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Damage detection of building structures under ambient excitation through the analysis of the relationship between the modal participation ratio and story stiffness

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ABSTRACT

This paper presents a new approach for the damage detection of building structures under ambient excitation based on the inherent modal characteristics. In this study, without the extraction of modal parameters widely utilized in the previous studies on damage detection, a new index called the modal participation ratio (MPR), which is a representative value of the modal response extracted from dynamic responses measured in ambient vibration tests, is proposed to evaluate the change of the system of a structure according to the reduction of the story stiffness. The relationship between the MPR, representing a modal contribution for a specific mode and degree of freedom in buildings, and the story stiffness damage factor (SSDF), representing the extent of reduction in the story stiffness, is analyzed in various damage scenarios. From the analyses with three examples, several rules for the damage localization of building structures are found based on the characteristics of the MPR variation for the first mode subject to change in the SSDF. In addition, a damage severity function, derived from the relationship between the MPR for the first mode in the lowest story and the SSDF, is constructed to identify the severity of story stiffness reduction. Furthermore, the locations and severities of multiple damages are identified via the superposition of the presented damage severity functions. The presented method was applied to detect damage in a three-dimensional reinforced concrete (RC) structure.

1. Introduction

Buildings are often damaged due to continuous deterioration caused by environmental stressors and unexpected severe loads caused by natural disasters, such as earthquakes or typhoons. Serious damage can lead to the collapse of a building, which can result in significant human and property losses. In this regard, structural health monitoring (SHM) technology has been actively developed to ensure the safety of buildings [1–4], and the application of this technology to actual real-life buildings [5–9] covers the real-time monitoring of stress, displacement, and vibrational characteristics. The unique characteristics of a building can be expressed by modal parameters such as natural frequency, mode shape, and damping ratio.

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Since the modal parameters that are extracted via vibration measurement that is based on the SHM system of a building [10–12] are inherent characteristics, they have been used for model updating and damage detection technology [13–15] to identify the state and evaluate the safety of a building.

A modal parameter can be expressed as a function of a structural system, in other words, a function of mass, stiffness, and damping. When a structure is damaged, for example, by reduced stiffness, the value of its modal parameter changes. For decades, studies on damage detection have been widely carried out by focusing on modal parameters, which are natural characteristics extracted from the vibration responses of a building structure [16]. These modal parameter-based damage detection methods are divided into two types. The first type of method detects damage by estimating the changes in stiffness of a damaged structure based on model updating, which minimizes the difference in the modal parameters between the measurement and the finite element (FE) model. The other type of method identifies the relationship between modal parameters and the damage location or extent by implementing an artificial neural network (ANN).

The ANN has been widely adopted for damage detection in structural engineering due to its powerful and outstanding performance with respect to computational pattern recognition [17]. Bakhary et al. [18] proposed an ANN model that constructs a relationship between modal parameters (natural frequency and mode shape) and the elastic modulus of a building before and after being damaged. A statistical approach was suggested to consider the effects of uncertainties on the development of an ANN model. That approach was applied to the numerical damage detection of a portal frame, which considered the first three modes, and the damage detection of a concrete slab, where the first two modes were considered, through experiments with an impact hammer test to obtain modal parameters. Gonzalez and Zapico [19] developed an ANN model using modal parameters for the damage detection of a building. In that model, the natural frequency and mode shape in the low modes were set as inputs, while the mass and stiffness of the beams and columns of a building were set as outputs. The results showed that the modal error was sensitive to the results of damage detection. Goh et al. [20] proposed an approach to detect damage using a multi-stage ANN model with modal parameters. To solve the issue related to limited sensor systems in the structures, unmeasured mode shapes were predicted in the first stage of the proposed ANN model by using measured modal parameters such as mode shapes and natural frequencies for the first three modes. Then, the stiffness reduction factor defined by the elastic modulus was predicted in the second stage of the ANN model by using measured and predicted modal parameters. The proposed ANN model was applied to detect damage in a concrete slab model. Until recently, many studies applied various types of ANN for the damage detection of building structures [21–23].

In addition, various model updating techniques have been developed for the damage detection of building structures. Wu and Li [24] used the modal parameters of the first five modes to update an eigenvalue sensitivity-based FE model for steel structures before and after being damaged. Their proposed damage detection method could identify the rotational stiffness of joints and the reduction of the elastic modulus. The method was verified by a vibration test of steel-framed specimens. For all modes under consideration, the same weight value was assigned to an object (error) function during model tuning. The model updating method proposed by Wang et al. [25] utilized the particle swarm optimization algorithm to minimize the proper orthogonal modes of measurement and the model. An updated model was used to identify the location and degree of story stiffness reduction of a three-story shear frame. Paultre et al. [26] performed a forced vibration test to detect the damage to a two-story concrete structure. The stiffness reduction factor was used as a variable in the model updating, which minimizes the difference in modal parameters between the model and measured-frequency response function. Using this method, the location and degree of damage were identified. Yu et al. [27] attempted to extract modal parameters more efficiently by proposing a component mode synthesis method based on the substructuring approach. The modal parameters for the first ten modes, which were extracted using that method, were used for model updating, which identified the damaged structural element of a large-scale frame structure and the corresponding stiffness reduction factor. Zhang and Aoki [28] presented a model updating method for damage detection using the mode shape of the first mode and the natural frequency of lower modes extracted via a peak-picking method. The proposed model updating method was applied to a four-story shear frame building.

Some studies on model updating [29–33] assigned a different weight to each mode in the error function of the formulation to construct an updated model. For example, Reynders et al. [33] proposed a model updating method that considered a different weight for each mode by using the natural frequency and mode shape to detect the stiffness reduction of a damaged structure. The weight value was assigned to the error function by using modal phase collinearity and the standard deviation of multiple measured natural frequencies, which were calculated differently for each mode. As each mode has a different effect on structural response, the contribution of each mode needs to be considered differently in damage detection using modal parameters. However, no clear basis has been provided for assigning a different weight to each mode for damage detection. Although some other studies on model updating [34–36] could not cover damage detection, they proposed a model updating method by using the modal participation mass ratio (MPMR), which was introduced to evaluate the modal contribution in the theory of structural dynamics, to consider the contributions of modes in finding the optimal updated model.

In addition, the extraction of modal parameters used for damage detection is affected by the environmental conditions of the target structure. Many studies [9,37,38] have shown that the natural frequency and damping ratio vary with the amplitude level of the measured vibration data, which are used for the extraction of modal parameters. The extracted modal parameters were discovered to be influenced by the ambient temperature and humidity [39,40]. In addition to such ambient conditions, the types of system identification (SI) methods, which are applied to extract modal parameters, also influence the results of extraction. In particular, even when an SI method is applied, the extracted modal parameters vary according to the values of variables required in the SI method [9,41]. Unlike the extraction of modal parameters via an analytical study or vibration test