Structural Damage Identification Using Modal Strain Energy Method

V.B. Dawari, P.P. Kamble and G.R. Vesmawala

Abstract Civil Engineering structures are prone to deterioration and damage during their service life period. Structural health monitoring is gaining high importance in conjunction with damage assessment and safety evaluation of structures. Vibration based damage identification techniques are global methods that are able to assess the condition of the entire structure at once. In this paper, the damage detection potential of two damage indices based on modal strain energy are evaluated for beam structures under different damage scenarios with respect to locations, severities and single and multiple damages. The appropriate finite element models of beam structures are developed and analysed for first five flexural modes using commercial software ANSYS. The algorithms available in the literature use flexural mode shapes for calculation of damage indices. In the present study, normalized mode shapes as well as normalized curvature mode shapes are used for computation of damage indices. The numerical results demonstrate that the indices could successfully detect and locate the damages in the beam models. In addition, there is improvement in the performance of damage indices in terms of reduction in presence of false alarms.

Keywords Damage detection algorithm · Modal strain energy · Finite element analysis

1 Introduction

Nondestructive evaluation (NDE) is one of the powerful tool which helps in assessing the structural condition of structures. These techniques provide valuable information about the condition of a structure at given locations. Vibration based

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damage identification techniques are global methods that are able to assess the condition of the entire structure at once. These methods are based on the fact that damage in a structure alters dynamic characteristics of the structure. The change is characterized by changes in the Eigen parameters that are natural frequency, damping values and the mode shapes associated with each natural frequency. In recent years, significant research and development has been carried out on the use of these methods, in particular modal methods for structural damage detection [1].

There are many damage indices presented in the literature based on different vibration parameters such as frequencies, mode shapes, damping values, mode shape derivatives, flexibility values, and strain energy values [2–6]. Among these damage indices, the strain energy based damage indices have high stability in detecting and localizing the damage as presented by Alvandi and Cremona [7].

Stubbs et al. [3, 4] developed the damage index based on modal strain energy change and applied it to localize the damage in a steel bridge. Further, Cornwell et al. [8] extended this method to plate structure. Park et al. [9] developed another form of strain energy based damage index to localize the damage in 3D truss bridge using numerical and experimental models. They observed that false indications of damage may occur at or near nodal points with the damage index. To minimize such false alarms, many researchers adopted improvements to the strain energy method [9–12].

In this paper, the study is conducted to investigate the capabilities and limitations of different damage detection algorithms based on modal strain energy changes for locating and evaluating damages. The damage index adopted from the literature uses flexural mode shapes for calculation of modal strain energy. In this paper damage index calculations are updated so as to use normalise displacement and curvature mode shapes. The updated damage index is evaluated for damaged steel beam structures under different damage scenarios with respect to locations, severities and single and multiple damages. First five flexural modes are analysed by modal analysis of appropriate finite element models of beam structures using commercial software ANSYS to derive the damage indices.

2 Damage Detection Algorithms

For a particular mode shape, $\phi_j(x)$, the energy associated with that mode shape of a general Euler–Bernoulli beam, is given by

$$U_i = \frac{1}{2}\int_0^l EI\left(\frac{d^2\phi_i}{dx^2}\right)^2 dx \tag{1}$$

If the beam is subdivided into N_d, divisions, then the fractional strain energy F_{ij} energy associated with each sub-region j from a_j to a_{j+1} due to the ith mode is given by

$$F_{ij} = \frac{U_{ij}}{U_i} = \frac{\frac{1}{2}(EI)_j \int_{a_j}^{a_{j+1}} \left(\frac{d^2\phi_i}{dx^2}\right)^2 dx}{U_i} \tag{2}$$

Similar quantities can be defined for the damaged structure, in which a superscript asterisk is used to denote the damaged state.

$$F_{ij}^{*} = \frac{\frac{1}{2}(EI)_j^{*} \int_{a_j}^{a_{j+1}} \left(\frac{d^2\phi_i^{*}}{dx^2}\right)^2 dx}{U_i^{*}} \tag{3}$$

The damage index proposed by Cornwell et al. [8] normally indicated false alarms at or near the node points of modes. Park et al. [9] therefore modified the expression as shown as Eq. (4).

$$(\beta_{ij})_1 = \frac{(k)_j}{(k)_j^{*}} = \frac{\frac{F_{ij}^{*}+1}{F_{ij}+1} + 1}{2} \tag{4}$$

When several modes m are used, expression takes the form of damage index

$$(\beta_{ij})_1 = \frac{\frac{\left(\sum_{i=1}^{m} F_{ij}^{*}\right)+1}{\left(\sum_{i=1}^{m} F_{ij}\right)+1} + 1}{2} \tag{5}$$

Li et al. [10] and Shih et al. [11] proposed a new damage index. The peak values of the damage index above the datum level 1 indicate the damage locations. To overcome this limitation (i.e., the division by zero difficulty) caused in β_1, an approximation is made such that the axis of reference for the modal sensitivities is shifted by a value of 1.0. Adding unity to both the numerator and the denominator.

$$(\beta_{ij})_2 = \frac{k_j}{k_j^{*}} = \frac{\left(\int_j \left[\phi_i''^{*}(x)\right]^2 dx + \int_0^L \left[\phi_i''^{*}(x)\right]^2 dx + \right) * \int_0^L \left[\phi_i''(x)\right]^2 dx}{\left(\int_j \left[\phi_i''(x)\right]^2 dx + \int_0^L \left[\phi_i''(x)\right]^2 dx + \right) * \int_0^L \left[\phi_i''^{*}(x)\right]^2 dx} \tag{6}$$

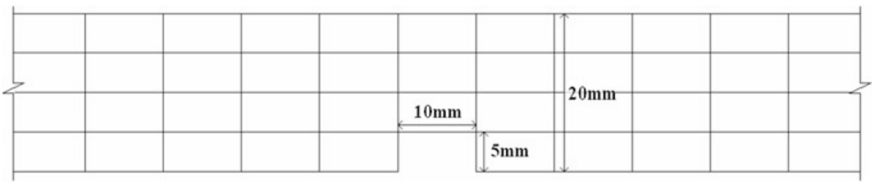

Fig. 1 Flaw size 'A' simulated in FEM

To account all available m number of modes, the damage index is given as

$$(\beta_j)_2 = \frac{\sum_{i=1}^{m} Num_{ij}}{\sum_{i=1}^{m} Denom_{ij}} \tag{7}$$

A judgement based thresh-hold value is selected and used to determine which of the j elements are possibly damaged.

Transforming the damage indicator values into the standard normal space, normalized damage index Zj can be obtained:

$$Z_j = \frac{B_j - \mu_{\beta j}}{\alpha_{\beta j}} \tag{8}$$

where $\mu_{\beta j}$ = mean of βj values for all j elements and $\alpha_{\beta j}$ = standard deviation of β_j for all j elements.

These damage indices could successfully predict single damage localisation but could not locate multiple damages. The indices depend on the summation of the combination of mode shape curvatures. Though mode shape vectors have been normalized, mode shape curvatures are not normalized. Values of mode shape curvature are dependent on the shapes of each individual mode shape. The summation of non-normalized mode shape curvatures may distort the damage index in favour of higher modes, which can result in false damage identifications. To reduce the problem of false alarms, an attempt is made to update these algorithms by using mass normalized mode shapes and normalized mode shape curvatures. In this work value of Z is considered to be 3 for damage.

3 Numerical Studies

Finite element simulation of three beam structures are used in the present study: Simply supported beam with span of 2.8 m; Two span continuous beam with each span length of 2.8 m and; Three span continuous beam with each span length of 2.8 m. The finite element beam models have isotropic material properties of steel whose modulus of elasticity and density are 200 GPa and 7,850 kg/m^3, respectively with cross section dimensions of 40 mm width and 20 mm depth. The beams are modeled with 560 number of 8 nodes brick elements (Solid185) of size 5 mm along the length with ANSYS v13. To simulate damage, the beam is cut to cause flaws on the tension face of the beam. Two different sizes of flaws are induced: Flaw size "A" is with length 10 mm, width 40 mm and depth 5 mm and flaw size "B" is with length 20 mm, width 40 mm and depth 5 mm. The flaws simulated in FEM are shown in Fig. 1. Seven damages cases investigated are detailed out in Table 1.

First five flexural modes of beam structures are extracted for intact and damaged beams from the FE analysis. The preliminary finite element model validation is

Table 1 Damage cases considered in the present study

Damage case	Span (of length (L) 2.8 m each)	Description of the damage
D1	Single	Damage ‘B’ at L/2
D2	Single	Damage ‘B’ at L/4 and L/2
D3	Single	Damage ‘B’ at L/4 from each side
D4	Two	Damage ‘A’ at L/4 of first span and B at 3L/4 of second span
D5	Two	Damage ‘A’ at L/4 and L/2 of first span, ‘B’ at L/2 of second span
D6	Three	Damage ‘A’ at L/2 of first span and B at L/2 of third span
D7	Three	Damage ‘B’ at L/2 of second span and ‘A’ at L/2 and 3L/4 of third span

Table 2 Validation of FE model for single span simply supported beam

State	Frequency mode	Present study	Experiment (Hz) Shih et al. [11]	FEM (Hz) Shih et al. [11]
Undamaged	Mode 1	05.86	5.94	5.84
	Mode 2	23.42	24.38	23.33
Damaged at mid-span	Mode 1	05.79	5.63	5.65
	Mode 2	23.42	23.13	23.33

carried out based on the experiment results presented by Shih et al. [11] as shown in Table 2. Two updated damaged indices are initially evaluated using the combined effect of first five normalized flexural mode shapes and curvature mode shapes. Then normalized updated indices are calculated from them as Z_1^* and Z_2^*. The normalised updated damage indices are plotted against the length of the beam.

4 Results and Discussions

The five mode shapes and their corresponding mode shape curvatures obtained from the results of FE analysis are used for calculating the updated modal strain energy based damage indices on beams. The plot of updated damage indices along the beam for damage cases are shown in Figs. 2, 3, 4, 5, 6, 7 and 8. The location of damaged elements is indicated through the spikes with magnitudes greater than 2 for single spans and 3 for multiple spans. Multiple numbers of peaks as in Figs. 5, 6, 7 and 8 clearly indicate the multiple damages in the beam. Both updated damage indices are able to correctly locate the damage in beams in all damage cases. For the beams with multiple spans, it is observed that, all damage indices show false alarms additional to the location of damages near to the support in terms of additional spikes (Figs. 6 and 8).

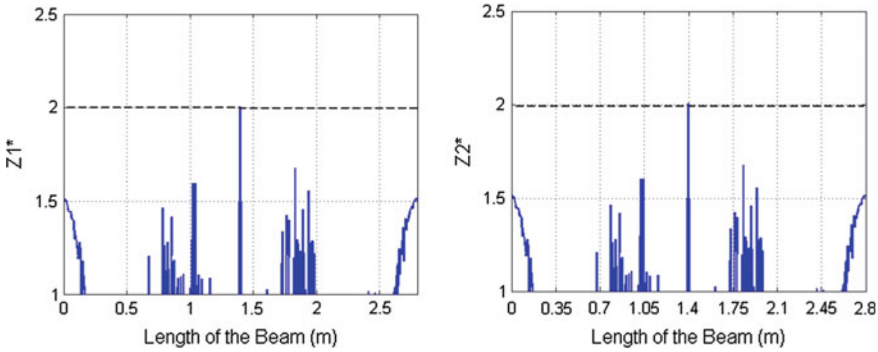

Fig. 2 Damage case: D1

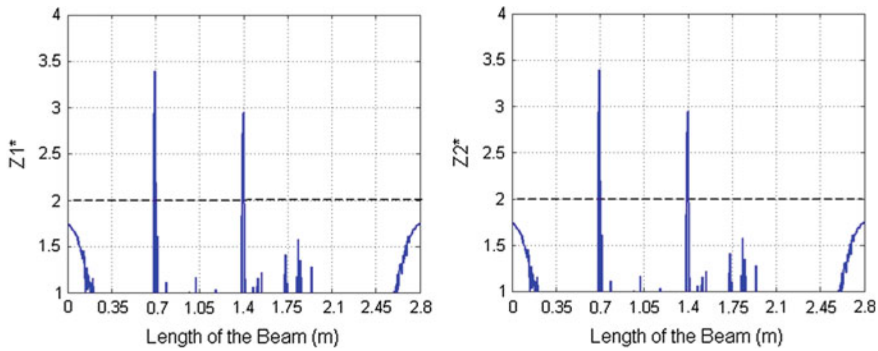

Fig. 3 Damage case: D2

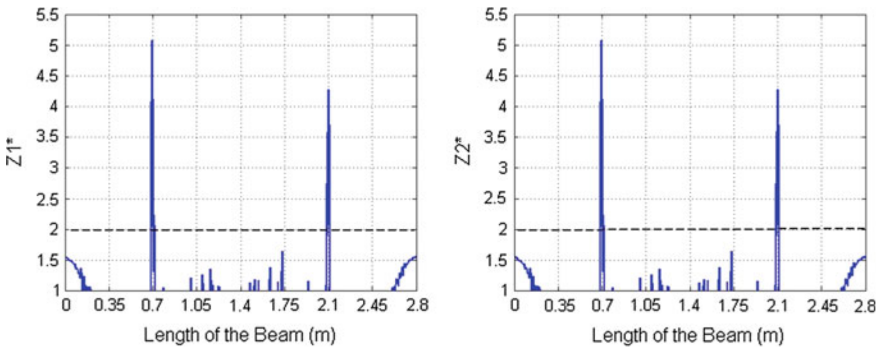

Fig. 4 Damage case: D3

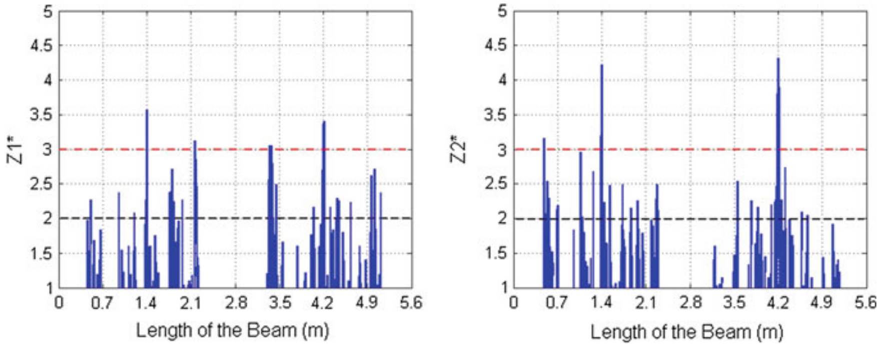

Fig. 5 Damage case: D4

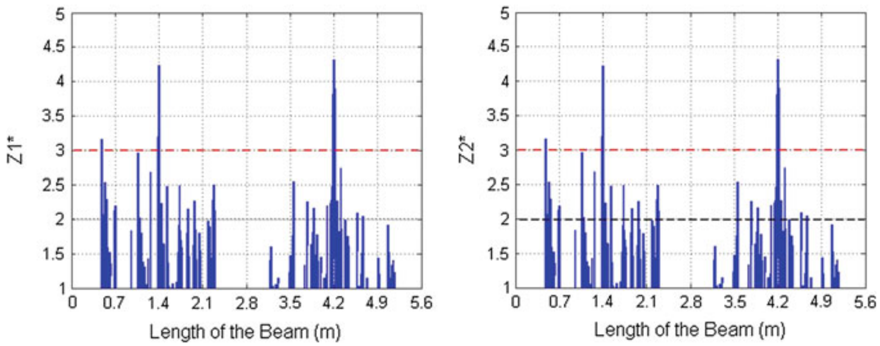

Fig. 6 Damage case: D5

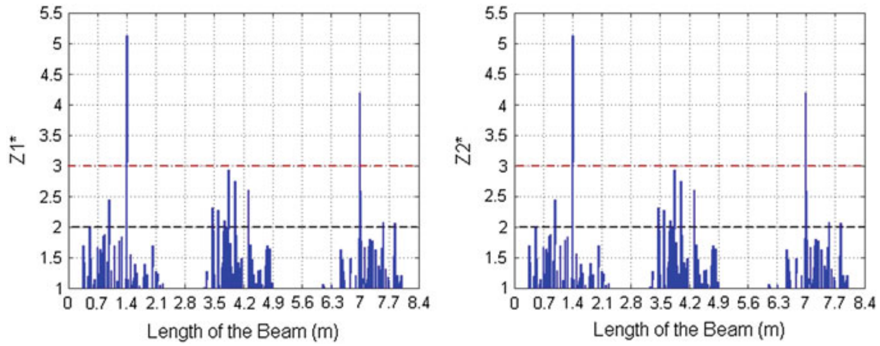

Fig. 7 Damage case: D6

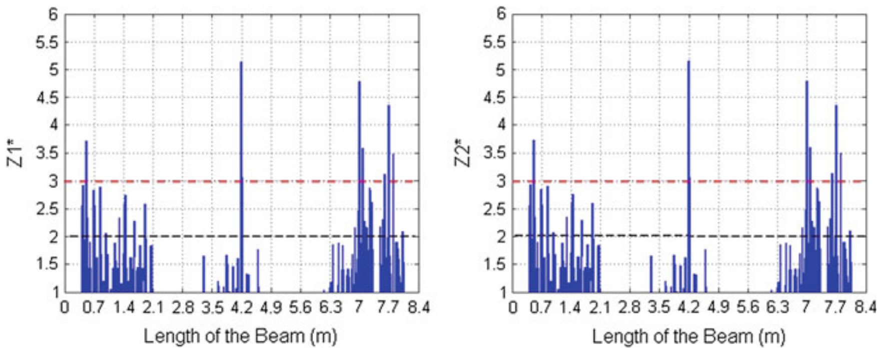

Fig. 8 Damage case: D7

5 Conclusions

A damage localisation method using modal strain energy changes is presented in this paper. Finite element analyses of the healthy and damaged steel beam models for different damage scenarios are carried out to extract first five flexural mode shapes. Two updated damage indices based on modal strain energy method, are evaluated using combined mode shapes. The peak values of each damage index indicate possible damage locations. Numerical results demonstrate that the damage indices successfully locate the single and multiple damage cases in single span beam. For beams with multiple spans and multiple damages, the damage indices located the damage with a few additional false alarms. The damage localisation method using updated damage indices perform better as compared to the original method in terms of giving less false alarms for damage localisation.

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