Construction and Building Materials 112 (2016) 69–83

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Ductile crack initiation and propagation of structural steels under cyclic combined shear and normal stress loading

Liang-Jiu Jia [a,1], Toyoki Ikai [b], Kazuki Shinohara [b], Hanbin Ge [b,*]

[a] Research Institute of Structural Engineering and Disaster Reduction, Tongji Univ., Shanghai 200092, China
[b] Dept. of Civil Eng., Meijo Univ., 1-501 Shiogamaguchi, Tempaku-ku, Nagoya 468-8502, Japan

HIGHLIGHTS

- A cyclic ductile fracture model with both crack initiation and propagation rules is proposed.
- The fracture parameter for the crack initiation rule can be obtained from tensile coupon tests.
- A calibration method for the crack propagation rule is proposed using Charpy impact tests at transition region.
- Cyclic loading tests on three steels under cyclic combined shear and normal strain loading are conducted.
- Numerical simulation is conducted using a method with minor mesh-dependence.

ARTICLE INFO

Article history:
Received 20 September 2015
Received in revised form 4 February 2016
Accepted 23 February 2016

Keywords:
Ductile fracture
Crack initiation
Crack propagation
Combined loading
Cyclic loading
Structural steel

ABSTRACT

Ductile fracture preceding brittle fracture was observed in welded steel moment resisting frames during past strong earthquakes. Studies on ductile fracture were mainly focused on steels under normal stress loading, while seldom for those under combined shear and normal stress loading, which is also a common stress state for structural components, e.g., fillet welded joints and partial penetration welded joints. Ductile fracture of structural steels under combined shear and tension has been investigated through monotonic experiments in a previous study, and this paper aims to clarify the corresponding cyclic loading cases. Two series of specimens are manufactured, where they are respectively under pure shear, combined shear and normal stress loading. Meanwhile, a coupled fracture model considering material deterioration is proposed to simulate both ductile crack initiation and propagation, where a method to simply obtain the material parameter of the propagation rule is also proposed and validated through comparison between experimental and numerical results.

1. Introduction

In past strong earthquakes, brittle fracture of welded steel moment resisting frames (WSMRF) has been witnessed at numerous connections [1–3], where ductile fracture preceding brittle fracture was found to trigger the subsequent connection rupture [4]. Numerous research efforts were devoted to clarify the failure mechanisms, e.g. [4,5], and improve seismic performance of the welded connections, e.g. [6–9], after the 1994 Northridge earthquake and the 1995 Hyogoken-Nanbu earthquake.

Great research efforts have been devoted to improve seismic performance of connections in the steel frames, while ductile fracture prior to brittle fracture has not drawn much attention, which may be partially due to poor computational capacities of computers and lack of proper analytical approach. Different from conventional fracture mechanics problems, where the main analysis objects are cracked bodies, ductile fracture in structural engineering commonly occurs in uncracked bodies after experiencing a large amount of plastic strain.

Void growth models (VGM) [10,11] based on the void growth theory [12], and the Gurson model and GTN model [13–15] are employed to analyze ductile fracture problems of steel structures, e.g. [16,17]. However, these models are mainly developed for monotonic loading, and limited research [18–22] was carried out on ductile fracture under cyclic large strain loading (CLSL).

Recently, partial penetration illustrated in Fig. 1(a) due to improper welding and assembling sequences [23] or fatigue [24,25] was observed at full-penetration welded connections of WSMRF bridge piers during routine inspection. These connections are susceptible to cracking at weld roots of the incomplete penetration [26], and propagate along the weld throats as shown

---

[*] Corresponding author.
E-mail addresses: lj_jia@tongji.edu.cn (L.-J. Jia), gehanbin@meijo-u.ac.jp (H. Ge).
[1] Former Post Doctoral Researcher, Meijo Univ., 1-501 Shiogamaguchi, Tempaku-ku, Nagoya 468-8502, Japan.

http://dx.doi.org/10.1016/j.conbuildmat.2016.02.171
0950-0618/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

C_i	A material parameter related to the i-th backstress
D_{ini}	Damage index for the crack initiation rule
D_{prop}	Damage index for the crack propagation rule
E	Young's modulus
E_d	Unloading modulus of a damaged material
${}_vE_{shelf}$	Upper shelf Charpy impact energy
E_t	Charpy impact energy at a temperature of t
G	Absorbed energy of a unit area
G_c	Threshold value of G
Q_∞	The maximum size of the isotropic hardening component
J_2	The second deviatoric stress invariant
J_3	The third deviatoric stress invariant
L	The Lode parameter
R	Isotropic hardening component of the plasticity model
T	Stress triaxiality
k	Material parameter related to the isotropic hardening rate
l_c	Characteristic length of an element
t	Temperature
w	Crack width
w_1	Crack width when D_{prop} reaches unit
$\boldsymbol{\alpha}$	Total backstress tensor of the kinematic component of the Chaboche model
$\boldsymbol{\alpha}_\mathbf{i}$	The i-th backstress tensor
β	Angle between normal of the minimum cross section and horizontal direction
γ_i	A material parameter related to the i-th backstress
θ	Lode angle
ξ	One of the Haigh-Westergaard coordinates
σ_1	The first principal stress
σ_2	The second principal stress
σ_3	The third principal stress
σ_e	Effective stress of a damaged material
σ_{eq}	Equivalent stress
$\boldsymbol{\varepsilon}_\mathbf{p}$	Plastic strain tensor
ε_{eq}^p	Equivalent plastic strain
$\varepsilon_{eq,ini}^p$	Equivalent plastic strain at fracture initiation
χ_{cr}	Material parameter related to the crack initiation rule
ω	A parameter related to the Lode angle

in Fig. 1(b). The cross section of the weld throat is subjected to combined shear and normal stresses. Besides, shear dampers, e.g. [27,28], are also widely employed in structures, which employ metallic materials under combined shear and moment loading to absorb energy during earthquakes. Shear failure as illustrated in Fig. 2 was also found at beam webs of WSMRF bridge piers during the 1995 Hyogoken-Nanbu earthquake [29]. To quantitatively evaluate the seismic performance of the aforementioned structural components, it is necessary to investigate ductile fracture mechanisms under the combined stress state. However, to date, ductile fracture of structural steels under the combined shear and normal stress loading has seldom been investigated [30–32], especially for cyclic loading.

In a previous study, experimental and numerical study on ductile fracture under combined shear and tension was investigated [33], and a ductile fracture model with only a crack initiation rule was employed to simulate the cracking under monotonic loading. This paper aims to study both ductile crack initiation and propagation of three structural steels under cyclic combined shear and normal stress loading, and propose a practical approach to predict the whole cracking process up to rupture. Two types of specimens were manufactured, i.e., pure shear loading (PS series), and combined shear and normal stress loading (ST series). Experiments on the specimens were carried out under incremental cyclic loading. A single-parameter crack propagation rule is added to a previously proposed cyclic ductile fracture model [34], where the corresponding parameter of the crack propagation rule can be obtained from a Charpy impact test. Numerical analyses on both ductile crack initiation and propagation of the specimens were also conducted using the previously proposed cyclic fracture model and the newly proposed one, where a validated cyclic plasticity model [19] was employed simultaneously for the simulations. Comparison between the experimental and numerical results indicates that the newly proposed one can well simulate both the crack initiation and propagation of the specimens, while the previously proposed one cannot.

2. Coupled and uncoupled ductile fracture models under cyclic loading

A ductile fracture model, hereafter called uncoupled fracture model, was proposed to simulate ductile crack initiation under CLSL [34], where a damage index D_{ini} for ductile crack initiation is defined in a small increment,

$$\mathrm{d}D_{ini} = \begin{cases} \dfrac{\mathrm{d}\varepsilon_{eq}^p}{\chi_{cr} \cdot e^{-\frac{3}{2}T}} & T \geqslant -1/3 \\ 0 & T < -1/3 \end{cases} \tag{1}$$

where χ_{cr} = material parameter, $\mathrm{d}\varepsilon_{eq}^p$ = incremental equivalent plastic strain, T = stress triaxiality defined by the ratio of hydrostatic pressure to the equivalent Mises stress for metals. By postulating that damage increment follows the Miner's rule, the damage increments under different stress triaxilities can thus be summed, and ductile fracture initiation of a material is postulated to occur when D_{ini} reaches unit. The term 'ductile fracture initiation' herein denotes micro-crack initiation at a scale of 0.01–0.1 mm. In this study, micro-crack initiation is assumed to occur when the damage index D_{ini} reached unit. Macro-crack initiation is defined at the instant when the crack length is larger than 1 mm, which is termed "crack initiation" in this study.

A crack propagation rule based on an energy balance approach [35] is employed in this study, where it is postulated that a certain amount of energy G_c is absorbed by formation of a unit area of crack surface. The stored energy is released when a crack propagates. The crack propagates when the released energy is equal to or greater than the absorbed energy. This approach can straightforwardly simulate both crack initiation and propagation with relatively large mesh sizes, while common fracture mechanics methods is only applicable to crack propagation of cracked objects. A damage index, D_{prop}, for ductile crack propagation can be defined,

$$D_{prop} = \frac{G}{G_c} \tag{2}$$

where G = current absorbed energy of a unit area since the instant of fracture initiation as illustrated in Fig. 3, G_c = the threshold value for absorbed energy of a unit area. G_c can be calculated from the following equation using the correlation between the effective stress and crack width, w_1 [35].

$$G_c = \int_0^{w_1} \sigma_e \mathrm{d}w \tag{3}$$

where w_1 = crack width when D_{prop} reaches unit, σ_e = the effective stress of a damaged material as illustrated in Fig. 3, which can be defined as follows to consider material deterioration