振動計測による梁部材のクラック検出

Crack Detection in Beam-Type Structures using Vibrational Measurements

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1. Introduction

Structural damage detection using vibration measurements can be considered as a global non-destructive health monitoring technique. Since damage alters the dynamic characteristics of a structure, namely its eigen properties (natural frequencies, modal damping and modes of vibration), several techniques based on experimental modal analysis have been developed in recent years. Most of referenced vibration based damage identification methods are based on changes in mode shape, resonant frequencies and modal damping1), 2), 3), 4), 5). Damage Index Method is one of the most referenced damage identification methods. This method is based on changes on mode shapes before and after damage as will be described in more details in section 5. The drawbacks of this method is that detecting small damage needs measuring higher modes which are usually difficult to measure experimentally. In this paper, Damage Index Method will be applied using operational mode shape instead of using modal shape. Damage Index Method will be applied to experimental and numerical data extracted from simple steel beam after making single and multiple cracks. Obtained results using operational mode shapes are compared to the results when modal data are used. Simplicity, no need for measuring excitation force and no need for measuring higher modes are the main advantages of the new technique.

2. Measuring modal data using Cross Spectral Density

Mode shapes and resonant frequencies are usually determined using conventional FRF spectral analysis techniques, which require the measurement of the forcing function. In the case of continuous health monitoring of structures, ambient vibrations are used as excitation force. For example ambient vibrations in bridges may be caused by traffic, wind, water waves, seismic ground motions or other environmental factors. One difficulty with determining the dynamic parameters of a structure undergoing ambient vibrations is that the forcing function is not precisely characterized.

Another technique for measuring modal data without measuring the excitation force was introduced by McLamore, et al. (1971). In this work the motion of a bridge at different positions was measured then PSD for the motion response was used to estimate resonant frequencies. Mode shapes were estimated from Cross Spectral Density (CSD) between each measuring channel and one reference channel4).

3. Damage detection using operational mode shapes

In this method, Cross Spectral Density for the measured acceleration between one reference channel and different measuring points are calculated. Amplitude and phase information contained in Cross Spectral Density of the various accelerometer readings at all frequencies in the measurement range and not just the modal frequencies will be compared before and after damage using Damage Index Method. In other words, the amplitude of Cross Spectral Density at all frequency components on the measurement range is used instead of using modal amplitude, which can be called as Operational Mode Shapes. Therefore, a small range of measurement can be used without the need for measuring modal data or higher modes and moreover Cross Spectral Density is calculated from the acceleration response without the need for measuring the excitation force. Therefore, ambient vibration can be used as excitation source for continuous health monitoring for structures.

4. Experimental measurements

4.1 Experimental setup and numerical model

In this research simple steel beam supported by four bolts in both sides has been examined before and after making some cracks as shown in Fig. 1. The multi-layer piezoelectric actuator is used for local excitation. The main advantage of using piezoelectric actuators is that it produces vibration with different frequencies ranging from 0 to 400 Hz that is effective in measuring mode shapes6),7). Seven accelerometers were positioned on the top flange and one accelerometer was used as a reference channel as shown in Fig. 2. Cubic polynomial was used to approximate CSD amplitude between each two sensors in order to create artificial degrees of freedom4). Therefore, the total distance between accelerometers is divided to 120 nodes. Two cases of damage are introduced to the beam. Case 1 of damage is simulated by making one crack, 2mm * 40 mm, at node 40 and Case 2 of damage is simulated by making 2 cracks with the same dimensions at nodes 40 and 90 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 beam8).

4.2 Measurement of Cross Spectral Density and mode shapes

Fig. 3-a shows CSD between channel 3 and the reference channel for the undamaged beam. The test

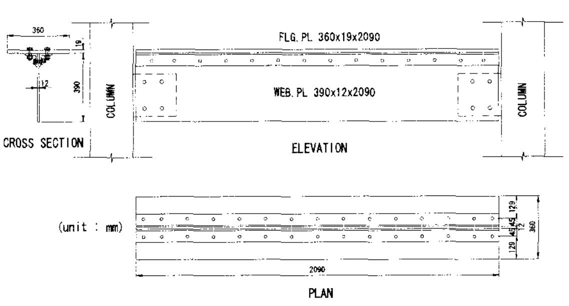


Fig. 1 Beam Dimensions

was repeated four times and significant changes in CSD were noticed in some frequency range before making any damage. On the other hand, in some other frequency range there is no significant change in CSD even after repeating the test four times. The same remark was noticed for the damaged beam. Therefore, it is very important to choose the frequency range in which changes in CSD is due to damage not because of noise or measurement errors. Fig. 3-b shows comparison between CSD for the undamaged and damaged beam with one crack. Thin lines indicate CSD for the undamaged case and thick lines indicate CSD for the damaged beam. In this figure, change in CSD in the frequency range from 1to 150 Hz is obviously due to noise or measurement errors not due to damage but on the other hand change in CSD in the frequency range from 300 to 340 Hz is obviously due to damage. The same remarks are shown when two cracks were made to the beam as shown in Fig. 3-c.

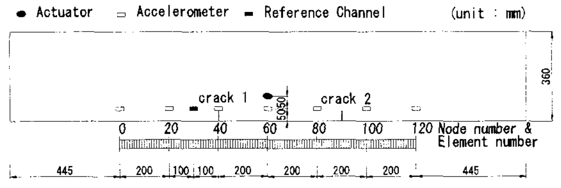


Fig. 2 Actuator and accelerometers positions and node numbers

5. Damage Index Method

This method[9] 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 i^th mode strain energy is related to the change in curvature of the mode at location j. The damage index for this location and this mode, β_{ij}, is defined as

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

where ψ'' (x) $\psi^{*''}$ (x) are the second derivative of i^th mode shape corresponding to the undamaged and damaged structure, respectively. L is beam length and a, b are the limits for element j. When more than one mode is used, damage index is defined as the sum of damage indices from each mode as follows

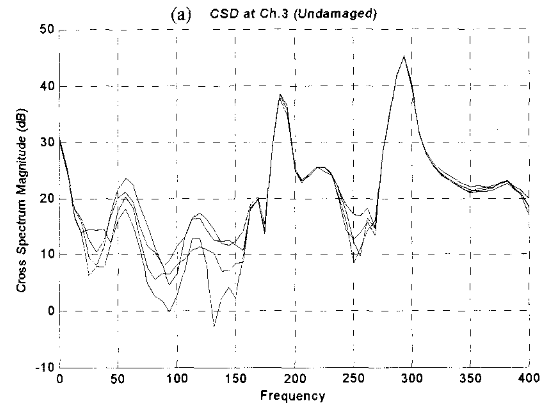
$$\beta_j = \sum_{i=1}^{n} \beta_{ij} \tag{2}$$

where n is the number of modes. Assuming that the collection of the damage indices, β_j, represents a sample population of a normally distributed random variable, a normalized damage localization indicator is obtained as follows

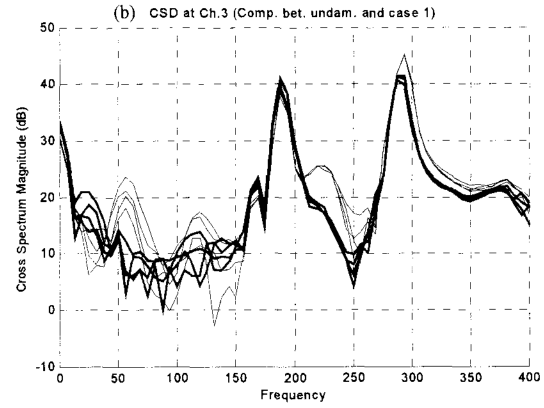
$$Z_j = \frac{\beta_j - \overline{\beta_j}}{\sigma_j} \tag{3}$$

where $\overline{\beta_j}$ and σ_j represent the mean and standard deviation of the damage indices, respectively. A statistical decision making procedure is employed to determine if the normalized damage index, Z_j, is associated with a damage location. Values of two standard deviations from the mean are assumed to be associated with damage locations[3), 4)].

(a) CSD at Ch.3 (Undamaged)



(b) CSD at Ch.3 (Comp. bet. undam. and case 1)



(c) CSD at Ch.3 (Comp. bet. undam. and case 2)

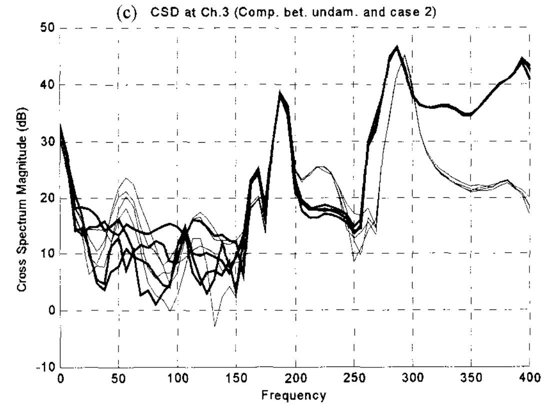


Fig. 3 Cross Spectral Density at Channel 3

6. Damage Index Method applied to experimental and numerical using modal data and operational mode shapes.

6.1 First: experimental data

Fig. 4-a shows the results when Damage Index Method is applied to detect damage at node 40 using 2 mode shapes. In this figure, the value of damage index exceeds 2 at nodes 41 and 58, which indicates damage at these nodes. The indicated position at node 41 is very accurate position but the indicated position at node 58 is less accurate. Fig. 4-b shows the results when Damage Index Method is applied using operational mode shapes in the frequency range from 300 to 340 Hz. In this figure, the absolute value of damage index exceeds 2 at node 39 only. Therefore, the indicated position of damage using operational mode shapes is more accurate than using modal data.

Similarly, Figs 5-a and 5-b show the results when Damage Index Method is applied to detect damage at nodes 40 and 90 using modal data and operational mode shapes, respectively. The same frequency range from 300 to 340 Hz is used for operational mode shapes. In Fig. 5-a the indicated positions are at nodes 39 and 99 but the damage index value are just above 2 at node 39. The indicated positions of damage, when operational mode shapes are used, are indicated more clearly at node 40 than at node 81as shown in Fig. 5-b.

6.1 Second: numerical data

The data extracted from the numerical model is used to compare with the experimental results. More mode shapes can be measured from the numerical model; therefore the results of Damage Index Method using many mode shapes can be compared with the results of the same method when operational mode shapes are used. Since no noise in the numerical data the lower range of frequency, from 40 to 70 Hz, is used for operational mode shapes in order to show that this method is capable of detecting small damage using lower modes.

The obtained results when Damage Index Method is applied to the numerical data for different cases of damage are shown in Figs. 6 and 7. Fig. 6-a shows the results when Damage Index Method is applied to detect damage at node 40 using the first four mode shapes and Fig. 6-b shows the results when operational mode shapes are used in the frequency range from 40 to 70 Hz. The obtained results are similar except that in Fig. 6-a, where modal data are used, a false indicated position of damage at node 60 is about to appear. When Damage Index Method is applied using modal data to detect multiple cracks, only one position is indicated at node 81 and a false position indicated at node 61 as shown in Fig. 7-a. On the other hand, Fig. 7-b shows the results when operational mode shapes are used. Crack at node 40 is indicated at node 21 and crack at node 90 is indicated at nodes 81 and 99.

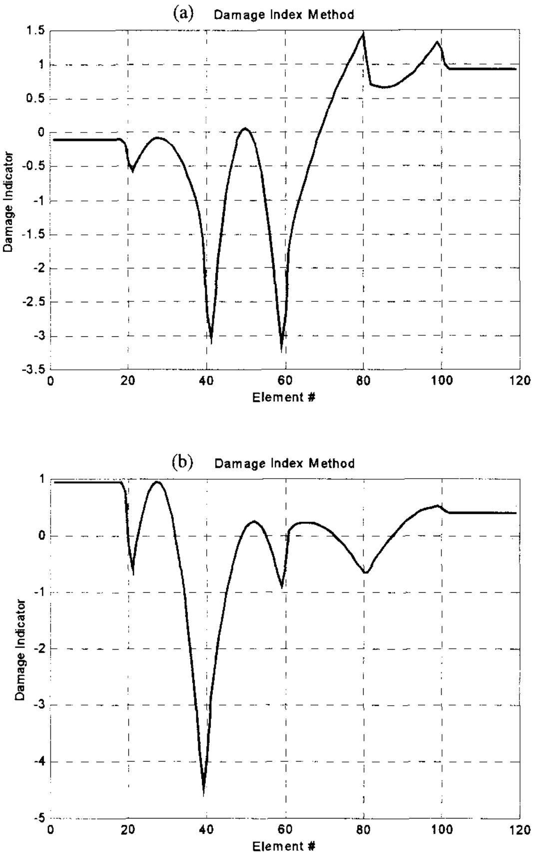


Fig. 4 Damage Index Method applied to experimental data for crack at node 40

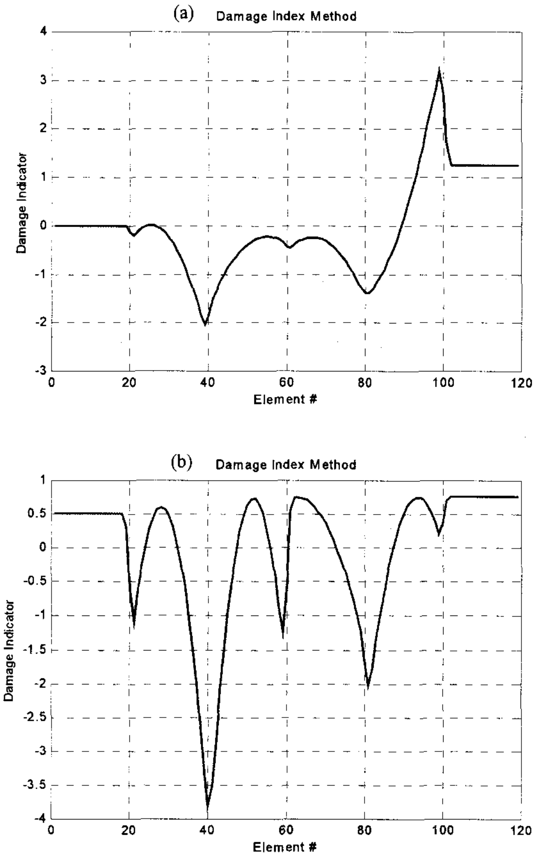


Fig. 5 Damage Index Method applied to experimental data for cracks at node 40 and 90

7. Conclusion

(1) It is important to repeat the vibration test for the healthy structure and compare the results in order to

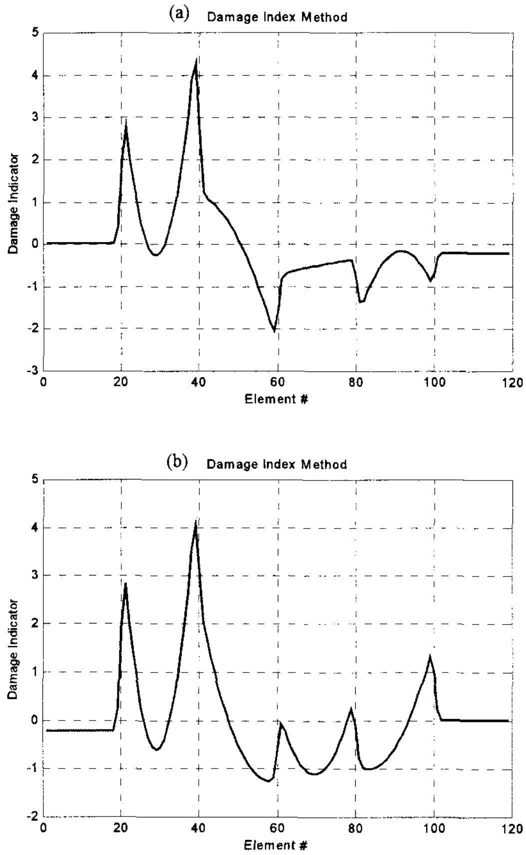


Fig. 6 Damage Index Method applied to numerical data for crack at node 40

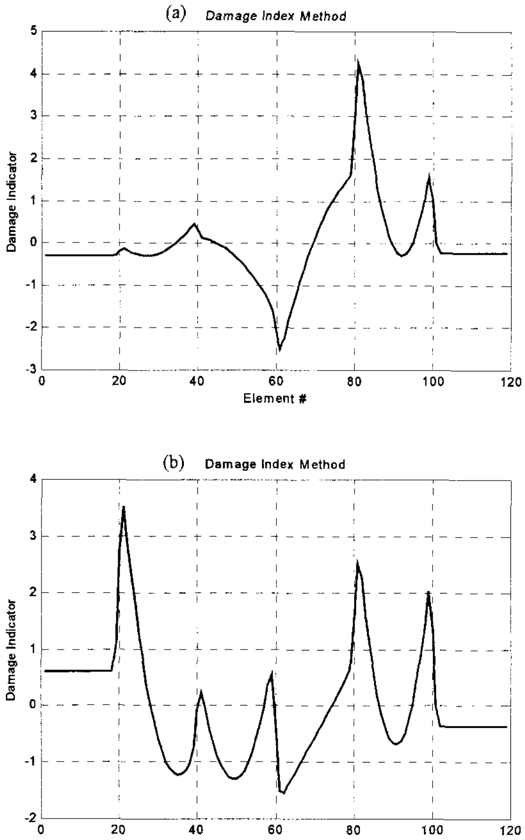


Fig. 7 Damage Index Method applied to numerical data for cracks at node 40 and 90

determine the frequency range in which the measurements are stable.

(2) When Damage Index Method is applied using operational mode shapes, more accurate results in detecting and localizing the damage are obtained than using modal data.

(3) Low range of frequency can be used when operational mode shapes are used to detect small damage without the need for measuring higher modes.

(4) Cross Spectral Density is calculated from the acceleration response between each channel and a reference channel hence, modal data or operational mode shapes are calculated without measuring the excitation force. Therefore, ambient vibration can be used for continuous health monitoring for structures.

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