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Effects of variability in ambient vibration data on model updating and damage identification of a 10-story building

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ABSTRACT

This study presents linear finite element (FE) model updating and damage identification of a ten-story reinforced concrete building using ambient vibration measurements. Structural damage was induced to the building by removing six perimeter infill walls. Ambient acceleration response of the structure was recorded before and after the induced damage which are referred to as the reference state and damaged state of the building, respectively. An operational modal analysis method is used to identify the natural frequencies, damping ratios, and mode shapes of the structure using different sets of ambient vibration measurements at the reference state and the damaged state of the building. An initial linear FE model of the structure is created based on in-situ geometry measurements and testing of material samples. The initial model is then updated to reference models using different sets of ambient vibration measurements at the reference state of the building. The updated model parameters reveal considerable variation despite the fact that the identified modal parameters exhibit a much lower level of variability. A subset of the updated reference models are subsequently employed to detect the location and extent of the induced damage by updating the equivalent stiffness of 12 wall substructures using the measured data at the damaged state. Although the identified damage is generally in good agreement with the induced structural damage, the results are found to be sensitive to the variation of the identified modal parameters.

1. Introduction

Civil engineering structures can be damaged due to extreme events such as earthquakes, or accumulate damage over time due to various sources including severe environmental conditions, service loads, and/or material deterioration. Reliable damage identification and condition assessment methods are needed to assure their safety and serviceability. A comprehensive damage identification process includes the (i) detection of damage, (ii) localization of damage, (iii) quantification of damage extent, and (iv) prediction of remaining service life of the structure [1]. Visual inspection is the most common approach in practice to detect structural damage; however, the major shortcoming of this approach is that it can become costly, time demanding, and more importantly, it could be hindered by lack of access to the critical areas [2,3]. Alternatively, vibration-based damage identification methods can be used for the condition assessment of large and complex structures [4,5]. These methods monitor the global state of the structural health by analyzing its vibration response to ambient or forced excitations. These methods rely on the hypothesis that structural damage causes observable changes in the dynamic properties of civil structures. Hence, damage can be estimated from the changes in the dynamic properties through the solution of an inverse problem. Comprehensive reviews of vibration-based damage identification methods can be found in [6–9].

Finite Element (FE) model updating is one of the most commonly used vibration-based approaches for damage identification of civil structures [10–15]. The FE model updating framework is capable of detecting, localizing, and quantifying structural damage, while the updated FE models can potentially be employed for structural response prediction which may lead to an updated life-cycle information of the structure [16,17]. In the FE model updating process used for damage identification, a linear elastic

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model of the structure is often considered and the structural damage is estimated as the loss of stiffness in the structural elements. The updating process is performed at an initial reference state and then at the current/damaged state of the structure by matching the measured data in those states, respectively. This methodology has been widely used for damage identification of different types of structures [18–23], however several challenges still remain when applied to actual large structures. Some of these challenges include the (i) low sensitivity of vibration data to structural damage [24], (ii) influence of modeling errors [25–27], (iii) high computational cost associated with updating large models [28,29], (iv) sensitivity of vibration measurements to environmental and ambient conditions [30–33], and (v) complications when extending the framework to nonlinear models and nonlinear structural response [34–36].

The FE model updating framework is implemented in this paper to identify the damage induced to a ten-story reinforced concrete building. First, an initial FE model of the building is created based on data obtained from *in-situ* measurements and laboratory tests of geometric and material properties. Then, the initial model is updated to reference models by matching the model-predicted modal parameters to those identified from different sets of the measured ambient vibration data. This calibration process is repeated 40 times using the modal parameters identified from 40 different vibration datasets at the reference state resulting in 40 reference models. An average reference model is also defined based on the average values of the updating parameters over the 40 reference models. The average and three distinct reference models are then calibrated to match the modal parameters at the damaged state of the building. The re-calibrated models can be used to estimate the structural damage. The variability of updating stiffness parameters are investigated and compared with the observed variability in the identified modal parameters at both the reference and damaged states. Finally, the robustness of the presented damage identification framework is evaluated by comparing the estimated damage with the imposed damage to the structure.

2. Description of building and dynamic tests

2.1. General characteristics of the building

The ten-story reinforced concrete building considered in this study was constructed in 1914 in Utica, NY. It consisted of a slab-column structural system with exterior concrete infill walls. A five-story clay masonry structure was attached to the main structure in the south side. The building was demolished on March 2, 2014 following a number of ambient vibration and forced vibration tests [37] using the equipment of NEES at UCLA. Fig. 1 shows the west view of the building and the plan view of a typical floor.

2.2. Induced damage

Damage was induced to the building by removing six exterior infill walls. The induced damage would reduce the lateral stiffness of the structure in a manner similar to effects of a potential earthquake on the structure. The damage was induced by removing: (i) two walls at the west side of the third story, (ii) two walls at the north side of the third story, and (iii) two walls of the second story, one at the west side and one at the north side. In this study, the "reference state" refers to the initial state of the building and the "damaged state" refers to the building state after the removal of the six walls. The damaged walls of the building are illustrated in Fig. 2.

2.3. Dynamic tests

Fifty-two hours of ambient vibration response of the building were recorded before and after the wall demolitions. The acceleration response of the structure was measured using an array of 60 accelerometers including 24 uniaxial and 36 tri-axial sensors. The sensors were force-balance Kinematrics accelerometers which were synchronized by a GPS clock with accuracy of less than 1 ms [38,39]. These accelerometers are capable of recording accelerations between 0.1 mg and 2 g with a sampling rate of 200 Hz. Quanterra Q300 A/D data loggers were employed for data acquisition [39]. This is a low-power, 24-bit system with dynamic range of approximately 135 dB root-mean-square (RMS). The accelerometers measured accelerations along the X, Y, and Z directions at the North-East (NE) and South-West (SW) corners of each story as shown in Fig. 1(b). More details about the building, instrumentation and the dynamic testing of the building can be found in [37].

3. System identification

3.1. Identified modal parameters

The recorded acceleration time histories are divided into sets of 5-min long windows. A total of 312 5-min datasets are available at the reference state and 22 datasets at the damaged state of the building. The selection of 5-min long windows is based on a preliminary sensitivity study conducted to define the optimal window length, similar to an earlier study by the authors [40]. Conducting system identification using different sets of recorded data provides a measure of variability for the identified modal parameters. The ambient vibration data are filtered by a bandpass (0.5–8.5 Hz) Finite Impulse Response (FIR) filter of order 2048. This frequency range includes the first three modes of the structure which are extracted using the Natural Excitation Technique combined with Eigensystem Realization Algorithm (NExT-ERA) [41,42]. The higher vibration modes of the building are not considered for the model updating process in this study because (1) these modes are not identified as accurately and consistently as the first three modes (e.g., there are some missed identifications for the higher modes), (2) the modeling errors are larger for the higher modes and therefore these modes cannot be matched by just tuning a few parameters of the model [43], and (3) they have lower contribution to the dynamic response and performance of the building.

Table 1 presents the mean and coefficient-of-variation (CoV) of the identified natural frequencies and damping ratios at both the reference state and the damaged state of the structure. It can be observed that the identified natural frequencies decrease due to damage while the damping ratios exhibit no clear trend. Moreover, the identified frequencies show small variability across different datasets with the largest CoV being less than 1%. This is usually the case when the ambient data collected in a short period of time and the structure is not subjected to seasonal environmental changes. This variability is caused by (1) measurement noise and system identification errors, (2) changing ambient temperature, and (3) changing ambient excitation forces due to wind speed and activity in the building. While it is not possible to quantify the contribution from each source due to lack of information, the authors believe that the measurement noise and system identification errors have the smallest contribution to the total variability of identified modal parameters and the observed variability of modal parameters in this study are caused mainly by the changing ambient temperatures and excitation forces due to pre-demolition activities in the building.

Fig. 3 shows the identified natural frequencies versus measured air temperature for 142 data sets at the reference state. Note that