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Experimental and numerical investigation of ductile fracture of carbon steel structural components

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ABSTRACT

Ductile fracture of steel components cannot be avoided particularly due to large inelastic strain in extreme loading scenarios. Without considering damage model, conventional elasto-plastic constitutive material model cannot lead to accurate finite element (FE) modelling results when damage due to fracture exists. Metal fracture is a complex damage process in which damage onset, material deterioration and final fracture are related to development of material plasticity. Uniaxial tensile fracture and shear fracture are two typical failure modes of structural members. In this study, experimental investigations of monotonic tensile fracture and in-plane shear fracture under different strain rates in quasi-static loading range are presented for low-alloy structural carbon steel. The characteristic steel material properties are obtained insensitive to the chosen strain rate. A semi-empirical process is used to calibrate the damage properties (damage onset and softening criteria) through FE modelling of the coupon samples based on a continuum damage mechanics (CDM) model. Deterioration of the carbon steel properties was found related to the evolution of equivalent plastic strain, and particularly there is a linear relationship for the in-plane shear scenario. The verified damage onset and shear softening are then used for modelling of a welded steel tubular connection experiencing punching shear fracture phenomenon. It is shown that modelling result of the steel connection is significantly improved when the proposed fracture modelling is adopted.

1. Introduction

In a series of experimental research conducted on steel tubular connections under static and cyclic loading at ambient temperature [1,2] and under fire and post-earthquake fire [3,4], fracture was found to be one of the main failure phenomena. Different with the concentrically braced frames popularly used in high seismic regions [5,6], the investigated steel connections in above studies are the simple types of I-beam to steel tubular column connection which are usually used in moderate seismic regions. For steel structural components particularly the beams and columns under increasing static or seismic load, damage usually occurs as local buckling followed by global buckling and finally the possible local fracture [7]. However, for beam-to-column connections of moment resisting frames (MRF) in practice, the possible damage or failure patterns could be different according to the various configuration details. Although deformation of the MRF connections is usually restrained by design codes, local fracture of beam flange, column panel, welds and heat affected zone around welds are shown inevitable particularly when large deformation occurs. It is necessary to investigate ductile steel fracture to understand the whole stage behaviour of the above types of connections including fracture phenomenon.

Due to lack of consideration of material softening and the fracture damage at large deformations, finite element modelling (FEM) with conventional elasto-plastic material model has significantly overestimated the behaviour of the steel connections at ultimate loading state [1,2]. However, the steel fracture commonly observed in previous experimental researches [8,9] is usually neglected in FE modelling analyses. Steel structural performance with fracture phenomena can only be reasonably predicted when material softening and fracture are considered [10–12].

It is generally recognized that ductile fracture of metal materials occurs through the nucleation, growth and coalescence of small internal voids or cavities [13,14]. Microscopic details of a steel shear coupon before and after testing are shown in Fig. 1. As shown in Fig. 1a, sparsely distributed micro defects such as voids and cracks exist in natural steel material. The fractured cross-section of the shear coupon after failure is shown in Fig. 1b, in which a large coalesced crack is presented. Degradation of material properties is an irreversible process. Although several approaches can be used for fracture analysis, it is a considerable challenge when FEM is used to simulate full-scale steel structural components with fracture damage particularly for 3-D models. To evaluate the metal fracture, conventional fracture mechanics have been established mainly based on a stress intensity factor K and a

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Nomenclature

A, B, n	Factors
C_1, C_2	Factors
D	Damage variable
D_f	Damage variable at fracture point
E_{init}	Initial elastic modulus of steel
e_f	Elongation ratio corresponding to the nominal shear stress at failure
e_u	Elongation ratio corresponding to the nominal ultimate shear stress
F_u	Ultimate strength of structural components
f^*	Effective void volume fraction
L_0	Gauge length to measure elongation
l	A ratio
q_1, q_2, q_3	Factors for GTN model
R	Radius of an isolated void
R_0	Initial radius of an isolated void
δ_f	Loading displacement at fracture point
δ_u	Loading displacement corresponding to σ_u or F_u
ε	Strain
ε_f	Strain corresponding to the yield stress point
ε_{nom}	Nominal strain
ε_p	Plastic strain
$\overline{\varepsilon}_p$	Equivalent plastic strain
$\overline{\varepsilon}_p^{critical}$	Critical equivalent plastic strain
$\overline{\varepsilon}_{p,0}$	Equivalent plastic strain at damage onset
$\overline{\varepsilon}_{p,f}$	Equivalent plastic strain at fracture point
ε_{true}	True strain
ε_u	Strain corresponding to the ultimate stress point
ε_y	Elongation ratio of uniaxial coupon at failure
η	Stress triaxiality ratio
σ	Stress
$\overline{\sigma}$	Flow stress of the matrix material
σ_{eq}	Equivalent or von Mises stress
σ_f	Nominal strength at failure
σ_m	Hydrostatic stress
σ_{nom}	Engineering stress
σ_{true}	True stress
σ_u	Nominal ultimate stress
σ_y	Nominal yield stress
τ_f	Nominal shear stress at failure
τ_u	Nominal ultimate shear stress

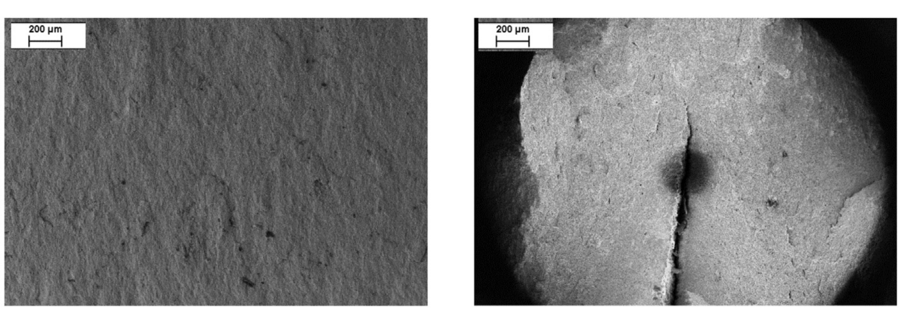
path-independent J-integral around the tip of a crack [15]; however these variables completely neglect the micromechanical material behaviour. The conventional fracture mechanics is usually difficult to determine the critical pre-existing crack, particularly in full-scale structural components. To overcome the above defects, local approaches have been proposed in recent years to describe the material damage process, such as the continuum damage mechanics (CDM) model [16,17] and micro-mechanical models [14,18].

In this paper, considering the typical fracture patterns such as punching shear fracture of the tubular column panel under monotonic quasi-static loading [1,2], steel ductile fracture is investigated. In the previous investigation of steel connections [1,2], it was found that the joint region rotated around its rotation axis. Such that even the steel beam-column connections were subjected to loading with constant rate on the beam end, strain rates of the joint regions (beam flanges, beam web, column face and lateral walls) were actually different. Therefore, uniaxial tensile coupons and in-plane shear coupons are taken from the tubular column wall (thickness: 5 mm), and monotonic loading coupon tests at ambient temperature under strain rates in a small range are performed. Continuum Damage Mechanics (CDM) model and one of the micro-mechanics models (GTN model) are adopted in the numerical investigation in this study. Based on the CDM model, a material damage model is established and verified by adopting suitable damage onset locus and softening criterion. Thus, the damage parameters are calibrated through a semi-empirical “trial and error” process coupling of FEM and the test data. Mesh-sensitive analysis of the damage parameters is also carried out. Finally, the damage model established in this study for the in-plane shear scenario at ambient temperature under quasi-static loading is adopted in modelling of a steel connection with shear fracture failure. An improved modelling result is reached, showing that material softening and fracture cannot be ignored in FEM when large plastic strain is involved in carbon steel structural components.

2. Ductile fracture theory

2.1. Micro-mechanical model

Pioneering work has been carried out by researchers such as McClintock [13] and Rice & Tracey [14]. It was shown that the damage in metal material is related to the nucleation, growth and coalescence of micro-voids or cracks. Void coalescence is thought to occur when the void growth ratio R/R_0 (R is the radius of an isolated void and R_0 is the initial radius of the void) reaches a critical value $(R/R_0)_c$ which is assumed to be a material constant and can be determined experimentally. Material behaviour degrades with the development of the voids after the critical value. Due to the fact that the triaxiality η (a ratio between σ_m, hydrostatic stress and σ_{eq}, the equivalent or von Mises stress) usually remains unchanged while the plastic strain increases rapidly [19], the critical equivalent plastic strain $\overline{\varepsilon}_p^{critical}$ can be deduced to be an expression of the triaxiality η. The triaxiality η indicates various loading states, such as in-plane pure shear state ($\eta = 0$) and uniaxial tension state ($\eta = 1/3$). The Rice & Tracey model can be taken as fracture criteria



a) b)

Fig. 1. Microscopic details of steel material: a) Pre-existing micro voids & cracks; b) Micro cracks after fracture failure.