The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Damage Identification Using Damage-Induced Inter-Story Deflection for High-Rise Building

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ABSTRACT

This paper presents a new modal flexibility based damage identification method using the damage-induced inter-story deflection (DIID) for high rise building structures. Analytic study showed that abrupt changes in inter-story deflection were occurred from damaged location. For the multiple damages in high-rise building, baseline modification was proposed to identify the locations of damages. By substituting the baseline to the prior damage location, it can prevent the undetectable damages occurring at posterior to the first damage location. In order to evaluate feasibility of damage detection performance of the proposed method to high-rise building, numerical simulation and experiment were conducted to 10-story building model. The proposed method was successfully found the location of damage both single and multi-damage. And comparative studies with other damage detection methods were conducted to confirm the superiority of the proposed method.

1. Introduction

Civil infrastructures, such as high-rise buildings and long-span bridges, are increasing gradually. These structures are generally designed to endure for decades. However, they are exposed to severe environmental and service loading due to fatigue, corrosion, natural hazards, etc. In order to maintain their serviceability and prevent structure failure, continuous maintenance is necessary. Due to the cost effectiveness and necessity for regular monitoring, structure health monitoring (SHM) is imperative. During the past decades, SHM has been an important research topic in the field of civil engineering. Especially, vibration based approach has been rapidly expanding using structure vibration characteristics, such as natural frequencies, mode shapes, modal damping, modal flexibility and so on (Doebling et al, 1996, Sohn et al. 2003).

Comparing with other vibration based damage detection methods, the damage detection method based on the modal flexibility is advantageous to localize the structure damage. (Pandy and Biswas et al, 1994) proposed a damage detection

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method by using changes in modal flexibility. (Zhang and Aktan et al, 1998) studied uniform load surface (ULS) and (Wu and Law et al, 2004) used ULS curvature to localize and quantify the damage.

Conventional flexibility based damage detection approaches have several drawbacks such as no obvious relation between damage and damage features, noise vulnerable and requirement of an intact finite element model. To increase the reliability and applicability of damage detection method, overcoming the drawbacks of conventional damage detection methods is necessary.

This study proposed a new damage detection method for high-rise building structure by using the damage-induced inter-story deflection (DIID) obtained from modal flexibility matrices. The proposed damage detection method can localize the location of damage for the multiple damage as well as single damage without the use of a finite element model. The experimental validation for the proposed method was conducted.

2. Theory

The general equation of damage-induced deflection can be obtained as

$$\Delta u = G_D(\Delta K u_0) = G_D \Delta F \tag{1}$$

where $G_D = (K_0 - \Delta K)^{-1}$ is the flexibility matrix of the damaged system and $\Delta F = \Delta K u_0$ is the force producing the damage-induced deflection of the damaged structure caused by the stiffness loss of the intact system. ΔF may be considered as 'the force additionally distributed by the damage' because ΔF is the force carried by the damaged portion of the structure in the intact structure.

Consider a shear building structure with a column damage of a proportional stiffness reduction. Then, ΔF can then be obtained as

$$\Delta F = \Delta K u_0 = \begin{Bmatrix} 0 \\ \alpha_e f^e \\ 0 \end{Bmatrix} \tag{2}$$

where $\Delta K = diag(0, \alpha_e k^e, 0)$; α_e is the damage severity, $0 < \alpha_e < 1$, k^e is the beam elementary stiffness matrix indicating the intact columns at the damaged floor, and $f^e = k^e u^e = \{V, M - V, M\}$ is the stress resultant force of the beam element in the intact state.

Eq. (1) and (2) indicate that the damage-induced deflection can be evaluated by applying $\alpha_e f^e$ to the damaged structure. It is notable that f^e only affects the damaged parts, not the rest of the structure. Consequently, the damage-induced inter-story deflection (DI-ID) appears only at the damaged floor, not at the un-damaged floors. In other words, the DI-ID at the *i* –th floor indicates the damage is located at the *i* –th floor.

However, there is no DI-ID if the sum of external forces above the *i* –th floor is zero, since f^e at the *i* –th floor is zero. In order to avoid this problem, the positive shear inspection load (PSIL) is used as the load vector **F**, which produces only positive shear forces at all floors. Although several load cases can play a role as a PSIL, the authors recommend using the PSIL. This may be the most robust and simplest choice. More detailed information on the PSIL can be found in (Koo et al. 2010).

Finally, the relation between the DI-ID $\Delta u^{IS}(i)$ and the damage locations can be expressed as (Koo et al. 2010)

$$\text{Damage occurs at } i \text{–th floor } \Leftrightarrow \Delta u^{IS}(i) > 0 \text{ under a PSIL} \tag{3}$$

In order to implement Eq. (3) for damage detection, statistical approaches are preferred because of measurement noises. An index Z_i of the DI-ID is used to notice existence of damage, and damage locations can be identified using Z_i from following condition (Koo et al. 2010)

$$\text{Damage exists at the } i\text{-th floor if } \quad Z_i > Z^{Threshold} \tag{4}$$

$$Z_i = \frac{u^{IS}(i) - \bar{u}_0^{IS}(i)}{\sigma\left(u_0^{IS}(i)\right)} \tag{5}$$

$$u^{IS}(i) = u(i) - u(i-1) \tag{6}$$

where $u^{IS}(i)$ is a concurrent inter-story deflection under a PSIL, $u_0^{IS}(i)$ is the intact inter-story deflection under a PSIL, and $\bar{u}_0^{IS}(i)$ and $\sigma\left(u_0^{IS}(i)\right)$ are the mean and the standard deviation of $u_0^{IS}(i)$, respectively.

3. Experimental Validation

Experimental validations were conducted on a 10-story high-rise building model, as shown in Fig. 1. Ambient vibration tests were performed under shaking table excitation with random loads and ten accelerometers were installed on each floor. The sampling frequency is 100Hz and anti-aliasing filter was applied to raw measurement signals. Table 1 shows the modal parameter changes due to damage.

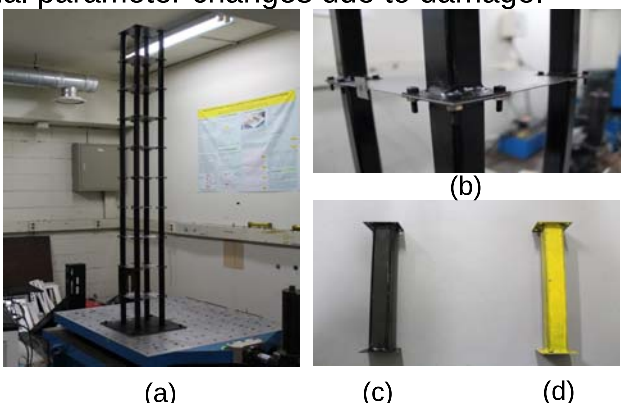

Fig. 1 (a) Experimental model (b) Connection between columns and floors
(c) Intact column (d) Damage column

Table 1. modal parameter changes due to damage

Case	The first mode			The second mode			The third mode		
	f_1(Hz)	$\Delta f_1/f_1$	MAC	f_2(Hz)	$\Delta f_2/f_2$	MAC	f_3(Hz)	$\Delta f_3/f_3$	MAC
IC	3.153	-	1.0000	16.50	-	1.0000	43.25	-	1.0000
DC1	3.120	-1.05%	0.9999	16.27	-1.39%	0.9999	42.48	-1.78%	0.9996
DC2	3.087	-2.09%	0.9999	16.27	-1.39%	0.9998	42.30	-2.20%	0.9994

For the single damage case (DC1), damage at the first floor was clearly identified by the modified damage index Zi_m and there is no values exceeding the second. For multi-damage case (DC2), it was also clear that Zi_m identifies damage at the first floor. Moreover, Zi_m value at the third floor exceeded the second baseline, which means that other damages may occurred in the structure. From additional process to localize multiple damages based on the second baseline, the damage at the third floor was exactly identified without any false negative damage detection, as shown in Fig. 2.

4. Conclusion

In this study, a new damage detection approach for high-rise buildings was developed using the DIID estimated by modal flexibility. From these various tests, it was found that the damage locations can be successfully identified by the proposed approach for multiple damages as well as single damage.

ACKNOWLEDGEMENT

This work is financially supported by Korea Minister of Ministry of Land, Transport and Maritime Affairs(MLTM) as 「U-City Master and Doctor Course Grant Program

REFERENCES

Doebling S.W., Farrar C.R., Prime M.B. and Shevitz D.W. (1996), “Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review”, *Technical Report*.

Sohn H., Farrar C.R., Hemez F.M., Shunk D,D,, Stinemates D.W. and Nadler B.R. (2003), “A Review of structural health monitoring literature: 1996–2001”, *Technical Report*.

A.K. Pandey and M. Biswas (1994), “Damage detection in structures using changes in flexibility”. *Journal of Sound and Vibration* **169**, 3-17.

Zhang Z. and Aktan A (1998), “Application of modal flexibility and its derivatives in structural indentification”, *Res Nondestruct Eval*, **10**, 43-61

Koo, K.Y., Sung, S.H., Park, J.W. and Jung, H.J.(2010), “Damage detection of shear building using deflections obtained by modal flexibility”, *Smart Materials and Structures,* **19**, 115026