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NONLINEAR ANALYSIS OF DAMAGE EVOLUTION FOR STEEL STRUCTURES UNDER EARTHQUAKE

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Abstract- The evolution of plastic deformation and damage in steel frame buildings caused by seismic action is simulated based on a modified damage model. This model combines nonlinear isotropic and kinematic hardening criteria with a damage evolution law expressed in terms of plastic displacement. A nine-story steel frame is chosen as a reference structure, and a nonlinear damage analysis is performed using ABAQUS with the El Centro earthquake accelerogram as input. The results reveal that the beam ends on the upper floors exhibit more obvious plastic deformation and form damage domains, which is consistent with the observed seismic damage of high-rise steel structures during the Northridge earthquake.

Keywords- Plastic Deformation, Damage Evolution, Nonlinear, Steel Frame

1. INTRODUCTION

The mechanical behavior of steel structures under earthquake conditions is typically nonlinear. To meet the requirements of a nonlinear analysis, many hysteresis models for steel members have been established. The simplest models are the ideally elastic-plastic model and other models that describe the strain hardening effect, such as the isotropic hardening model and kinematic model, are also proposed. In addition, a more complex constitutional model, in which both the hardening and the Bauschinger effect are taken into account, can be employed [1]. However, none of the above models considers the effect of damage accumulation in the materials, and accurate failure predictions can only be obtained if microstructural damage is incorporated into the constitutive relation. This requirement has led to the development of various fracture approaches and failure criteria for interpreting the behavior of structural components under seismic loading. Following the initial framework proposed by Lemaitre [l], several damage models have been derived and validated experimentally [2,3]. Anisotropic damage evolution was considered in Brunig and Zheng et al. [4,5]. Ding developed a damage model of steel based on plastic strain theory and energy dissipation [6]. Wang introduced the isotropic accumulation damage model and performed verification by using numerical examples [7]. In a study by Mashayekhi, an elastic-plastic damage model was used to simulate the ductile damage process of a flat rectangular notched bar [8]. This paper utilizes an extended damage model that considers both isotropic and kinematic hardening effects and introduces a damage evolution law expressed in terms of plastic displacement rather than equivalent plastic strain. In this study, the model is validated by performing nonlinear damage analysis on a nine-story steel frame in ABAQUS. The damage behavior of the structure is also simulated.

2. EXTENDED DAMAGE MODEL

From a physical point of view, damage can be defined as the progressive loss of material load carrying capability as a result of irreversible processes that occur in the material microstructure during the deformation history. Microvoids and microcracks are assumed to be evenly distributed in all directions, and thus the damage indicator D can be expressed as a scalar quantity. The damage variable is defined as the net area of a unit surface cut by a given plane and is corrected for the presence of existing cracks and cavities in the Lemaitre damage model [1]. Furthermore, from the hypothesis of strain equivalence, the effective stress tensor, $\tilde{\sigma}$, and stress deviator, $\tilde{s}$, can be represented as:

$$\tilde{\sigma} = \frac{\sigma}{1-D} \qquad \tilde{s} = \frac{s}{1-D} \tag{1}$$

where σ is the stress tensor and s is the stress deviator for the undamaged material.
The nonlinear isotropic/kinematic model can be used to more accurately simulate the inelastic behavior of steel materials when subjected to cyclic loading, and it is generally used with the von Mises yield surface, which is defined by the function:

$$F = f(\sigma - \alpha) - \sigma^0 \tag{2}$$

where $f(\sigma\text{-}\alpha)$ is the equivalent von Mises stress, σ^0 is an isotropic hardening component that describes the change of the equivalent stress, and α is a nonlinear kinematic hardening component that describes the translation of the yield surface in stress space through the backstress. According to the strain equivalence principle [1], the yield function of a damageable ductile material can be obtained if the Cauchy stress is substituted with an effective stress:

$$f(\sigma - \alpha) = \sqrt{\frac{3}{2}\left(\frac{s}{1-D} - \alpha^{dev}\right)\left(\frac{s}{1-D} - \alpha^{dev}\right)} \tag{3}$$

where s is the deviatoric stress tensor (defined as $s=\sigma+pI$, where p is the equivalent pressure stress and I is the identity tensor) and α^{dev} is the deviatoric part of the backstress tensor. For metallic materials, the associated plastic flow using von Mises yield surfaces generally predicts the behavior accurately. From the hypothesis of generalized normality, the plastic flow equation is given as:

$$\dot{\varepsilon}^{pl} = \dot{\bar{\varepsilon}}^{pl} \frac{\partial F}{\partial \sigma} = \frac{3}{2} \dot{\bar{\varepsilon}}^{pl} \frac{(s - \alpha^{dev})}{f(\sigma - \alpha)} \tag{4}$$

where $\dot{\bar{\varepsilon}}^{pl} = \sqrt{\frac{2}{3} \dot{\varepsilon}^{pl} : \dot{\varepsilon}^{pl}}$ is the equivalent plastic strain rate and $\dot{\varepsilon}^{pl}$ is the rate of plastic flow.
In Equation (2), the isotropic hardening behavior of the model, σ^0, can be expressed as a function of equivalent plastic strain in the simple exponential form [9]:

$$\sigma^0 = \sigma|_0 + Q_\infty (1 - e^{-b\bar{\varepsilon}^{pl}}) \tag{5}$$

where $\sigma|_0$ is the yield stress at zero plastic strain, Q_∞ is the maximum change in the size of the yield surface, and b defines the rate at which the size of the yield surface changes as plastic straining develops. The kinematic hardening that introduces nonlinearity is defined as:

$$\dot{\alpha} = C\frac{1}{\sigma^0}(\sigma - \alpha)\dot{\bar{\varepsilon}}^{pl} - \gamma\alpha\dot{\bar{\varepsilon}}^{pl} \tag{6}$$

where C is the initial kinematic hardening modulus and γ determines the rate at which the modulus decreases, with an increase in plastic deformation. The material parameters Q_∞, b, C, and γ can be obtained from material tests. In addition, neither isotropic nor kinematic hardening parameters are difficult to measure experimentally for a given material. If limited test data are available, then they can be specified based on the stress-strain data from the first half cycle of a unidirectional tension or compression experiment, or on the symmetric strain cyclic test data and stable cyclic stress-strain data. Alternatively, the references for similar material data can also be used for the required parameters.

The ductile criterion is a phenomenological model for predicting the onset of damage. Damage initiation can be assumed if the following condition is satisfied:

$$\omega_D = \int \frac{d\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_D^{pl}(\eta, \dot{\bar{\varepsilon}}^{pl})} = 1 \tag{7}$$

where ω_D is a state variable that increases monotonically with plastic deformation, and $\bar{\varepsilon}_D^{pl}$ is the equivalent plastic strain at the onset of damage, which is a function of the stress triaxiality η and the strain rate. Here, $\eta=-p/q$, and q is the von Mises equivalent stress.

If material damage occurs, then the stress-strain relationship no longer accurately represents the behavior of the material. The stress-strain relationship introduces a strong mesh dependency based on strain localization [9], in which the energy dissipated decreases as the mesh is refined. To follow the stress-softening branch of the stress-strain response curve, a different approach is required. Hilleborg's fracture energy proposal can be used to reduce this mesh dependency by creating a stress-displacement response after damage initiates. Using brittle fracture concepts, Hilleborg defines the energy required to open a unit area of crack, G_f, as a material parameter. Using this approach, the damage evolution law can be specified in terms of the equivalent plastic displacement, $\bar{u}^{pl}$, or in terms of the fracture energy dissipation, G_f:

$$D = \frac{1 - e^{-\alpha(\bar{u}^{pl}/\bar{u}_f^{pl})}}{1 - e^{-\alpha}} \qquad D = 1 - \exp\left(-\int_0^{\bar{u}^{pl}} \frac{\sigma_y \dot{\bar{u}}^{pl}}{G_f}\right) \tag{8}$$

Both of these equations take into account the characteristic length of the element to alleviate any mesh dependency of the results. In these equations, a is a parameter related to the material and can have a value between 0 and 3 for structural steel, and σ_y is the yield stress after damage. The fracture energy G_f is given as:

$$G_f = \int_{\bar{\varepsilon}_0^{pl}}^{\bar{\varepsilon}_f^{pl}} L\sigma_y d\bar{\varepsilon}^{pl} = \int_0^{\bar{u}_f^{pl}} \sigma_y d\bar{u}^{pl} \tag{9}$$

This expression introduces the definition of equivalent plastic displacement, $\bar{u}^{pl}$, as the fracture work conjugate of the yield stress after the onset of damage. L is the characteristic length, which is defined based on the element; for beams, the integration point length is used. This definition of the characteristic length is used because the direction in which the fracture will occur is initially unknown.

3. APPLICATION TO A STEEL BUILDING UNDER EARTHQUAKE CONDITIONS

As shown in Figs. 1 and 2, the nine-story steel structure has floor plan dimensions of 30 m × 30 m with 6-m bay spacing, and the height of the first story is 4.5 m and 3.9 m at the remaining floors. The building is designed with two different lateral load-resisting systems, including a braced frame in one direction and a non-braced frame in another. The cross-section of the members consists of built-up box columns and H-shaped beams and braces. The steel components are made of Q235 steel with a nominal yield and tensile strength of 235 MPa and 390 MPa, respectively. The Young's modulus and ultimate tensile strain are assumed to be 206 GPa and 0.25, respectively.

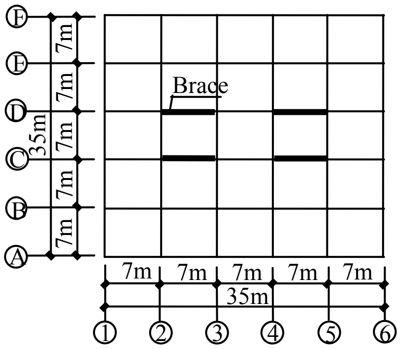

Fig. 1 Layout of brace plan

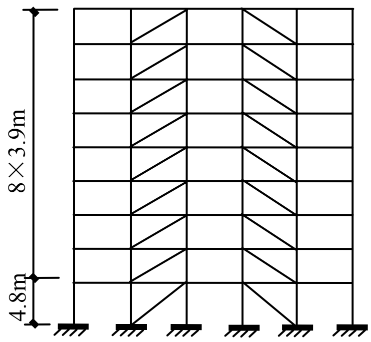

Fig. 2 Layout of brace elevation

For the damage analysis of steel structures, the two-line or three-line hysteresis model is typically used. Although this model is simple and relevant, is does not describe the nonlinear properties of strain hardening. By using the aforementioned isotropic/kinematic hardening damage model in which both the cyclic hardening effect and damage evolution are taken into account, the damage development process can be more accurately simulated if the El Centro recorded accelerograms are selected as inputs. Figure 3 shows the stress-strain data obtained from the stabilized cycle of a specimen that was subjected to symmetric strain cycles. If the test data are not available, then the method in reference [10] or numerical analysis can be performed, and the stress-strain relationship can also be defined.

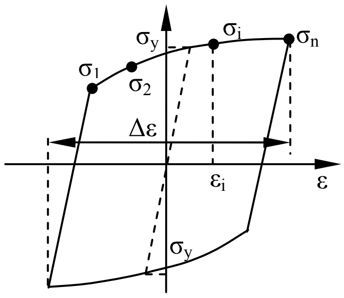

Fig. 3 Nonlinear hardening model

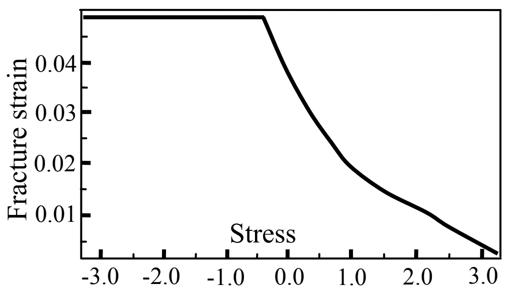

Fig. 4 Curve of fracture strain and triaxiality

Stress triaxiality (η=-p/q) accounts for the multiaxial state of stress that the material experiences, which may increase the propensity for fracture. Previous studies [11,12] demonstrated that the triaxiality of stress is a major factor leading to fracture of steel buildings during an earthquake. Hence, a three-dimensional nonlinear finite element analysis that considers material nonlinearity must be performed to precisely determine the triaxiality demands on the members. In this study, this criterion is adopted to determine the onset of damage and fracture in steel structures. The model assumes that the equivalent plastic strain at the onset of damage is a function of stress triaxiality ($\bar{\varepsilon}_D^{pl}(\eta, \dot{\bar{\varepsilon}}^{pl})$). The fracture strain and triaxiality curve is plotted according to the approach provided in the literature [11], as shown in Fig. 4.

Using the previously mentioned methods, the monotonic tensile stress-strain curve of Q235 steel was experimentally measured, and the damage parameters were determined. Therefore, the nonlinear analysis can be performed in the ABAQUS/explicit code by inputting various elastic-plastic and damage parameters. Because of symmetry, the plastic zones and damage domains of the steel frame can be shown on one half of the structure, as shown in Fig. 5 and Fig. 6.

4. RESULTS AND DISCUSSION

(1) Figure 5 shows that regions of plastic deformation are concentrated in the column and beam ends, and the first plastic zone occurred at the top of the bottom column in the side framework. As the earthquakes continued, the plastic regions traveled from the bottom story to the top and primarily focused on the two ends of the frame column. For the middle frame, the beams in the structure experienced inelastic action on two sides from a time of 3.6 s. By the end, almost all of the structural beams underwent plastic deformation.

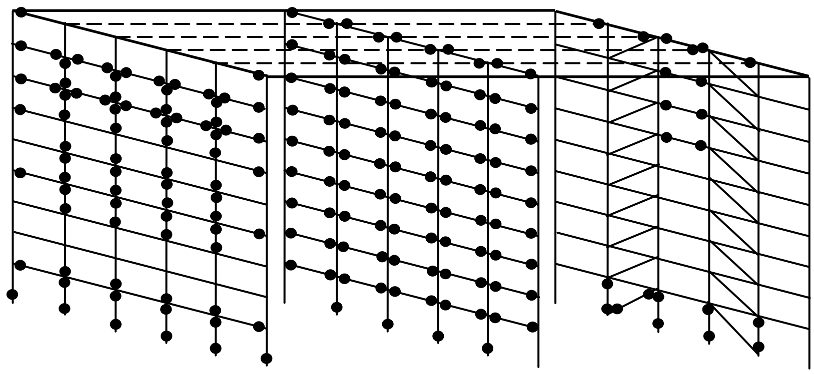

Fig. 5 Plastic zone of frames (the numbers reflect the order in which the zone occurred)

(2) Figure 6 presents the predicted damage process of the steel frame. Initially, the frame deforms homogeneously at the column and beam ends. At 4.6 s, plastic deformation propagated and introduced damage, which initially formed at the top floor and was accompanied by the maximum plastic deformation. However, the damage was relatively small with a damage value of about 0.0065. In the deterioration process, a material element gradually loses its load-carrying capability until complete fracture. As the earthquake continued, the maximum damage value (0.239) was located at the two upper floors and gradually spread to a maximum of four stories. At the end of the

earthquake (a time of 20 s), the maximum damage value was 0.595. As shown in Fig. 7, the damage was primarily concentrated on the beam end of the top few floors, which is in good agreement with results in the literature [12].

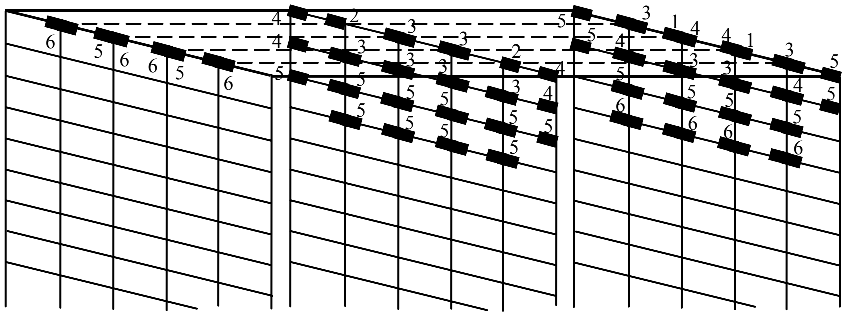

Fig. 6 Damage evolution of the steel frame (the numbers indicate the order in which the damage occurred)

5. REFERENCES

1. J. Lamaitre, A continuous damage mechanics model for ductile fracture, *Journal of Engineering Materials and Technology* **107**, 83-89, 1985.
2. N. Bonora, A non-linear CDM model for ductile failure, *Eng. Fract. Mech.* **58**, 11-28, 1997.
3. N. Bonora, D. Gentile, A. Pirondi and G. Newaz, Ductile damage evolution under triaxial state of stress: theory and experiments, *Int. J. Plast.* **21**, 981-1007, 2005.
4. M. Brunig, An anisotropic ductile damage model based on irreversible thermodynamics, *Int. J. Plast.* **19**, 1679-1713, 2003.
5. H. Zheng and M. H. Yu, Finite element analysis of steel members based on damage constitutive relations, *Journal of Gansu University of Technology* **29**, 104-108, 2003.
6. Y. Ding, F. Guo and Z. X. Li, Elasto-plastic analysis of spatial trusses under earthquake excitations considering damage accumulation effect, *Engineering Mechanics* **22**, 54-58, 2005.
7. L. K. Wang, J. P. Hao, J. F. Zhang, and M. H. Wang, Plastic-zone method of steel structure considering isotropic plastic damage, *Journal of Xian Jiao tong University* **42**, 885-890, 2008.
8. M. Mashayekhi, and S. Ziaei-Rad et al, Ductile crack growth based on damage criterion: Experimental and numerical studies, *Mechanics of Materials* **39**, 623-636, 2007.
9. ABAQUS Analysis User's Manual Version 6.8, Section 18.2.2, Section 19.2.2, 2006.
10. A. Pirondi, N. Bonora, Modeling ductile damage under fully reversed cycling, *Computational Materials Science* **26**, 129-141, 2003.
11. W. Z. Wang, Crack criterion and fracture tests of structural steel, *Engineering Mechanics* **25**, 27-31, 2008.
12. A. A. Shama and M. S. Zarghamee, Seismic damage evaluation of a steel building using stress triaxiality, *Engineering Structures* **25**, 271-279, 2003.