Measurement 102 (2017) 220–229

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

A model updating method with strain measurement from impact test for the safety of steel frame structures

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ARTICLE INFO

Article history:
Received 13 October 2016
Accepted 8 February 2017
Available online 11 February 2017

Keywords:
Model updating
Modal parameter
Strain measurement
Impact test
Steel frame

ABSTRACT

Conventional model updating methods for structures mainly use modal parameters, which are global structural responses such as natural frequency, mode shape, and modal damping obtained through vibration measurements. A model updated using those modal parameters can accurately estimate global structural responses and is used to evaluate the state of a structure. However, when using modal parameters only in model updating, a difficulty arises regarding safety assessment and response prediction of local structural members. To ensure safety of structural members, this study proposes a model updating method using the strains measured from the impact tests in structural members of steel frame in addition to modal parameters. In the model updating technique proposed in this study, error functions are set as the differences between measured and model's modal parameters and the maximum strain subject to impact force, and the functions are minimized using a multi-objective optimization algorithm. The strain responses predicted in the updated model are used in the safety assessment of structural members in steel frames. The proposed method was experimentally verified through impact hammer loading tests on a planar steel moment frame. Furthermore, the stresses obtained from the model updated with modal parameters only and the model updated by the proposed method were compared.

1. Introduction

Structural health monitoring studies have been actively conducted to identify the state of building structures and to evaluate their safety [1–6]. The safety of structural members in a building or the state at the system level is evaluated through system identification using the responses obtained from sensors installed in a building [7–12].

A building consists of numerous structural members, which produce various loading paths. The structural members that provide relatively small contributions to the safety at the system level do not significantly influence the overall safety and collapse mechanisms. However, when major structural members such as main columns which affect overall building safety are aged and damaged, diagnosis for their repairs or reinforcements are required. Consequently, many studies on the safety evaluation of structural members have been conducted. For the safety evaluation of structural members, various technologies measuring strains, predicting the maximum strain or strain distribution, and detecting damage have been developed [13–17]. As structures have become larger and taller, the number of structural members to be monitored has increased. For a number of target structural members, sensing methods for direct strain measurements have exhibited various limitations, such as higher costs due to the increase in the number of sensor locations, difficulty in wiring, issues concerning power supplies, and the enormous amount of data processing necessary. Accordingly, with limited measured information, various studies have attempted to evaluate the safety of buildings through model updating based on system identification.

System identification is performed to extract modal parameters, such as natural frequency, mode shape, and damping, from the vibration measurements in a building. Modal parameters obtained from system identification are utilized in model updating [18–25] for establishing base line model, detecting damage and predicting the structural response. Most conventional model updating studies have tried to make models representing behaviors similar to the real structure by using modal parameters obtained from measurements. Manual methods involving trial and error and novel methods using optimization algorithms, such as evolutionary computation, are employed to determine the structural parameters that minimize differences between the modal parameters

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http://dx.doi.org/10.1016/j.measurement.2017.02.013
0263-2241/

extracted through the sensors installed in a structure and those obtained from a finite element (FE) model. Models updated by those model updating method with modal parameters can be used to investigate the state of a structure at the system level.

For the safety assessment of structural members in a building, previous model updating methods using modal parameters included studies on searching locations of unsafe structural members and identifying severities of damages [26–35]. Those studies focused on the safety evaluation of structural members based on modal parameter changes of the damaged structure compared to healthy structure. Previous conventional studies on model updating with only modal parameters showed some limitations in terms of damage assessment of structural member. Some studies on model updating [26,33] could not identify locations of the damaged and undamaged members, precisely. In other words, the methods often identified the undamaged members as damaged, even if damaged members are guessed correctly. Other studies on model updating could not predict the severity of damage, present the severity of damage quantitatively, or could estimate the severity of damage with poor accuracy, even though it performed well at identifying the damage location [29,30]. In addition, rough comparisons between the actual structure and updated model for safety evaluation of structural members were shown even though it could identify the damaged location because it could not clearly quantify the severities of damages to the specimens in structural experiments for steel or RC frames [27,28,34]. Especially, most studies exhibited limitations in the local response prediction of structural members, such as displacement and strain, although some of them could identify the locations and severities of damage in local members to some extent. Because most previous studies have generally used modal parameters or structural characteristics extracted from modal parameters in model updating, it is difficult to predict local responses and evaluate the safety of structural members. To solve this problem, several studies have employed local responses from structural members to model updating for the safety evaluation or response prediction in local structural members. Kurata et al. [31] used dynamic strain measurements for identifying safety of structural members in a steel frame. The location and severity of fracture of a steel frame beam-column joint were predicted from the bending moment changes obtained by dynamic strain measurements. Wang et al. [32] performed model updating using global and local responses of a long-span bridge. The updated model was used to predict the modal parameters of a bridge as well as the displacements and strain responses.

In this study, a model updating method using strain measurement from impact test in addition to modal parameters is proposed for the safety evaluation of a steel frame to overcome the limitations on safety assessment of structural members in conventional model updating methods with only modal parameters. The modal parameters of a building obtained from vibration measurements and the strain responses obtained through impact hamming for a major structural member, such as a column, are used in the presented model updating method. In the model updating, error functions are set as the differences in modal parameters and strain responses between measurements and the model to be updated. Error functions for modal parameters are set up as many as the number of modes under consideration. Error functions for strain responses are additionally established. Those multiple error functions are minimized by a multi-objective optimization technique, non-dominated sorting genetic algorithm-II (NSGA-II) [36]. The decision parameters to be determined in the model updating are set up as properties related to stiffness, such as the rotational stiffness of joints and flexural stiffness of structural members in the steel frame. In the model updating method, contributions of the modes under consideration to the responses of the structures are considered when selecting a final solution among the multiple Pareto solutions generated by NSGA-II. The proposed solution selection rule assigns a weight based on the modal participation factor to the error function of each mode to consider different influences of modes on the structural behaviors and determines the final solution. The proposed method was verified through an impact hammer tests for a planar steel frame specimen. The validity of the proposed method was verified by comparing strains from updated model and measurements. Furthermore, the conventional model updating method with only modal parameters was compared with the proposed method through the prediction of strain responses.

2. Model updating method

2.1. Acquiring of global and local responses

The modal parameters of building structures are typically extracted through the system identification of vibration measurement data using accelerometers. Because it is difficult to excite a building, and even if excited, because it requires high cost and a large effort, the vibrations are typically obtained under ambient measurement conditions. For the measured data, the modal parameters are typically extracted through the output-only system identification technique [37] because the input signals (loads) are unknown. In this study, the modal parameters used in model updating are assumed to be obtained through the system identification of vibration data measured in the building; however, in the case of the planar steel frame specimen with two story used in this study, system identification is performed using the force and acceleration values obtained from the impact hammer loading tests. Using the measured input signals and output signals, a frequency response function (FRF) is obtained, and the natural frequency and mode shape are extracted.

In the model updating of this study, in addition to the modal parameters of the structure, the responses of local structural members such as columns or beams in the frame are used in the formulation. The strain values measured at the columns in the steel frame are selected as the responses of structural members. In this study, the strain measurement data are obtained by loading the impact hammer around locations in the structural members where the strain sensors are installed. During the model updating process, the force values, i.e., input signals from the impact loading, and strain values, i.e., output signals, are all required. The error function for strain responses is formulated based on the difference between the measured strain value and the strain value extracted from the model. The measured strain value in the error function is the strain value measured from the impact hammer loading. The strain value of the model is obtained by solving the equations of motion (EOM) of the finite element (FE) model. The time history of force data obtained during hammer loading are input to the EOM of the FE model. In addition, the time history of strain data are obtained at the strain measurement location. The maximum strain value among the time history strain data is used in the formulation as the safety evaluation criteria of the members.

2.2. Formulation

The decision parameters to be determined in the model updating are set to rational stiffness in joint, flexural stiffness, and damping of target structure. To find decision parameters during the model updating, the error functions are established using measured information and those decision parameters in model and minimized to reflect actual behavior of structure. The error functions are set up for the modal parameters and strain responses. At first, for modal parameters, error functions are established as