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Modal flexibility-based damage detection of cantilever beam-type structures using baseline modification

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ABSTRACT

This paper presents a new damage detection approach for cantilever beam-type structures using the damage-induced inter-storey deflection (DIID) estimated by modal flexibility matrix. This approach can be utilized for damage detection of cantilever beam-type structures such as super high-rise buildings, high-rise apartment buildings, etc. Analytical studies on the DIID of cantilever beam-type structures have shown that the DIID abruptly occurs from damage location. Baseline modification concept was newly introduced to detect multiple damages in cantilever beam-type structures by changing the baseline to the prior damage location. This approach has a clear theoretical base and directly identifies damage location(s) without the use of a finite element (FE) model. For validating the applicability of the proposed approach to cantilever beam-type structures, a series of numerical and experimental studies on a 10-storey building model were carried out. From the tests, it was found that the damage locations can be successfully identified by the proposed approach for multiple damages as well as a single damage. In order to confirm the superiority of the proposed approach, a comparative study was carried out on two well-known damage metrics such as modal strain-based damage index approach and uniform load surface curvature approach.

1. Introduction

Civil infrastructure such as bridges and buildings is exposed to severe environmental and service loadings over time due to fatigue, corrosion, natural hazards, etc. It is necessary to acquire accurate and real-time information on the damage state of these structures to prevent catastrophic failure, increase cost-effectiveness of maintenance, and prolong service life. For this purpose, structural health monitoring (SHM) for civil engineering has received considerable attention. Especially, research on global approach, called vibration-based approach has been rapidly expanding using various vibration characteristics, such as natural frequencies, mode shapes, mode shape curvatures, modal damping ratio, and modal flexibility, obtained from measured vibration data. The crucial advantage of the vibration-based approach is that structural condition of a massive civil structure can be assessed using a relatively small number of sensors. Extensive literature reviews on the vibration-based damage detection method can be found in [1–3].

Modal flexibility has shown itself to be a promising damage descriptor due to its high sensitivity to damage [4]. Pandey and Biswas [5] proposed a damage detection approach that uses changes in modal flexibility for the first time. In practice,

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the structural modes are rarely all identified from the measured vibration data. But, the flexibility matrix can be accurately estimated from only a few lower modes because it is inversely proportional to the squares of the natural frequencies. This approach was experimentally demonstrated on a three-span reinforced-concrete highway bridge [6]. Zhang and Aktan [7] and Park et al. [8] studied the uniform load surface (ULS) and its curvature. The ULS was found to have much less truncation effect and was least sensitive to experimental error. Displacement coefficients and profiles are presented as promising kernel condition and damage indices along with real-life examples by Catbas et al. [9]. Wu and Law [10] applied the ULS curvature to plate-type structures for damage detection and quantification. It was found that the ULS curvature is sensitive to damages, even with truncated, incomplete, and noisy measurements. In combination with the ULS curvature, two new damage detection algorithms (i.e., the generalized fractal dimension and simplified gapped-smoothing methods) are proposed by Wang and Qiao [11]. Catbas et al. [12] compared the performance of both the ULS and its curvature, and confirmed that the curvature is more advantageous. Another well-known flexibility-based approach is the damage locating vector (DLV) approach, which is based on changes in modal flexibility and uses an intact finite element model. The DLV have the property of inducing stress fields whose magnitude is zero in the damage elements [13]. Many researchers [14–16] carried out a series of studies on using the DLV approach to identify various damages in a truss structure. Subsequently, Bernal [17] developed the stochastic dynamic DLV (SDDLV) method to achieve damage localization using output-only information and to provide richer information on structural damage employing dynamic flexibility matrices. Koo et al. [18] developed the damage-induced deflection approach based on modal flexibility to localize multiple damages without the finite element model. Yu and Chen [19] are studied by combining the structural modal flexibility and the particle swarm optimization (PSO) technology. Kazemi et al. [20] developed a new two-phase procedure in order to localize the faults and corresponding severity in thin plate structures. Two effective damage detection methods for localizing and quantifying structural damage in shear frames are presented by Amiri et al. [21].

However, conventional flexibility-based approaches have several drawbacks such as no obvious relationship between damage and damage features, noise vulnerable characteristic, and the requirement of an intact finite element model. Those drawbacks have to be overcome to increase the robustness, reliability, and applicability in damage detection for civil infrastructure under various environmental effects, and inevitable measurement noise.

This paper proposes a new damage detection approach for cantilever beam-type structures that uses the damage-induced inter-storey deflection (DIID) obtained from modal flexibility matrices. This approach can be utilized for damage detection of cantilever beam-type structures such as super high-rise buildings, high-rise apartment buildings, etc. A bending moment is dominant in a total behavior of the structures [22]. The proposed approach has a clear theoretical base and directly identifies multiple damage locations as well as a single damage location without the use of a finite element model. Baseline modification concept was newly proposed to detect multiple damages in cantilever beam-type structures by changing the baseline to the prior damage location. In order to verify the feasibility of the proposed method, the theoretical background is introduced first. Next, numerical and experimental investigations are presented for a 10-storey building model with two damage scenarios. Finally, the modal strain-based damage index approach [23,24] and ULS curvature approach [7,10,11] are compared to show the effectiveness of the proposed approach.

2. Theory

2.1. Estimation of inter-storey deflection using modal flexibility

The modal flexibility matrix $\mathbf{G}_m$ using m lower mode can be expressed as

$$\mathbf{G}_m = \mathbf{\Phi}_m \mathbf{\Lambda}_m^{-1} \mathbf{\Phi}_m^T = \sum_{i=1}^{m} \frac{\mathbf{\Phi}_i \mathbf{\Phi}_i^T}{\omega_i^2} \tag{1}$$

where $\mathbf{\Lambda}_m = [\backslash \omega_i^2 \backslash]$ for which ω_i is the i-th structural natural frequency, i=1, 2,…, m; $\mathbf{\Phi}_m = \{\phi_1, \phi_2, \ldots, \phi_m\}$; and ϕ_i is the i-th mass normalized mode shape. The mass-normalization on un-scaled mode shapes can be carried out by (1) system mass matrix, or (2) the known mass perturbation approaches [25,26].

The deflections under an arbitrary load $\mathbf{f}$ using modal flexibility matrix can be estimated as

$$\mathbf{u} = \mathbf{G}_m \mathbf{f} \tag{2}$$

where $\mathbf{u}$ is the deflection vector corresponding to the force vector $\mathbf{f}$. The positive bending inspection load (PBIL), which is the vector composed of unit value at all the sensor locations, is used as the force vector $\mathbf{f}$ to obtain modal flexibility-based deflections, which produces only positive bending moments at all the floors [18]. This load vector is beneficial to average all the sensor noises through the equivalent summations of all the sensor contributions.

Finally, by using modal flexibility-based deflections obtained from Eq. (2), the inter-storey deflection can be estimated as

$$\mathbf{u}_i^{\mathrm{IS}} = \mathbf{u}_{i+1} - \mathbf{u}_i \tag{3}$$

where $\mathbf{u}_i^{\mathrm{IS}}$ is the inter-storey deflection and $\mathbf{u}_i$ is the modal flexibility-based deflection at the i-th storey.