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BENCHMARK PROBLEMS IN STRUCTURAL ENGINEERING FOR MITIGATION OF SEISMIC VIBRATIONS

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Abstract- Many control algorithms and devices have been proposed over the last few decades, for protecting structures against severe dynamic loadings. However, because standard structures were not considered, direct comparison of different control strategies was not possible. To compare the results of passive, active and semi-active protective systems, and to direct future research efforts towards the most promising control strategies for alleviating dynamic responses, benchmark control problems on buildings and bridges have been developed. Thus, it becomes possible to study different aspects of the same problem in many countries, and in a coordinated fashion. By applying different control strategies to the testbed, and measuring the response to standardized loading, it is possible to directly compare the effectiveness of various control strategies. Findings of the studies can be combined in a rational manner that will result in a systematic presentation of results. The paper presents a review of the benchmark problems in structural engineering. Importance and need of benchmark problems is emphasized by presenting case studies on benchmark buildings and bridges.

Keywords: *Benchmark problem; dynamic loading; control strategies; energy dissipating devices; benchmark buildings and bridges.*

1. INTRODUCTION

The protection of civil structures, including material content and human occupants is a world-wide priority. The extent of protection may range from reliable operation and occupant comfort to human and structural survivability. Civil structures, including existing and future buildings, towers and bridges, must be adequately protected from a variety of events, including earthquakes, winds, waves and traffic. Use of passive, active and semi-active structural control devices to mitigate undesired responses to dynamic loads is the worldwide subject of research. However, even in controlled structures, it can be expected that large seismic events, such as the Northridge (1994) and the Kobe (1995) earthquakes, will cause structural members to exceed the elastic limit.

In the last two decades, many control algorithms and devices have been proposed for civil engineering applications, each of which has certain advantages, depending on the specific application and the desired objectives. The seismic response of nonlinear structures to severe earthquakes has also been studied and control algorithms for these structures have been proposed by a number of researchers. It is evident that different researchers use different structures and different criteria to show the efficacy and effectiveness of their own particular control strategies. Determination of the general effectiveness of structural control algorithms and devices is necessary to focus future structural control research and development.

Benchmark problems provide a common structure, and common evaluation methodologies, making

direct comparison of control strategies feasible. The comparison of results can be made in terms of a specified set of performance indices. Such problems have been established to explore a diversity of structural control problems, including seismically excited nonlinear buildings, wind-excited tall buildings, earthquake-excited cable-stayed bridge, linear and nonlinear smart base-isolated structures and the seismically excited benchmark highway bridge. The main concern of the benchmark problem is to conceive a competitive control system. Ideally, each proposed control strategy should be evaluated experimentally under conditions that closely model the as-built environment. However, it is impractical, both financially and logistically, for all researchers in structural control to conduct even small-scale experimental tests. An available alternative, denoted "software testbeds" by Caughey (1998), is the use of consensus approved, high-fidelity, analytical benchmark models to allow researchers in structural control to test their algorithms and devices and to directly compare the results. The American Society of Civil Engineers (ASCE) committee on structural control has developed the benchmark problems on buildings and bridges.

2. THE BENCHMARK BUILDING STRUCTURES

Yang, et al. (2004), proposed the first benchmark problem for wind excited buildings. The second benchmark problem, detailed in Spencer, et al. (1999), was the next generation benchmark control problem for seismically excited buildings. These two benchmark studies were successful, although the structural models were considered to remain perfectly elastic. Large magnitude earthquakes can however,

cause material yielding in the structural elements of civil structures, resulting in nonlinear responses.

Nonlinear benchmark studies have been done on the 3-, 9- and 20-story steel buildings Spencer, et al. (1999). High-fidelity nonlinear models of the structures are developed and designated as the nonlinear evaluation models. In the context of the study, the evaluation models are considered to be true models of the structural systems. Several evaluation criteria, measuring the effectiveness of the control strategies to reduce undesired responses of the evaluation model to ground excitation, are given, along with the associated control design constraints. Such studies are important for successful development of structural control devices and algorithms, and resolve issues that are critical in practical applications of structural control systems.

2.1 Benchmark Problem for Response Control of Wind-Excited Tall Buildings

The wind-excited benchmark building is a 76- storey, 306m concrete office tower proposed for the city of Melbourne, Australia (Yang et al., 2004). The building is tall and slender with a height-to-width ratio of 7.3; hence, it is wind sensitive. Wind tunnel tests (Samali et al., 2004) for the 76-storey building model have been conducted at the University of Sydney and the results of across-wind data are provided for the analysis of the benchmark problem. Performance of various dampers like tuned liquid column dampers, (Min et al., 2005), and variable stiffness tuned mass damper (Varadarajan and Nagarajaiah, 2004) on the benchmark building have been studied. Patil and Jangid (2009) performed numerical study of the wind-excited benchmark building with two alternative arrangements of Passive Linear Viscous Dampers and the Semi-active Viscous Fluid dampers, under the deterministic wind load.

The comparison of the response quantities/performance criteria is made to verify the effect of the alternate arrangements. Optimum location of dampers is found out based on the numerical simulations.

2.2 Benchmark Structural Control Problem for Base Isolated Benchmark Building

The benchmark structure is a base-isolated eight-storey, steel-braced framed building, similar to existing buildings in Los Angeles, California. Stories one to six have an L-shaped plan while the higher floors have a rectangular plan. The superstructure rests on a rigid concrete base, which is isolated from the ground by an isolation layer, and consists of linear beam, column and bracing elements and rigid slabs. Below the base, the isolation layer consists of a variety of 92 isolation bearings. In the nominal benchmark model, 31 of the bearings are linear elastomeric bearings and the remaining 61 are sliding

friction bearings. The floor plan is L-shaped. The superstructure bracing is located at the building perimeter. Metal decking and a grid of steel beams support all concrete floor slabs. The steel superstructure is supported on a reinforced concrete base slab, which is integral with concrete beams below, and drop panels below each column location. The isolators are connected between these drop panels and the footings below. The combined model of the superstructure (24 DOF) and isolation system (3 DOF) consists of 27 degrees of freedom.

3. THE BENCHMARK BRIDGE STRUCTURES

Seismic design of highway bridges draws great significance since bridges come under the category of lifeline structures. Strong near-fault ground motions such as Northridge, Kobe and Chi-Chi earthquake have caused severe effects on the stability of bridges. Kobe earthquake in Japan (17 January, 1995) and Chi-Chi earthquake in Taiwan (20 September, 1999) have demonstrated that the strength alone would not be sufficient for the safety of bridges during an earthquake. Extensive damage to highway and railway bridges occurred in the Kobe earthquake, including the 18-span bridge at Fukae, Hanshin Expressways. The catastrophic failure of highway bridges in the Chi-Chi earthquake was primarily due to large deck and bearing displacements and severe shear failure of piers. In view of the extensive damage of bridges during earthquake, the current research is focused on finding out more rational and substantiated solutions for protection of bridges. Based on the Bill Emerson Memorial Bridge constructed in Cape Girardeau, Missouri, USA, a benchmark problem on cable-stayed bridges has been generated (Dyke et al. 2003). Agrawal et al. (2009) developed a benchmark problem on Highway bridges, based on the 91/5 highway bridge located in southern California.

3.1 Benchmark Control Problem of a Seismically Excited Cable-Stayed Bridge

The benchmark problem for a seismically excited cable-stayed bridge is focused on proposing new semi-active control strategies. It is based on a cable-stayed bridge in Cape Girardeau, Missouri, USA. A three-dimensional linearized evaluation model was developed to represent the complex behavior of the full-scale benchmark bridge. The goal of the benchmark study is to provide a testbed structure on which researchers can systematically compare and evaluate the relative merits of proposed structural protection for cable stayed-bridges. Magnetorheological (MR) dampers, which belong to the class of controllable fluid dampers, are proposed as the supplemental damping devices (Dyke, 2003). Saha and Jangid (2009) investigated the earthquake response of benchmark cable-stayed bridge with passive hybrid control systems, consisting of high

damping rubber bearing, lead-rubber bearing, friction pendulum system and resilient-friction base isolator (R-FBI) supplemented with the linear and non-linear viscous fluid damper (VFD).

3.2 Benchmark Structural Control Problem for Seismically Excited Highway Bridge

A highway overcrossing or bridge, connecting major transportation routes, is a key node in transportation network. It must continue to function after an earthquake. Therefore, a higher level of performance with less structural damage is required for such bridges. Recent earthquakes such as Northridge and Kobe have demonstrated the importance of maintaining the operation of bridge structures. For highway bridges, seismic isolation bearings in combination with passive, semi-active and active control systems are used as protective systems. The highway bridge model developed by Agrawal et al (2009) is that of the 91/5 highway overcrossing in Southern California. Seismic design considerations were duly considered in the design of this bridge, as it is located very close to two major faults and its critical role as a principal overcrossing. The superstructure of the bridge consists of a two-span continuous, cast-in-situ pre-stressed concrete (PC) 3-cell box-girder and the substructure is in the form of PC outriggers.

Madhekar and Jangid (2009) investigated the dynamic response of the benchmark highway bridge isolated with variable friction pendulum system (VFPS) under six earthquake motions. The study is based on the finite-element model of the benchmark highway bridge. The seismic response of bridge isolated with VFPS is compared with the conventional friction pendulum system (FPS). A parametric study is carried out to study the effects of the maximum coefficient of friction, initial time period and isolation period of VFPS. The response of bridge is also compared with the corresponding uncontrolled case and with the FPS. It is concluded that with the installation of VFPS, the seismic response of the bridge under near-fault motions can be controlled significantly.

4. CONCLUSIONS

Numerical simulation results of Benchmark buildings and bridges have verified that the newly developed control strategies work very well in controlling the response of the benchmark structures to a variety of earthquake ground motions. Thus, these devices can be successfully implemented practically.

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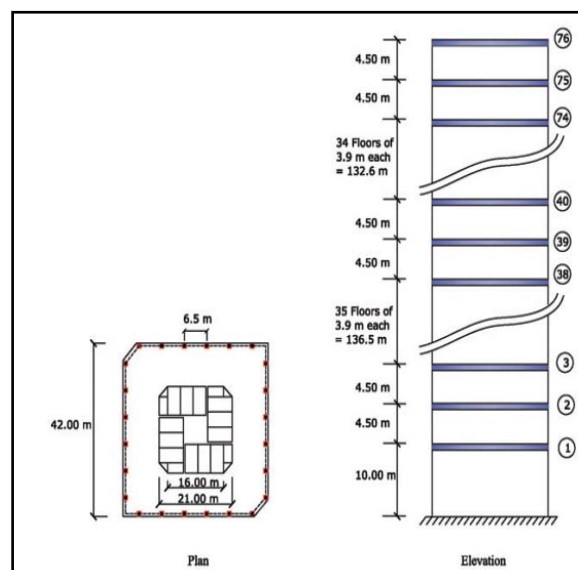


Figure 1. Benchmark building (Yang et al., 2004)

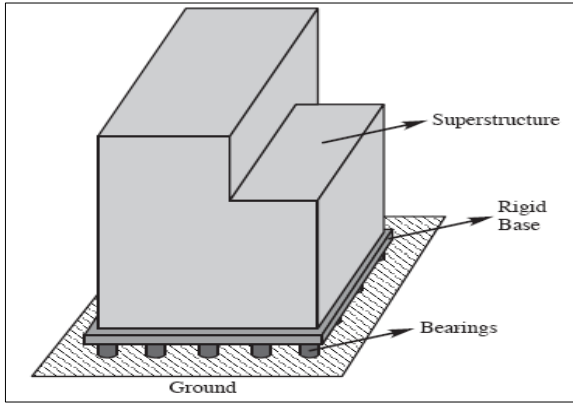


Figure 2. A representative figure of the benchmark building

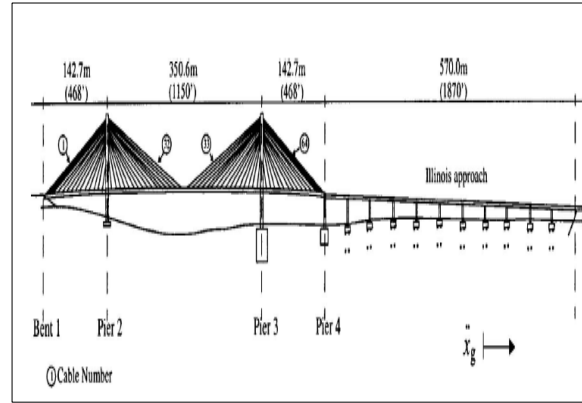


Figure 3. Benchmark Structural Control Problem for Seismically Excited Highway Bridge

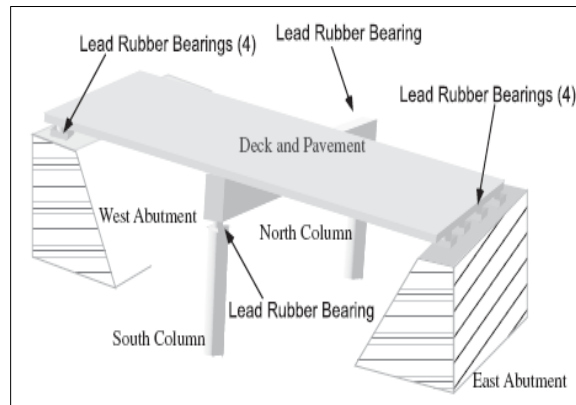


Figure 4. Schematic of Benchmark Highway Bridge

