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Finite element simulation of ultra low cycle fatigue cracking in steel structures

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ABSTRACT

This paper proposes a new method of simulating ductile fracture in steel structures under large amplitude cyclic straining experienced in earthquakes. The method is developed based on an existing micromechanical model originally proposed for predicting crack initiation in ultra-low cycle fatigue, ULCF. It involves a step-by-step simulation of material degradation within the framework of conventional nonlinear FEM. The method is validated through simulating fracture in a structural detail (column-to-base plate connection) for which several cyclic tests has been previously conducted. It is found that the method can successfully predict the cracking site, its propagation path, the number of cycles corresponding to crack initiation, and also final fracture.

1. Introduction

Traditional high and low cyclic fatigue life estimation methods such as K and J have been mainly developed based on the assumptions of presence of initial sharp cracks and also small scale yielding. However, when steel structures are subjected to seismic loads, their failing components experience ultra-low cycle fatigue, ULCF, which involves a few (generally less than 20) cycles of large plastic strains (several times the initial yield strain). Moreover, the assumption of initial sharp cracks is subjected to considerable uncertainty in such cases. That is why the conventional fracture mechanics approaches are not so practical for treating ULCF.

Several methods have already been proposed for predicting crack initiation in ULCF, which are able to resolve the shortcomings (see, e.g., Tateishi et al. [1,2], Xue [3], Hommel and Meschke [4], Kuroda [5], Kanvinde and Deierlein [6]). Among them, the micromechanically based cyclic void growth model, CVGM, of Kanvinde and Deierlein [6] is one of the most recent ones. The model was originally developed for predicting fracture initiation under monotonic loads; however it was subsequently extended to cyclic loads based on the underlying mechanism of microvoids growth and coalescence (Anderson [7]). The accuracy of this method has been verified in several studies (Kanvinde and Deierlein [8], Myers et al. [9]).

CVGM assumes that fracture initiates whenever a specific criterion is satisfied over a characteristic length (of order of 0.1 mm for steels). However, it is already known that crack initiation does not always coincide with the final failure of steel components and they may continue carrying loads thereafter. As examples, tests on column-to-base plate connections carried out by Myers et al. [9] and Fell et al. [10] showed that cracks initiate quite earlier than the eventual failures. Hence, considering the crack initiation phase solely is not adequate for simulating the behavior of steel structures and, for the cases in which the crack propagation phase has comparable share in the fatigue life, both phases shall be concurrently accounted for.

The numerical modeling of crack initiation and propagation in steel structures under monotonic loads has been the subject of many researches. Chen and Lambert [11] implemented the physically based Gurson–Tevergaurd model and handled the problem within the framework of continuum damage mechanics, CDM. Xue and Wierzbicki [12] also used damage plasticity theory to model ductile fracture initiation and propagation. Lequesne [13] employed cohesive elements to simulate crack propagation in steel moment connections. Huang [14] and Uriz and Mahin [15] are among the few investigators who have studied details of crack propagation in steel structures under ultra-low cyclic fatigue, ULCF. They implemented a continuum damage plasticity model in the commercial LS-DYNA software and simulated crack propagation in concentric bracings.

This paper aims to introduce a method of predicting fracture initiation and propagation in steel structures based on the cyclic void growth model initially proposed by Kanvinde and Deierlein [6] for predicting microcrack initiation in the process of ULCF. The paper starts with the explanation of underlying micromechanisms of ductile fracture in mild steel, the CVGM, as well as its calibration procedure. Then, it continues with a section describing the new method of fracture prediction and its implementation in FEM. Finally, the validity of the method is demonstrated in a set of column-to-base plate connection analyses which compare well with test results.

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2. Ultra low cycle fatigue

2.1. Macroscopic crack initiation

The ultra-low cycle fatigue of structural steel involves extremely large plastic strains and very few numbers of cycles to failure. Accordingly, the micromechanisms underlying the ULCF are basically quite similar to those of the ductile fracture under monotonic loading. It has already been confirmed that the initial ductile fracture of steel is microscopically characterized by the three main stages of: (1) microvoids nucleation, (2) their growth, and (3) coalescence (see, e.g. [7]). During the first stage, voids form in the second-phase particles or inclusions such as carbides either by fracture of particles or debonding of particle–matrix interfaces (Fig. 1a). Next, during the growth stage, which is driven by tensile hydrostatic stresses and plastic stretches, the voids expand around the inclusions (Fig. 1b). Finally, the ligaments connecting neighboring voids fail, coalescences occur, and thus microcracks are born (Fig. 1c).

Despite the above mentioned similarities between the micromechanisms of macrocracking under monotonic and ULCF conditions, there also exist some differences. For instance, simple microscopic comparisons of the fractured surfaces reveal that dimples are shallower for the samples failed under cyclic loads. The following two reasons explain why the reversing excursions accelerate failure of connecting ligaments.

- First, the shrinkage or squeezing of the voids under negative mean stresses increases their maximum curvature radii and thus accentuates the effect of stress concentration.
- Second, the cyclic plastic straining might nucleate secondary voids in the ligaments.

The first serious attempt to develop a continuum-level numerical model for the prediction of ductile fracture in metals goes back to the pioneering works of Rice and Tracey [16] and McClintock [17] on the growth of ideal spherical and cylindrical voids, respectively. They identified that

$$\frac{dR}{R_0} = \gamma e^{1.5\eta} d\epsilon_p \tag{1}$$

where R_0 and R are the initial and current average radii of the void, respectively. ϵ_p is the equivalent plastic strain and γ is a material constant to be calibrated. η is called the stress triaxiality and is equal to

$$\eta = \frac{\sigma_m}{\sigma_e}. \tag{2}$$

σ_m is the mean stress and σ_e is the von Mises effective stress. Integrating Eq. (1), the total void growth can be estimated.

Borrowing this idea, many researchers such as Hancock and Mackenzie [18], Panontin and Sheppard [19], and Chi et al. [20,21], have proposed their criteria for the prediction of macrocrack initiation under monotonic loads by assuming a critical tolerable void radius at the onset of coalescence phase. Recently, a new member of such models has been introduced by Kanvinde and Deierlein [8] and named the void growth model, VGM. They proposed that, for monotonic loads, a macrocrack initiates when the equation below is satisfied over a predefined characteristic length of l^*.

$$VGI^{\text{Monotonic}} > VGI^{\text{Monotonic}}_{\text{Critical}}. \tag{3}$$

Here, $VGI^{\text{Monotonic}}$ stands for the void growth index and is equal to

$$VGI^{\text{Monotonic}} = \int e^{1.5\eta} d\epsilon_p. \tag{4}$$

$VGI^{\text{Monotonic}}_{\text{Critical}}$ in Eq. (3) is the material critical void growth index. The calibration of this critical index, as shown in Fig. 2, is based on a comparison between the experimental results of a uniaxially loaded notched cylindrical bar with those of its numerical simulation [8]. To be more precise, the calibration process requires that first the point on the empirical force–displacement curve in which the specimen begins to fracture (point A in Fig. 2) is identified and then the *VGI* is numerically extracted at the same state and assigned to the $VGI^{\text{Monotonic}}_{\text{Critical}}$. It is of crucial importance to note that it has been previously shown that the values of void growth index across the fracture surface of a notched cylindrical bar are nearly equal [8]. Hence, the $VGI^{\text{Monotonic}}_{\text{Critical}}$ corresponds to the initiation of microcrack over the characteristic length and not its completion. This point will be considered in the development of our crack propagation model in the next section.

Kanvinde and Deierlein [8] followed an approach proposed by Hancock and Mackenzie [18] to measure the characteristic length, i.e. they assumed that the principle behind the physical fracture is the linkage of two or more holes formed by the coalescence of inclusion colonies. Subsequently, they suggested determining l^* based on averaging the sizes of approximately 15 measured plateaus and valleys in fractographs. Furthermore, they measured the characteristic lengths of various structural steels and showed that they are in the range of 0.18 to 0.30 mm.

Kanvinde and Deierlein [6] extended their idea to cyclic loads and developed a new version of VGM currently known as the cyclic void growth model, CVGM. The backbone of CVGM is identical to that of VGM, however the model is refined as outlined below to numerically capture the effects of reversing loads on the growth and coalescence phases. They assumed that a macrocrack initiates when

$$VGI^{\text{Cyclic}} > VGI^{\text{Cyclic}}_{\text{Critical}} \text{ for } l > l^*. \tag{5}$$

$VGI^{\text{Cyclic}}_{\text{Critical}}$ is the critical cyclic void growth index.

Considering void shrinkage under compressive (negative) triaxialities, Eq. (4) has been upgraded to the following form

$$VGI^{\text{Cyclic}} = \sum_{\text{Tensile Cycles}} \int e^{|1.5\eta|} d\epsilon_p - \sum_{\text{Compressive Cycles}} \int e^{|1.5\eta|} d\epsilon_p. \tag{6}$$

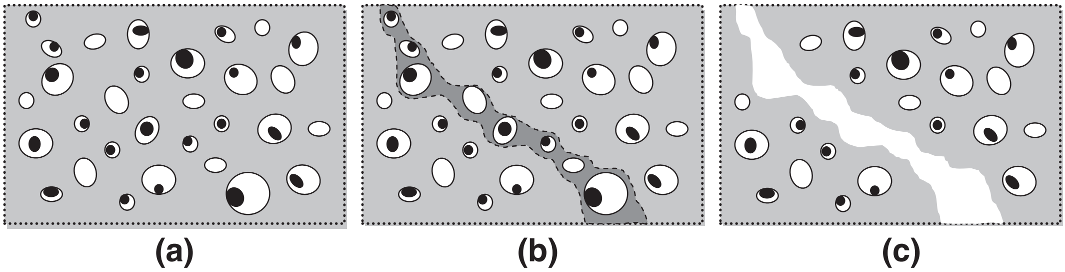

Fig. 1. Micromechanism of ductile fracture in metals [7]. (a) Void nucleation, (b) void growth, and (c) void coalescence.