A Prediction Model For Ductile Fracture of Steel Bridge Piers

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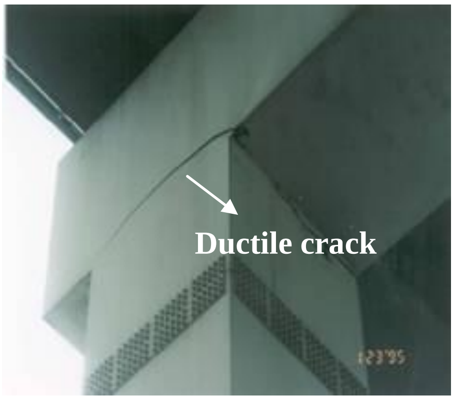
SUMMARY:
A cyclic ductile damage model is presented to simulate the ductile fracture failure of steel bridge piers due to large amplitude cyclic straining in structural steels, which is often the governing limit state in thick-walled steel structures subjected to earthquakes. This model is based on the modified two-surface-plastic model for cyclic loading, damage accumulative index and evolution law, a choice of element deletion whereby elements can be removed from the calculations once the material stiffness is fully degraded. It can simulate the ductile crack propagation until structural failure induced by the ductile fracture. The effects of extremely low-cycle fatigue (ELCF) and local buckling can be taken into account in this model.

Keywords: steel bridge pier, ductile fracture, extremely low-cycle fatigue (ELFC), accumulative damage, cyclic ductile damage model

1. GENERAL INSTRUCTIONS

Structural investigations following the 1994 Northridge earthquake and 1995 Kobe earthquake revealed that the combination of high fracture toughness demands caused by poor detailing of beam-column or column-base connections and low material toughness resulted in widespread fractures in these structural details (Fell, 2008) (as shown in Figure 1). Because no similar damage ever being reported in Japan before, the ductile fracture was not considered in seismic design prior to the Kobe earthquake and the corresponding evaluation methods were lacking. Nowadays, the necessity to consider ductile fracture (including the ductile crack initiation, propagation and failure, as shown in Figure 2) in the phase of seismic design for steel structures, especially in steel bridge piers with thick-walled cross section, has been gradually realized.

It is well-known that a precise evaluation of the safety or performance of a structure is required for natural hazards. Currently, the tools used by structural engineering researchers to simulate earthquake-induced ductile crack are not as sophisticated as other aspects of structural analysis. Common fracture prediction methodologies are often based on varying degrees of empiricism rather than fundamental mechanics, only realizing the relatively coarse prediction of ductile crack initiation, and can not simulate the ductile crack propagation until structural failure induced by the ductile crack. In such cases, commonly used simplified analysis methods may not be able to give a true picture of actual damage or losses. Therefore, a more advanced and accurate analysis method is needed to simulate the seismic behaviour that can occur at the element and structural level and to track the evolution of damage from onset to eventual member and structural failure.



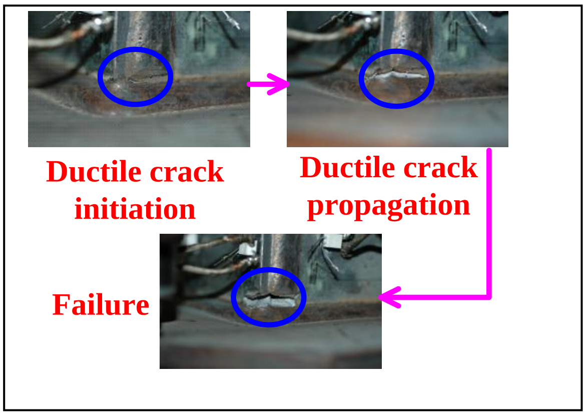


Figure 1. Ductile fracture in steel bridge pier in the 1995 Kobe earthquake

Figure 2. Ductile crack initiation, propagation and failure of steel bridge pier

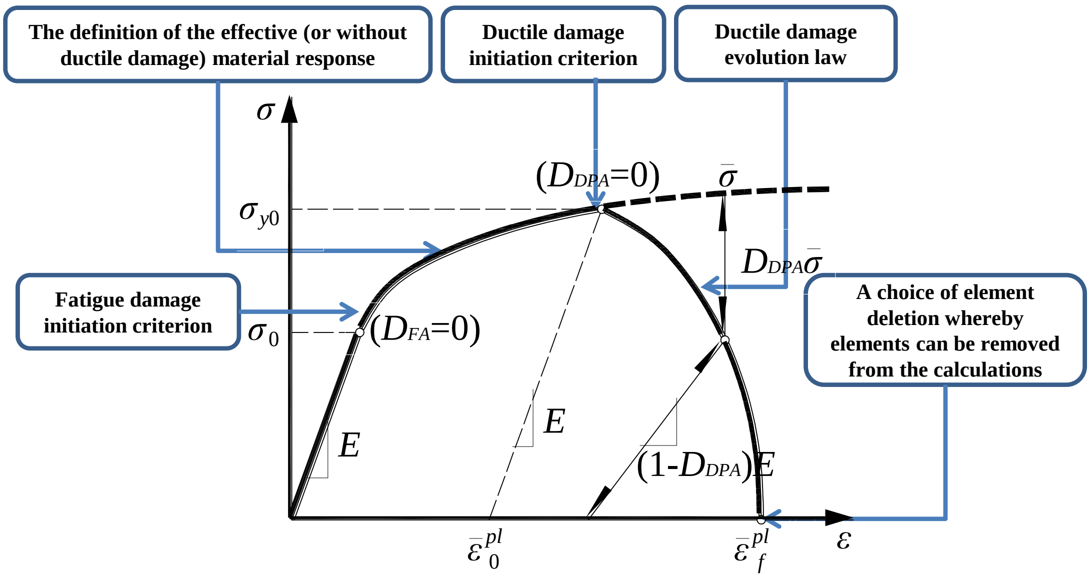


Figure 3. Cyclic ductile damage model of fracture including ductile crack initiation, propagation and failure

2. REVIEW OF MATERIAL MODELING FOR STEEL MEMBERS

The accuracy needed in extremely low-cycle fatigue (ELCF) is a more crucial problem than in low or high cycle fatigue (Dufailly and Lemaitre, 1995). In the case of extremely low-cycle fatigue (ELCF) failure, a more sophisticated, valid model is needed for three-dimensional states of stresses and complex histories of loading with the possibility of linear or non-linear accumulation of damage, and for allowing the coupling with plasticity to model the influence of fatigue damage on the phenomenon of strain hardening.

In this study, for the proposed damage mechanism model of ductile structural steel subjected to earthquake-induced cyclic loading, the following three distinct parts compose: the definition of the effective (or without ductile damage) material response; a ductile crack initiation criteria (including ductile damage initiation criterion, ductile damage evolution law and fatigue damage evolution law); a choice of element deletion whereby elements can be removed from the calculations once the material stiffness is fully degraded.

2.1 The definition of the effective material response

Engineering components and structures are typically subjected to cyclically varying loading conditions, which can eventually force the material to undergo cyclic plastic flow. Ductile fracture involves a large amount of plastic deformation and can be detected beforehand. The accumulation of plastic deformation with the number of cycles is a source of damage that, sooner or later, will lead to material failure. Therefore a precise cyclic plastic model is necessary, which can consider cyclic plastic, stiffness deterioration, nonlinear hardening and yield plateau. In past research, the multi-component combined isotropic/kinematic plasticity model is employed (Kanvinde and Deierlein, 2004; Fell, 2008; Huang and Mahin, 2008; Huang and Mahin, 2008; Myers et al., 2009; Huang and Mahin, 2010; Myers, 2010). The validity of the plastic model including strain rate decomposition, yield criterion, isotropic and kinematic hardening behaviour is verified by computer simulations. Besides, a modified two-surface model (M2SM) developed by Nagoya University (Shen et al., 1992; Shen et al., 1995) for steels with yield plateau has been verified to agree satisfactorily with the experimental results (Ge et al., 2000), and its validity in predicting the cyclic behaviour of steel structures has been established in previous research (Usami and Ge, 1998). With respect to model parameters of the M2SM, detailed descriptions can be found in the literature (Shen et al., 1992; Shen et al., 1995).

2.2 Ductile crack initiation criteria

In previous research, the fracture failure of steel members undergoing plastic deformation is described as a sequence of three events, i.e. initiation of a ductile crack (fibrous crack), stable growth of the ductile crack, and sudden propagation of a brittle crack (cleavage crack) (Kuwamura and Akiyama, 1994). In fact, before these three events, the damage accumulation has occurred and the four-phase fracture failure description, which consists of the damage accumulation, is more suitable. In the traditional fatigue mechanics, fatigue accumulative damage increases with applied cycles in a cumulative manner which may lead to fracture (Fatemi and Yang, 1998). Based on the traditional damage plastic mechanics, the damaging process is self-similar with respect to the ratio of the plastic strain to the fracture strain on any deviatorically proportional loading path at any given pressure (Xue, 2007). The problem of ELCF, with its extensive plasticity and limited cyclicity, may be treated an interaction between the mechanisms of ductile fracture and fatigue fracture. Therefore, the ELCF is more accurately conceptualized as an interaction between ductile fracture and fatigue fracture. In summary, the ELCF model's accumulative damage is composed of two parts: fatigue accumulative damage (D_{FA}) and ductile plastic accumulative damage (D_{DPA}). The overall damage can be expressed as in Eqn. (1). Table 1 reveals differences between D_{FA} and D_{DPA}.

$$D = D_{FA} + D_{DPA} \tag{2.1}$$

(1) Modified Manson-Coffin models

In the conventional low-cycle fatigue (LCF) regime, Manson and Coffin independently proposed the following empirical fatigue life relationship that is referred to as the Manson-Coffin relation:

$$\Delta\varepsilon_p N_f^k = C \tag{2.2}$$

where $\Delta\varepsilon_p$ and N_f are the plastic strain amplitude and the number of cycles to failure, respectively; k and C are the material constants. Eqn. (2.2) is represented by a linear relation on the log-log coordinates of the $\Delta\varepsilon_p$ and N_f. Besides, the damage accumulation for low-cycle fatigue (LCF) under random loading history is based on the Miner's rule (Miner, 1945). This method assumes that the effect of each cycle is independent, and the damage index D_i is defined as n_i/N_i, where n_i and N_i are the number of cycles and fatigue life for the i^{th} strain amplitude, respectively. In engineering practice, the cumulative damage index D is equal to zero when there is no damage and is equal to unity when failure occurs. The cumulative damage index D is expressed as follows:

$$D = \sum D_i = \sum (n_i / N_i) = 1.0 \qquad (2.3)$$

Table 1. Differences between D_{FA} and D_{DPA}

Fatigue accumulative damage (D_{FA})	Ductile plastic accumulative damage (D_{DPA})
The number of sites of microcracks initiation is large and the damage is not very localized as it is for low-cycle fatigue (LCF) and even more so for high cycle fatigue	The onset of fracture is detected by the condition for strain localization.
No damage threshold needs to be considered.	The damage threshold should be considered.
It is dependent on the accumulative plastic strain.	It is dependent on the equivalent plastic strain.

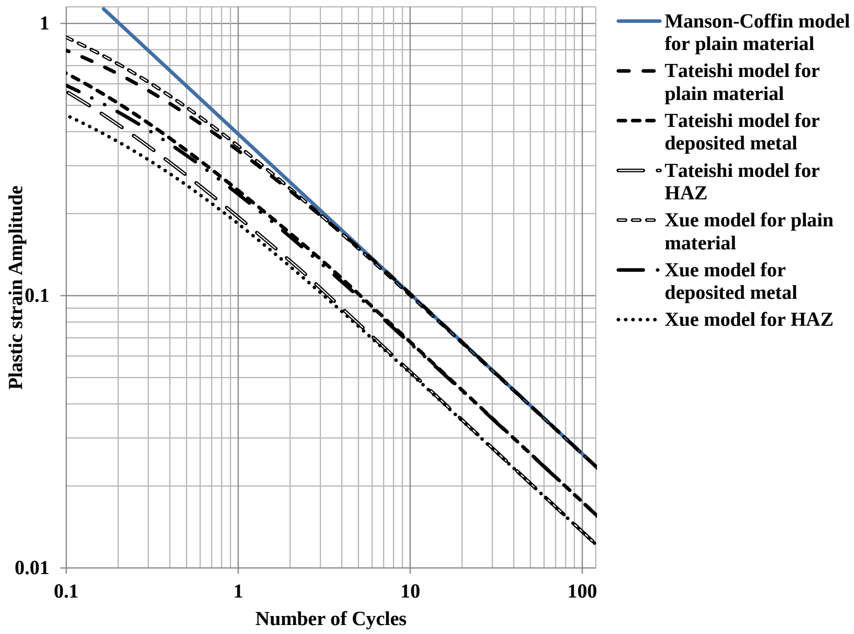


Figure 4. SN curves of different models

However, in the very low-cycle regime, often referred to as extremely low-cycle fatigue (ELCF), an over-estimation of fatigue life by the Coffin-Manson relationship has been observed (Kuroda, 2001; Xue, 2008; Nip et al., 2010). It has been shown in previous studies (Kuroda, 2001; Tateishi et al., 2007) that when number of reversals to failure falls below approximately 200, the strain-life relationship may deviate from the Coffin-Manson model, due to changes in the damage mechanisms (Nip et al., 2010). As the strain amplitudes increases from the LFC regime to the ELCF regime, the failure mode changes from fatigue fracture to ductile fracture. As stated as in Table 2, models accounting for the combined effects of ductile and fatigue damage have been proposed to establish strain-life relationships that cover both the LCF and ELCF regimes (Hatanaka and Fujimitsu, 1984; Kuroda, 2001; Tateishi et al., 2007; Xue, 2008). All of these models consider the effect of ductile damage by modifying the Coffin-Manson relationship. Figure 4 shows the fatigue strength of plain material, deposited metal and HAZ under constant strain amplitude, which come from some different models as described above. However, these models allow computation of damage just at the end of each cycle rather than during the response. While these represent important advances in the fatigue-fracture prediction methodology, the accuracy needed in ELCF is a more crucial problem than in low or high cycle fatigue because, for example, one more or less cycle for a ten cycles process of fatigue is already an error of 10% (Dufailly and Lemaitre, 1995). Therefore, this method may be not suitable for the case where the number of cycles to failure is less than ten because this will not allow a point in a material to fracture until the end of a full cycle (Huang and Mahin, 2010).

(2) Cyclic Void Growth model (CVGM)

The mechanism of ELCF is controlled by void growth and coalescence, and therefore the CVGM, developed by Kanvinde and Deierlein (2007; 2008), extends upon the widely used void growth model (VGM) (Kanvinde and Deierlein, 2006), developed by Rice and Tracey (1969) and others (McClintock, 1968) for monotonic loading. The fracture condition, Eqn. (2.6) occurs when the fracture demand exceeds the fracture toughness. Voids grow during tensile cycles, where tensile cycles are defined to occur whenever the mean stress at a material point is positive, and voids shrink during compressive cycles, similarly defined as whenever the mean stress is negative (Myers et al., 2009).

$$VGI_{cyclic} = \frac{\ln\left(\frac{R}{R_0}\right)}{C} = \sum_{\substack{tensile\\cycles}} \int \exp\left(\left|1.5T\right|\right) \mathrm{d}\bar{\varepsilon}_p - \sum_{\substack{compressive\\cycles}} \int \exp\left(\left|1.5T\right|\right) \mathrm{d}\bar{\varepsilon}_p \tag{2.4}$$

$$VGI_{cyclic}^{critical} = f(D) \cdot VGI_{monotonic}^{critical} \tag{2.5}$$

$$VGI_{cyclic} \geq VGI_{cyclic}^{critical} \tag{2.6}$$

In the VGM and CVGM, the initiation of a ductile fracture is triggered when the length of the micro-fracture reaches a characteristic length l^*. It overcome several limitations of standard fracture mechanics approaches which cannot be applied to components that undergo large scale yielding prior to fracture, or to structural details that do not feature a sharp flaw or crack. However, calibration of these models typically requires the testing of CNT specimens and complementary finite element simulations (Myers et al., 2009), they require determining the microcrack length using a finite element model, and therefore the mesh of the finite-element model must be appreciably smaller than l^*. However, since l^* is in the order of 0.1 mm (Chi et al., 2006; Kanvinde and Deierlein, 2006), the application of these micromechanical models to a connection which has a complex geometry, and therefore a complex stress-strain distribution requires a fine mesh and large computational power (Iyama and Ricles, 2009). Besides, it cannot simulate the crack propagation, the structural deterioration and failure.

(3) Leblond Model

The Leblond model (Leblond et al., 1995) extends a porous metal constitutive model (GTN model) originally developed by Gurson (Gurson, 1977), and subsequently modified by Needleman and Tvergaard (1984). In this model, the effects of material damage are considered through the constitutive model. A key parameter within the constitutive model is *f*, the void volume fracture (i.e. the ratio of the volume of voids to the total volume) of the material.

(4) Continuous Damage Mechanics Model

Bonora (1997) proposed a Continuum Damage Mechanics (CDM) model in which the constitutive behaviour under ELCF is coupled with the damage state. The main features of the CDM model are: ① Material damage is a non-linear function of the equivalent plastic strain; ② The modulus of the elasticity depends on the damage, where increases the material damage result in decreases in the modulus of elasticity; ③ Damage accumulates and its effects are active only during tensile loading (i.e. when the mean stress is positive). The CDM model predicts that compressive loading does not contribute to the process of ductile fracture. It is different than that of the CVGM which assumes that compressive loading has two effects on ductile fracture: voids shrink and the fracture demand decreases; damage accumulates as a function of the equivalent plastic strain.

Dufailly and Lemaitre (1995) has a relatively simple modification for damage evolution in cyclic loading:

$$\dot{D} = \begin{cases} \left[\frac{Y}{S}\right]^t \dot{\bar{\varepsilon}}^{pl} & \sigma_1 > 0 \\ 0 & \text{otherwise} \end{cases} \tag{2.7}$$

In which, S and t are material constants. Y is a power function of the associated variable. $\dot{\bar{\varepsilon}}^{pl}$ is the equivalent plastic strain rate. σ_1 is the maximum principal stress. Huang and Mahin (2010) revised the damage evolution relationship as follows:

$$\dot{D} = \begin{cases} \left[\frac{Y}{S}\right]^t \dot{\bar{\varepsilon}}^{pl} & \frac{p}{\bar{\sigma}} > -\frac{1}{3} \\ 0 & \text{otherwise} \end{cases} \tag{2.8}$$

In which, $p/\bar{\sigma}$ is the stress triaxiality. For the structural steel in tri-axial stress fields, Eqn. (2.8) can be expressed as followed:

$$\dot{D} = \begin{cases} \dot{D} = \left\{ \frac{\bar{\sigma}^2 \left[\frac{2}{3}(1+\nu) + 3(1-2\nu)\left(\frac{p}{\bar{\sigma}}\right)^2 \right]}{2E(1-D)^2 S} \right\}^t \dot{\bar{\varepsilon}}^{pl} & \frac{p}{\bar{\sigma}} > -\frac{1}{3} \\ 0 & \text{otherwise} \end{cases} \tag{2.9}$$

In which, $\bar{\sigma}$ is the equivalent stress, ν is the Poisson's ratio, E is the elastic modulus, S is the material constant, and σ_y is the yield stress. The best method of calibrating damage parameters is unknown because of current lack of detailed extremely low-cycle fatigue (ELCF) data. Additional research and material testing is needed. In the previous research (Huang and Mahin, 2010), the values of S and t are $\sigma_y/200$ and 1, respectively.

(5) Stiffness degradation

Fig. 3 illustrates the characteristic of stress-strain behaviour of a material undergoing damage. In the context of an elastic-plastic material with isotropic hardening, the damage manifests itself in two forms: softening of the yield stress and degradation of the elasticity. The overall ductile damage variable D_{DPA} is introduced and can be obtained based on effective plastic displacement or energy dissipated during the damage process. Based on the principle of strain equivalence (Lemaitre, 1972): “Any strain constitutive equation for a damage material by the effective stress”. The damaged stress tensor $\boldsymbol{\sigma}_{DPA}$ and damaged elastic modulus E_{DPA} can be expressed as following:

$$\boldsymbol{\sigma}_{DPA} = (1 - D_{DPA})\bar{\boldsymbol{\sigma}} \tag{2.10}$$
$$E_{DPA} = (1 - D_{DPA})E \tag{2.11}$$

2.3 Choice of element removal

Elements with severe damage should be treated in order to simulate crack initiation and propagation. An upper bound, $D_{\max}$ to the overall damage variable D is specified. There are two different treatments. The first choice is that an element is removed from the mesh if D reaches $D_{\max}$ at all of the section points at any one integration location of an element. Another choice is that an element remains active in the simulation and element deletion turned off.

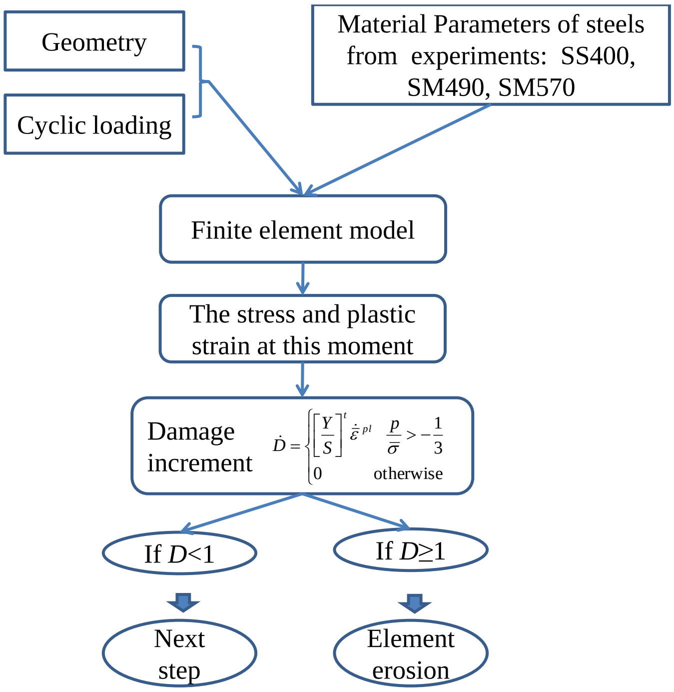


Figure 5. Calibration procedure for simulation of ductile crack initiation, propagation and failure

3. A CALIBRATION PROCEDURE FOR SIMULATION OF DUCTILE CRACK INITIATION, PROPAGATION AND FAILURE

Based on the above review of previous prediction models, ductile crack occurs when the damage index equals to 1.0. The evolution of damage including ductile and fatigue damage is a function of cyclic strain amplitude of each cycle, cycle number and material properties. In order to accurately the total procedure of extremely low-cycle fatigue (ELCF) failure, a calibration procedure for simulation of ductile crack initiation, propagation and failure is stated as shown in Figure 5. First of all, geometry and cyclic loading pattern should be determined. Material parameters of structural steels are obtained from tension tests of coupons. Secondly, finite element model can be established including weld. According to the proposed model of this study, nonlinear analysis is conducted to obtain the stress and strain states at this moment. Based on the obtained stress and strain, damage increment and accumulative damage can be achieved. Afterwards, the material point of this element can be regarded as totally losing stiffness.

4. CONCLUSIONS

This study describes a relatively new prediction model to predict ductile crack initiation, propagation and failure due to extremely low-cycle fatigue (ELCF). ELCF involves very large strains and few cycles, and it exhibits mechanisms distinct from low-cycle fatigue or ductile material failure. In order to accurately simulate the total procedure of ductile crack initiation, propagation and failure, a cyclic ductile damage model was proposed in this study. The proposed damage mechanism model of ductile structural steel consists of four distinct parts: the definition of the effective material response; a ductile crack initiation law; a choice of element deletion whereby elements can be removed from the calculations once the material stiffness is fully degraded. And the accumulative damage includes not only fatigue damage but also ductile damage. Their differences are compared in this study. Overall, the cyclic ductile damage model offers an exciting alternative to ductile fracture with the potential to overcome the disadvantage of traditional models that can not simulate the ductile crack propagation until structural failure induced by extremely low-cycle fatigue (ELCF).

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