

Damage Diagnosis of Frame Structures Using Modified Modal Strain Energy Change Method

Ting-Yu Hsu¹ and Chin-Hsiung Loh²

Abstract: This work presents a modified modal strain energy change (M-MSEC) method and its corresponding iteration process to detect damage to frame structures. Analytical results of a three-dimensional frame structure demonstrate that the quantity of damage can be identified correctly by using different modes in the M-MSEC method. A full-scale experimental study is also performed to evaluate the robustness of the M-MSEC method on damage detection as well as damage quantification. Satisfactory results are shown in relation to the modeling error, noise effect, and limited measurements.

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Introduction

Structural damage induces changes in modal information, such as natural frequencies, mode shapes, and modal damping. These modal characteristics have been employed to detect the location and quantity of damage. Several techniques for obtaining this information have been proposed in recent years (Doebbling et al. 1996). Modal strain energy (MSE), i.e., a function of mode shape and elemental stiffness, has been adopted initially as the indicator for modal selection (Lim and Kashangaki 1994; Doebbling et al. 1997), and has later been considered as a damage indicator (Stubbbs and Kim 1996; Shi et al. 1998). Moreover, the sensitivity of the modal strain energy change (MSEC) with respect to the local damage is derived, and is applied to identify the location and quantity of damage (Shi et al. 2000). The MSEC method was later improved, and the modal truncation errors as well as the finite-element modeling error in higher modes were reduced (Shi et al. 2002). The corresponding modal expansion for incomplete mode shape measurement, damage localization through modal strain energy change ratio (MSECR), and the elemental MSE threshold has been discussed to enhance the accuracy of the MSEC method (Hsu and Loh 2006).

Studies on damage diagnosis have only concentrated on the lump value of the damage extent of elements for simplification. In practice, when structure is damaged, equally reduction of stiffness in each degree of freedom (DOF) of elements cannot happen unless the element is removed or completely damaged. Further-

more, because different directional modes may make different contributions to the stiffness of different DOFs of elements, the diverse lump damage extent is obtained using different directional modes for the same elements, since the damage extent of different DOFs of the elements may be distinct (Hsu and Loh 2006). Consequently, obscure extents of damage to elements are obtained. This study considers a 3D steel frame structure composed of beam-column elements. The stiffness of a beam-column element relates directly to its sectional properties. Therefore, the elemental stiffness matrix is considered as the combination of stiffness matrices contributed by different sectional properties. The original MSEC method is modified to identify the stiffness loss contributed by different sectional properties of elements using adequate corresponding mode shapes. Accordingly, the damage extent of elements can be identified more accurately by the modified MSEC method, and all modes and their combinations become useful tools for identifying the damage extent of an element. Additionally, because the natural frequencies are determined much more accurately than the mode shapes, the sensitivity equation of an eigenvalue can also be added to the MSEC method. Verification of the proposed method through both numerical and experimental study of a 3D frame structure is conducted using very limited measurements, as is common in civil engineering structures. The experimental study of this application to a 3D test structure is performed on a shaking table to examine the effectiveness of damage detection of the proposed method.

Method for Damage Localization

The MSECR is employed to locate the damage. The basic idea of MSE is defined as the product of the elemental stiffness matrix and the second power of the mode shape component. For the j th element in the i th mode, the MSE before and after the occurrence of damage is given by

$$MSE_{ij} = \Phi_i^T K_j \Phi_i \quad \text{and} \quad MSE_{ij}^d = \Phi_i^{dT} K_j \Phi_i^d \quad (1)$$

where Φ_i denotes the i th mode shape of the undamaged state; K_j denotes the undamaged elemental stiffness of the j th element; superscript T denotes the transpose, and superscript d denotes the damaged state. In the modal strain energy of the damaged case,

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