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Damage identification study of a seven-story full-scale building slice tested on the UCSD-NEES shake table

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ABSTRACT

A full-scale seven-story reinforced concrete building section was tested on the UCSD-NEES shake table during the period October 2005–January 2006. The shake table tests were designed to damage the building progressively through four historical earthquake records. At various levels of damage, ambient vibration tests and low-amplitude white noise base excitations with root-mean-square accelerations of 0.03 g and 0.05 g were applied to the building, which responded as a quasi-linear system with parameters evolving as a function of structural damage. Modal parameters (natural frequencies, damping ratios and mode shapes) of the building were identified at different damage levels based on the response of the building to ambient as well as low-amplitude white noise base excitations, measured using DC coupled accelerometers. This paper focuses on damage identification of this building based on changes in identified modal parameters. A sensitivity-based finite element model updating strategy is used to detect, localize and quantify damage at each damage state considered. Three sets of damage identification results are obtained using modal parameters identified based on ambient, 0.03 g, and 0.05 g RMS white noise test data, respectively. The damage identification results obtained in all three cases do not exactly coincide, but they are consistent with the concentration of structural damage observed at the bottom two stories of the building. The difference in the identified damage results is mainly due to the significant difference in the identified modal parameters used in the three cases. The assumption of a quasi-linear dynamic system is progressively violated with increasing level of excitation. Therefore, application of nonlinear FE model updating strategies is recommended in future studies to resolve the errors caused by structural response nonlinearity.

1. Introduction

In recent years, structural health monitoring has received increasing attention in the civil engineering research community with the objective to develop methods able to identify structural damage at the earliest possible stage and to evaluate the remaining useful life of structures (damage prognosis). Vibration-based, nondestructive damage identification makes use of changes in dynamic characteristics (e.g., modal parameters) to identify structural damage. Experimental modal analysis (EMA) has been used as a technology for identifying modal parameters of a structure based on low amplitude vibration data. It should be emphasized that the success of damage identification based on EMA depends strongly on the accuracy and completeness of the identified structural dynamic properties. Extensive reviews on vibration-based damage identification were provided by Doebling et al. [1,2] and Sohn et al. [3].

Damage identification consists of: (1) detecting the occurrence of damage, (2) localizing the damage areas, and (3) estimating the extent of damage in the various damage areas [4]. Numerous vibration-based methods to achieve these goals have been proposed in the literature. Salawu [5] presented a review on the use of changes in natural frequencies for the purpose of damage detection only. Pandey et al. [6] introduced the concept of using curvature mode shapes for damage localization. Methods based on changes in identified modal parameters to detect and localize damage have also been further developed for the purpose of damage quantification. Among these methods are strain-energy based methods [7] and the direct stiffness calculation method [8]. Another class of sophisticated methods consists of applying sensitivity-based finite element (FE) model updating for damage identification [9]. These methods update the physical parameters of a FE model of the structure by minimizing an objective function expressing the discrepancy between FE predicted and experimentally identified

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structural dynamic properties that are sensitive to damage such as natural frequencies and mode shapes. Optimum solutions of the problem are reached through sensitivity-based constrained optimization algorithms. In recent years, sensitivity-based FE model updating methods have been applied successfully for condition assessment of structures [10,11].

A full-scale seven-story reinforced concrete building section was tested on the UCSD-NEES shake table in the period October 2005–January 2006. The objective of this test program was to verify the seismic performance of a mid-rise reinforced concrete wall building designed for lateral forces obtained from a displacement-based design method, which are significantly smaller than those dictated by current force-based seismic design provisions in the United States [12,13]. The shake table tests were designed to damage the building progressively through several historical seismic motions. At various levels of damage, ambient vibration tests were performed and several low-amplitude white noise base excitations were applied through the shake table to the building which responded as a quasi-linear system with dynamic parameters evolving as a function of structural damage. Different input–output and output-only system identification methods were used to estimate modal parameters (natural frequencies, damping ratios and mode shapes) of the building in its undamaged (baseline) and various damaged states for three different levels of input excitation (i.e., ambient, 0.03 g and 0.05 g root-mean-square white noise base excitations) [14].

In this study, a FE model updating strategy is applied for damage identification of the building in various damaged states. The objective function for damage identification is defined as a combination of natural frequency and mode shape residuals measuring the discrepancy between the FE predicted and experimentally identified modal parameters. Three cases of damage identifications are considered in this study, namely: (1) residuals are constructed from the modal parameters identified based on ambient vibration data, (2) residuals are formed using the modal parameters identified based on 0.03 g root-mean-square (RMS) white noise base excitation test data, and (3) residuals are formed using the modal parameters identified based on 0.05 g RMS white noise base excitation test data. The damage identification results obtained from these three cases are compared to each other and also to the damage observed in the building (from pictures, video cameras, and inferred from strain sensors).

2. Test specimen, test setup and dynamic experiments

2.1. Seven-story reinforced concrete building slice

The test structure which represented a section of a full-scale reinforced concrete wall building consisted of a main wall (web wall), a back wall perpendicular to the main wall (flange wall) for transversal stability, a concrete slab at each floor level (except at the base), an auxiliary post-tensioned column to provide torsional stability, and four gravity columns to transfer the weight of the slabs to the shake table platen. Slotted slab connections were placed between the web and flange walls at floor levels to minimize the moment transfer between the two walls, while allowing the transfer of the in-plane diaphragm forces. Fig. 1 shows the building mounted on the shake table. More details about the building can be found in [12,13].

2.2. Instrumentation layout

The building was instrumented with a dense array of over 430 data channels from DC coupled accelerometers, strain gages, potentiometers, and linear variable displacement transducers (LVDTs) sampled simultaneously using a nine-node distributed data acquisition system. The technical characteristics of the accelerometers are: MEMS-Piezoresistive MSI model 3140, amplitude range: ±5 g, frequency range (min): 0–300 Hz, voltage sensitivity: 400 mV/g. The data acquisition system used consisted of nine 16-bit resolution National Instruments PXI chassis. Each chassis had eight SCXI 1520 modules which were individually configured to handle eight channels of strain gages, accelerometers, relative displacement, and/or pressure sensors.

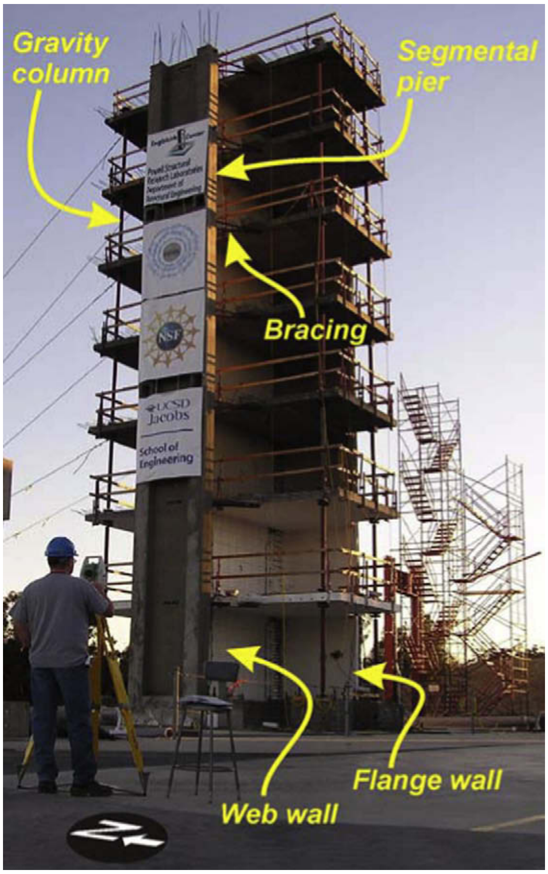

Fig. 1. Test structure.

In this study, data from 14 longitudinal acceleration channels (on the web wall at each floor level and at mid-height of each story) were used to identify the damage at different states of the building. The measured acceleration responses were sampled at a rate of 240 Hz resulting in a Nyquist frequency of 120 Hz, which is much higher than the modal frequencies of interest in this study (<25 Hz). These measured data were band-pass filtered between 0.5 Hz and 25 Hz using a high order (1024) FIR filter. Fig. 2 shows the Fourier Amplitude Spectra (FAS) of two filtered acceleration time histories recorded at floor levels 1 (first floor above the table) and 7 (roof) during a 0.03 g RMS white noise base excitation test (left column) and an ambient vibration test (right column) performed on the building in its undamaged state. From this figure, it is observed that: (1) the FAS plots are very jagged/noisy which may be due to rattling of many loose connections especially from the slackness between the threaded rod and the nut in the gravity columns (1.5 mm of slackness) when they go from tension to compression or vice versa as well as the slackness at both ends of the steel braces connecting the slabs to the post-tensioned column, (2) the first longitudinal vibration mode has a predominant contribution to the measured response, especially at the higher floors, which renders the identification of higher (than the first longitudi-