Journal of Constructional Steel Research 139 (2017) 449–456

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

The strain-weighted energy damage model for structural steel under cyclic loading

Yueshi Chen, Yiyi Chen *

State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
Department of Structural Engineering, Tongji University, Shanghai 200092, China

ARTICLE INFO

Article history:
Received 25 September 2016
Received in revised form 25 September 2017
Accepted 30 September 2017
Available online xxxx

Keywords:
Damage model
Energy dissipation
Experiment for large plastic strain
Structural steel
Fracture prediction

ABSTRACT

By analyzing the energy dissipation capacity of structural steel under cyclic loading, it is found that the strain-weighted energy dissipation is a good parameter to quantify the damage. A new damage model is proposed for structural steel under cyclic loading using the maximum plastic strain and strain-weighted energy dissipation. The accuracy of the model is validated in the cyclic tests of Chinese structural steel Q345 and Q420 under large strain ($\pm 10\%$). Compared to the other models considering the combination of maximum deformation and energy dissipation, the calibration process is simplified, and the model provides better insight into damage accumulation as each parameter has a clear meaning. The model is able to predict fracture of structural steel using cyclic test data or only tensile test data.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Steel structures have great ability to resist earthquakes for their ductility and energy dissipation capacity. However, when the steel structure undergoes plastic deformation, the inevitable damage would accumulate till the structure fails. Under strong earthquakes, this kind of failure is associated with large inelastic strain amplitudes and occurs after a small number of cycles (in the order of ten). Therefore, this kind of failure could be categorized into low-cycle fatigue (LCF) or extremely low-cycle fatigue (ELCF) [1].

There are three ways to predict this kind of failure. The first one is fatigue life prediction which focuses on the relationship of the strain amplitude and the number of the cycles to failure. It is based on famous Manson-Coffin relationship [2,3]. Kuroda [4] and Tateishi et al. [5] modified this relationship considering the nature of extremely low cycle fatigue. Lignos et al. developed a numerical model to predict the fracture steel connection fractures due to LCF [6]. Secondly, micro-mechanics models are proposed by studying the nucleation, growth, and coalescence of micro voids. Kanvinde et al. proposed the cyclic void growth model to predict the ductile fracture initiation in structural steels due to ELCF [7]. Iyama and Ricles estimated the fatigue life of welded beam-to-column connections combining the LCF concept and micromechanics model [8]. Another effective way is to introduce the damage index to describe damage state quantitatively. It should have the following properties [9]:

1. The range of damage index should be 0 to 1. When $D = 0$, there is no damage accumulation; When $D = 1$, it means that the failure occurs.
2. Damage index should be a monotonic increasing function as the damage accumulation is an irreversible process.

Usually, the damage index is defined by certain cumulative quantity. Ge and Kang established a strain-based damage model to predict ductile crack initiation in steel bridge piers [10]. Castiglioni et al. proposed a cumulative energy reduction index for LCF failure of steel beam-to-column joints [11]. Many damage index models are established considering the combination of maximum deformation and energy dissipation [12–15]. One of most widely used model is the Park and Ang model (PA model) [13]

$$D = \frac{\delta_{\max}}{\delta_u} + \frac{\beta}{F_y \delta_u} \int dE \tag{1}$$

where δ_{max} is the maximum displacement experienced, δ_u is the ultimate displacement under monotonic loading, F_y is the yield strength, $\int dE$ is the dissipated hysteretic energy, and β is a weight factor. It is simple and has been calibrated using data from various structures damaged during past earthquakes [16]. However, this model presents some deficiencies. The weight factor for the maximum deformation is $1 + \beta$ and β for the others, which makes the model do not give a value of one for failure under monotonic loading [15]. The dependence of the damage on the deformation range is not considered. The physical

* Corresponding author at: State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China.
E-mail addresses: chenyosea@gmail.com (Y. Chen), yiyichen@tongji.edu.cn (Y. Chen).

https://doi.org/10.1016/j.jcsr.2017.09.034
0143-974X/© 2017 Elsevier Ltd. All rights reserved.

meaning of β is not clear, and the experimental determination of the β is also difficult [17].

The model is modified by Kumar and Usami (KU model) [15] as

$$D = (1-\beta)\left(\frac{\delta_{max}-\delta_y}{\delta_u-\delta_y}\right)^c + \beta\sum_{i=1}^{N}\left(\frac{E_i}{F_y(\delta_u-\delta_y)}\right)^c \tag{2}$$

where δ_y is the yield displacement, E_i is the dissipated hysteretic energy, β and c are two parameters. The weight factor is modified as 1 for the maximum deformation and β for the others. The parameter c from the Manson-Coffin type relationship is introduced to consider the effect of different deformation amplitude. The model gave better results than PA model in the test by the authors. Meanwhile, the problem related to parameter β still exists, and the determination of the parameters remained complicated as both two parameters need to be obtained by data regression of cyclic test data.

The damage models mentioned above are based on the uniaxial behaviors of structural members. The damage evolution process in structural steel could also be quantified by plastic strain and energy dissipation in the similar form [18]. Meanwhile, the failure of structural members could also be modeled through the uniaxial material behaviors. One way is to evaluate the local plastic strain history near ductile crack initiation location [10], and the other way is to model the structural member as a conglomeration of discrete fibers [19]. Recently, much excellent experimental work has been done on the behaviors of structural steel under uniaxial cyclic loading [20–22]. While the stress-strain relationship, as well as the damage evolution process, has been analyzed, the methods to quantify damage are still limited.

In this study, a damage model termed "strain-weighted energy model" (SWE model) is proposed by modifying KU model for uniaxial behaviors of structural steel. The model aims to quantify the damage related to energy dissipation without introducing the parameter β and offer simple calibration method for engineering application. The energy dissipation capacity under cyclic loading is analyzed by the Ramberg-Osgood function [23] and the Manson-Coffin relationship. It is found that the strain-weighted energy is a good parameter to measure damage. The model is verified and compared with PA model and KU model by large strain cyclic tests of Chinese structural steel Q345 and Q420 under large strain ($\pm$10%). The method to predict fracture of structural steel by this model is also demonstrated.

2. Model elaboration

As the damage is the linear combination of deformation and energy dissipation, the model is written as

$$D = D_d + D_e \tag{3}$$

where D_d is the damage related to deformation (called "deformation damage") and D_e is related to energy dissipation (called "energy damage"). The detailed elaboration of the model is shown as follows. To make this model capable when the strain range is large, the stress and strain mentioned in the model elaboration section are true stress and true strain.

2.1. Deformation damage

Considering the characteristic of damage in structural steel, plastic strain is adopted to measure the degree of damage for structural steel. Replacing the displacement in the KU model by plastic strain, the damage caused by deformation is written as

$$D_d = \left(\frac{\varepsilon_{pm}}{\varepsilon_f}\right)^{\frac{1}{\gamma}} \tag{4}$$

where ε_{pm} is the maximum plastic strain, ε_f is the fracture strain under monotonic loading and γ is the low cycle fatigue ductility exponent from the Manson-Coffin relationship

$$\Delta\varepsilon_p \cdot N^{\gamma} = C \tag{5}$$

where $\Delta\varepsilon_p$ is the plastic strain amplitude; N is the number of cycles to fracture. γ and C are material constants.

2.2. Energy damage

Firstly, consider the situation when strain amplitude is constant. The Ramberg-Osgood function (R-O function) is used to relate strain and stress in the cyclic situation.

$$\varepsilon = \begin{cases} \dfrac{\sigma-\sigma_l}{E_s} + \left(\dfrac{\sigma-\sigma_l}{K}\right)^m + \varepsilon_l, & \text{loading} \\ \dfrac{\sigma-\sigma_u}{E_s} - \left(\dfrac{\sigma-\sigma_u}{K}\right)^m + \varepsilon_u, & \text{unloading} \end{cases} \tag{6}$$

where E_s is the elastic modulus, m is a strain hardening exponent, and K is a modular parameter, (ε_l,σ_l) is the starting point during the loading process and (ε_u,σ_u) is the starting point during the unloading process.

If we set the strain amplitude as $\Delta\varepsilon_i$, the hysteretic energy per cycle (the area of the hysteresis loop) [24] is

$$W_i = \frac{m-1}{m+1}\Delta\varepsilon_{pi}\Delta\sigma_i \tag{7}$$

where $\Delta\varepsilon_{pi}$ is the plastic strain amplitude and according to the R-O function

$$\Delta\sigma_i = K(\Delta\varepsilon_{pi})^{1/m} \tag{8}$$

Then

$$W_i = \frac{m-1}{m+1}K(\Delta\varepsilon_{pi})^{1+\frac{1}{m}} \tag{9}$$

Thus, the energy required to fracture under constant strain amplitude is

$$W_{fi} = N_i W_i = \frac{m-1}{m+1}KC^{\frac{1}{\gamma}}(\Delta\varepsilon_{pi})^{1+\frac{1}{m}-\frac{1}{\gamma}} \tag{10}$$

Next, under variable strain amplitude, the Miner's law [25] is introduced to measure the damage accumulation

$$D_e = \sum_n \frac{w_i}{W_{fi}} \tag{11}$$

where w_i is the energy dissipation during the cyclic loading process, and W_{fi} is corresponding energy required to fracture.

Substitute the Eq. (10) to the Eq. (11), the energy damage is obtained

$$D_e = \sum_n \frac{(\Delta\varepsilon_{pi})^{\frac{1}{\gamma}-\frac{1}{m}-1} \cdot w_i}{\frac{m-1}{m+1}KC^{\frac{1}{\gamma}}} \tag{12}$$

Many ways have been proposed to calibrate the material constant C by tensile coupon test. A recent study by Xue [26] suggested that the monotonic test corresponds to $N = 0.5$ and $\Delta\varepsilon_p = \varepsilon_f$. This assumption is proved to be able to unify low cycle fatigue and extremely low cycle

Download English Version:

https://daneshyari.com/en/article/4923268

Download Persian Version:

https://daneshyari.com/article/4923268

Daneshyari.com