EXPERIMENTAL PHASE II OF THE STRUCTURAL HEALTH MONITORING BENCHMARK PROBLEM

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ABSTRACT

This paper introduces the second experimental phase of the activities of the IASC-ASCE Structural Health Monitoring Task Group, involving the application of structural health monitoring techniques to data obtained from a four story steel frame structure tested in August 2002 at the University of British Columbia. These Phase II experimental studies follow a series of analytical studies focusing on a model of the same structure. In the experiment, damage was simulated by removing bracing or loosening bolts within the structure. Three types of excitation were considered: electrodynamic shaker, impact hammer, and ambient vibration. In the shaker tests an electrodynamic shaker on the top floor of the frame was used to excite the structure. Accelerometers were placed throughout the structure to provide measurements of the structural responses. The data and a complete description of the experimental setup are also available at *http://wusceel.cive.wustl.edu/asce.shm/* for potential participants to download and examine. Subsequent papers in this session will consider solution procedures for this problem.

INTRODUCTION

A goal of structural health monitoring (SHM) research is for future buildings and bridges to have built-in monitoring systems that can tell the owner that repair or maintenance is required, how immediate the need for maintenance is, and where in the structure the damage is located. These SHM techniques would supplement, and in time, potentially supplant, visual inspection. These strategies would provide automated, quantitative information that will improve decision-making regarding repair/replacement priorities. Implementation of these techniques may also ultimately result in lower life-cycle costs than periodic on-site visual inspections, and hence a more cost-effective solution. Furthermore, advance notice of the presence of damage will reduce the economic impact of structural damage in a region, as repairs can be made early to avert potentially catastrophic damage scenarios.

Structural health monitoring techniques have been under development for over a decade. SHM is a current topic of widespread interest in the civil engineering community. Several recent workshops and special journal issues have focused on SHM and damage detection, *e.g.* [3–6, 14]. Various structural health monitoring algorithms have been developed and implemented on experimental models and full-scale structures. Primarily these studies have focused on laboratory scale structures, however in Hong Kong, full scale implementation of SHM systems on several bridges has been conducted for several years [10, 12].

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Because the techniques are applied to different structures under various conditions, the relative merits of each algorithm are not obvious. Thus, the community would benefit from a comparison of several algorithms when applied to the same problems. The IASC-ASCE Task Group on Structural Health Monitoring Benchmark Problems is charged with developing benchmarks to study the efficacy of various structural health monitoring methods. The task group was formed in response to a plan developed at the 1996 *International Workshop on Structural Control* to create three task groups (one per region, Europe, Asia, and North America) to investigate problems in structural health monitoring [4]. The North American task group was formed in 1999 under the auspices of the International Association for Structural Control (IASC) and the Dynamics committee of the ASCE Engineering Mechanics Division.

The IASC-ASCE SHM Task Group has been developing a series of benchmark SHM problems, beginning with a relatively simple problem and proceeding on to more realistic and more challenging problems. The purpose of these studies is to evaluate the potential of this technology for civil engineering structures. So far, there have been two phases of these benchmark problems focusing on health monitoring strategies when applied to data generated with an analytical model of the benchmark structure [8, 9]. In the analytical studies, the structure was damaged by removing the stiffness contributions of various structural members. Phase I considered issues such as sensor noise, modeling errors and incomplete sensor information. This problem was the focus of sessions at the *13th ASCE Engineering Mechanics Conference* in Austin, Texas in 2000, and the ASME/ASCE Joint Mechanics and Materials Conference in San Diego in 2001. Portions of an upcoming special issue of the *ASCE Journal of Engineering Mechanics* will also be devoted to various solution methods for this problem [9]. Phase II of this problem focused on uncertainties in the structural parameters, less severe damage cases, and concluded with some blind tests [1]. This second phase of the SHM benchmark problems was the focus of sessions at the *15th ASCE Engineering Mechanics Conference* in New York in 2002 and the *3rd World Conference on Structural Control* in Como, Italy in 2002. The blind test results were presented, along with the solution, at the *XXI International Modal Analysis Conference* in Kissimmee, Florida in 2003 [11].

The results of these phases of the analytical studies were encouraging. Thus, an experimental phase of this study was initiated by the Task Group. The steel frame at the University of British Columbia (UBC) was the test specimen [2,13]. Experiments were conducted on August 3–7, 2002. Damage was simulated by removing bracing within the structure or loosening bolts connecting beams to columns. Three sources of excitation were considered: ambient vibrations, impact hammer tests, and electrodynamic shaker tests. Accelerometers placed throughout the structure provided measurements of the structural responses. This paper provides details on the structure and experimental setup, as well as instrumentation and testing procedures used during the experiment. The various damage cases considered in the experiments are summarized herein. The data recorded during the testing of the UBC structure, a video of the experiment, and a complete description of the experimental setup are available on the ASCE Structural Health Monitoring Task Group's web page [7].

EXPERIMENTAL SETUP

Benchmark Structure

The subject of the experimental benchmark problem is the 4-story, 2-bay by 2-bay steel-frame scale-model structure shown in Fig. 1. It is located in the Earthquake Engineering Research Laboratory at the University of British Columbia (UBC). For the tests, the structure was mounted on a concrete slab just outside of the structural testing laboratory on the UBC campus to simulate typical ambient vibration conditions. The nine vertical columns are bolted to a steel base frame, and the lower flanges of two of the base beams are encased in concrete, fixing the steel frame to the concrete slab.

The structure is 2.5 m × 2.5 m in plan and is 3.6 m tall. The members are hot-rolled, grade 300W steel (nominal yield stress 300 MPa (42.6 kpsi)). The sections are specifically designed for this scale model test structure. The columns are B100x9 sections and the floor beams are S75x11 sections. A photograph showing the typical beam-column connection and bracing system is provided in Fig. 2.

In each bay the bracing system consists of two 12.7 mm (0.5 in) diameter threaded steel rods placed in parallel along the diagonal. Note that the fixture connecting the braces to the structure adds a degree of flexibility to the braces. This should be considered by researchers who may consider building analytical models of the structure.

To make the mass distribution reasonably realistic, one floor slab is placed in each bay per floor: four 1000 kg slabs at each of the first, second and third levels, four 750 kg slabs on the fourth floor (see Fig. 3). On each floor two of the masses were placed off-center to increase the degree of coupling between the translational motions of the structure. Additionally, the masses are fixed to the structure using two channel sections to bolt each mass to the steel frame. The mass of each channel section is approximately 9.75kg for a total of 19.5 kg per mass for two channels (see Fig. 3).

FIGURE 1: STEEL-FRAME SCALED BENCHMARK STRUCTURE.

FIGURE 2: CLOSE-UP OF BEAM-COLUMN CONNECTIONS.

FIGURE 3: PHOTOGRAPH SHOWING MASS PLACEMENT.

Excitation Cases

Ambient vibration and two types of forced excitations are considered in the tests. Ambient vibration includes excitations present from the environment due to wind, pedestrians, and traffic. The forced excitation cases consider both impact hammer tests, and broadband excitations provided by an electrodynamic shaker.

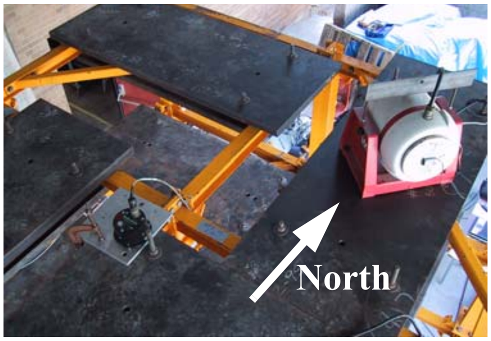

FIGURE 4: PHOTOGRAPH OF ELECTRODYNAMIC SHAKER PLACEMENT.

FIGURE 5: IMPACT HAMMER.

In the shaker tests, the force input to the structure is provided by a Ling Dynamic Systems electrodynamic shaker (Vibrator Model V450 Series). To apply sufficient force to the structure, mass is attached to the end of the shaker. Thus the total moving mass driven by the shaker is equal to the mass of the armature plus the mass attached to the shaker. The overall mass of the body of the shaker is 81.6 kg, The moving mass of the shaker includes the armature (0.426 kg, included in the 81.6 kg) and the supplemental masses attached to the end of the shaker (2.95 kg, not included in the 81.6 kg). A photograph of the shaker installation is shown in Fig. 4. The shaker is placed on the top floor of the structure along the diagonal in the center of the SW bay. The shaker has a maximum capacity of 311 N (70 lbf), a stroke of 19 mm, and a maximum achievable velocity of 2.5 m/sec. The command to the shaker is a band-limited white noise with components between 5–50 Hz. Additionally, in a few configurations, a sine sweep input was employed.

In the impact hammer tests, a Dynatron 5803A 12 lbf Impulse Hammer was used. The impact hammer has a force transducer, and this measurement was recorded during the hammer tests. The maximum force that can be provided with this hammer is 5000lbf, and a medium/soft tip was used on the hammer head during the tests. In each test a series of 3–5 hammer hits were recorded. Two impact locations were selected including a hit on the south face in the north direction, and a hit on the east face in the west direction. Both impacts were placed at the first floor of the structure in the southeast corner. See Fig. 6 for a diagram of the hammer impact locations.

A complete description of all of this equipment is available on the Task Group web site within the Phase II Experimental Benchmark files [7].

Data Acquisition and Instrumentation

Fifteen accelerometers were placed throughout the frame (see Table 1 and Fig. 6) to measure the responses of the test structure and on the base of the frame. FBA sensors were placed along the east and west frames of the structure to measure the motion in the north-south direction (along the strong axis). EPI sensors were placed near the center column of the frame, and oriented to measure the east-west motion of the structure (along the weak axis). Sensors were nominally in the same locations on each day, but were removed from the structure each evening and replaced each morning. Specific locations are provided in the data files. Additionally, in the tests in which beams of the frame were loosened, the sensors (that would have been attached to the loosened beam) were moved to the next frame.

To record the shaker force excitation, one accelerometer was placed on the shaker to measure the acceleration of the moving mass. Additionally, a force transducer on the tip of the hammer was employed to measure the force input to the structure in the impact tests.

A 16-channel DasyLab acquisition systems was used to record the structural responses. Anti-aliasing filters were used in the shaker tests and the ambient tests. In these two types of tests, the data was sampled at 250 Hz. In the hammer tests, a sampling rate of 1000 Hz was used, the anti-aliasing filters were turned off on the channel recording the impact force. Details on the sampling rates in various tests are provided within the data files from the experiments. In the data files provided on the web site, the sensor gains are already accounted for and the values are provided in physical units (*e.g.*, *g*, mm). For more details on the specific data files available, see the web site [7].

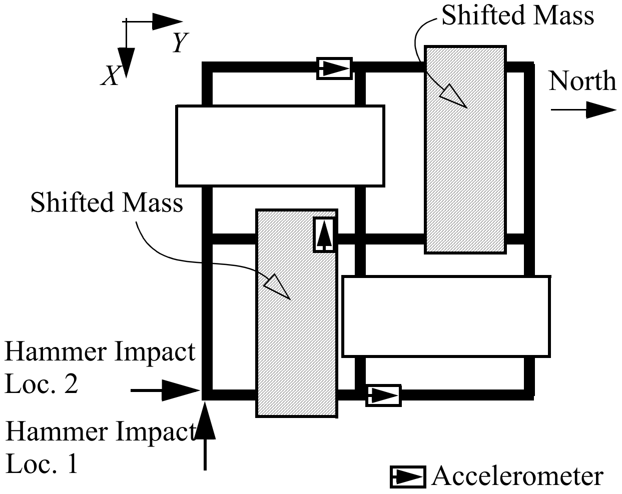

FIGURE 6: DIAGRAM SHOWING HAMMER IMPACT LOCATIONS, AND PLACEMENT OF ACCELEROMETERS, MASSES, AND SHAKER.

During the shaker testing, data acquisition was started several seconds after the excitation was turned on to ensure that the system had reached a steady state condition. In the hammer tests, the data acquisition system was started prior to the first impact, and a series of three to five hits was recorded within each test. Several tests were also conducted by placing extra accelerometers on the base to which the structure is fixed. The specific details of these supplemental tests are also explained on the web site [7].

TABLE 1. CHARACTERISTICS OF THE INSTRUMENTATION.

	Sensor Model	**Sensor Characteristics**		
		Frequency Range	Conditioner Antialiasing Filter Cutoff	Sensitivity
Accelerometers	FBA	DC–50 Hz	50 Hz	5 Volts/g
	EPISensor	DC–200 Hz	50 Hz	5 Volts/g
	IC Sensors (on Shaker)	DC–1 kHz	50 Hz	0.222 V/g
Hammer	Dytran 5803A Impact Hammer (force transducer)	DC–1 kHz (med-soft tip)	–	1.12 mV/lbf

TEST CONFIGURATIONS

A series of tests were conducted on the structure with various damage scenarios. In the tests, damage is simulated by removing braces in the structure or by loosening the bolts at beam-column connections. The various test cases are described in Table 2. In the first test, denoted Case 1, the nominal structure is tested with all braces in place. Case 7 considers the unbraced frame, and the frequencies of this structure are significantly lower than those of the fully braced frame.

In this experimental benchmark, the researcher is left to decide which cases to examine. Note that Cases 2 through 9 could each be considered as damage scenarios when Case 1 is viewed as the undamaged case. Alternatively, Cases 8 and 9 could be considered as damage scenarios when Case 7 is viewed as the undamaged case, and there are several other such comparisons that one could make. Plots showing some typical recorded data are shown in Fig. 7.

TABLE 2. DESCRIPTION OF TEST CASES.

Case	**Configuration**
1	Fully braced configuration
2	All east side braces removed
3	Removed braces on all floors in one bay on southeast corner
4	Removed braces on 1st and 4th floors in one bay on southeast corner
5	Removed braces on 1st floor in one bay on southeast corner
6	Removed braces on all floors on east face, and 2nd floor braces on north face
7	All braces removed on all faces
8	Configuration 7 + loosened bolts on all floors at both ends of beam on east face, north side
9	Configuration 7 + loosened bolts on floors 1 and 2 at both ends of beam on east face, north side

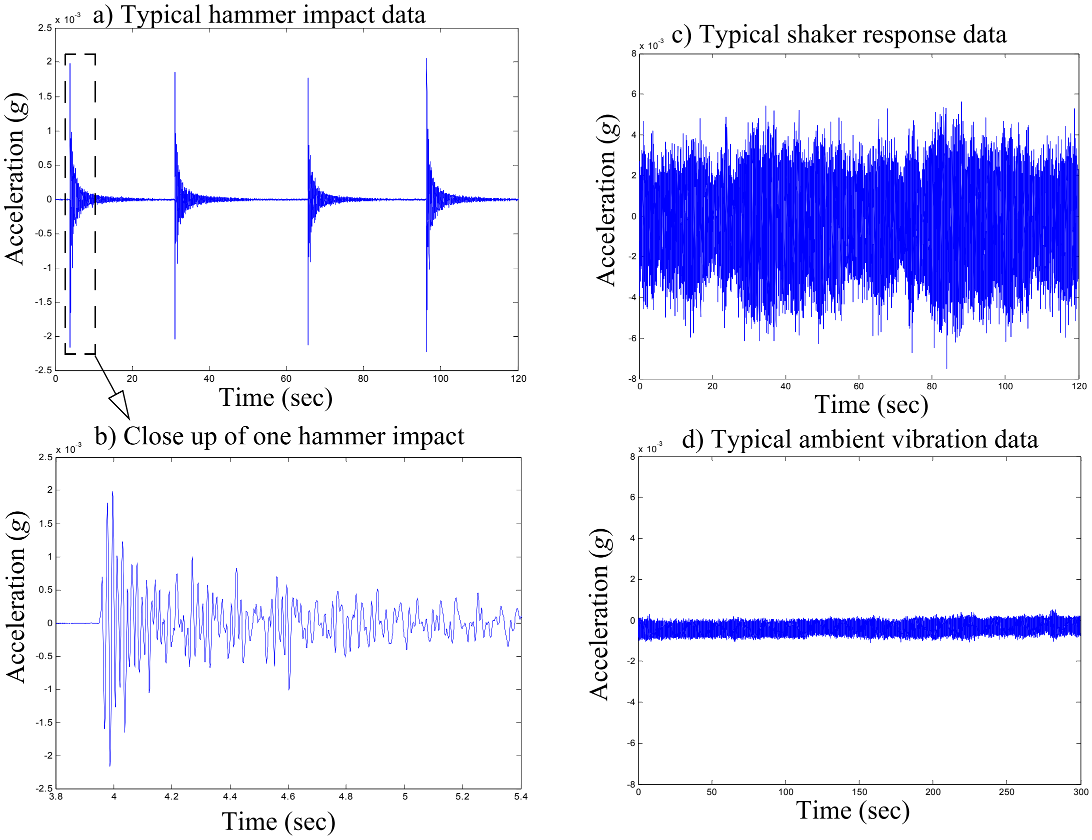

FIGURE 7: PLOTS OF REPRESENTATIVE DATA FILES (4th FLOOR, WEST SIDE, CASE 1).

SUMMARY

Experiments have been conducted to obtain data for the Experiment Phase II of the IASC-ASCE Benchmark Problem in structural health monitoring [7]. Phase I of the analytical portion of this benchmark problem is being published as a focus of a future issue of the *ASCE Journal of Engineering Mechanics* [9], and Phase II has been presented by various researchers at conferences [1]. The Task Group would appreciate any comments or suggestions on this project. More details on this study, as well as the current and future efforts of the Task Group, are available on the Task Group's web site [7].

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