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Seismic damage assessment of RC structures under shaking table tests using the modified direct stiffness calculation method

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ABSTRACT

The modified direct stiffness calculation (DSC) method for application to damage detection of RC frames based on the *stiffness variation index* (SVI) is comprehensively studied. Judging from the fact that few techniques were successfully applied to field problems, the objective herein is to apply the modified DSC method to RC frames, and to ensure that it really works. The vibration data recorded of a 12-story RC model frame under a series of shaking table tests (62 scenarios under four earthquakes of various levels) were adopted. The SVI adopted is based on two key parameters: (1) the modal curvature, which is *more sensitive* to structural damage than the mode shape frequently used, and (2) the modal moment, which is rather insensitive to ambient noises, as it is calculated from the *force equilibrium condition*. By comparing the present results with those based on a typical index (MDLAC) and the damage status of the frame in the tests, it is concluded that the modified DSC method, along with the SVI, can be reliably applied to the damage detection of RC frames in practice.

1. Introduction

Structural damage causes changes in the physical properties, e.g., stiffness and damping, of the structure. The changes in structural properties alter the dynamic response of the structure with reference to its initial pre-damaged condition. Over the past few decades, various techniques for system identification (SI) and structural health monitoring (SHM) of existing structures have been developed. A general literature review of the SI, SHM and relevant techniques can be found in Refs. [1,2].

Various damage indices were proposed for damage identification of structures, among which natural frequencies have been the one adopted by many researchers [3–6]. However, it is commonly known that measured natural frequencies do not always reveal noticeable changes due to the occurrence of local damages [7]. Although the mode shapes of a structure can be obtained by experimental means, the changes in mode shapes from the undamaged to damaged states may not be such remarkable [8]. Li et al. [9] proposed an approach for damage identification by minimizing the difference between a measured response vector and the reconstructed response vector obtained by the transmissibility matrix. Kim et al. [10] studied the co-ordinate modal assurance criterion (COMAC), enhanced COMAC (ECOMAC), absolute difference of strain mode (ADSM) shapes, and an alternative index based on the strain mode shapes. They compared the results of damage identification using these indices and showed that these indices did not perform well in damage identification. On the other hand, other parameters such as mode shapes, flexibility, frequency response functions (FRFs) and curvatures are found to be sensitive to small perturbations. Although they can be used as sensible indices for damage identification, they face problems such as the uncertainty in the environment, nonlinear damage process, as well as optimal locations for sensors and noise contamination in field monitoring, all of which need to be resolved [11–15].

Wei et al. [16] introduced the nonlinear auto-regressive moving average family of models with exogenous inputs to assess internal delaminating for some multi-layer composite plates. Shi et al. [17] adopted the improved modal strain energy to determine and locate damages for a two-story steel portal frame. Messina et al. [18] developed the multiple damage location assurance criterion (MDLAC) index using numerical data for two truss structures. Both the identified locations and sizing algorithms are validated experimentally using a three-beam test structure. Subsequently, the MDLAC has gained attention from several researchers [19–21] for damage detection using numerical simulation and data recorded from test and real structures. Maeck [22] and Huth et al. [23] proposed the *direct stiffness calculation* (DSC) method based on

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cross-sectional stiffness using the data collected for a simply supported beam.

Although the aforementioned works have made significant progress on methods of damage identification, difficulties still exist in their applications to real problems [24]. As parts of the effort to make applicable the DSC method along with the *stiffness variation index* (SVI), both numerical and experimental investigations were conducted on the damage detection of continuous beams and simple beams [25,26], the simplest types of structures governed by bending actions. By comparing the baseline stiffness with those obtained for different damage scenarios with measurement noises, the technique was numerically tested for the Truckee River Bridge in California [27]. The objective of this paper is to further the applicability of the above idea to damage detection of real framed structures, i.e., a reinforced concrete (RC) frame, composed of members dominated both by bending actions and axial forces, using both the numerical simulation and shaking table tests for a comprehensive series of seismic scenarios. The following is a summary of the technique used.

2. Modified DSC method

The original DSC method is based on the basic relationship between bending moment and bending stiffness. For a Bernoulli-Euler beam with the shear deformation neglected, the bending stiffness *EI* can be expressed in the *modal sense* as follows:

$$EI = \frac{M}{d^2\varphi/dx^2} = \frac{M}{\kappa} \tag{1}$$

where M and κ are the *modal moment* and the *modal curvature* at the same cross-section, i.e., coordinate x, of the beam, and φ is the mode shape function. Eq. (1) is valid for structures of which the deformation of each mode is considered small.

A general assumption in damage identification is that the mass of a structure remains unchanged after the occurrence of each damage, but the stiffness decreases accordingly [25,26]. For a structure in free vibration, the equation of motion is:

$$\mathbf{M\ddot{U}} + \mathbf{KU} = \mathbf{0} \tag{2}$$

where $\mathbf{K}$ is the stiffness matrix and $\mathbf{M}$ the mass matrix of the structure. Assuming that the displacement of the structure is of the harmonic type, we can transform the preceding equation into the following:

$$\mathbf{K}\varphi_{\mathbf{m}} = \omega_{\mathbf{m}}^2\mathbf{M}\varphi_{\mathbf{m}} \tag{3}$$

where ω_m is the mth frequency and φ_m is the corresponding mode shape. One interpretation with Eq. (3) is that the mth mode shape can be regarded as the displacement vector generated by the mth modal inertia force on the right-had side. To conform to Eq. (1) in the modal sense, the inertia forces can be calculated using the natural frequencies and mode shapes.

Let $\boldsymbol{x_i}$ and $\boldsymbol{x_{i+1}}$ denote two adjacent measurement sections of the beam, and $\phi_m(x)$ the experimentally determined mth mode shape, which is piecewise continuous. From the dynamic equilibrium of the beam segment in Fig. 1, the bending moment M_{i+1} and shear force V_{i+1} at section $\boldsymbol{x_{i+1}}$ of the mth mode can be calculated from those (M_i and V_i) at section $\boldsymbol{x_i}$ as

$$M_{i+1} = M_i - \int_{x_i}^{x_{i+1}} \omega_m^2 \rho A \varphi_m(x)(x_{i+1} - x)dx + V_i(x_{i+1} - x_i) \tag{4a}$$

$$V_{i+1} = V_i - \int_{x_i}^{x_{i+1}} \omega_m^2 \rho A \varphi_m(x)dx \tag{4b}$$

where ρ is the material density and $\boldsymbol{A}$ the cross-sectional area of the beam. At the end ($i = 0$) of the beam, the quantities M_0 and V_0 are calculated for each mode shape, which in turn depend on the inertial forces of the entire beam, as implied by Eq. (3). Therefore, the bending moment M and shear force V can be calculated in a recursive manner.

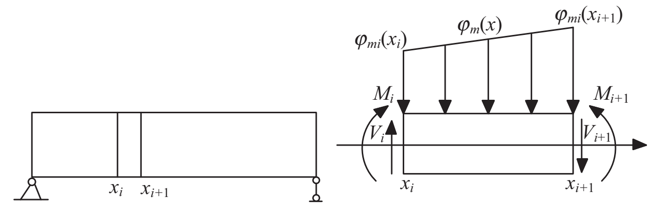

Fig. 1. Sign convention of internal forces and modal displacements.

The application of the DSC method requires the determination of modal curvatures. In the original DSC method, the modal curvatures are determined by a penalty-based smoothing procedure [22], by defining the objective function Π as the one containing the difference between the approximate and measured displacement mode shapes, with enforcement for the continuity of rotations and curvatures as follows:

$$\Pi = \int \frac{(v - \varphi_m^b)^2}{2} dx + \frac{\alpha L_e^2}{2} \int \left(\psi - \frac{dv}{dx}\right)^2 dx + \frac{\beta L_e^4}{2} \int \left(\kappa - \frac{d\psi}{dx}\right)^2 dx \tag{5}$$

where v is the lateral displacement, ψ is the rotation angle, κ is the curvature, ϕ_m^b is the measured mode shape, L_e is the length of the element, and $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are non-dimensional penalty factors. This procedure suffers from the drawback that it is hard to choose appropriate penalty factors $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$, as too high values of the factors may lead to locking of the system. For a structure with unknown damage locations, the penalty factors for each mode shape in the same damage status may not be the same and have to be determined separately. In addition, discrepancies were found in some coefficients of the variational matrix of the objective penalty function Π used to calculate the modal curvatures [28]. The above limitation of the original DSC method makes it difficult to apply to practical problems.

Alternatively, an improved DSC method was proposed with the modal curvature κ_m directly calculated from the measured deformation shape φ_m of the mth mode using the central difference method as [25–27]:

$$\kappa_m = \frac{\varphi_m(i+1) - 2\varphi_m(i) + \varphi_m(i-1)}{(\Delta l)^2} \tag{6}$$

where Δl denotes the distance between two adjacent sections of measurement. With the modal curvatures and modal bending moments made available, the bending stiffness at each location can be calculated using Eq. (1). As conventional, we assume that the mass of the beam remains unchanged after damage, but the stiffness decays accordingly. Consequently, a damage index called the *stiffness variation index* (SVI) was introduced [25–27]:

$$SVI = \left| \frac{EI_{\text{damaged}} - EI_{\text{undamaged}}}{EI_{\text{undamaged}}} \right| \tag{7}$$

where EI_{damaged} denotes the equivalent stiffness back-calculated from Eq. (1) for a specific location of the damaged beam, and $EI_{\text{undamaged}}$ the stiffness at the same location for the undamaged beam; the latter can be obtained from the original structural design. The SVI as defined in Eq. (7), is based on the *EI* value calculated from Eq. (1), which is a function of modal curvature and modal moment of each structural member. If the original design data is not available, it is still possible to predict the location and severity of the

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