Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Damage Detection of Bridge Structures Using Modal Flexibility under Temperature Variations

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Abstract: Changes in the measured structural responses, such as deflections and modal properties, induced by damage could be significantly smaller than those by environmental effects such as temperature and temperature gradients. To make the structural health monitoring more reliable and applicable to real structures, it is highly desirable to develop a methodology to distinguish the changes due to the structural damage from those by the environmental variations. In this study, a novel method to extract the damage-induced deflection under temperature variations is presented using the outlier analysis on the correlation of deflection components obtained using the modal flexibility matrix. The main idea is that temperature change in a bridge would produce global increase or decrease in deflections over the whole bridge. On the other hand, structural damages may cause local variations in deflections near the damage locations. Hence, the correlation analysis between the deflection measurements may show high abnormality near the damage locations. The proposed procedure may be summarized: (1) identification of the modal flexibility matrix from acceleration measurements, (2) calculation of the positive-bending-Inspection-load deflection using the modal flexibility for each damage and temperature case, (3) construction of the outlier-threshold for the correlation of the intact deflection at different locations, and (4) damage detection using the outlier analysis on the correlation of the deflection for damage cases. To verify the applicability of the proposed method, a series of laboratory tests were carried out on a bridge model with a steel box-girder. Nineteen experiments were carried out for the first 2 days under daily temperature variations to construct the correlation data for the intact deflection, and 51 experiments were performed for two damage scenarios for the next 12 days. It has been found that the damage existence and location were detected successfully for a case with relatively small damage under the temperature variations.

1. INTRODUCTION

Vibration-based structural health monitoring system uses changes in vibration features such as natural frequencies, damping ratios and deflections. In practical situations, structures are often subjected to changes in environmental and operational conditions (e.g., temperature, temperature gradients, etc.) which may mask the changes caused by structural damages. If the effects of these environmental variations are not taken into account in the damage detection process, the vibration-based structural health monitoring becomes unreliable (Wahab and Roeck 1997, Cornwell *et al.* 1999, Sohn *et al.* 1999, Lloyd *et al.* 2000, Peeters and Roeck 2001, Lucas *et al.* 2001 and Ni *et al.* 2005).

One of the methods used to solve this problem is to establish correlation between the measured vibration characteristics and the corresponding environmental conditions such as ambient temperature (Sohn *et al.* 1999, Peeters and Roeck 2001 and Ni *et al.* 2005). The reference state of the structure may be parameterized to reflect the different environmental conditions, and the structural damage is only responsible for the additional changes from the reference states. However, these approaches have difficulties in defining and measuring the reference states of the structures. Another approach is to analysis only the identified vibration features excluding the environmental variables. Kulla *et al.* (2001) applied a linear factor analysis, consisting of an iterative process to eliminate environmental and operational effects. Manson (2002) and Yan *et al.* (2004) applied the principal component analysis (PCA) to remove the environmental effects as an embedded variable.

In this study, the outlier analysis was applied to the correlated deflection obtained by using the modal flexibility to detect the novelty in the deflection. The paper is organized as follows: First, a new load concept, so called positive-bending-Inspection-load, is introduced to simplify the inverse mapping from the damaged-induced deflection to the damage location. Second, the correlated nature in deflections under temperature variation was introduced to establish the intact deflection correlation and third, the outlier analysis on the correlated deflection was introduced to measure the novelty in deflection.

2. DEFLECTION & DAMAGE DETECTION

2.1 Positive-Bending-Inspection-Load (PBIL)

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10.3182/20080706-5-KR-1001.1828

To detect the damages based on the additional deflection, the inverse mapping from the additional deflection to the damage location is needed to be constructed. A way to simplify the inverse mapping is the moment positiveness at the damage location, which guarantees the additional deflection has the span maximum at the damage location. Thus, a new load concept, so called Positive-Bending-Inspection-Load (PBIL), was developed. The PBIL is defined as a load which guarantee the positive moments in the region under investigation. The PBIL makes the additional deflection have span maximum at the damage location so that maximum deflection indicates the possible damage location. An example of PBIL is shown in Figure 1 for 3 span continuous beam systems. The load is a positive bending load for 1st and 3rd span region and the inverted load is a positive bending load for 2nd span region.

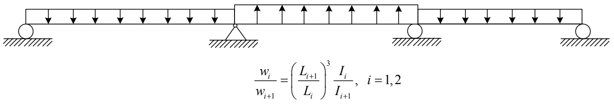


Figure 1: Example of the positive-bending-Inspection-load for 3 span continuous beams

2.2 *Deflection Estimation by Modal flexibility matrix*

The deflection under a PBIL can be approximately estimated by using the modal flexibility with the points load realization of the PBIL as follows.

$$\{u\} = [G_m]\{f_{PL}\} \tag{1}$$

where u is the deflection under the PBIL, fPL is the points load realization of the PBIL and Gm is the modal flexibility matrix which can be represented as [11].

$$[G_m] = [\Phi][\Lambda]^{-1}[\Phi]^T \tag{2}$$

where $[\Phi] = \left[\{\Phi_1\},\{\Phi_2\},\cdots,\{\Phi_n\}\right]$ is the mode shape matrix, $\{\Phi_i\}$ being the i-th mode shape. The diagonal matrix of rigidity $[\Lambda]$ correspond to $[\omega_i^2]$, where ω_i is i-th frequency and n is the total number of measured mode shapes.

2.3 *Outlier Analysis for correlated deflections*

The deflection in a bridge would increase or decrease together over the whole structure according to the temperature change. This behavior introduces the correlation in the deflections at any two points in the bridge. The typical example for the correlated deflections is shown for the test bridge in Figure 2 .

The normal states of deflections can be defined by constructing the correlation of intact deflections under the PBIL and the novelty can be defined as a statistical distance from the correlation of the intact deflection. Specifically, the novelty index can be defined as shown in Eqn. (3) and Figure 3.

$$Z(i,j) = \frac{Y_i - \bar{Y}_i \mid Y_j}{\sigma(Y_i \mid Y_j))} \tag{3}$$

where Yi denotes the PBIL deflection at the i-th node.

The novelty index $Z(i,j)$ has a physical meaning of an excessive deflection at i-th node. When the novelty index $Z(i^*,j^*)$ have its maximum value at (i^*,j^*), the i*-th node is the possible damage location.

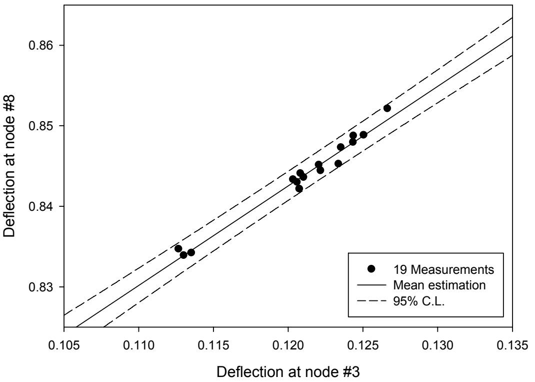


Figure 2: Typical example for the correlated deflection under the temperature variations

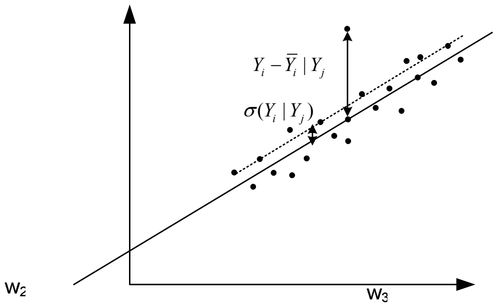


Figure 3: The outlier analysis for the correlated deflection

3. EXPERIMENTAL STUDY

3.1 *Overview*

To verify the applicability of the proposed method, a series of laboratory tests were carried out on a bridge model with a steel box-girder shown in Figure 4. The bridge is a simply supported, 10m long, and composed of 5 segmental boxes inter-connected by bolts and plates. The crack damages were imposed by the saw cut as shown in Figure 7 and Table 1. The total numbers of 21 accelerometers were evenly placed on the upper part of one girder (Figure 5 and 6). Free vibrations induced by successive impact loads were measured for 10 minutes with 100 Hz sampling rate. Nineteen measurements were carried out for the first 2 days under daily temperature variations to construct the correlation of the intact deflection, and 51 measurements were performed for two damage scenarios for the next 6 days. The detailed experimental specification is shown in Table 2.

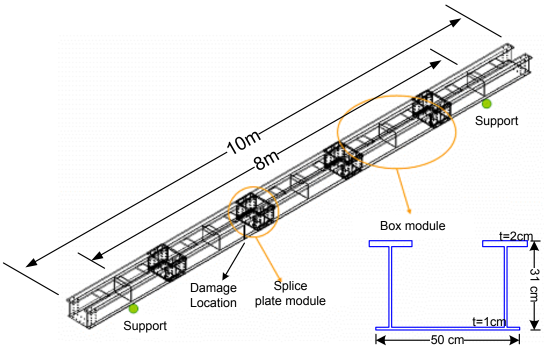


Figure 4: The steel box-girder test bridge

Figure 5: The overview of experiments

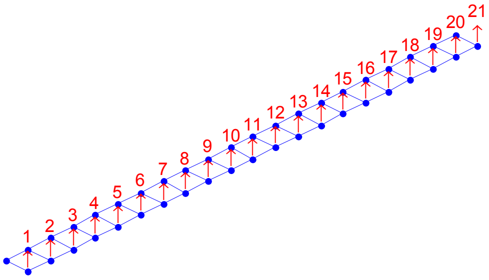


Figure 6: The sensor locations

Figure 7: The imposed damage

Table 1 Damage scenario

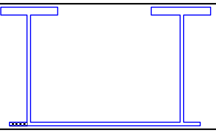
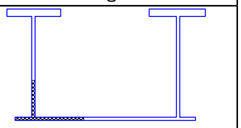
Case	Damage #1	Damage #2
Section Shape		
Description	Flange cut by 4cm	Web cut by 9cm, bottom plate cut by 15cm
Inertia of Moment	4% Reduction	13% Reduction
Area	3% Reduction	14% Reduction

Table 2 Total number of measurements for each damage case

case	Total # of Meas. (Date)	Exp #
Intact	14 (May 23) 5 (May 24)	1-14 15-19
1	2 (May 24)	20-21
2	2 (May 24) 2 (May 25) 45 (June 5˜6)	22-23 24-25 26-70

3.2 Temperature Effects: the Natural Frequencies

The 1st and 2nd natural frequencies of the test bridge were estimated for 70 measurements during 5 days under the daily temperature variation about 10°C. There are 19 measurements for the intact case, 2 measurements for the damage case 1, and 49 measurements for the damage case 2. Figure 8 shows a variation of the 1st natural frequency along with temperature variation. It was observed that the 1st natural frequency had a distinct inverse-relationship with the temperature. The estimation results ware shown in Figure 9. Changes in the two natural frequencies show no significant trend related to the damages. Moreover, the frequency change by the damage case 1 was completely masked by the change due to temperature variations.

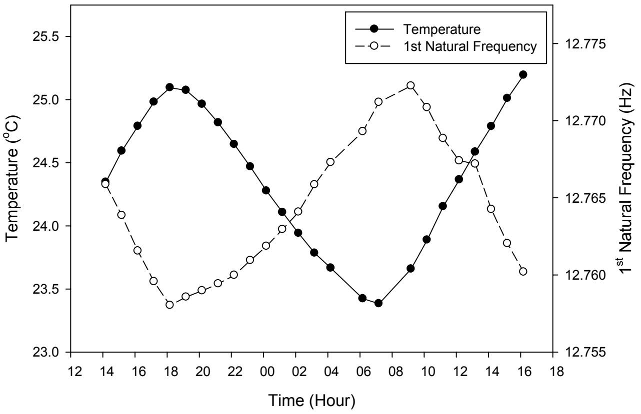


Figure 8: Deviation of the 1st natural frequency under the temperature variation

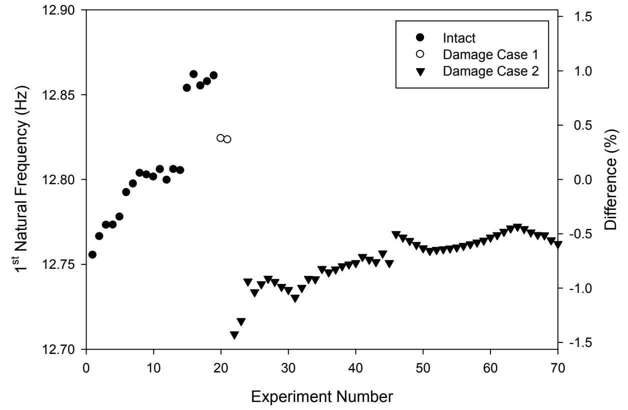


Figure 9: Deviation of the 1st natural frequency under the temperature variation

3.3 *Temperature Effects: Deflection under the Positive-Bending-Inspection-Load*

The PBIL deflection of the test bridge were estimated by using the equation (1) with the modal flexibility matrix and the point load which is a realization of the PBIL for a simple beam as illustrated in Figure 8. The modal flexibility matrix was constructed by the first two natural frequencies and mode shapes. The ambient deviation of the PBIL deflection was shown in Figure 11 representing the daily tempeature variation for 2 days. The ambient deviation of the PBIL from its mean-value was shown in Figure 12.

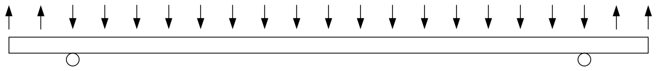


Figure 10: The points load realization of the PBIL for the test bridge (1 ton/point)

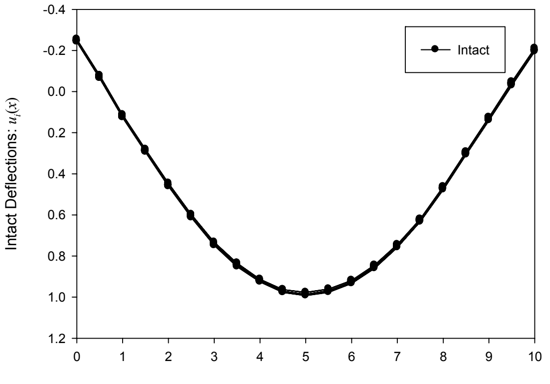


Figure 11: PBIL deflections (Intact case)

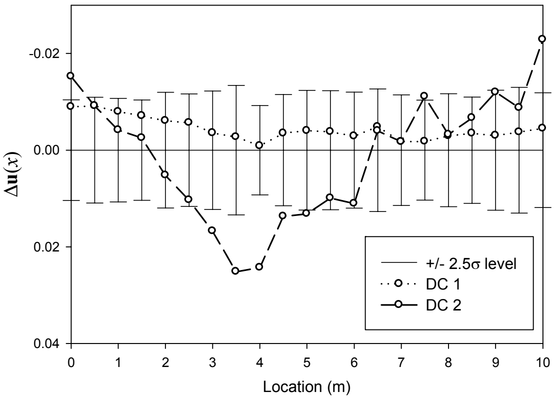


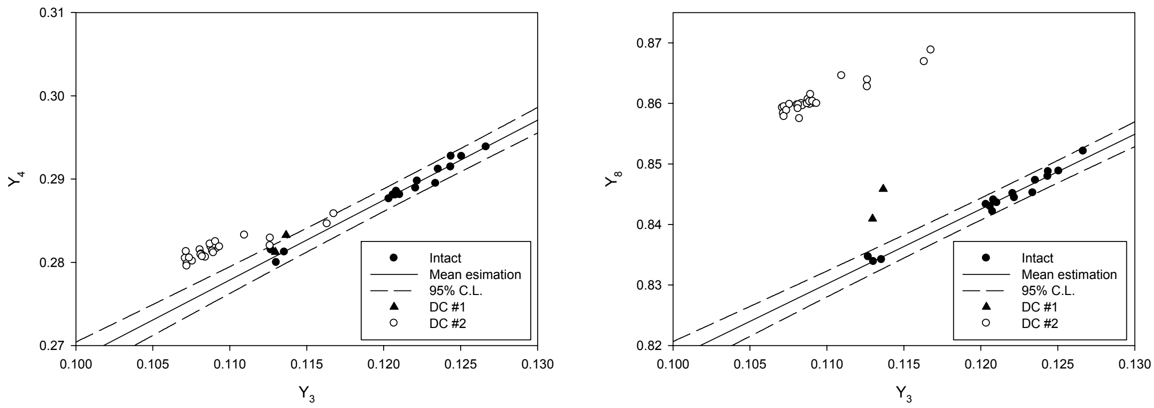
Figure 12: Deviation of Intact deflection

It was observed that the increase of the deflection due to the damage case 1 falls inside the ±2.5σ(99% C.L.) of the intact deflection deviation (σ) under the daily temperature variation. Thus the damage case 1 may not be distinguishable due to the temperature effect. The damage case 2 may be distinguishable because the deflection change due to the damage case 2 falls outside the ±2.5σ(99% C.L.) at node 7, 8 and 9 which reveals the real damage at the 8-th node. However, if the temperature variation increases, the damage case 2 may not become distinguiable. An approach which effectively deals with the temperature effects is highly needed.

3.4 *Outlier Analysis for Correlated Deflections*

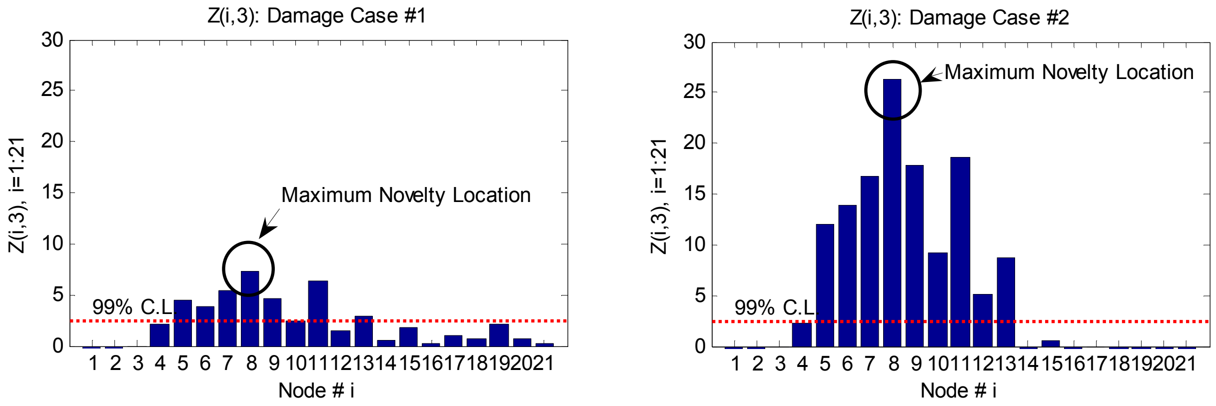
The outlier analysis for the correlated deflections, as discussed in the previous section, was carried out for each damage case. The intact deflection correlation was constructed based on the 19 intact measurements as shown in Figure 12 for the deflection pairs, i.e., Yi and Y3, (i=4,6,8,10). The solid lines represent the mean value estimates of the intact deflection correlation and dotted lines represent ±2.5σ(99% C.L.) of the intact deflection correlation. The (+) mark represents the damaged deflection for the damage case 1 and (*,□,◊) marks represent the damaged deflection for the damage case 2. The novelty index can be calculated by equation (3). It is clearly observed that the novelty index increase to have maximum at Z(8,3) which indicates 8-th node is possible damage location. This observation coincides with the real damage location at 8-th node.

The novelty index was summarized in Figures 12 and 13. It was found that the novelty index clearly identify the inflicted damage at 8-th node for both of the two damage cases. Especially, it is worthy to notice that the novelty can clearly identify the damage location for the relatively small damage case 1 as well as the severe damage case 2.



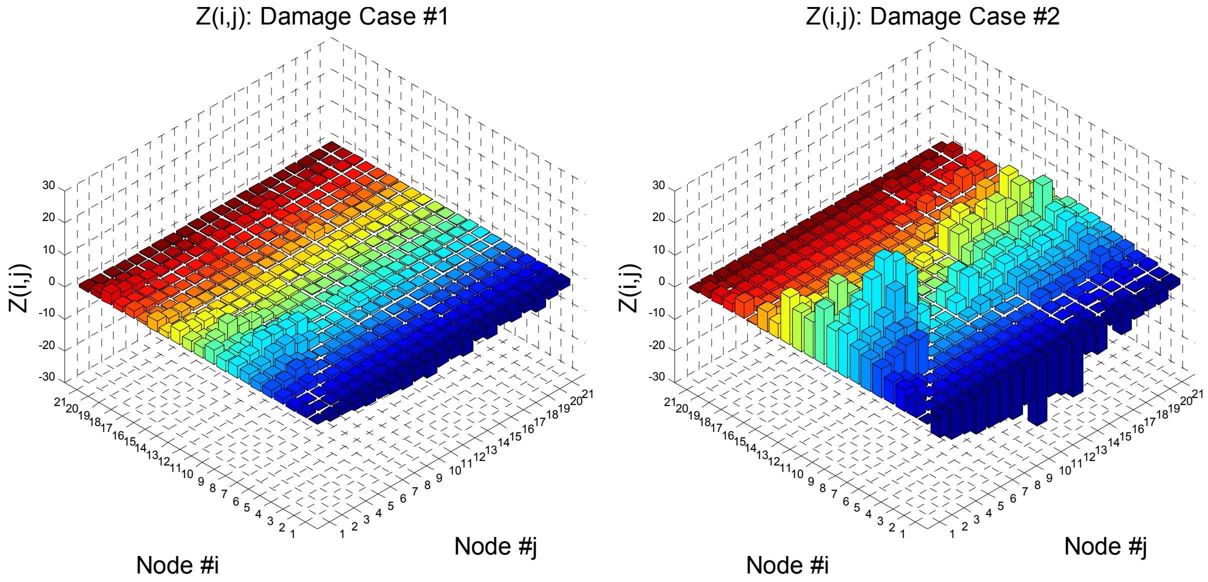
(a) Y_3 *vs.* Y_4 *(b)* Y_3 *vs.* Y_8

Figure 13: The outlier analysis for the correlated deflections



(a) Damage case #1 (b) Damage case #2

Figure 14: Novelty Index Z(i,3)



(a) Damage case #1 (b) Damage case #2

Figure 15: Novelty Index Z(i,j)

CONCLUSIONS

Based on the experimental study on the test bridge under the daily temperature variation, the results can be summarized as follows.

- A new load concept, so called positive-bending-Inspection-load (PBIL), was developed to obtain information about the damage location immediately from the additional deflection induced by damages. The maximum location of the addition deflection is the possible damage location when the PBIL is imposed to a bridge.
- It was found from the experimental study that the deflections are highly correlated under the daily temperature variation and these deflections can be used to define the normal states of the deflections.
- The outlier analysis for the correlated deflections can be utilized to detect damages and it was successfully applied to the test bridges to locate the relatively small damage as well as the severe damage under the daily temperature variation.

ACKNOWLEDGEMENTS

The authors would like to thank the Smart Infra-Structure Technology Center(SISTeC) at KAIST and the Center for Environmental and Safety Measurements at Korea Institute of Standards and Science (KRISS). Their financial supports are greatly acknowledged.

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