STRUCTURAL DAMAGE DETECTION USING VIBRATION-BASED DAMAGE IDENTIFICATION

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1. INTRODUCTION

Damage detection based upon changes in vibration characteristics is one of the few methods that can monitor the structure on a global basis. The basic idea of this method is that any changes in the physical properties of the structure (mass, stiffness and boundary conditions) will in turn cause changes in its modal characteristics (resonant frequency, modal damping and mode shapes)(1). In this paper, change in frequency and four different damage detection methods based on change in mode shapes have been summarized and applied using experimental and numerical data from an undamaged and damaged steel beam. Effectiveness in detecting and localizing the damage is compared for the different methods.

2. EXPERIMENTAL AND NUMERICAL DATA

In this research a simple steel beam supported by four bolts in both sides has been examined before and after releasing some bolts. Two multi-layer piezoelectric actuators were used for excitation(2). The main advantage of using piezoelectric actuators is that they produce vibration with different frequencies ranging from 0 to 400 Hz that was effective in measuring higher modes. Accelerometers were positioned on one line 5 cm from the bottom line of the front flange as shown in Fig. 1. Case 0 represents the undamaged beam, Case 1 represents one bolt released, the upper right bolt, from the left support and Case 2 after releasing two bolts, the upper right and the lower right bolts as shown in Fig.2. The finite element model of the actual beam is created using Structural Analysis Program, SAP2000. The model is benchmarked against the measured frequencies of the actual beam. Case 1 of damage in the numerical model is simulated by removing the springs in all directions X, Y, and Z at 4 nodes and Case 2 is simulated similarly by removing springs at 8 nodes. Mode shapes and resonant frequencies for the undamaged beam and for each case of damage are determined from cross power spectrum between each accelerometer and one reference channel. Change in frequencies and mode shapes due to damage will be examined using different damage identification methods.

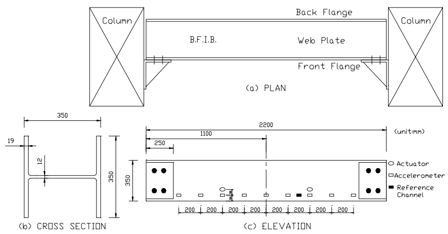

Fig. 1 Actuators and accelerometers position

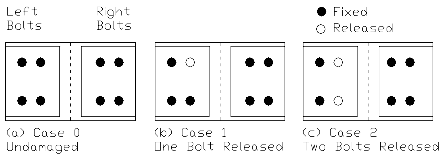

Fig. 2 Damage cases

3. DAMAGE DETECTION METHODS BASED ON CHANGE IN FREQUENCY

Table 1 shows the change in frequency in the numerical model after each case of damage. It is apparent that change in frequency is very small even after introducing the second level of damage. The remarkable change occurs at mode 10 for both cases of damage since this mode is vertical and it is the most sensitive for releasing any bolts. The second method for comparing the change in resonant frequency is using Gabor spectrogram. In this spectrogram the frequency components at each time are plotted using colored spectrum. Comparing frequency spectrogram for the undamaged beam, Case 0, and Case 2 of damage for experimental data reveals very small change in the spectrogram as shown in Fig. 3.

Table 1 Frequency comparison

Mode No.	Frequency (Hz)				
	Case 0	Case 1	% Diff.	Case 2	% Diff.
1	25.10	25.07	-0.10	25.05	-0.20
2	41.82	41.80	-0.04	41.78	-0.08
3	116.17	116.07	-0.09	115.94	-0.20
4	149.95	149.90	-0.04	149.84	-0.08
5	174.58	174.42	-0.09	174.19	-0.22
6	205.12	204.93	-0.09	204.67	-0.22
7	216.23	214.32	-0.89	212.37	-1.82
8	249.37	249.25	-0.05	249.13	-0.10
9	281.60	281.52	-0.03	281.42	-0.06
10	306.84	301.57	-1.75	293.93	-4.39
11	329.83	327.52	-0.70	325.73	-1.26
12	346.48	346.36	-0.03	346.25	-0.06
13	379.57	379.21	-0.09	378.95	-0.16

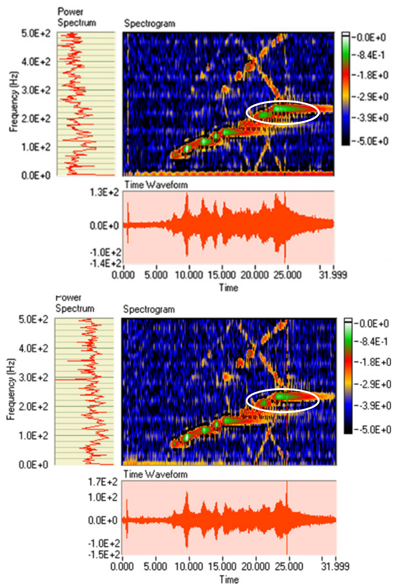

Fig. 3 Frequency spectrogram

4. DAMAGE DETECTION METHODS BASED ON CHANGE IN MODE SHAPES

4.1 DAMAGE INDEX METHOD

This method(1), (3) is used to detect and locate damage in structures using mode shapes before and after damage. For a structure that can be represented as a beam, a damage index, β, is developed based on the change in strain energy stored in the structure when it deforms in its particular mode shape. For location j on the beam this change in the ith mode strain energy is related to the change in curvature of the mode at location j. The damage index for this location and for ith mode is defined as follows

$$f_{ij} = \left[\int_a^b \left[\psi_i''(x)\right]^2 dx + \int_0^L \left[\psi_i''(x)\right]^2 dx\right] \Big/ \int_0^L \left[\psi_i''(x)\right]^2 dx \tag{1}$$

where $\psi_i''(x)$ represents the second derivative of ith mode, L is beam length and a, b are the limits for element j.

$$\beta_j = \left(\sum_{i=1}^{n} f_{ij}^{*}\right) \Big/ \left(\sum_{i=1}^{n} f_{ij}\right) \tag{2}$$

Damage index for element j, β_j, is calculated from the summation of f_{ij} over the measured modes, n. The asterisk represents the damaged modes. A normalized damage localization indicator is obtained as follows

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$$Z_j = \frac{\beta_j - \overline{\beta_j}}{\sigma_j} \quad (3)$$

where $\overline{\beta_j}$ and σ_j represent the mean and standard deviation of the damage indices, respectively. Values of two standard deviations from the mean are assumed to be associated with damage locations.

4.2 MODE SHAPE CURVATURE METHOD

For a beam cross section subjected to a bending moment M(x), the curvature at location x, $v''(x)$, is given by[(1), (4)]

$$v''(x) = M(x) / (EI) \quad (4)$$

where E = the modulus of elasticity and I = the moment of inertia of the section. Given the mode shape before and after damage, it is shown that the curvature of the beam is proportional to the inverse of the stiffness for a given moment. Therefore, any reduction in the stiffness of the structure associated with damage will increase the curvature. Maximum difference in mode shape curvature before and after damage indicates the position of damage.

4.3 CHANGE IN FLEXIBILITY METHOD

Flexibility matrix, [F], of a structure may be expressed in terms of modal parameters as follows[(1), (5)]

$$[F] \approx [\Phi][\Omega]^{-1}[\Phi]^T \approx \sum_{i=1}^{n} \frac{1}{\omega_i^2}\{\phi_i\}\{\phi_i\}^T \quad (5)$$

where $\{\phi_i\}$ = the ith mass-normalized mode shape, $[\Phi]$ = the mode shape matrix=$[\phi_1, \phi_2, \ldots \phi_n]$, (ω_i) = the ith modal frequency, $[\Omega]$ = the modal stiffness matrix = diag. (ω_i^2), and n = the number of measured or calculated modes. Therefore the change in flexibility caused by the damage can be obtained as follows

$$[\Delta F] = [F] - [F^*] \quad (6)$$

where ΔF represents the change in flexibility matrix. Now, for each column of matrix ΔF let δ_j be the absolute maximum value of the elements in the jth column. Hence,

$$\delta_j = \max\left|\delta_{ij}\right|, \ i = 1,\ldots n \quad (7)$$

where δ_{ij} are elements of matrix ΔF and n is the number of degrees of freedom. The degree of freedom corresponding to the maximum value of δ_j indicates the position of damage.

4.4 CHANGE IN UNIFORM LOAD SURFACE CURVATURE

In this method[(1), (6)] the change in curvature is obtained from the uniform flexibility shape instead of the mode shapes. Thus, the uniform load flexibility corresponds to the sum of the unit load flexibilities. In terms of the unit load flexibilities, the curvature change is evaluated as follows

$$\{\Delta\} = \sum_{i=1}^{n}\left|\left\{F_i^{*''}\right\} - \left\{F_i^{''}\right\}\right| \quad (8)$$

where F and F^* are formulated using equation (5), $\{\Delta\}$ represent the absolute curvature change and n the number of degrees of freedom. The degree of freedom corresponding to the maximum value of $\{\Delta\}$ indicates the position of damage.

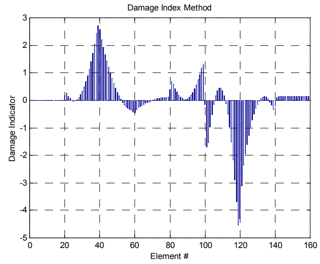

Fig. 4 Damage index method for Case 1

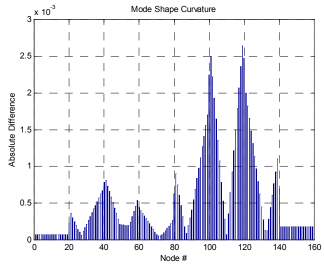

Fig. 5 Mode shape curvature method for Case 1

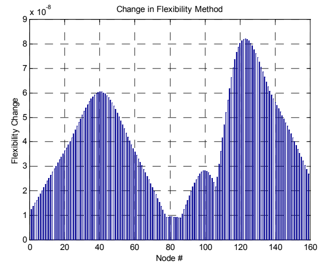

Fig. 6 Change in flexibility method for Case 1

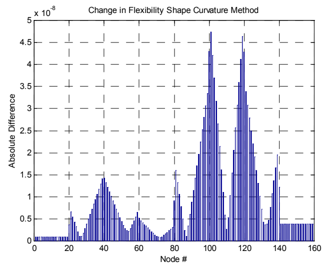

Fig. 7 Change in uniform load curvature method for Case 1

4.5 DAMAGE IDENTIFICATION METHODS APPLIED TO EXPERIMENTAL DATA

In Fig. 4, damage index exceeds the value of two at elements 40 and 120, which indicates the occurrence of damage. For the change in mode shape curvature method the maximum change occurs at nodes 100 and 120 as shown in Fig. 5. The same remarks are obtained for change in flexibility method and change in flexibility shape curvature method as shown in Fig. 6 and Fig.7 respectively. After applying the same methods for Case 2 of damage it was noticed that the damage measure is increasing at the same position with increase of damage. The results of the same methods obtained from the numerical model have shown a good agreement with the experimental results.

5. CONCLUSION

Examining the change in resonant frequency has shown low sensitivity for damage detection. Damage methods, which are based on change in mode shapes, have proven a better and more sensitive indicator of damage. These methods could determine the vicinity of damage position but no method could determine the exact position of damage and moreover sometimes they indicate false position of damage. Change in some mode shapes are more sensitive depending on the type of damage occurred, therefore it is important to measure these modes to improve the ability to detect that type of damage. Finite element model for the actual structure can be used for producing many different patterns, sizes and positions of damage and hence identifying the results of different damage identification methods for each type of damage. These results can be used to estimate the type and position of damage from the results of the actual structure.

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