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Ductile cracking simulation of uncracked high strength steel using an energy approach

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ABSTRACT

Ductile crack initiation and propagation simulation is of great importance in metal structures, which is one of main failure modes. Research objects of common fracture mechanics are solids with existing cracks. However, ductile fracture of uncracked solids is also one of the main concerns in structural engineering, especially for strong seismic loading. There is a great difficulty in simulating both crack initiation and propagation of uncracked solids using conventional fracture mechanics. A simple unified method to simulate the two stages with acceptable accuracy is thus required. For ductile crack initiation, a number of models based on the void growth concept have been proposed. However, research on ductile crack propagation is still limited, and there is still a lack of simple approaches to simulate both ductile crack initiation and propagation of uncracked solids. This paper aims to investigate ductile crack initiation and propagation of high strength steel under high stress triaxiality by combination of the void growth model for ductile crack initiation and an energy balance approach for ductile crack propagation. In this paper, a straightforward approach to obtain the ductile fracture energy only using smooth tension coupon tests is proposed. Two series of single edge notched specimens with different notch depths and notch configurations are manufactured. Both experimental and numerical studies under monotonic tension are conducted. The ductile crack initiation and propagation processes of notched high strength steel specimens are simulated with acceptable accuracy using the proposed approach.

1. Introduction

Subsequent progressive brittle fracture after ductile cracking [1] of welded connections in steel moment resisting frames (SMRF) has been observed during the 1994 Northridge and the 1995 Kobe earthquakes [2–5]. A number of studies have been conducted to clarify the failure mechanisms of the aforementioned failure modes, e.g., [1,6–11] and to improve seismic performance of the welded connections, e.g., [12–14], after the two strong earthquakes.

Before studying brittle fracture, it is of great importance to evaluate the preceding ductile crack initiation and crack propagation. Besides, ductile fracture of steel members under cyclic large plastic strain loading was also reported during the 1995 Kobe earthquake, i.e., ductile cracking of steel bracings in a garage as shown in Fig. 1. There are great difficulties in simulating both crack initiation and crack propagation of uncracked ductile metal structures. One difficulty lies in the uncracked solids with large-scale yielding at the crack tip, which makes conventional crack propagation technologies for linear elastic fracture mechanics and elastic-plastic fracture mechanics not applicable.

A number of ductile crack initiation models termed void growth models (VGMs) [6–8,15,16] were proposed to evaluate crack initiation of metals, and this category of ductile fracture models are based on the concept of void growth [17,18]. Ductile crack is postulated to initiate when voids reach a critical size and coalesce with each other [19]. VGMs can generally evaluate ductile crack initiation of structural steel and structural members with good accuracy [15,20–23], since structural steels are commonly ductile, where void growth and void coalescence are critical stages dominating ductile fracture initiation.

To date, research on ductile crack propagation of metals without existing cracks is still limited. However, the issue of ductile crack propagation is important for evaluation of strength, ductility and energy dissipation capacity of metal structures, since load-carrying capacity sometimes decreases only when a substantial large crack is developed. For a VGM, ductile crack propagation is commonly postulated to occur simultaneously as the crack initiation, or the ductile crack initiation index reaches a threshold value over a critical length [6]. Ductile crack initiation and propagation are commonly simulated by element deletion for initially uncracked solids, and an element is removed when the crack initiation index reaches unit. Acceptable accuracy can be obtained for these approaches when there is no large gradient for

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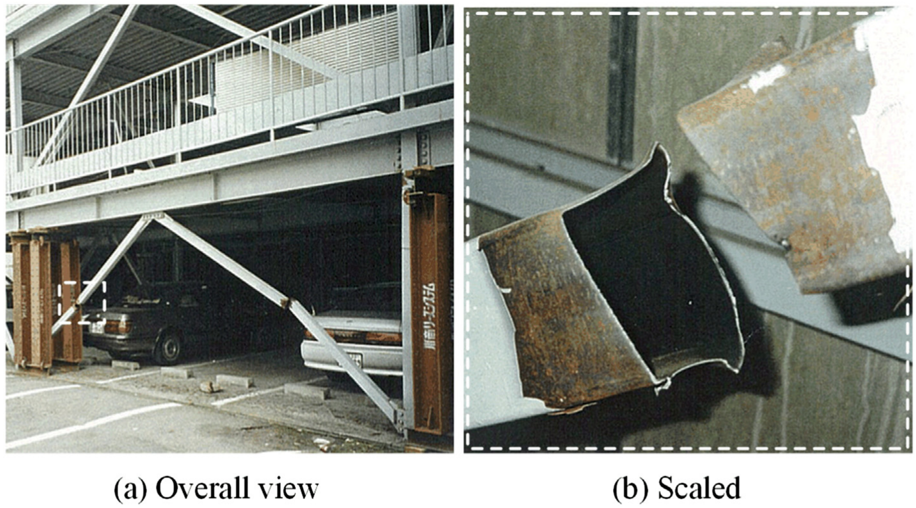

Fig. 1. Ductile fracture of bracings during the 1995 Kobe earthquake.

the crack initiation index, i.e., no large strain gradient or stress triaxiality gradient. For these cases, a ductile crack propagates almost simultaneously with crack initiation. This can be observed during the final rupture of a smooth tension coupon, where a crack propagates immediately after crack initiation, even though the cracked surface is 100% ductile. Besides, these approaches can also simulate crack propagation of metals with low toughness, where brittle fracture will occur soon after ductile crack initiation. However, they cannot simulate well for the cases where a large gradient for the crack initiation index is involved, such as bending, especially for high strength steel with high toughness in structural engineering. A ductile fracture model with only a crack initiation rule generally overestimates the crack propagation rate, especially for the cases where non-uniform strain distribution prevails, e.g., [24].

To accurately evaluate both crack initiation and crack propagation of uncracked ductile metal structures under cases with non-uniform strain distribution, a ductile fracture model with both crack initiation and crack propagation rules is required. A crack propagation rule defined in terms of ductile fracture energy is proposed in the literature [31]. The main merit of the crack propagation rule is that the mesh dependence effect can be greatly mitigated, and large element sizes can thus be employed to simulate cracking propagation of large-scale whole structures. This rule has been successfully applied to concrete structures, while its application to metal structures has seldom been found as far as the authors know. Besides, it is difficult to calibrate the fracture energy correlated with the crack propagation rule. Commonly, three-point bending tests on sharply-notched specimens are required, where a large number of loading cycles are applied to the pre-cracked specimens to create a sharp fatigue crack at the crack tip. This treatment is to exclude the energy due to plastic straining at the crack front.

In a previous study of the authors [24], the fracture energy was obtained through Charpy impact tests, while it is found that the Charpy impact energy still includes a large amount of energy due to plastic straining. In practice, structural engineers commonly can only obtain tension coupon test results, and it is of significant practical value if one can obtain all the fracture parameters necessarily required by a ductile fracture model from common tension coupon test results. However, there is still no such approach proposed in the literature according to the authors' knowledge.

This paper aims to propose and validate a straightforward method to obtain both the crack initiation and crack propagation correlated parameters only using tension coupon tests. The investigated object is high strength steel under high stress triaxiality. Shear fracture related cases [25–29] with low and medium stress triaxiality are out of scope of this study. A series of single edge V-notched tension (SEVNT) and single edge U-notched tension (SEUNT) specimens were manufactured and experimentally pulled to rupture under quasi-static loading. Numerical simulations were also carried out, where the parameters of crack initiation and crack propagation rules were both calibrated using common tension coupon tests. The main difficulties in achieving the target lie in the simulation method of the uncracked specimens without existing cracks and also the approach to obtain the fracture energy by only using the tension coupon tests. Comparison between the experimental and numerical results indicates that the newly proposed method to obtain the ductile fracture energy of the ductile crack propagation rule can well simulate both the crack initiation and propagation of the specimens without existing cracks.

2. Ductile fracture model

2.1. Ductile crack initiation rule

A ductile crack initiation rule was proposed to simulate ductile fracture under cyclic large plastic strain loading [20], where a damage

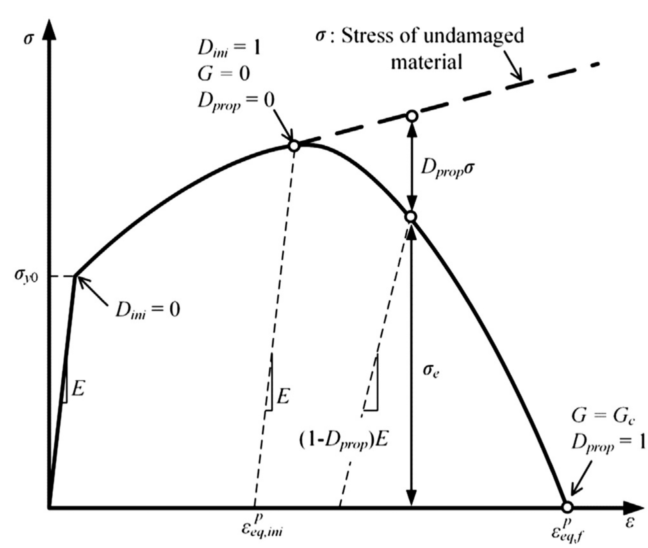

Fig. 2. Illustration of a ductile fracture model.