon_{eq} \quad (2)$$

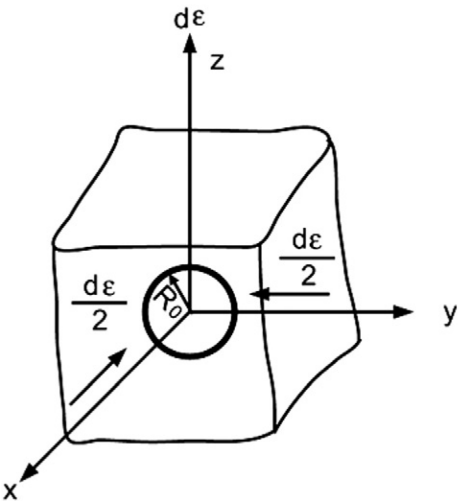

Fig. 1. Illustration of Rice–Tracey model (adapted from [12]).

where R_0 is the initial radius of the void. If stress triaxiality, T, is constant during the whole loading history, then Eq. (2) gives

$$\varepsilon_{eq} = \ln\frac{R}{R_0} \Big/ \left(0.283 e^{\frac{3}{2}T}\right). \quad (3)$$

Based on a term of critical void growth index, χ_{cr}, [15–17] void coalescence is assumed to occur when $\frac{R}{R_0}$ reaches a threshold. Assuming an ideal case that the stress triaxiality is constant during the whole loading history, the relationship between fracture strain (equivalent strain) and stress triaxiality can be formulated according to Eq. (3).

$$\varepsilon_f = \ln\frac{R_f}{R_0} \Big/ \left(0.283 e^{\frac{3}{2}T}\right) = \chi_{cr} \cdot e^{-\frac{3}{2}T} \quad (4)$$

where ε_f and R_f are fracture strain and the radius when fracture occurs respectively, χ_{cr} is a model parameter defining the critical value for void growth.

In fact, the stress triaxiality, T, is not constant during general loading conditions till the fracture of a material. In order to extend the above equation to general loading cases associated with non-constant T, Miner's rule [18] is employed to evaluate cumulative damage under various stress triaxialities. The Miner's rule is commonly applied to predicting high-cycle fatigue fracture life of structures under cyclic loading histories with various stress ratios. It is a linear rule assuming that there are m different loading cycles with various stress ratios for a material, S_i, each with n_i cycles. If the material under loading stress ratio of S_i fails under N_i cycles, failure of the material will occur if the following criterion is satisfied.

$$\sum_{i=1}^{m} \frac{n_i}{N_i} = 1 \quad (5)$$

Similarly, it is postulated in this study that the whole loading history is divided into m different increments with various stress triaxiality for a material, T_i, each with an incremental equivalent strain of $d\varepsilon_{eq,i}$. If the material under stress triaxiality of T_i fails when the equivalent strain reaches $\varepsilon_{f,i}$, fracture of the material will occur if the following criterion is satisfied.

$$\sum_{i=1}^{m} \frac{d\varepsilon_{eq,i}}{\varepsilon_{f,i}} = 1 \quad (6)$$