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Editorial

Benchmark structural control problem for a seismically excited highway bridge: Phase I and II

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SUMMARY

Benchmark problems in structural response control have served the international structural controls community as virtual test beds to compare different control algorithms since the first benchmark problem was proposed in 1996 through the sponsorship of the ASCE Structural Control Committee and Task Group on Benchmark Problems, the U.S. Panel on structural control, and International Association of Structural Control and Monitoring (IASCM). These problems offer well-developed models of structural system focusing on the response control of seismic and wind-excited buildings, seismically excited long-span cable-stayed bridges and seismically excited base-isolated buildings using prescribed earthquakes and standard set of evaluation criteria. They have been used by the entire community of researchers, educators, students and practitioners to investigate numerous control devices and algorithms. In 2004, the authors, in collaboration with Professor Ping Tan of Guangzhou University in China and Professor Jian Zhang of the University of California, Los Angeles, developed the benchmark structural control problem for a seismically excited highway bridge through the sponsorship of the ASCE committee on Structural Control and Task Group on Benchmark Problems, the U.S. Panel on structural control and International Association of Structural Control and Monitoring (IASCM). This special issue focuses on contributions to this benchmark structural control problem for a seismically excited highway bridge. Copyright © 2009 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Benchmark problems in structural response control have served the international controls community well since the first benchmark problem was proposed in the mid-1990s [1]. Since that

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time, benchmark problems have been established to explore a diversity of structural control problems including seismically excited nonlinear buildings [2], wind-excited tall buildings [3], earthquake-excited cable-stayed bridge [4–5], and linear and nonlinear smart base-isolated structures [6–9]. These benchmark control problems have had a major and lasting impact on the structural engineering field by providing well-developed and standardized test beds and comparative studies to an entire community of researchers, educators, students and practitioners.

The benchmark structural control problem for a seismically excited highway bridge is based on an actual bridge in Southern California. The benchmark problem package consists of three-dimensional nonlinear finite element model with 430 degrees of freedoms for the evaluation of structural response with competing control approaches/algorithms and a reduced-order model for the controller design. This reduced-order controller design model is obtained by the eigenmode reduction method, which is a more general method and is more accurate in representing the dynamics of full-order bridge model [10]. The finite element model has a total of 108 nodes, 4 rigid links, 70 beam elements, 24 springs, 27 dashpots and 8 user-defined bearing elements. The superstructure of the bridge, including the deck and the bent beam, are assumed to be elastic. Both the abutments and deck-ends are assumed to be rigid and have a skew angle of 33°. Structural member nonlinearities are included to capture the inelastic moment–curvature behavior of columns and shear–displacement relationship of bearings.

The benchmark highway bridge model is based on the newly constructed 91/5 over-crossing, located in Orange County of southern California. It is a continuous two-span, cast-in-place pre-stressed concrete box-girder bridge. The Whittier–Ellsinore fault is 11.6 km (7.2 miles) to the northeast, and the Newport–Inglewood fault zone is 20 km (12.5 miles) to the southwest of the bridge. The bridge has two spans, each of 58.5 m (192 ft) long spanning a four-lane highway and has two abutments skewed at 33°. The width of the deck along east span is 12.95 m (42.5 ft) and it is 15 m (49.2 ft) along west direction. The cross section of the deck consists of three cells. The deck is supported by a 31.4 m (103 ft) long and 6.9 m (22.5 ft) high pre-stressed outrigger that rests on two pile groups, each consisting of 49 driven concrete friction piles. The columns are approximately 6.9 m (22.5 ft) high. The pile groups at both end abutments consist of vertical and battered piles. The bridge deck is isolated using four traditional nonseismic elastomeric pads at each abutment, and the total eight fluid dampers are installed between the end abutments and deck (four dampers at each end) to reduce seismic responses. However, in the evaluation model, lead–rubber bearings are used to replace eight traditional nonseismic elastomeric pads, since the seismic isolation bearing (lead–rubber bearings) can provide improved seismic performance. Consequently, passive fluid dampers (originally installed in the bridge on 91/5 over-crossing) are not considered to be installed in the evaluation model. Control devices are to be installed between the deck and the end abutments of the bridge to investigate their effectiveness.

The benchmark package consists of a new nonlinear and computationally efficient three-dimensional nonlinear dynamic analysis Matlab/Simulink program to facilitate a direct comparison of results of different control algorithms [11]. A host of control devices can be installed in the bridge. The control algorithms may be passive, active or semi-active. The seismic response of highway bridges subjected to near-fault pulse-type ground motions has been the subject of intense debate in the past decade. The primary problem in such cases is the large ductility demands on bridge piers and large displacement demands on bridge bearings if the bridge superstructure is isolated by bearings. Many control strategies, including supplemental

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nonlinear passive dampers, semi-active dampers and active devices, can improve the safety of bridge components during such earthquakes by reducing peak response quantities.

As the deck of the bridge is fixed to the center outrigger in the Phase I highway bridge problem in Agrawal *et al.* [10], a Phase II model of the highway bridge has been developed by Nagarajaiah *et al.* [12] by installing lead–rubber bearings between the deck and the center outrigger to simulate the behavior of a based-isolated highway bridge. A sample semi-active controller using magnetorheological (MR) dampers has been developed for this phase using nonlinear Lyapunov control algorithm for a system with time-varying damping.

2. SEISMICALLY EXCITED HIGHWAY BRIDGE BENCHMARK PROBLEM

The main objective of developing seismically excited highway bridge benchmark problem is to facilitate a standardized test bed for a comparative study of numerous competing control strategies and control devices. The problem consists of three parts: (1) part I, definition of the Phase I benchmark problem [10]; (2) part II, Phase I sample controllers for the bridge in which the bridge deck is fixed to the outrigger in the center [11]; and (3) part III, Phase II definition paper with sample controller design [12]. This special issue consists of 11 papers contributed by the participants of the study, which have proposed different devices, passive, active, and semi-active control strategies, evaluated and reported their results and compared the results with that of the sample controllers. Each research team has adhered to prescribed practical control constraints and has evaluated the performance of their control designs by prescribed performance indices.

Tan and Agrawal [11] present design of sample controllers for the Part II, Phase I of benchmark highway bridge problem. This study presents three types of sample controllers, namely nonlinear viscous dampers, ideal hydraulic actuators and MR fluid dampers. For each of the three sample control system, a total of 16 control devices are proposed to be placed orthogonally between the deck-ends and abutments for the reduction of earthquake-induced response of the highway bridge. An H_2/LQG control algorithm is selected for the active case and a clipped optimal control algorithm is chosen for the semi-active case. The modeling and sample control system designs presented are not intended to be competitive. Participants of this benchmark study are expected to employ more competitive control designs for their own control strategies. These control strategies may be passive, active, semi-active or a combination thereof.

Nagarajaiah *et al.* [12] present the Part III, Phase II of highway bridge benchmark problem with sample semi-active control design. In the Phase I of the highway bridge benchmark problem, the bridge deck is fixed to the outrigger in the center of the bridge. In this Phase II of the highway bridge model, the bridge deck is isolated at the abutments and the center bent/piers by using a total of ten lead–rubber bearings. Four isolators placed between the deck and the abutment are located at the east and the west abutments. The isolators between the outrigger bent and the piers are placed on top of the south column and the north column. A sample semi-active controller is implemented using MR dampers and a nonlinear Lyapunov control algorithm for a system with time-varying damping. It is shown that the Phase II sample Lyapunov semi-active controller is effective in reducing the base displacements [12].

Ali and Ramaswamy [13] have proposed a two stage state feedback control design approach by combining Linear Quadratic Regulator and Optimal Dynamic Inversion (ODI) to monitor the voltage supplied to MR dampers for semi-active vibration control of the bridge. The first

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stage contains a primary controller that provides the force required to obtain a desired closed-loop response of the system. In the second stage, an ODI approach is used to obtain the amount of voltage to be supplied to each of the MR dampers such that it provides the required force prescribed by the primary controller. They have applied this controller design approach to both Phase I and Phase II benchmark problems. Their simulation results show notable improvement in evaluation criteria without using higher control forces than those for sample controllers.

Pradono *et al.* [14] have proposed a simple displacement-based controller to simulate effective negative stiffness effects through a MR damper. They have demonstrated the applicability of the approach through experimental verification of the proposed control algorithms. Applications of this controller to the Phase II benchmark building model demonstrates that the proposed approach can reduce peak mid-span displacement and peak bearing displacement without increasing peak base shear. However, other response quantities increase significantly. Although evaluation criteria are much higher than those by sample semi-active controller in Agrawal and Tan [11], the proposed approach is using much smaller level of control force and can be implemented by a passive hardware configuration.

Ning *et al.* [15] propose adaptive fuzzy sliding mode control (AFSMC) that combines the advantages of sliding mode control (SMC), adaptive control and fuzzy control without compromising stability or robustness. Switching-type control law based on conventional SMC and uncertainty part of the equivalent control is approximated by a fuzzy controller to attenuate the chattering phenomenon of SMC and harmful effects caused by uncertainties. In order to reduce the complexity of the fuzzy rule bases, adaptive technique based on Lyapunov stability theorem is employed. AFSMC is also integrated with clipped optimal strategy to demonstrate its efficiency for semi-active MR dampers. By applying this approach to the Phase I highway bridge benchmark problem, they have demonstrated that the response quantities of the highway bridge can be reduced to a satisfactory level by the proposed approach. Overall, the performance of active and semi-active controllers designed by the proposed approach is very competitive with those by the sample controllers, except that the peak mid-span acceleration by their approach is slightly higher.

Narasimhan [16] propose a direct adaptive control scheme for the active control of the bridge. The controller is based on the premise of direct adaptive control, wherein the system response is made to follow a desired trajectory. The control force in this approach is calculated using a single hidden layer nonlinearly parameterized neural network in conjunction with a controller. Stable tuning laws for the free parameters of the nonlinearly parameterized network are derived based on Lyapunov theory. Performance of this control scheme is evaluated using the Phase I highway benchmark bridge model. The results show that the adaptive control scheme is capable of reducing most of the peak response quantities to the same level as that by the sample controller.

Pujol *et al.* [17] have presented a new nonlinear damper based on a passive static hyperbolic function depending only on the base velocity. This function ensures energy dissipation capability with always bounded control force. With the design of appropriate passive hardware, the proposed approach can be implemented as an effective passive system. Pujol *et al.* [17] have applied the proposed control scheme to the Phase I highway bridge benchmark problem using a generic active control scheme. The simulation results illustrate that the peak and normed base shear, the peak and normed mid-span displacements and the peak and normed mid-span accelerations have been significantly reduced by using the proposed hyperbolic controller as compared with those by the purely passive isolation scheme. Overall, the performance of the

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proposed approach is significantly better than that of sample passive control and is quite competitive to that by the sample active controller.

Choi *et al.* [18] have investigated the performance of the MR damper-based smart passive control system employing an electromagnetic induction (i.e. EMI) system for the benchmark highway bridge model. The proposed smart passive system is based on an MR damper-based control system without a feedback control part, including a power supply, controller and sensors. It consists of a MR damper and an EMI system consisting a permanent magnet and a coil, which produces electrical energy (i.e. induced current) proportional to the rate of the change of the movement of an MR damper according to the Faraday's law of EMI. They have applied the proposed smart damping system to the Phase I highway bridge benchmark problem. The numerical results show that the smart passive system has the comparable performances to the conventional semi-active control system requiring a feedback control system. In particular, the proposed approach reduces all peak response quantities except during N. Palm Springs and Rinaldi earthquakes. Some response quantities are seen to be amplified during these two earthquakes.

Casciati *et al.* [19] has proposed hysteretic base isolator system by coupling a sliding support with inclined bars in shape memory alloy (SMA). The isolation system has been designed to support a circular steel plate serving as superimposed tray, where the system to be isolated is mounted. The inclined bars are installed in a manner to control the horizontal displacements, while the vertical load is transferred from the superimposed tray to the base by a steel cylinder. Based on experimental force–deformation hysteresis loop of the device, they have proposed an analytical model of the damper by combining the characteristics of nonlinear viscous damper with that of a backbone curve simulating stiffness of SMAs. They have applied the proposed passive system to the Phase II highway bridge benchmark bridge. It is observed that peak response quantities, expect few during Chichi earthquake, increase significantly. Nevertheless, the proposed device presents an interesting concept towards the development of effective passive damping systems.

Zhang *et al.* [20] have proposed a base displacement restraining damping device for the response control of the Phase II seismically excited highway bridge. The SMA restraining damping device is a passive control device employing superelastic Cu–Al–Be alloy wires as its core recentering component, which restrains the based-isolated bridge from excessive displacement responses. The performance of the passive control devices is analyzed in terms of the performance indices at a variety of ambient temperatures of 23, 0, -25 and -50°C, respectively. The results of this simulation-based benchmark control study show that the proposed passive control device can effectively reduce the excessive displacement responses and permanent bearing deformations of the benchmark base-isolated bridge subjected to strong ground motions, and temperature seems to have little effect on the performance of the superelastic Cu–Al–Be restraining damping device in bridge response control. Overall, it is observed that all response quantities are amplified with respect to corresponding uncontrolled value. However, the bridge installed with the proposed device doesn't develop plastic hinge under all prescribed earthquakes.

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This is the first 3D benchmark nonlinear highway bridge problem for structural control in which controller performance is evaluated using the full 430 DOF nonlinear FEM model. Proposed controllers demonstrate the potential of structural control systems in protecting the safety of highway bridges. The special issue owes its success to the excellent contributions of the participating researchers, all of which met the high review standards of the journal. The special issue guest editors wish to acknowledge the valuable support of the journal editors Professor T. T. Soong and Professor Lucia Farivelli during all stages of the effort.

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