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Damage index for crack initiation of structural steel under cyclic loading

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ABSTRACT

A damage index for crack initiation (DICI) with damage accumulation effects considered was introduced in this study. Cyclic tension and compression tests of notched bars were used to verify the proposed DICI. The local cyclic elasto-plastic stress–strain responses, used to calculate DICI, were analyzed using the incremental plasticity procedures of ABAQUS finite element code for various strain amplitudes. Two crack initiation criteria with DICI used, single point criterion and characteristic length criterion, were employed to investigate the crack initiation behavior of the specimens. The single point criterion for crack initiation is met when DICI exceeds 1 at any point of the continuum. The characteristic length criterion for crack initiation is met when DICI exceeds 1 over a critical length equal to the characteristic length. It was found that the single point criterion is applicable to fatigue crack initiation and ductile crack initiation separately, while the characteristic length criterion is feasible to simulate fatigue crack initiation and ductile crack initiation simultaneously.

1. Introduction

Brittle fracture in steel buildings occurred during the 1994 Northridge earthquake and the 1995 Hyogoken Nanbu earthquake can actually take place only after several or dozens of cyclic loadings [1,2]. The characteristic of this type of fracture is that ductile crack occurs first before sudden propagation of the crack in a brittle manner. The size of the ductile crack can be small or relatively large. To understand the law of ductile crack propagation, it is necessary to find a method to predict ductile crack initiation.

There are several approaches to predict ductile fracture of metals under cyclic large strain loading, e.g., critical plastic strain criterion model, void growth model, Gurson–Tvergaard–Needleman (GTN) model and cohesive zone model. Ductile fracture under monotonic loading has been investigated by a number of researchers, e.g., [3–8], while studies on ductile fracture under cyclic loading are still limited [9–12], especially for the transition between fatigue fracture and ductile fracture.

In this paper, ductile crack initiation models were summarized first. Then damage index for crack initiation (DICI) based on the critical plastic strain criterion model was introduced in incremental form to predict crack initiation under cyclic large strain loading. Two types of criteria, i.e. single point criterion and characteristic length criterion, were introduced to investigate crack initiation behavior of steels under various fracture modes, i.e., fatigue fracture and ductile fracture. Based on the experiments of Kuwamura [13], finite element analysis was conducted to validate the applicability of the DICI and the two related crack initiation criteria to the two fracture modes.

2. Crack initiation for ductile metal

2.1. Summary of crack initiation models

In general, ductile cracking in metal occurs through a process of void nucleation, growth, and coalescence. Generally, computational theories of fracture mechanics of metal include three categories of ductile crack initiation models: model with void implicitly considered, model with void explicitly considered, and model without void considered. Three representative models corresponding to each category, respectively, are introduced in the following sections.

2.1.1. Critical plastic strain criterion model

Longitudinal and equivalent plastic strains are used for uniaxial and multiaxial stress states, respectively, to evaluate ductile crack by the critical plastic strain criterion. Although this kind of criterion can predict ductile crack roughly, it cannot take into account some important factors that have effects on the occurrence of ductile crack. That is, plastic strain only is not appropriate to predict ductile crack, as the necessity of considering the effect of stress state is pointed out. Especially, it is necessary to consider the effect of stress triaxiality. Formulae proposed by Hancock and MacKenzie [14], Kuwamura and Yamamoto [15], and the stress modified critical strain (SMCS) [16] are representative models for the critical plastic strain criterion. Although plastic constitutive theories without considering void are used in these models, the effect of void is considered implicitly by introducing the stress triaxiality.

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For cyclic loadings, the Manson–Coffin law is often used as an empirical method to determine crack initiation.

2.1.2. GTN model

A representative model with void explicitly considered is the Gurson–Tvergaard–Needleman (GTN) model [17]. There are micro-voids originated from inclusions or impurities in ductile metal. When stress increases, voids grow up and coalesce. When stress increases more, ductile failure happens. A yield function for porous metal was derived from a spherical void model by Gurson [18]. Tvergaard modified the yield function by introducing a factor. Needleman and Tvergaard modified the development law of the volume fraction of the void. The GTN model treats a porous metal as a homogeneous continuum, where the effect of voids is considered through the continuum material averagely. The main difference between a traditional plastic model and the GTN model is that the former does not take hydrostatic pressure into account while the latter does.

The above GTN model considered isotropic hardening only and cannot be applicable to cyclic loadings. Leblond considered both the isotropic hardening and kinematic hardening, and extended the GTN model to cyclic loadings [19].

2.1.3. Cohesive zone model (CZM)

In the cohesive zone model, crack path is assumed previously. Crack path is treated as a thin layer of material with its own material properties [20]. The traction–separation method is used to decide whether a crack develops. For cyclic loadings, cyclic cohesive zone model (CCZM) is introduced for simulating crack propagation [21].

2.2. Proposed damage index for crack initiation (DICI)

From Rice and Tracey's derivation [22], it has been shown that void growth rate is proportional to exponent of the stress triaxiality. The stress triaxiality is defined as follows:

$$T_r = \sigma_m / \sigma_e \tag{1}$$

where σ_m is mean or hydrostatic stress, and σ_e is von Mises' equivalent stress. Based on this derivation, Hancock and Mackenzie expressed the crack initiation plastic strain by the following relationship

$$\varepsilon_{pd} = \alpha \exp(-1.5 T_r) \tag{2}$$

where α is a material dependent constant, and the coefficient of 1.5 in the exponent is theoretically derived.

Eq. (2) is mainly applicable to monotonic loading, and it cannot be employed directly for the cases where the stress triaxiality covers both positive and negative values. In this paper, a state variable, ω_d, namely DICI, is introduced to evaluate the cumulative damage leading to the crack initiation, as shown in Eq. (3):

$$\omega_d = \int \frac{d\varepsilon_p}{\varepsilon_{pd}} = \int \frac{1}{\alpha} \exp(1.5 T_r) d\varepsilon_p \tag{3}$$

where ε_p is the equivalent plastic strain. The ratio of incremental equivalent plastic strain to the crack initiation plastic strain expressed in Eq. (2), i.e., $d\varepsilon_p/\varepsilon_{pd}$ is supposed as incremental damage herein. The integration of $d\varepsilon_p/\varepsilon_{pd}$ is defined as ω_d, and the physical implication of ω_d is cumulative damage. ω_d increases monotonically with ε_p. At each increment of an FE analysis, incremental increase in ω_d is computed as follows:

$$\Delta\omega_d = \frac{1}{\alpha} \exp(1.5 T_r) \Delta\varepsilon_p \geq 0. \tag{4}$$

Through this definition, crack initiation under cyclic loading can be evaluated by the monotonic increasing index, ω_d.

2.2.1. Single point criterion

The single point criterion for crack initiation is met when the following condition is satisfied at any point of the continuum.

$$\omega_d = 1. \tag{5}$$

2.2.2. Characteristic length criterion

The characteristic length criterion for crack initiation is met when the following condition is satisfied.

$$\omega_d \geq 1 \quad \text{for} \quad r \geq l^*. \tag{6}$$

Here r is the maximum distance between any two points of the area over which ω_d exceeds 1. The parameter, l^*, termed characteristic length, is determined as average size of the dimple plateaus and valleys which are commonly observed at the fracture surface [14].

This criterion includes a length scale to describe the critical volume of the continuum over which ductile crack initiation index is exceeded. The inequality $r \geq l^*$ implies that crack initiation will occur when ω_d exceeds 1 over a critical length of r equaling to the characteristic length. Thus, this criterion has two parameters, α and l^*, which has to be calibrated first.

3. Verification by FEA

3.1. Summary of experiment used in FEA

The experimental results from Kuwamura [13] were used to verify the proposed DICI. The configuration of the test specimens is shown in Fig. 1. The specimens have an hourglass-type shape with a circumferential notch at the mid-length. The depth of the notch is 1 mm; the radius of the notch root is 0.5 mm, and the diameter of the minimum cross section is 12 mm. The material is SM490 of Japanese Industrial Standard. Deformation controlled cyclic loading tests were performed with a gauge length of 30 mm spanning the center notch. Deformation amplitude, namely δ, is between 0.06 mm and 1.00 mm. The number of cycles until crack initiation at the notch root was recorded.

3.2. Finite element analysis

Since the section of the specimens is circular and the loadings are axisymmetric, it can be simplified as an axisymmetric model. FEA model is illustrated in Fig. 2. The edge length of the mesh near the notch root is 0.03 mm. ABAQUS 6.9 was used to conduct the analysis [23]. An axisymmetric solid element type, CAX4R, is employed as it is computational efficient for plastic deformation problems. Material properties used in the analysis are illustrated in Fig. 3, which are based on the true stress–true strain data and obtained by coupon test results. As for the plasticity model, a combined nonlinear isotropic/kinematic hardening model termed Chaboche model was used, with three backstresses to describe the nonlinear kinematic hardening effect, and

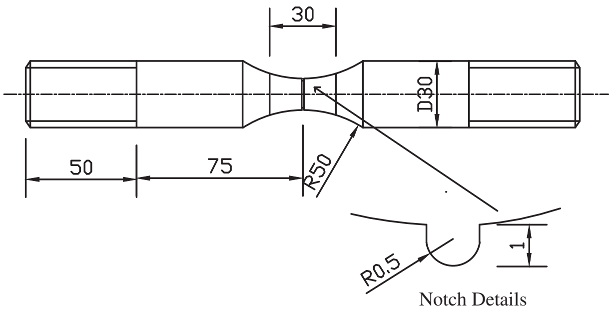

Fig. 1. Configuration of the test specimen [13].