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Seismic damage evolution of steel–concrete hybrid space-frame structures

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A B S T R A C T

This paper presents a study on the seismic damage evolution and failure process of steel–concrete hybrid structures through simulation and tests. For steel members, the Krieg–Key constitutive model with a plasticity damage model is used to simulate the damage of steel. For concrete members, the improved Faria–Oliver model is adopted to analyze the damage of concrete. After that, these material models are assigned to fiber elements. The fiber element is adopted to establish a finite element model of steel–concrete hybrid structures. In order to evaluate the effectiveness of this modeling method, shaking table tests are conducted on a scaled test model of a three-storey steel–concrete hybrid structure. The test result shows that the proposed damage model and fiber elements are effective to simulate the seismic damage evolution and failure process of steel–concrete structures.

1. Introduction

The damage of structures during earthquake is a critical issue in the field of civil engineering because a severe damage is a great threat to life and property. Meanwhile, more and more new structural members or systems have been adopted to satisfy the needs of the development of the world. A steel–concrete hybrid (mixed steel material property and concrete material property) member or structural system has attracted much attention because of their excellent mechanical behavior, such as steel–concrete composite shear walls [1], steel–concrete–steel sandwich composite shell structures [2,3] and steel–concrete composite moment resisting frames [4]. Furthermore, a large number of steel–concrete hybrid structures have been located in seismic regions. Subjected to strong earthquake ground motion, the damage of steel–concrete hybrid structures will result in the local failure or overall collapse of the structures. Therefore, it is significant to study the damage evolution and failure process of steel–concrete hybrid structures under severe earthquakes.

In numerical simulation, two important problems have to be considered to study the seismic behavior of steel–concrete hybrid structures. One is the selection of appropriate material models including a steel material model and a concrete material model. The other is the selection of appropriate elements in finite element analysis. For the former problem, a significant amount of research work has been carried out to study the damage evolution law of steel and concrete in the past decades. Lemaitre and Chaboche adopted an isotropic plastic damage model of steel, which is based on a large number of uniaxial tensile tests [5,6]. Their proposed isotropic model differs from the fact that the damage is generally anisotropic in practice. Therefore, Sidoroff proposed an anisotropic damage model on the assumption of equivalent energy [7]. In addition, Krawinkler and Zohrei conducted a large number of tests to study the cumulative damage in steel structures under seismic excitation [8]. Shen and Dong presented a damage model of steel in one dimensional stress state [9]. The establishment of their model is based on the results of low cyclic loading tests. Mazars and Pijaudier-Cabot developed a damage model of concrete material considering unilateral effects [10,11]. The response of concrete structures was investigated in cyclic loading tests without considering the plastic behavior of concrete under compression. Cervera et al. established a damage model considering material failure and unilateral effects in concrete structures under cyclic loadings [12,13]. These damage models cannot simulate the plastic deformation and stiffness reduction of concrete structures. Therefore,

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some researchers proposed some elastic–plastic anisotropic damage models which are based on the equivalent stress space [14–24]. They observed that the simultaneous action of anisotropic damage and elasto-plasticity significantly affected the accuracy of numerical results. For the latter problem, fiber elements are usually adopted in the finite element analysis of steel–concrete hybrid structures. The fiber elements can significantly improve the calculation efficiency due to its lower computational cost. Taucer et al. [25,26] adopted fiber elements, which is based on the flexibility method, to model the softening property of concrete members. Chen and Huang used fiber elements to conduct the seismic analysis of a reinforced-concrete frame [27,28].

As described above, many efforts have been devoted to the seismic analysis of steel–concrete hybrid structures. However, an adequate constitutive model of steel and concrete is less developed for steel–concrete hybrid structures. This limitation motivated the authors to study an adequate model for analyzing the seismic damage evolution and failure process of steel–concrete hybrid structures. In this paper, a modified Krieg–Key constitutive model is used with a plasticity damage model for steel material [29]. The Bauschinger effect and stress hardening are considered. Meanwhile, the improved Faria–Oliver model is adopted to analyze the damage of concrete [24]. These material models, including strength criterion, failure model and damage criterion, are compiled in the subroutines of the commercial code LS-DYNA using fiber elements. The fiber elements, involving the subdivision of concrete shapes and steel rebars' composite section into small elements, need two constitutive models. These two models are the concrete damage model and modified Krieg–Key constitutive model for steel rebars, respectively. The fiber element is adopted to establish a finite element model of steel–concrete hybrid structures. In order to evaluate the effectiveness of the proposed simulation method, a scaled model of a three-storey steel–concrete hybrid space-frame structure is conducted in shaking table tests. With the application of this numerical method, the seismic damage evolution and failure process of steel–concrete hybrid space-frame structures are demonstrated in this paper.

2. Steel material model

2.1. Krieg–Key model

The Krieg–Key model is formulated in terms of the Von Mises yielding rule. This Krieg–Key model also considers the Bauschinger effect and a mixed hardening rule by defining hardening parameters. Furthermore, the Krieg–Key model is accurate and efficient to describe the mechanical properties of metal materials subjected to severe earthquake. The Von Mises yielding rule can be expressed as:

$$\phi = \frac{3}{2}(S_{ij} - \alpha_{ij})(S_{ij} - \alpha_{ij}) - \sigma_{yij}^2 = 0 \tag{1}$$

where σ_{yij} is the initial yield stress; S_{ij} is the deviator stress tensor; α_{ij} is the kinematic tensor.

The Krieg–Key model can be defined as:

$$\sigma_{yij} = \sigma_{0ij} + \beta E_p \varepsilon_{eff}^p = \sigma_{yij}(\varepsilon_{eff}^p, \beta) \tag{2}$$

$$E_p = \frac{EE_t}{E - E_t} \tag{3}$$

$$\varepsilon_{eff}^p = \int_0^t \left(\frac{2}{3}\dot{\varepsilon}_{ij}^p \dot{\varepsilon}_{ij}^p\right)^{1/2} dt \tag{4}$$

$$S_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk} \tag{5}$$

where σ_{0ij} is the yield stress; ε_{eff}^p and $\dot{\varepsilon}_{ij}^p$ are the equivalent plastic strain and the rate of effective plastic strain, respectively; E, E_p and E_t are the elastic modulus, the plastic modulus and the tangent modulus, respectively, $1/3\sigma_{kk}$ is the hydrostatic pressure; β is the hardening parameter. Moreover, $\beta = 0$ for kinematic hardening, $\beta = 1$ for isotropic hardening, and $0 < \beta < 1$ for mixed hardening.

When $0 < \beta < 1$, $\dot{\varepsilon}_{ij}^p$ can be expressed as:

$$\dot{\varepsilon}_{ij}^p = \dot{\varepsilon}_{ij}^{p(i)} + \dot{\varepsilon}_{ij}^{p(k)} \tag{6}$$

$$\dot{\varepsilon}_{ij}^{p(i)} = \beta \dot{\varepsilon}_{ij}^p \tag{7}$$

$$\dot{\varepsilon}_{ij}^{p(k)} = (1 - \beta)\dot{\varepsilon}_{ij}^p \tag{8}$$

where $\dot{\varepsilon}_{ij}^{p(i)}$ and $\dot{\varepsilon}_{ij}^{p(k)}$ are the ratios of plastic strain rate for the isotropic hardening phase and kinematic hardening phase, respectively.

According to the plastic flow law, the kinematic tensor α_{ij} can be expressed as:

$$\alpha_{ij} = \int d\alpha_{ij} = \int \frac{2}{3} E_p (1 - \beta) d\lambda (s_{ij} - \alpha_{ij}) \tag{9}$$

where $d\lambda$ is the increment of plastic multiplier.

From the incremental theory, the increment of effective plastic strain can be expressed as:

$$d\varepsilon_{eff}^p = \left(\frac{2}{3} d\varepsilon_{ij}^p d\varepsilon_{ij}^p\right)^{1/2} = \frac{2}{3} d\lambda \sigma_y \tag{10}$$

The increment of total strain $d\varepsilon_{ij}$ includes the increments of elastic and plastic strains. Correspondingly, the increment of stress can be expressed as:

$$d\sigma_{ij} = C_{ijkl}^e d\varepsilon_{kl}^e = C_{ijkl}^e (d\varepsilon_{kl} - d\varepsilon_{kl}^p) = C_{ijkl}^{ep} d\varepsilon_{kl} \tag{11}$$

$$C_{ijkl}^e = 2G\left(\delta_{ik}\delta_{jl} + \frac{v}{1 - 2v}\delta_{ij}\delta_{kl}\right) \tag{12}$$

$$C_{ijkl}^{ep} = C_{ijkl}^e - C_{ijkl}^p \tag{13}$$

where G is the shear modulus; v is the Poisson ratio; δ_{ij} is the Kronecker sign function; C_{ijkl}^e, C_{ijkl}^p and C_{ijkl}^{ep} are the elastic tensor, the plastic tensor and the elastic–plastic tensor, respectively.

So $d\lambda$ and C_{ijkl}^p can be derived from Eqs. (1)–(13):

$$d\lambda = \frac{(s_{ij} - \alpha_{ij}) d\varepsilon_{ij}}{\left[2\sigma_y(\varepsilon_{eff}^p, \beta)/9G\right](3G + E_p)} \tag{14}$$

$$C_{ijkl}^p = \frac{(s_{ij} - \alpha_{ij})(s_{kl} - \alpha_{kl})}{\left[\sigma_y(\varepsilon_{eff}^p, \beta)/9G^2\right](3G + E_p)} \tag{15}$$

2.2. The Krieg–Key failure criterion

In terms of the Krieg–Key model, a failure criterion is also proposed herein. In numerical simulation, the failure criterion provides a critical mechanical state in which the corresponding element or basic particle can be mathematically eroded with a comparatively small physical error. The Krieg–Key failure model is expressed as:

$$\Gamma = \frac{\sum \Delta\varepsilon_{eff}^p}{\varepsilon_f} \tag{16}$$

where $\Delta\varepsilon_{eff}^p$ is the increment of the effective plastic strain and ε_f is the failure strain, Γ is the failure parameter. The failure occurs when $\Gamma = 1.0$. The failure parameter Γ does not affect the reduction of