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Health monitoring of a steel moment-resisting frame subjected to seismic loads

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A B S T R A C T

Structural health monitoring (SHM) offers the potential to evaluate the safety and integrity of the civil infrastructure. By obtaining accurate information about the condition of the structure, appropriate preventive measures can be taken to prolong the service life and prevent the catastrophic failure of the structure. Application of effective damage detection strategies can reduce the life-cycle costs as well. Damage reduces the stiffness and modifies the modal properties of a structure. Therefore, changes in modal properties can be used to detect damage in the structure. Although extensive research has been conducted on structural diagnosis by measuring the vibrational signals of structures, more research is still needed for development of reliable and effective damage detection techniques. This paper presents a study on damage detection of a 3-story steel moment-resisting frame structure instrumented by a network of wireless sensors and cable-based accelerometers. Experimental data from shake table testing and numerical results from finite element simulation were used for damage identification through two approaches. In the first approach, the finite element model of the structure was calibrated and used to locate and quantify the elemental stiffness loss on the basis of the experimentally-identified modal parameters. Moreover, a direct search algorithm was used for minimization of an objective function representing the difference between predicted and measured dynamic parameters of the structure. In the second approach, damage identification was performed through application of the Modal Assurance Criterion (MAC) and detection of the changes between undamaged and damaged conditions. Results of this study are indicative of capability and effectiveness of both approaches in identification of damage.

1. Introduction

Damage may be defined as a change introduced into a system that adversely affects its current or future performance. The term 'damage' may not be meaningful without a comparison between two different states of the system, one of which is assumed to represent the initial, and often undamaged, state. On this basis, definition of damage can be limited to changes in material and/or geometrical properties of structural systems, including changes to the boundary conditions and system connectivity. In general, damage begins at the material level and then progresses to component and system level damage under appropriate loading conditions. Damage can accumulate incrementally over long periods of time or may occur on much shorter time scales as a result of scheduled or unscheduled discrete events [16].

Considering the strategic and monetary value of the civil infrastructure, early and accurate detection of damage can be quite effective in maintaining the safety, reducing the lifetime operating costs, and improving the performance of structures. Accordingly, structural health monitoring systems are implemented in critical structures with the aim of detecting the damage occurrence and obtaining helpful information regarding the location, nature, and severity of the damage [20,21].

Various damage detection techniques and methodologies have been developed over the past 30 years or so. Doebling et al. [5,6] provided comprehensive review of detection, location, and characterization of structural damage via techniques that examine changes in measured structural vibration response. A more recent review on damage detection techniques and health monitoring techniques based on linear and non-linear vibrational measurements was reported by Sinou [23]. In particular, several effective techniques have been developed in recent years and applied for damage identification in framed steel structures. For example, Pal et al. [18] evaluated the performance of several damage detection algorithms for health monitoring of joints in steel frame structures via numerical and experimental approaches. Döhler and Hille [7] applied a statistical subspace-based damage detection method successfully and evaluated its performance through numerical simulations and testing of an artificially-damaged steel frame structure. Lately, Betti et al.

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[2] applied a combined approach based on artificial neural networks and genetic algorithms for structural damage identification. The performance of their approach was verified through analytical and experimental investigations on a three-story steel spatial frame instrumented by a series of accelerometers and progressively damaged by cutting one of its columns just above the first story. Rasouli et al. [19] proposed a two-stage method to properly identify the location and the extent of damage in shear frames based on story displacement index and modal residual force. The efficiency of this method was shown numerically by implementing the technique to three five-, ten-, and twenty-five-story shear frames. Recently, Liu et al. [11] developed an intelligent SHM system for the Tianjin 117 high-rise building in China. An integrated SMAE software was developed based on the Microsoft Windows platform in order to evaluate structural performance of steel high-rise structures. Based on this study, it was concluded that further research and development on the sensitivity, stability, and aging current sensing technologies are required in order to achieve reliable SHM systems for the civil infrastructure.

With recent advances in low-cost wireless sensing and data acquisition technology, wireless sensors and sensor networks have been considered as efficient substitutes for traditional tethered monitoring systems. Wireless sensors can especially play great roles in processing and screening the structural response data for signs of structural damage [13]. Sundaram et al. [24] presented a review of the research and development activities in the field of smart wireless sensors and also discussed some applications of smart sensing, monitoring, and damage detection techniques developed for the civil infrastructure. In a reported study by Lu et al. [12], a wireless sensing system was designed for applications in structural monitoring and damage detection. The effectiveness of this system in estimating the damage was verified through utilization of data from shaking table tests and low-level white noise excitations. In another study, Lei et al. [10] established a smart wireless sensor network for autonomous structural damage detection, and demonstrated its performance by applying it to detect the structural damage of a multi-story building. Mosallam [15] developed a wireless optical-fiber sensing system as a part of an innovative diagnostic/prognostic system (DPS) for light-weight military bridges. The DPS protocol utilizes both remote sensing and numerical simulation that predicts the residual strength as well as provides instantaneous repair procedures.

This paper describes the implementation of two approaches for damage identification of a 3-story steel moment-resisting frame structure instrumented by a network of wireless sensors as well as a set of cable-based accelerometers. Damage detection was performed by using experimental data from shake table testing and numerical results from finite element simulation of the structure. In the first approach, the finite element model of the structure was calibrated and then used to locate and quantify the elemental stiffness loss on the basis of the modal parameters identified experimentally. As well, a direct search algorithm was used for minimization of an objective function representing the difference between the predicted and measured dynamic parameters of the structure. In the second approach, damage identification was carried out through application of the Modal Assurance Criterion (MAC) and detection of the changes between undamaged and damaged conditions.

2. Experimental program

2.1. Steel moment frame structure

The prototype structure used in this study was a 1/6 scale, single-bay, and three-story steel moment-resisting frame model (Fig. 1) that represents a rigid building. Elevation view of the test structure is shown in Fig. 2. The overall floor dimensions of the steel frame were 60 in. × 60 in. (1.524 m × 1.524 m) at all levels, and the height of each floor was 30 in. (0.762 m). Both columns and beams were made of ASTM A572 Grade 50 steel material with a typical size of S3 × 5.7. At each floor, 11-gauge steel plate was bolted to the top of the steel beams to represent rigid frame diaphragm action. As shown in Fig. 1, the mass of the frame specimen was represented by three 57 in. × 57 in. × 3 1/2 in. (1.45 m × 1.45 m × 88.9 mm) reinforced concrete blocks. The average weight of each concrete block was 886.0 lbs. (3940.93 N). The concrete blocks were attached to the steel plate diaphragm at each floor by four 1/2 in. (12.70 mm) diameter high-strength steel bolts. These steel bolts were welded to the steel plates by a 1/8 in. (3.175 mm) fillet weld.

The base plates of the frame were connected to steel adaptors, as seen in Fig. 1. The adaptors were made from steel channels with a stiffener plate, and were utilized to connect the frame-column base plates to the shake table. Additional stiffener plates were welded to the channels

Fig. 1. Three-story steel frame structure.

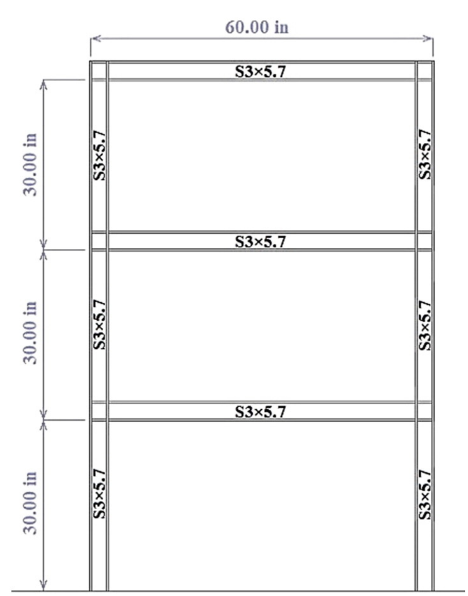

Fig. 2. Elevation view of the 3-story frame.