Development of experimental benchmark problems for international collaboration in structural response control

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ABSTRACT: In order to truly demonstrate the capability of various structural control systems in protecting the integrity of buildings during earthquakes, we propose to develop experimental benchmark models for: (i) a 3-story steel frame with dimensions 3.0m by 2.0m in plane and 3.0m height for each story, and (ii) a 6-story steel frame with dimensions 1.0m by 1.2m in plane and 1.0 m height for each story. These two experimental benchmark models will be made available to the international structural control community for testing various control algorithms and devices. The objectives of this paper are to: (i) introduce previous studies conducted by different organizations using these two benchmark structures, and (ii) propose the test-bed structures for an international collaboration on structural control through experimental benchmark studies.

1 INTRODUCTION

In the past two decades, many control algorithms and devices have been proposed for civil engineering applications. Each control algorithm and device have their own merit, depending on the application and the desired effect. The ability to make comparisons between systems employing these algorithms and devices is necessary to focus future efforts in the most promising directions and to establish standardized performance goals and specifications. One approach to achieve this goal is to set analytical benchmark models based on large experimental models that allow researchers in structural control to test their algorithms and devices and directly compare results. Several benchmark structural control models have been developed during last decade through the sponsorship of the ASCE Committee on Structural Control and the International Association of Structural Control and Monitoring (IASC). The main objective of developing these models has been a standardized evaluation of the performance of various control systems/algorithms when applied to different structural systems. An extensive analysis of benchmark structural control problems formed the basis for a special issue of Earthquake Engineering and Structural Dynamics (Spencer et al. 1998a,b). Recently, well-defined analytical benchmark problems have also been developed for bridge structures subjected to seismic excitation through the sponsorship of the ASCE Structural Control Committee (Agrawal et al. 2004). All benchmark problems in structural control developed during last 10 years are summarized in Table 1.

The main objective of developing benchmark models is for testing control algorithms. It provides a mechanism for researchers to try out ideas ahead of implementation. These benchmark problems were mainly considered for numerical study. However, experimental verification of the proposed control algorithms and testing devices (including sensors and actuators) also needs to be verified. Therefore, through the unification of numerical models and large-scale experiments, pursuit of experimental verification of seismically excited benchmark problems becomes more realistic. In order to truly demonstrate the capability of various structural control
systems in protecting the integrity of buildings during earthquakes, we propose to develop experimental benchmark models for: (i) a 3-story steel frame with dimensions 3.0m by 2.0m in plane and 3.0m height for each story, and (ii) a 6-story steel frame with dimensions 1.0m by 1.2m in plane and 1.0 m height for each story. The 3-story steel frame has been studied by many researchers to test various control strategies using MR-dampers. The 6-story steel frame is a new model being developed to investigate decentralized control approaches experimentally. These two benchmark models have been available to the structural control community worldwide to test various control algorithms.

Therefore, the objective of this paper is (i) to introduce previous studies conducted by different organizations using both benchmark test structures, and (ii) to propose a roadmap for the development of an open-access benchmark study that encourages international collaboration on structural control technology.

Table 1: Benchmark problems developed during the last 10 years.

<table>
<thead>
<tr>
<th>Systematic Development of Benchmark Problems</th>
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<tr>
<td>First generation benchmark problem for buildings:</td>
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<tr>
<td>- Spencer et al. 1998a, b</td>
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<td>Second generation benchmark problem for buildings:</td>
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<td>- Earthquake-excited 20-story building (Spencer et al. 1999)</td>
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<tr>
<td>- Wind-excited 76-story building (Yang et al. 1999)</td>
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<tr>
<td>Third generation benchmark problem for buildings:</td>
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<tr>
<td>- Earthquake-excited 3 multi-story nonlinear buildings (Ohtori et al. 2004)</td>
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<tr>
<td>- Wind-excited 76-story building (Yang et al. 2004)</td>
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<td>First generation benchmark problems for bridges:</td>
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<td>- Earthquake-excited cable-stayed bridge (Dyke et al. 2003)</td>
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<td>Benchmark structure on smart base-isolated building: Phase I and Phase II:</td>
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<td>Benchmark problems for highway bridges: Phase I and Phase II:</td>
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2 BECHMARK STRUCTURES

Two steel structures, a full-scale 3-story steel space frame and a scaled down 6-story steel frame, were designed for this benchmark study. They were designed by the National Center for Research on Earthquake Engineering (NCREE) for structural control research. The specifications for these two structures are discussed in the following sections.

2.1 3-story test structure

A three-story full-scale steel structure is designed and constructed at the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan. As shown in Figure 1, the three-story structure consists of a single bay with a 3m by 2m floor area and 3m tall 3 meter height for each story. The structure is constructed using H150x150x7x10 steel I-beam elements with each beam-column joint designed as a bolted connection. Concrete blocks are added and fastened to the floor diaphragms until the total mass of each floor is precisely 6,000 kg. The entire structure is tested upon a large-scale shaking table capable of applying base motion in 6 independent degrees-of-freedom. The structural behavior is modeled using a lumped mass shear-beam reduced-order structural model defined by 3 degrees-of-freedom (i.e. the lateral displacement of each floor). Based on the response of the bare frame, the damping and stiffness
matrices of a reduced-order model were identified using system identification techniques. The mass matrix is assumed to be known. Both mass matrix and stiffness matrices are obtained as:

\[
\mathbf{M} = \begin{bmatrix} 6000 & 0 & 0 \\ 0 & 6000 & 0 \\ 0 & 0 & 6000 \end{bmatrix} \text{kg} \quad \mathbf{K} = 1.0e+6 \begin{bmatrix} 3.6466 & -1.9530 & 0.1903 \\ -1.9530 & 3.5426 & -1.7797 \\ 0.1903 & -1.7797 & 1.6003 \end{bmatrix} \text{N/m}
\]

The identified natural frequencies corresponding to the first three modes of the structure are 1.08, 3.25, and 5.06 Hz, respectively. Furthermore, the damping ratio of the 1st, 2nd, and 3rd modes are experimentally verified at 1.6%, 1.7%, and 2.7%, respectively. The identified natural frequencies are consistent with the mathematical model. The V-shape bracing system can be added in each floor to provide supports for the installation of dampers. Different types of dampers can be used to control the structure for the shaking table test.

2.2 6-story test structure

As shown in Figure 2, the six-story scaled-down structure consists of a single bay with a 1.0 m by 1.5 m floor area and 1.0 m story height. The columns are constructed from steel bar stock with a rectangular cross sectional area of 150 mm by 25 mm. The beams used to construct the floors of the structure are L-sections roughly 50 mm by 50 mm with 5 mm thick walls. The floor construction is completed with a thick plate (2 cm thick) welded to the beams. The column-beam and column-base connections are all bolted. The identified first five system modal frequencies (using data-driven stochastic subspace identification method) are: 1.05Hz, 3.50Hz, 6.12Hz, 8.987Hz and 11.91Hz and the corresponding modal damping ratios are: 0.2%, 0.99%, 0.09%, 0.79% and 1.86%.

Figure 1: (a) Photo of the 3-story steel frame on NCREE shaking table. Three MR-dampers were installed on the frame structure with V-shape bracing system, (b) Schematic diagram of the 3-story pure frame structure.
Figure 2: (a) Photo of the 6-story steel frame structure. The V-shaped bracing system is for the installation of dampers in the structure. (b) Side view schematic diagrams of the 6-story steel frame structure.

The mass and stiffness matrices, as shown below, are developed using a finite element model of the structure that is ultimately condensed to a 6-story shear-type structure.

$$M = \begin{bmatrix} 862.85 & 0 & 0 & 0 & 0 & 0 \\ 0 & 862.85 & 0 & 0 & 0 & 0 \\ 0 & 0 & 862.85 & 0 & 0 & 0 \\ 0 & 0 & 0 & 862.85 & 0 & 0 \\ 0 & 0 & 0 & 0 & 862.85 & 0 \\ 0 & 0 & 0 & 0 & 0 & 803.98 \end{bmatrix} \text{ kg}$$

$$K = \begin{bmatrix} 2.49 \times 10^6 & -1.23 \times 10^6 & -1.23 \times 10^6 & -1.23 \times 10^6 & -1.23 \times 10^6 \\ -1.23 \times 10^6 & 2.46 \times 10^6 & -1.23 \times 10^6 & -1.23 \times 10^6 & -1.23 \times 10^6 \\ -1.23 \times 10^6 & -1.23 \times 10^6 & 2.46 \times 10^6 & -1.23 \times 10^6 & -1.23 \times 10^6 \\ -1.23 \times 10^6 & -1.23 \times 10^6 & -1.23 \times 10^6 & 2.46 \times 10^6 & -1.23 \times 10^6 \\ -1.23 \times 10^6 & -1.23 \times 10^6 & -1.23 \times 10^6 & -1.23 \times 10^6 & 1.23 \times 10^6 \end{bmatrix} \text{ N/m}$$

Several control tests have already been conducted on these two structures. For the three story steel structure, the following control experiments have been conducted:

a. Verification of re-settable semi-active stiffness dampers (Yang, et al. 2007),
b. Experimental validation of wireless sensors to command MR-dampers for structural control applications (Loh, et al. 2007),
c. Application of GA-optimized fuzzy logic control of a large-scale building for seismic loads (Shook, et al. 2007),
d. Implementation of closed-loop LQR structural control using wireless sensor networks (Lynch, et al. 2007),
e. Performance evaluation of semi-active equipment isolation systems for earthquake protection (Fan, et al. 2007).

For the 6-story steel structure, the following control and damage detection experiments have been conducted:
a. Decentralized sliding mode control of building using MR-dampers,
b. Finite element-based damage detection using experimental modal analysis result,
c. Partially decentralized control to minimize communication in wireless control systems.

3 EXPERIMENTAL HARDWARE

The overall experimental control benchmark includes a testing structure, control devices, sensing system and controller(s). Based on the 3-story steel frame structure as an example, the control experiment is described as follows:

**Test structure:** In order to develop a simulation model of the building, experimental response under random white noise excitation was obtained for the identification of the damping and stiffness matrices. Such matrices are then used to derive a reduced-order equation of motion. This reduced-order mathematical model only considers three shear-type degrees-of-freedom (DOF) with the natural frequencies 1.08 Hz, 3.25 Hz, and 5.06 Hz, respectively.

**Control devices:** In this experiment, MR dampers have been selected as the primary control device. For simulation purposes, a mathematical model for MR dampers is needed to evaluate the control force. The data from performance tests of MR dampers are used to estimate the damper model parameters. Since a complete semi-active control system needs a voltage driver to command the control devices as well as MR dampers, an inverse MR model must also be developed so as to generate a command voltage (or current) that achieves the desired control force.

**Sensing system:** Two groups of sensing and communication system are included in the experiment. The first sensing system is to measure structural responses (i.e. acceleration response from each floor including the base) from which desired control forces are calculated. The second sensing system is to measure the velocity between two ends of each control device (i.e. inter-story velocity) to calculate the control voltage. The relative velocity between two ends of a MR damper is required to calculate the control force and to then convert this force to a command voltage through the inverse MR damper model. In the shaking table experiment, both wired and wireless communication systems can be used. For example, a prototype system WiSSCon (Wireless Structural Sensing and Control System), designed for real-time wireless structural sensing and feedback control, can be used for control tests (Lynch et al. 2007). Figure 3 shows a schematic diagram of the instrumentation upon one floor of the test structure.

**Controller Design:** The main objective of the proposed benchmark study is to facilitate detailed investigations on various passive, active, and semi-active control strategies. The evaluation model developed in this research will remain invariant to the different applied control strategies. Participants in the benchmark study will have the flexibility of selecting the type, model, and location of control device(s), sensor(s), in addition to the ability to implement their own control algorithms. A control strategy can be applied to the evaluation model to simulate the structural response during applied earthquake ground motions. Figure 4 shows the simulator for the evaluation model. Researchers must include SIMULINK blocks for sensor(s), control device(s) and control algorithms to carry out numerical simulations. Finally, “evaluation criteria” can be applied to simulated structural response data to evaluate performance of control device(s) / algorithm(s) (Ohtori et al. 2004).
4. CONTROL SYSTEM DESIGN AND EXPERIMENT

Two benchmark problems are proposed to investigate various aspects of control systems and algorithms from a full-scale implementation point of view. The 3-story building model is proposed to investigate the effectiveness of various control devices using centralized control algorithms. Participants can consider a general centralized control system to derive control gains and compute control forces using global measurements of the structural system. This centralized control approach may be based on various control approaches, e.g., LQR, bang-bang, GA-optimized fuzzy logic, and non-linear Lyapunov control. It should be noted that the proper selection of control algorithm may be dependent on the available feedback measurements, the number of devices to be implemented and the type of nonlinearity present in the semi-active device and structure. The benchmark package will include a sample controller that researchers can use to design and compare their own control strategies (devices and algorithms).

In order to facilitate the investigation of implementation issues, such as the malfunction of sensors and actuators, the six story benchmark structure is proposed for investigation of decentralized control approaches. A fully decentralized controller only utilizes localized response...

Figure 3: Control setup using wireless sensing and control units connected directly to the control device (MR-damper).

Figure 4: SIMULINK block diagram for vibration control simulator.
information, i.e., response information at the location of the device. A decentralized sliding mode control (SMC) algorithm has been developed using this benchmark structure. For decentralized SMC, the control action of a particular controller (or damper) is determined only by the response at the controller’s location where sensors are installed in the damper, thus minimizing the wiring and sensor communication requirements. Figure 5 shows four tentative damper layout diagrams for decentralized control studies that will be presented in the benchmark package.

5. CONCLUSIONS

This paper presents the development of experimental benchmark problems based on two building structures that have been developed at NCREE, Taiwan, for international collaboration in structural response control. These two structures have been used by various international researchers to test their algorithms and devices using a large-scale 6 DOF shaking table during the last few years. Although several benchmark problems have investigated effectiveness of control devices/algorithms for large scale structures, e.g., 20 and 76-story tall buildings, cable-stayed bridge, base-isolated buildings and highway bridges, experimental verification of these control devices/algorithms on large scale model is now necessary to address the full-scale implementation issues that will be encountered in future industrial applications. This proposed benchmark study addresses this critical need by offering two large scale building models for study.

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7. REFERENCES


