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Multi-level seismic damage analysis of RC framed structures

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ABSTRACT

A comprehensive approach to assessing seismic damage in reinforced concrete frame structures is proposed considering damage at five levels, i.e. material-level, section-level, member-level, story-level and the overall structure-level. Utilizing the concept of equivalent deformation, a generalized damage model was developed for each level. The damage value of each level can be obtained by the integration of the damage at the material level. Moreover, an interaction impact factor was proposed to reflect the correlation of damage mechanisms between the different levels. Data from a shaking-table test of a 12-story frame structure was used to verify the damage assessment method.

1. INTRODUCTION

A damage model is usually used to assess the nonlinear behavior for structure-level or member-level but normally limited used for design. The most important reason is don't know the damage correlations between different structural levels. It is not like the force-based design method which can clearly calculate the force relations between the structure-level, storey-level, member-level, section-level and material-level. Therefore, it is necessary to propose a new damage model to calculate damage for every structural level and find a method to reflect the damage correlations between different structural levels.

Damage model can be defined by different mechanical indicators, such as stiffness, deformation, energy, vibration characteristics and so on. For example, the hysteretic energy-based damage model is often used to evaluate the damage for structure-level or member-level (Sucuoglu 2004). The deformation-characterized inter-storey drift ratio or plastic rotation were used to define damage model by Banon and Veneziano (1982) and Wang et al. (2013). The bearing capacity of the M-N relationship can be used to evaluate the damage of section-level (Kamaris 2013).

The stiffness means the deformation resistant capacity, i.e., the ratio of force to deformation, for any structural level. It is an ideal damage indicator for the multi-level damage model. In fact, the stiffness-based damage index in a well-known concrete plastic damage model (Lubliner 1989) has been used for the nonlinear numerical analysis. It is based on the strain equivalent principle (Lemaitre 1971). Furthermore, weight coefficient (such as the lengths or important factors of the damage zones) are usually used to consider the damage influences from different structural levels.

In this paper, a generalized stiffness-based damage model was proposed. Its arithmetic expression in an integrating form and the correlation impact factor were used

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to analyze the multi-level damage mechanism. Finnaly, a shaking table seismic test of a single-span 12-storey RC framed structure was analyzed by using the proposed method.

2 Multi-levels for RC framed structure

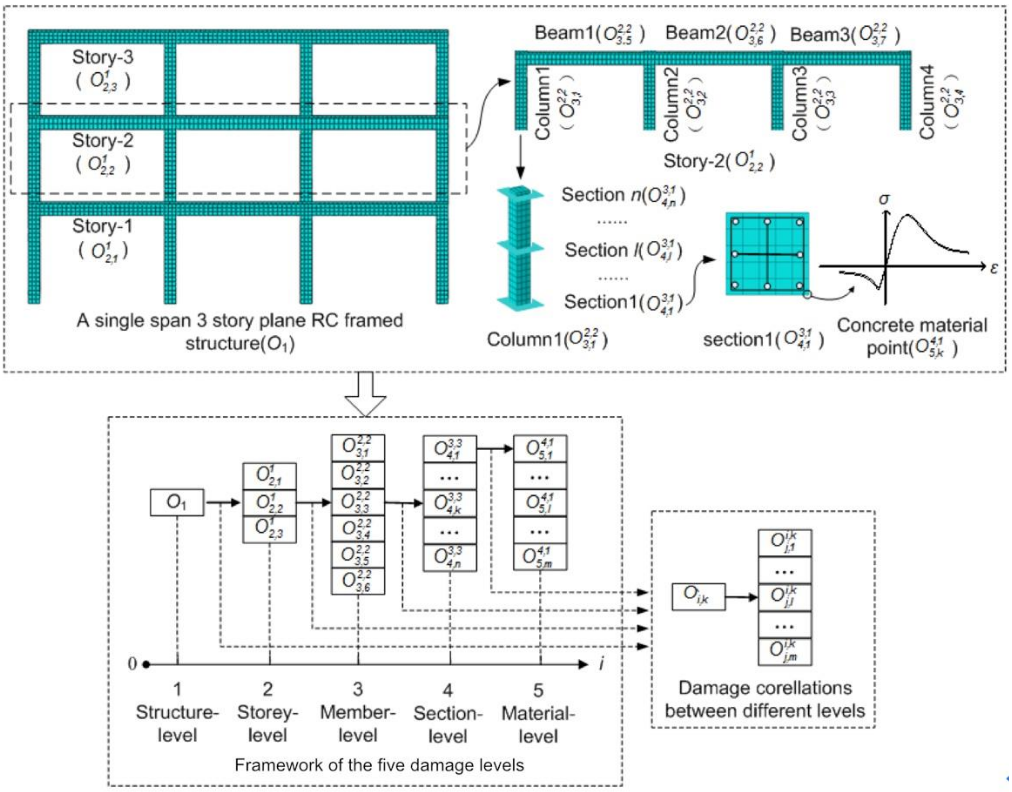

Fig.1 The example of multi-level definition

According to the definition, the affiliation framework of the five structural levels is expressed in Fig.1. Each structural level can be expressed as the analysis object O_i, in which the letter i means the structural level. The value of i is 1, 2, 3, 4 and 5 for the structure-level, storey-level, member-level, section-level and material-level, respectively. An example for the multi-level definition is shown in Fig.1. In Fig.1, the subscript i of $O_{i,k}$ denotes the structural level i and the subscript k is the object number, i.e. $O_{i,k}$ means the object k at level i and O_1 means the object at structure-level (the global structure). The superscript "i,k" of $O_{j,l}^{i,k}$ means it is a part of $O_{i,k}$, i.e. $O_{j,l}^{i,k}$ means the object l at level j as a part of $O_{i,k}$. As shown in Fig.1, the global structure is denoted as O_1 and storey-2 is denoted as $O_{2,2}^{1}$. In storey-2 ($O_{2,2}^{1}$.), the columns 1, 2, 3 and 4 are denoted as $O_{3,1}^{2,2}$, $O_{3,2}^{2,2}$, $O_{3,3}^{2,2}$ and $O_{3,4}^{2,2}$, respectively, and the beams 1, 2 and 3 are denoted as $O_{3,5}^{2,2}$, $O_{3,6}^{2,2}$ and $O_{3,7}^{2,2}$, respectively. In column 1 ($O_{3,1}^{2,2}$), section-1 can be written as $O_{4,1}^{3,1}$. The material point k of section-1 is denoted as $O_{5,k}^{4,1}$.

3 Stiffness-based seismic damage model

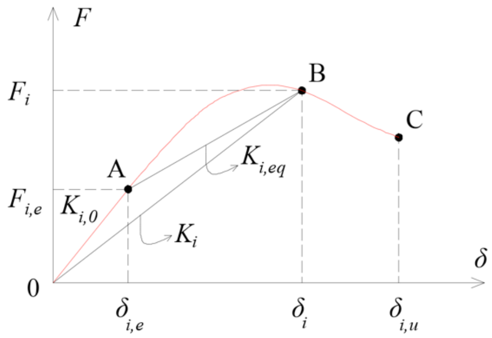

Fig.2 Generalized force-deformation relationship (Jianguang 2016)

In Fig.2, δ is the generalized deformation for every structural level, δ_i, $\delta_{i,e}$ and $\delta_{i,u}$ represent the deformation, elastic limit deformation and ultimate deformation of level *i*, respectively; F is the generalized force which corresponds to the generalized deformation δ, F_i represents the force for damaged configuration, $F_{i,e}$ is the elastic limit bearing capacity; $K_{i,0}$, K_i and $K_{i,eq}$ is the initial stiffness, secant stiffness and equivalent stiffness, respectively. The point A in Fig.2 is assumed to represent the initial damage state, so the generalized damage variable d_i is

$$d_i = 1 - \frac{K_{i,eq}}{K_{i,0}} \tag{1}$$

The free energy of concrete is assumed as (Oliver 1990)

$$\psi_5(\varepsilon, d_5) = (1 - d_5)\psi_5^0(\varepsilon) = (1 - d_5)\left[\frac{1}{2\rho_0}\varepsilon^T\sigma_0\right] = (1 - d_5)\left[\frac{1}{2\rho_0}\varepsilon^T E_0 \varepsilon\right] \tag{2}$$

$$d_5 = 1 - \frac{E_{eq}}{E_0}; \quad E_{eq} = \frac{\varepsilon E - \varepsilon_0 E_0}{\varepsilon - \varepsilon_0} \tag{3}$$

where ψ_5 and ψ_5^0 (*i*=5 means material-level) is the free energy of damaged material and undamaged material, respectively; d_5 is the material stiffness damage variable; ε and ε_0 is the strain tensor and elastic limit strain tensor of material, respectively ; σ_0 is the stress tensor of undamaged material ; ρ_0 is the material density ; E_0 is the initial elastic modulus, E_{eq} is the equivalent modulus, E is the secant stiffness.

The potential energy $W_{i,k}^p$ of object $O_{i,k}$ can be obtained by integrating ψ_5 with mass through the volume of $O_{i,k}$ and expressed as

$$W_{i,k}^p = \int_{V_{i,k}} \psi_5 dm = \int_{V_{i,k}} (1 - d_5)\psi_5^0 \rho_0 dV = (1 - d_5) W_{i,k}^{p,0} \tag{4}$$

where $W_{i,k}^{p,0}$ is the potential energy of undamaged object $O_{i,k}$, and $W_{i,k}^{p,0} = \int_{V_{i,k}} \psi_0 \rho_0 dV$. Thus, the stiffness damage $d_{i,k}$ of $O_{i,k}$ can be calculated from Eq.(4) and expressed as

$$d_{i,k} = 1 - \frac{W_{i,k}^{p}}{W_{i,k}^{p,0}} = \frac{\int_{V_{i,k}} \psi_5^0 dV - \int_{V_{i,k}} (1-d_5)\rho_0 \psi_5^0 dV}{\int_{V_{i,k}} \rho_0 \psi_5^0 dV} = \frac{\int_{V_{i,k}} d_5 \rho_0 \psi_5^0 dV}{\int_{V_{i,k}} \rho_0 \psi_5^0 dV} \approx \frac{\sum_e^{i,k} d_5 \psi_5^0}{\sum_e^{i,k} \psi_5^0} \tag{5}$$

where $\sum_e^{i,k}$ means the summation for all elements of object $O_{i,k}$. Eq.(5) shows that the stiffness damage $d_{i,k}$ for any structural level *i* can be calculated by the material damage d_5.

If the damage $d_{j,l}$ and the free energy $\psi_{j,l}^0$ of object $O_{j,l}^{i,k}$ are known, it has the relationships $\sum_e^{j,l} \psi_5^0 = \psi_{j,l}^0$ and $\sum_m \psi_{j,l}^0 = \sum_e^{i,k} \psi_5^0$. The damage $d_{i,k}$ of object $O_{i,k}$ ($j > i$) can be obtained by

$$d_{i,k} = \frac{\sum_m d_{j,l} \psi_{j,l}^0}{\sum_m \psi_{j,l}^0} \tag{6}$$

where $\sum_m$ means the summation for total parts of $O_{i,k}$, *m* is the part number of $O_{i,k}$.

Therefore, an impact factor $\gamma_{i,k}^{j,l}$ is proposed to calculate the damage influence from $O_{j,l}^{i,k}$ to $O_{i,k}$ in the expression

$$\gamma_{i,k}^{j,l} = \frac{d_{j,l} \psi_{j,l}^0}{\sum_m d_{j,l} \psi_{j,l}^0} \tag{7}$$

where $0 \le \gamma_{i,k}^{j,l} \le 1$, and the higher value of $\gamma_{i,k}^{j,l}$ means higher damage effect from $O_{j,l}^{i,k}$ to $O_{i,k}$.

4 Verification

A shaking table test of a 12-storey RC frame model (see Fig.3) of the State Key Laboratory of Disaster Reduction in Civil Engineering in Tongji University (2004) was used to verify the proposed method. This model has one single bay in the X or Y-direction, a total height of 3.6 m and storey height of 0.3 m. The compressive strength of concrete is from 5.74 MPa to 8.20 MPa. The cross-sectional size of all columns and beams are 50×60 mm and 30×60 mm, respectively. The average elastic modulus of concrete is 7.75×10^3 MPa. El-Centro waves were used as the input seismic motions. The values of input peak ground acceleration in X, Y and Z directions were 0.904 g, 0.769 g and 0.452 g, respectively.

Firstly, the damage influence from storey-level to structure-level were analyzed (see Fig.3(a)). It shows that the impact factor curves of storeys F4, F5 and F6 started to increase at about 0.25s and quickly reached to peak values of 0.39, 0.28, 0.18, respectively. The structure damage was caused by the storeys F4, F5 and F6 in the beginning and then caused by the storeys F2, F3, F7 and F8.

Comparatively, the damage influence from storey F5 and F6 were the most serious for the global structure. Thus, the damage influence from beam L5 and column Z5 to the storey F5 were analyzed in the following (see Fig.3(b)).

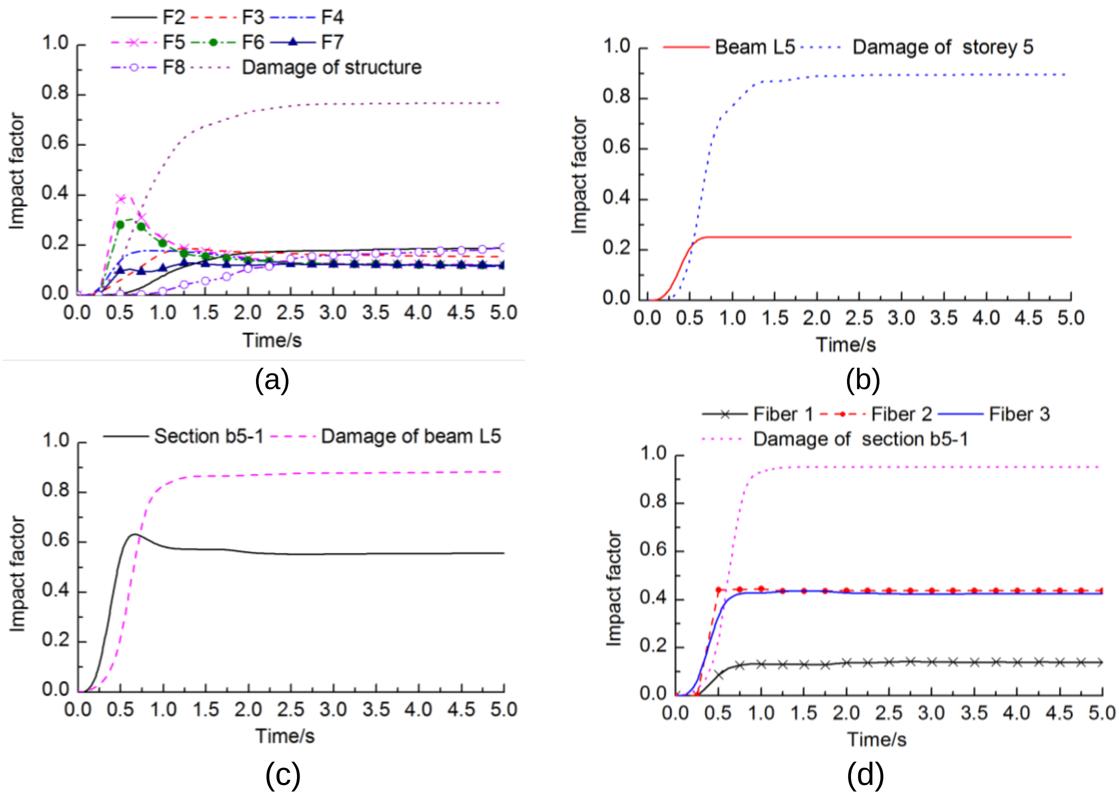

Fig.3 Damage correlations between different levels. (a) Storey-level to structure-level. (b) Member-level to storey-level. (c) Section-level to member-level. (d) Material-level to section-level.

In Fig.3(b), the impact factor values of column Z5 were very close to zero. It indicates that column Z5 did not affect storey F5. While the impact factor curve of beam L5 started to increase at o.25s and reached to the maximum value of 0.25. Meanwhile, the storey F5 reached to about half of its maximum value. It indicates that the damage storey F5 was mainly cause by the beams.

Furthermore, the damage effect from two cross sections (see Fig.4) and one diagonal section (see Fig.4) to beam L5 were analyzed as follows (see Fig.3(c)). Similarly, the damage of beam L5 was mainly caused by the cross-sectional damage.

Three material fibers (see Fig.4) were analyzed to reflect the damage influence from material points to the cross section b5-1. The impact factor curves of fiber 2 and fiber 3 were very close were larger than the value of fiber 1 (see Fig.3(d)).

Based on the above analysis, the failure of this 12-storey framed structure model was the plastic-hinge failure mode. The serious damage storeys were F5, F6 and F7. The damage of F5 was mainly due to the damage of beams.

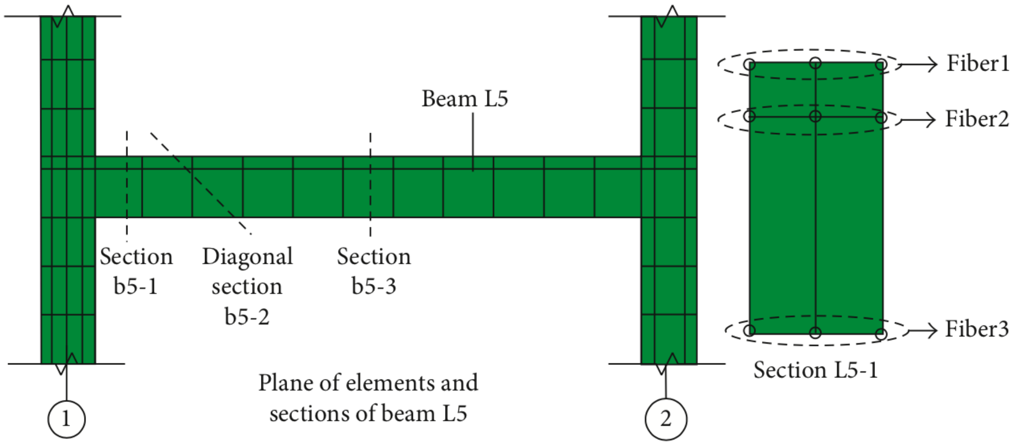

Fig.4 The analysis objects of member-level, section-level and material-level

7 Conclusions

A generalized stiffness damage model was proposed for all structural levels. Furthermore, an impact factor was proposed to reflect quantitatively the damage correlations between different levels. As an example, a single span 12 storey RC frame model was analyzed using this method. The results show that multi-level damage analysis method can evaluate the damage correlations between different levels.

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