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Semi-active Control Strategies for Seismic Responses of Cable-Stayed Bridges

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Abstract

This paper proposes a semi-active control strategy for seismic protection of cable-stayed bridges by examining the phase I benchmark control problem for seismic response of cable-stayed bridges. The benchmark problem is based on the Bill Emersion Memorial Bridge that is currently under construction in Cape Girardeau, Missouri, USA. In this paper, smart dampers (*e.g.*, variable orifice damper, controllable fluid damper, *etc.*) employing a clipped-optimal control algorithm, are proposed for bridge response control. To more effectively design a semi-active control system, a systematic study of appropriate weighting parameters for the proposed smart damping strategy is undertaken, including the inclusion of a Kanai-Tajimi shaping filter to better inform the controller about the frequency content of the ground motion. Because the semi-active damper is a controllable energy-dissipation device that cannot add mechanical energy to the structural system, the proposed control strategy is fail-safe in that the bounded-input, bounded-output stability of the controlled structure is guaranteed. To verify the effectiveness of the proposed semi-active control strategy, a set of numerical simulations is performed.

Keywords: *semi-active control, smart dampers, cable-stayed bridge, benchmark problem, seismic protection*

1. Introduction

In the field of civil engineering, many control algorithms and devices have been investigated over the last two decades to protect structures against natural hazards such as strong earthquakes and high winds. However, comparison of different control strategies directly is generally a challenging task, because standard structures were not considered. This problem can be addressed by employing *testbed* structures, that is, by developing benchmark studies. Benchmark control problems allow researchers to apply various control strategies, such as passive, active, semi-active or a combination thereof, to a specified problem, and to compare results directly in terms of a specified set of performance objectives. One goal of such a benchmark study is to direct future research efforts toward the most promising structural control strategies.

In recent years, the American Society of Civil Engineers (ASCE) Committee on Structural Control and the International Association of Structural Control (IASC) has actively investigated benchmark studies. The Committee developed a benchmark study, focusing primarily on the comparison of structural control algorithms for three-story building models (Spencer *et al.*, 1997; 1998a, b). The initial results of this study were reported at the 1997 ASCE *Structures Congress*, held in Portland, Oregon (ASCE 1997). A more extensive analysis of these benchmark structural control problems were published in a special issue of *Earthquake Engineering and Structural Dynamics* (EESD 1998). Subsequently, the IASC partnered with ASCE to develop the next generation of benchmark problems for dynamically excited buildings (IASC 1998). The current benchmark studies for the seismically excited building problem include: consideration of material nonlinearity of structural members; three types of building heights available for study; and a computationally efficient MATLAB® analysis tool (Ohtori *et al.*, 2000; http://cee.uiuc.edu/sstl/). The results of the above 3rd generation benchmark study will be reported in a special issue of *ASCE Journal of Engineering Mechanics* in 2003. Until recently, however, all of benchmark problems considered have focused on the control of buildings (EESD 1998;

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IASC 1998; Ohtori *et al.*, 2000).

More research on the seismic protection of cable-stayed bridges is needed due to a growing number of such structures throughout the world. The control of very flexible structures such as cable-stayed bridges is a unique and challenging problem. To effectively study the seismic response control of cable-stayed bridges, a benchmark problem for seismic protection has been developed by Dyke *et al.* (2003). This first generation benchmark control problem for cable-stayed bridges subjected to seismic loads considers the Bill Emerson Memorial Bridge currently under construction in Cape Girardeau, Missouri, USA, which will be completed in 2003. Based on detailed drawings of this cable-stayed bridge, a three-dimensional linearized evaluation model has been developed to represent the complex behavior of the bridge. For the control design problem, evaluation criteria also have been provided.

This paper focuses on the effectiveness of semi-active control strategies for seismic protection of cable-stayed bridges. To do this, the phase I benchmark cable-stayed bridge model provided by Dyke *et al.* (2003) is considered. The preliminary study on semi-active control using smart dampers for the benchmark cable-stayed bridge accomplished by Jung *et al.* (2001) is extended in this paper. Herein, smart dampers (*e.g.*, variable orifice damper, variable friction damper, controllable fluid damper, *etc.*), used in conjunction with a clipped-optimal control algorithm shown to perform well in previous studies involving controllable dampers (Dyke *et al.*, 1996; Dyke and Spencer, 1997), are proposed as part of a seismic hazard mitigation strategy. A Kanai-Tajimi shaping filter (Soong and Grigoriu, 1993) is appended to the model of the structure to better inform the controller about the frequency content of the ground motion, and an extensive parametric study is performed to obtain optimal values of the weighting parameters. Because a smart damper is an energy-dissipation device that cannot add mechanical energy to the structural system, the proposed control strategy is fail-safe, in that it guarantees the bounded-input, bounded-output stability of the controlled structure. To demonstrate the effectiveness of the proposed control strategy, a set of numerical simulation results are presented.

2. Benchmark Cable-stayed Bridge Problem

Fig. 1 shows the cable-stayed portion of the Bill Emerson Memorial Bridge, which is scheduled for completion 2003 in Cape Girardeau, Missouri, USA. Based on detailed drawings of the bridge, a three-dimensional linearized evaluation model has been developed to represent the complex behavior of the full-scale benchmark bridge. The stiffness matrices used in this linear model are those of the structure determined through a nonlinear static analysis corresponding to the deformed state of the bridge with dead loads (Wilson and Gravelle, 1991). Because this bridge is assumed to be attached to bedrock, the effect of the soil-structure interaction has been neglected. Herein, a one-dimensional ground acceleration is applied in the longitudinal direction.

The bridge model resulting from the finite element formulation (shown in Fig. 2), which is modeled by beam elements, cable elements, and rigid links, has a large number of degrees-of-freedom and high frequency dynamics. Application of static condensation to the full model of the bridge as a model reduction scheme resulted in a 419 DOF reduced-order model, designated the evaluation model. Each mode of this evaluation model has 3% of critical damping, which is consistent with assumptions made during the design of bridge.

To evaluate the capabilities of each proposed control strategy, eighteen evaluation criteria have been defined (Dyke *et al.*, 2003). The following three historical earthquake records are considered such as the 1940 El Centro NS, the 1985 Mexico City and the 1999 Gebze NS. The first six evaluation criteria (J_1–J_6) consider the ability of the controller to reduce peak responses. J_1 and J_2 are non-dimensionalized measures of the shear forces at the tower

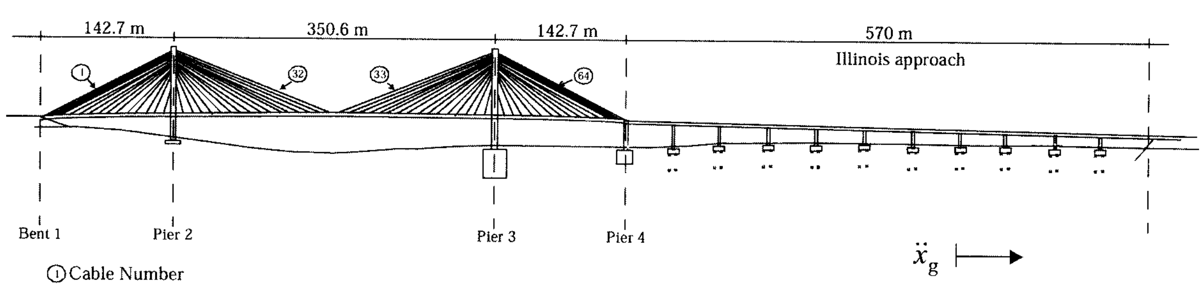


Fig. 1. Schematic of the Bill Emerson Memorial Bridge (Dyke et al. 2003)

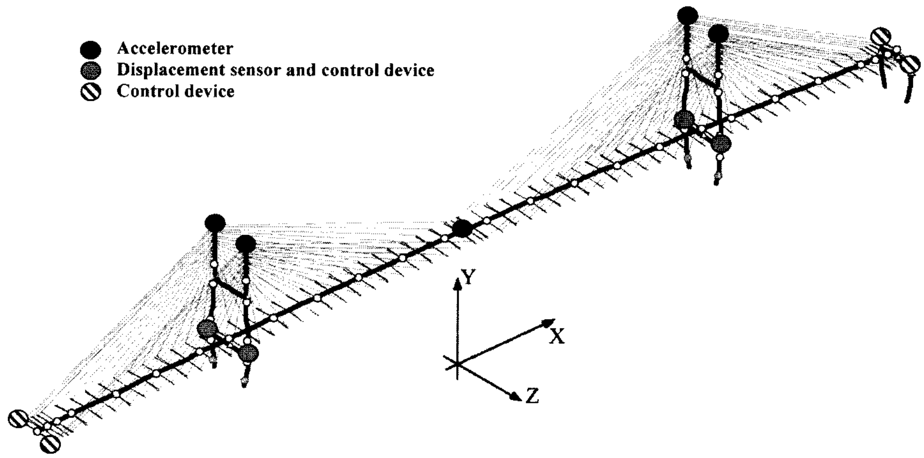


Fig. 2. Finite Element Model of the Bridge and Location of Sensors and Control Devices (Dyke *et al.* 2003)

base and the deck level in the towers, respectively. J_3 and J_4 are non-dimensionalized measures of the moments in the towers at the same locations. J_5 is a non-dimensionalized measure of the deviation of the tension in the stay cables from the nominal pretension. J_6 is a measure of the peak deck displacement at piers 1 and 4.

The second five evaluation criteria (J_7-J_{11}) consider normed (i.e., *rms*) responses over the entire simulation time. J_7 and J_8 are non-dimensionalized measures of the normed values of the base shear and the shear at the deck level in the towers, respectively. J_9 and J_{10} are non-dimensionalized measures of the overturning moment and the moment at the deck level in the towers. J_{11} is a non-dimensionalized measure of the normed value of the deviation of the tension in the stay cables.

The last seven evaluation criteria ($J_{12}-J_{18}$) consider the requirements of each control system itself. J_{12} deals with the maximum force generated by the control devices. J_{13} is based on the maximum stroke of the control devices. J_{14} is a non-dimensionalized measure of the maximum instantaneous power required to control the bridge. J_{15} is a non-dimensionalized measure of the total power required to control the bridge. J_{16} is a measure of the total number of control devices, J_{17} is a measure of the total number of sensors, and J_{18} is a measure of the resources required to implement the control algorithm. More details on the evaluation criteria can be found in Dyke *et al.* (2003) and Jung *et al.* (2001).

3. Semi-Active Seismic Control System

In this chapter, the proposed control system using semi-active control strategies is described in detail. The number and location of accelerometers and displacement transducers employed in this study are the same as those of the sample control system design in Dyke *et al.* (2003). Additionally, 24 force transducers are installed to measure the damper control forces applied to the structure (Jung *et al.*, 2002). The locations of the sensors are illustrated in Fig. 2.

3.1. Control Devices: Smart Dampers

In this study, a total of 24 smart dampers, such as variable orifice dampers, variable friction dampers and controllable fluid dampers, are considered. Eight dampers are placed between the deck and pier 2, eight between the deck and pier 3, four between the deck and bent 1, and four between the deck and pier 4. The locations of the control devices are shown in Fig. 2.

Each smart damper has a capacity of 1000 kN. For this initial study, the smart damper is assumed to be "ideal"; *i.e.*, it can generate the desired dissipative forces without considering saturation, delay, and dynamics of the device. Since actuator/sensor dynamics often limit achievable performance in reality (Dyke *et al.*, 1995), the semi-active control case considered herein (*i.e.*, the control system using "ideal" smart dampers) represents an upper bound on semi-active control system performance. Therefore, it can be fairly compared to the fully active control system, in which the actuator is also assumed to be "ideal".

The equations describing the forces produced by the smart dampers are

$$\mathbf{f} = \mathbf{K}_f\mathbf{u} = \begin{bmatrix} 2\mathbf{I}_{2\times2} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & 4\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & 2\mathbf{I}_{2\times2} \end{bmatrix}\mathbf{D}_d\mathbf{u} \tag{1}$$

$$\mathbf{y}_f = \mathbf{D}_d\mathbf{u} = D_d\mathbf{I}_{8\times8}\mathbf{u} \quad (2)$$

where $\mathbf{f}$ is the force output of devices applied to the structure, $\mathbf{y}_f$ is the force output of devices used for feedback in the control algorithm, D_d=100 kN/V is the gain for the device, and $\mathbf{K}_f$ is a matrix that accounts for the relationship between the input voltage and the desired control force, as well as the number of devices used at each device location, as shown in (1).

3.2. Semi-active Control Devices-based Control Strategies

The strategy of a clipped-optimal control algorithm for seismic protection of bridges using smart dampers is as follows: First, an "ideal" active control device is assumed, and an appropriate *primary* controller for this active device is designed. Then a *secondary* bang-bang-type controller causes the smart damper to generate the desired active control force, so long as this force is dissipative.

In this study, an H_2/LQG control design (Spencer *et al.*, 1994; Zhou *et al.*, 1996) is adopted as the *primary* controller. To better inform the controller about the frequency content of the ground motion, a Kanai-Tajimi shaping filter (Soong and Grigoriu, 1993) is incorporated into the model of the structure. The ground excitation is taken to be a stationary white noise, and an infinite horizon performance index is chosen that weights appropriate parameters of the structure, *i.e.*,

$$J = \lim_{\tau\to\infty}\frac{1}{\tau}E\left[\int_0^{\tau}\{\mathbf{z}^T\mathbf{Q}\mathbf{z}+\mathbf{u}^T\mathbf{R}\mathbf{u}\}dt\right] \quad (3)$$

where $\mathbf{R}$ is an identity matrix of order 8, and $\mathbf{Q}$ is the response weighting matrix. Herein, a stochastic response analysis has been performed to determine appropriate combination and values of the weighting parameters.

In the stochastic response analysis, the ground excitation is modeled as a filtered white noise corresponding to the Kanai-Tajimi spectrum with local site conditions given by parameters ω_g=17 rad/sec and ς_g =0.3 (Soong and Grigoriu, 1993). The transfer function of the Kanai-Tajimi filter in the Fourier domain has the form

$$H_{\ddot{x}_g w}(j\omega) = \frac{2\varsigma_g\omega_g j\omega+\omega_g^2}{-\omega^2+2\varsigma_g\omega_g j\omega+\omega_g^2} \quad (4)$$

The input $w(t)$ is a zero-mean ($E[w(t)]$=0) Gaussian white noise process with autocorrelation function $E[w(u)w(t)]$ $=G_{ww}(u,t)\equiv 2\pi S_0\delta(u-t)$, where the intensity S_0=0.0114, which is chosen such that the *rms* ground acceleration takes a constant value of $\sigma_{\ddot{x}_g}$ =0.12 g. Fig. 3 shows that the magnitude of the Kanai-Tajimi filter as a function of frequency, as well as the frequency content of the three

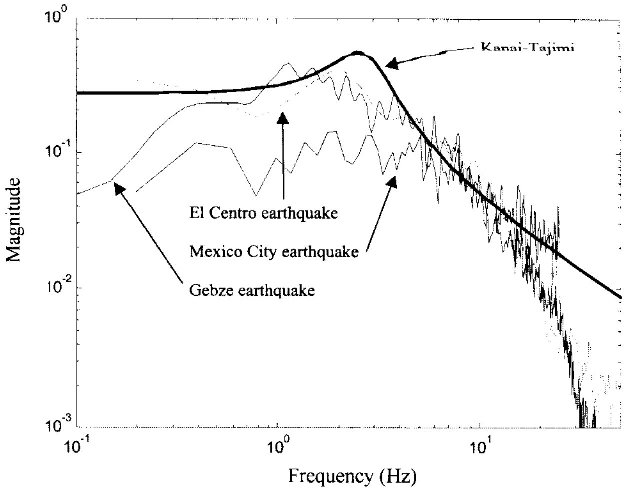


Fig. 3. Frequency Content of Earthquakes Considered and Adopted Kanai-Tajimi Shaping Filter

Table 1. The Responses of Interest for Appropriate Weighting Parameters

Responses	Corresponding weighting parameters, q_i
Base shear at piers 2 and 3	q_{bs}
Shear at deck level of piers 2 and 3	q_{sd}
Overturning moment at piers 2 and 3	q_{om}
Moment at deck level of piers 2 and 3	q_{md}
Deck displacement at bent 1 and pier 4	q_{dd}

Table 2. The Possible Combinations of Weighting Parameters for Q

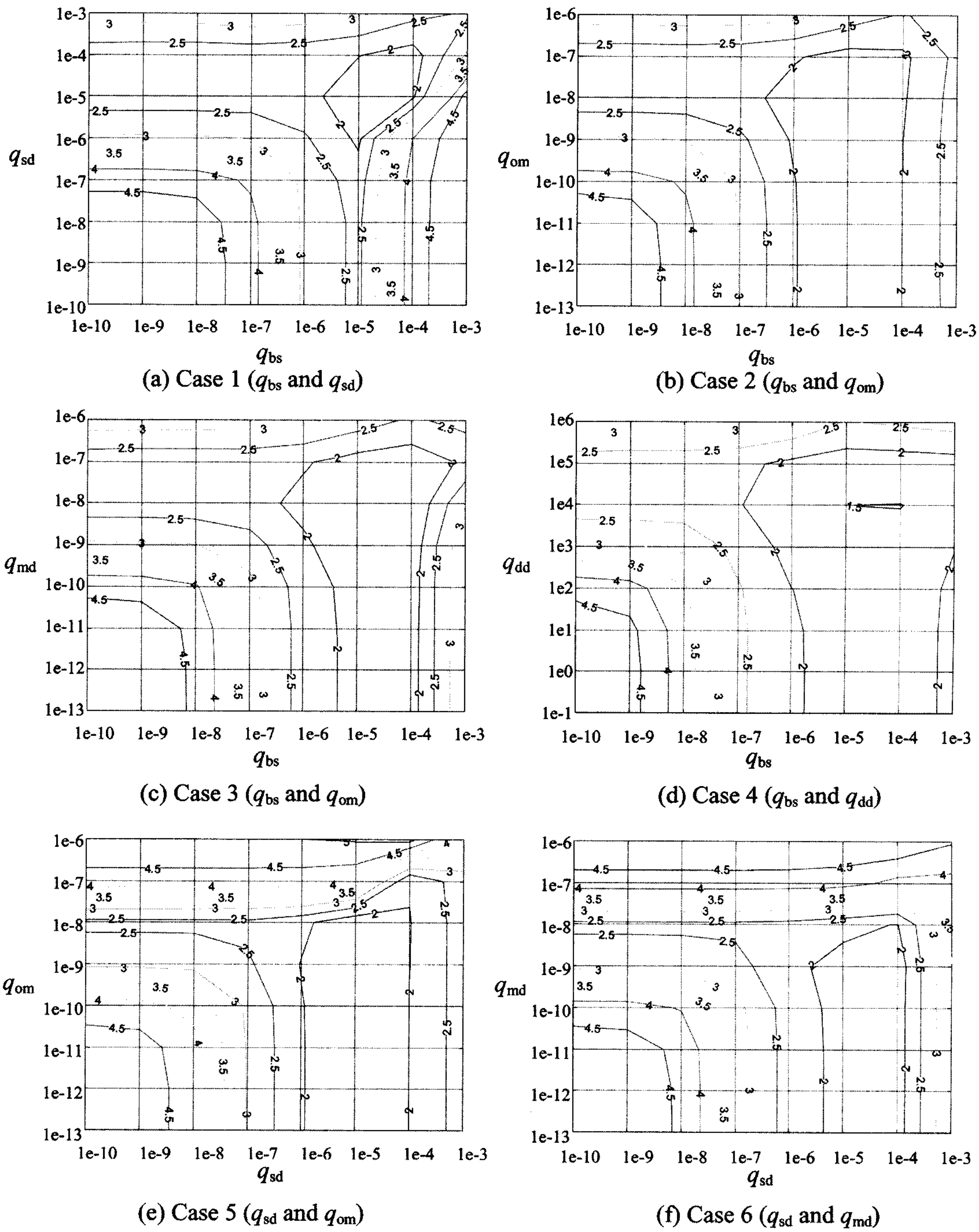
Case	q_i	q_j
1	q_{bs}	q_{sd}
2	q_{bs}	q_{om}
3	q_{bs}	q_{md}
4	q_{bs}	q_{dd}
5	q_{sd}	q_{om}
6	q_{sd}	q_{md}
7	q_{sd}	q_{dd}
8	q_{om}	q_{md}
9	q_{om}	q_{dd}
10	q_{md}	q_{dd}

historical earthquakes to be considered (1940 El Centro NS, 1985 Mexico City, 1999 Gebze NS).

To obtain the appropriate response weighting matrix $\mathbf{Q}$, the important responses for the overall behaviors of the bridge should be first selected as shown in Table 1. In this study, $\mathbf{Q}$ is considered as the combination of the two weighting parameters such as

$$\mathbf{Q} = \begin{bmatrix} q_i \mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & q_j \mathbf{I}_{4\times4} \end{bmatrix} \qquad (5)$$

Then, the appropriate $\mathbf{Q}$ can be found through the stochastic response analyses of the ten different combinations of the weighting parameters as shown in Table 2. Note that the



(a) Case 1 (q_{bs} and q_{sd})

(b) Case 2 (q_{bs} and q_{om})

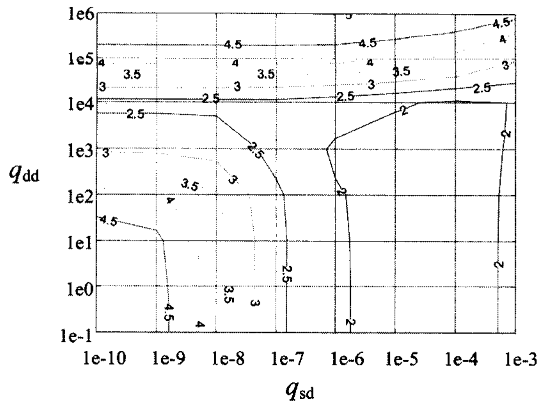
(c) Case 3 (q_{bs} and q_{om})

(d) Case 4 (q_{bs} and q_{dd})

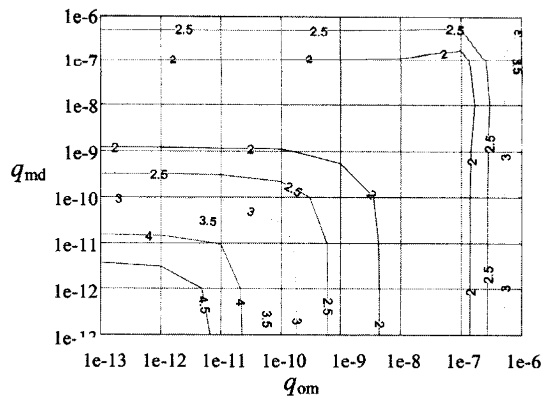
(e) Case 5 (q_{sd} and q_{om})

(f) Case 6 (q_{sd} and q_{md})

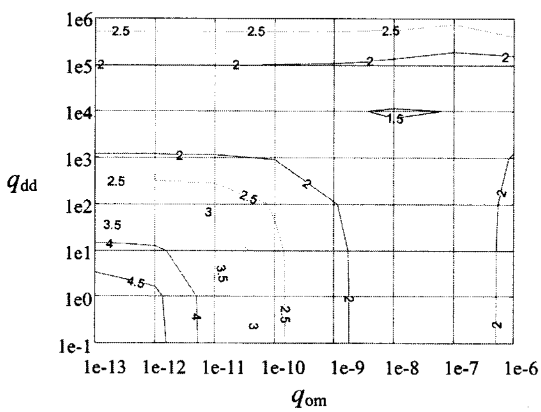
Fig. 4. Sum of Normalized *rms* Responses in Active Control Case



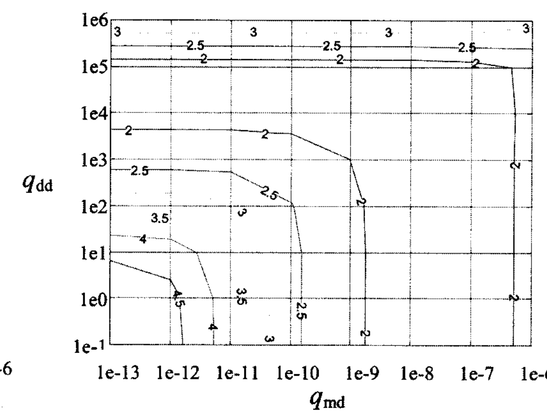
(g) Case 7 (q_{sd} and q_{dd})



(h) Case 8 (q_{om} and q_{md})



(i) Case 9 (q_{om} and q_{dd})



(j) Case 10 (q_{md} and q_{dd})

Fig. 4. Sum of Normalized *rms* Responses in Active Control Case (*Continued*)

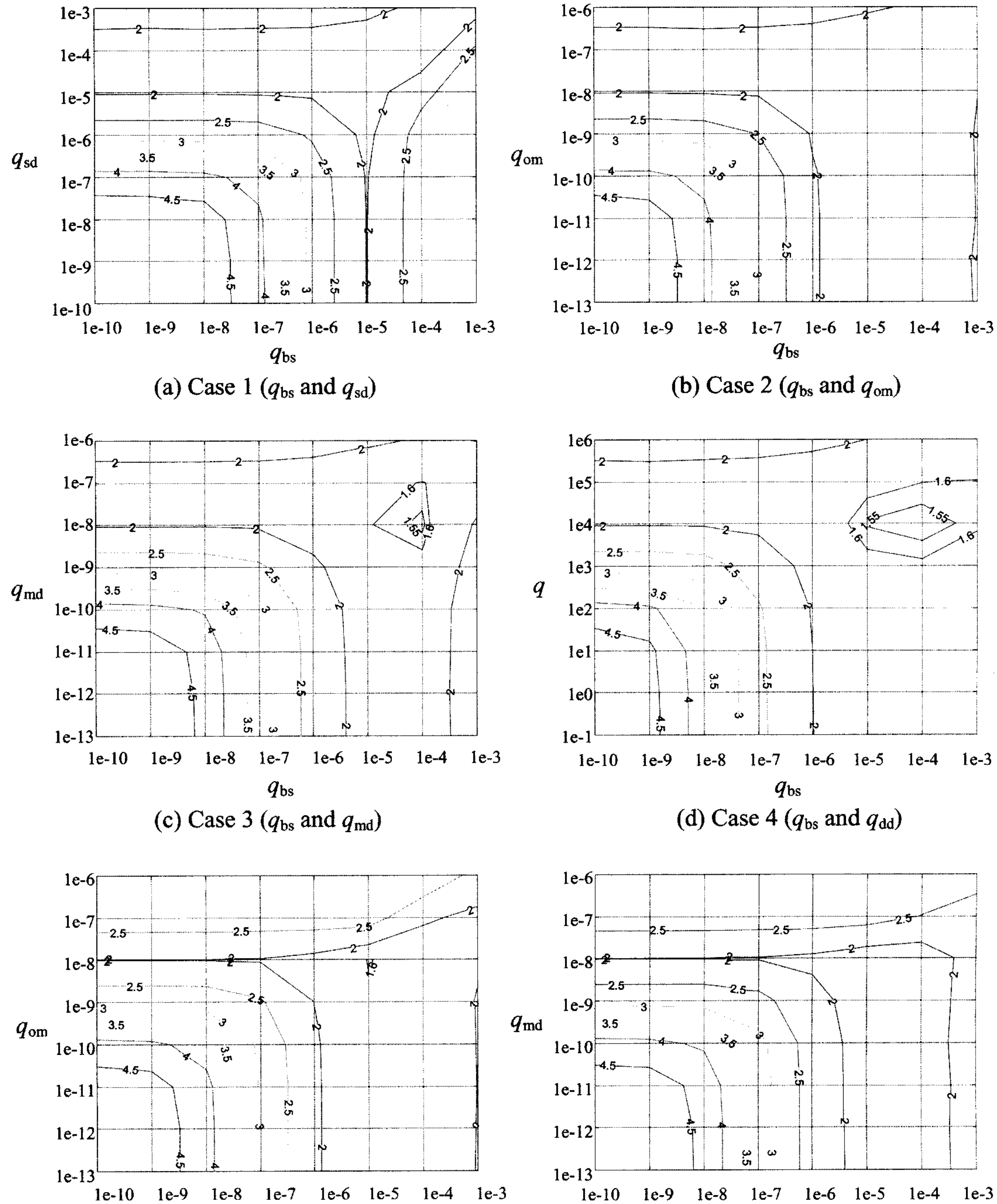
other parameters except the two weighting parameters chosen (*i.e.*, q_i and q_j) are set to zero when the response analysis is performed.

For the linear system such as the bridge model employing active control devices, the *rms* responses can generally be computed by solving a Lyapunov equation. In this study, however, the *rms* responses are calculated by performing simulation in the time domain (generated using SIMULINK® (1997)) to consider important characteristics of the control design model such as force saturation and control force feedback. The total simulation time in analysis is 1000 sec. The sum value of the normalized *rms* responses, including the base shear, the shear at deck level, the overturning moment, the moment at deck level, and the deck displacement, in the active control case is represented in Fig. 4. As can be seen from the figure, the Case 4 (*i.e.*, q_{bs} and q_{dd}) and the Case 9 (*i.e.*, q_{om} and q_{dd}) give the best reduction of the sum of the normalized *rms* responses. After the additional simulations by using the historical earthquake records considered in this study have been performed, the appropriate combination of the weighting parameters in active control case is determined as the Case 9 (*i.e.*, q_{om} and q_{dd}).

In the semi-active control case, computing the *rms* responses also requires simulation in the time domain, due to the nonlinear nature of smart dampers, as well as the characteristics of the control design model such as force saturation and control force feedback. The simulation results in the semi-active control case are shown in Fig. 5. As seen from the figure, the Case 4 (*i.e.*, q_{bs} and q_{dd}) and the Case 9 (*i.e.*, q_{om} and q_{dd}) give the best reduction of the sum of the normalized *rms* responses. Similarly to the active control case, after the additional simulations by using the historical earthquakes, the Case 9 (*i.e.*, q_{om} and q_{dd}) is determined as the appropriate combination of the weighting parameters in the semi-active control case.

By employing the above weighting matrices to obtain the *primary* controller (H_2/LQG), we can get the "desired" active control command.

Since the force generated by a smart damper is dependent



(a) Case 1 (q_{bs} and q_{sd})

(b) Case 2 (q_{bs} and q_{om})

(c) Case 3 (q_{bs} and q_{md})

(d) Case 4 (q_{bs} and q_{dd})

(e) Case 5 (q_{sd} and q_{om})

(f) Case 6 (q_{sd} and q_{md})

Fig. 5. Sum of Normalized *rms* Responses in Semi-Active Control Case

on the structure and its motion, it is not always possible to produce the "desired" force. For the general smart damping device, including variable orifice dampers, variable friction dampers and controllable fluid dampers, the *secondary* control strategy is given by

$$f_{sa,i} = \begin{cases} f_{a,i}, & f_{a,i} \cdot \dot{x}_{dev} < 0 \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where $f_{sa,i}$ is the control force of the ith smart damper, $f_{a,i}$

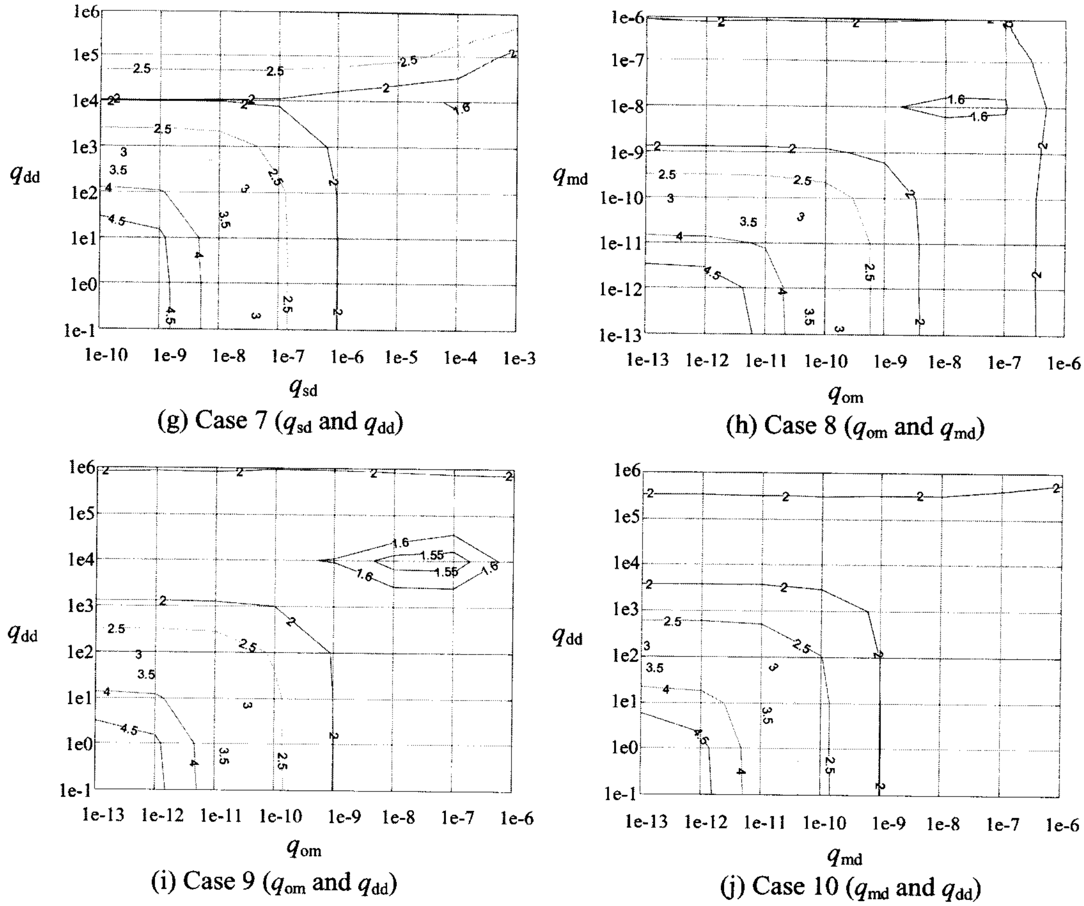


Fig. 5. Sum of Normalized *rms* Responses in Semi-Active Control Case (*Continued*)

is the "desired" control force of the *i*th device, and $\dot{x}_{dev}$ is the velocity across the *i*th damper. In this preliminary study, since the device is assumed to be "ideal", the control force given by (6) can be replaced as follows:

$$u_{sa,i} = \begin{cases} u_{a,i}, & u_{a,i} \cdot \dot{x}_{dev} < 0 \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

where $u_{sa,i}$ is the *i*th actual control command in Volts, $u_{a,i}$ is the "desired" control command.

Because the smart damper is an energy-dissipative device that cannot add mechanical energy to the structural system, special care must be taken in the design of the *primary* controller so that the "desired" control force $f_{a,i}$ is dissipative during the majority of the seismic event. The smart damper control design is depicted in Fig. 6.

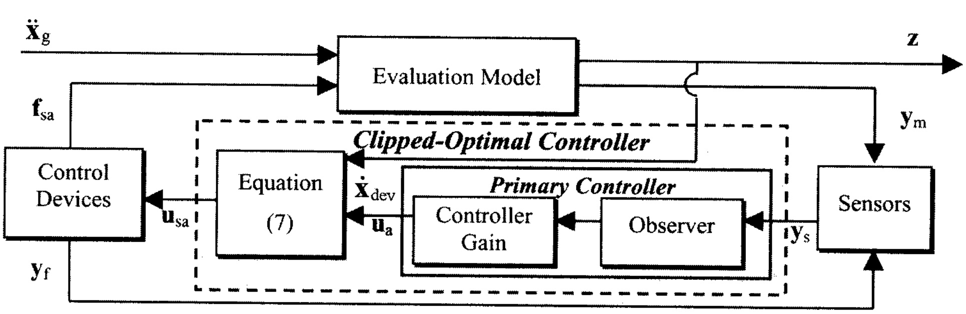
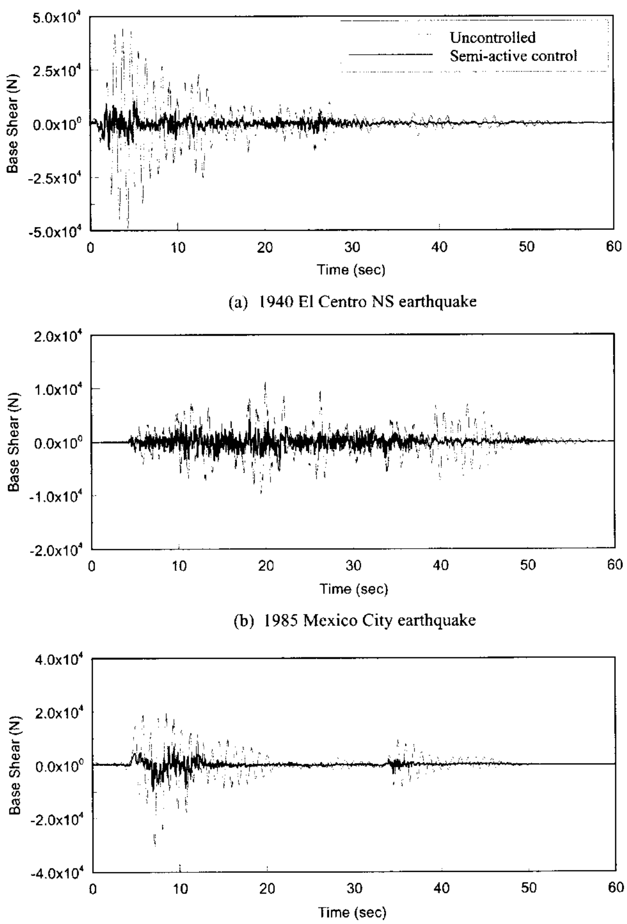


Fig. 6. Semi-Active Control Strategy Using Clipped-Optimal Algorithm

4. Numerical Analysis

To verify the effectiveness of the proposed control design, a set of simulations is performed for the three earthquakes specified. Then, simulation results of the proposed control design are compared to those of an active control design, which adopted the H_2/LQG method as control algorithm, the same number and location of the sensors/actuators being employed as in the case of the proposed control design. That is, the active control design considered herein is equal to the *primary* controller of the proposed design. In this preliminary study, the appropriate values of weighting parameters for the proposed control design and the active control design are chosen as follows (see (5)): q_{om}=1e-8 and q_{dd}=1e4.

In Fig. 7, the time-history of base shear at pier 2 of the controlled bridge for the active control and the semi-active control are compared to those of the uncontrolled bridge, which is the "as-built" bridge including the shock transmission devices, for the 1940 El Centro NS, 1985 Mexico City, and 1999 Gebze NS earthquakes. As seen from the figure, the proposed semi-active control case reduces the peak responses significantly for all the three earthquakes compared with the uncontrolled case (*i.e.*, 76.4% for the 1940 El Centro NS, 60.4% for the 1985 Mexico City, 69.5% for the 1999 Gebze NS).



(a) 1940 El Centro NS earthquake

(b) 1985 Mexico City earthquake

(c) 1999 Gebze NS earthquake

Fig. 7. Uncontrolled and Controlled Base Shear Forces

The calculated evaluation criteria for various control strategies are compared as shown in Table 3. While the controller presented in Dyke *et al.* (2003) is not intended to be a competitive control design, the associated performance indices are given in this table for the readers' reference. For the semi-active control strategies, J_{14} and J_{15}, which correspond to the non-dimensionalized maximum instantaneous power and total power, are not applicable. Note that in each case tension in the stay cables remained within the recommended region of allowable values presented in Dyke *et al.* (2003).

As shown in Table 3, the active and semi-active control methods perform well in all the earthquake cases, especially the case of the 1940 El Centro NS earthquake (*e.g.*, more than 75% reduction for the maximum overturning moment (J_3) as compared to the original design). The stroke of control devices (J_{13}) has the largest magnitude in the case of the 1999 Gebze NS earthquake. For the 1985 Mexico City and the 1999 Gebze NS earthquakes, the deck displacements (J_6) by the active and semi-active control cases increase significantly (75%-93% increase for the 1985 Mexico City earthquake, and 125%-129% increase for the 1999 Gebze NS earthquake) as compared to the uncontrolled case. These increases of the deck displacements are because the evaluation model for the controlled system is different from that for the uncontrolled system as already explained.

It is verified from the table that the performance of both active and semi-active control strategies proposed in this study are generally better than that in Dyke *et al.* (2003) because the proposed control methods use the optimized values and combinations of the weighting parameters. Also, the overall performance of the fully active control design is a little bit better than that of the proposed semi-active control design. That is, all the evaluation criteria of the active control system are 1.1%~12.4% smaller than those of the proposed system except the base shear (J_1) (5.9% larger). These results are because the semi-active control strategy can achieve the most of "desired" active control force calculated in the *primary* controller during the majority of the seismic event as shown in Fig. 8. The similar results were also reported in the recent studies (Dyke *et al.*, 1996; Ramallo *et al.*, 1999, *etc.*). Therefore,

Table 3. Evaluation Criteria for All the Three Earthquakes

Criterion	1940 El Centro NS earthquake			1985 Mexico City earthquake			1999 Gebze NS earthquake			Maximum		
	Dyke *et al.* (2003)	Active control	Semi-active control	Dyke *et al.* (2003)	Active control	Semi-active control	Dyke *et al.* (2003)	Active control	Semi-active control	Dyke *et al.* (2003)	Active control	Semi-active control
J_1	0.387	0.305	0.316	0.458	0.476	0.448	0.454	0.413	0.446	0.458	0.476	0.448
J_2	1.068	0.970	0.953	1.369	1.020	1.008	1.378	1.218	1.256	1.378	1.218	1.256
J_3	0.294	0.242	0.252	0.584	0.470	0.480	0.443	0.319	0.327	0.584	0.470	0.480
J_4	0.625	0.590	0.589	0.614	0.481	0.505	1.225	0.926	0.941	1.225	0.926	0.941
J_5	0.186	0.153	0.172	0.077	0.053	0.057	0.148	0.097	0.108	0.186	0.153	0.172
J_6	1.201	1.014	0.913	2.332	1.928	1.747	3.564	2.250	2.292	3.564	2.250	2.292
J_7	0.226	0.191	0.197	0.398	0.355	0.359	0.323	0.271	0.278	0.398	0.355	0.359
J_8	1.178	0.795	0.859	1.212	0.868	0.933	1.437	1.049	1.168	1.437	1.049	1.168
J_9	0.266	0.175	0.181	0.419	0.315	0.315	0.455	0.325	0.339	0.455	0.325	0.339
J_{10}	0.881	0.540	0.561	1.107	0.753	0.773	1.457	0.939	1.017	1.457	0.939	1.017
J_{11}	0.028	0.017	0.018	0.010	0.006	0.007	0.017	0.011	0.012	0.028	0.017	0.018
J_{12}	1.59e-3	1.96e-3	1.96e-3	5.74e-4	1.45e-3	1.44e-3	1.71e-3	1.96e-3	1.96e-3	1.71e-3	1.96e-3	1.96e-3
J_{13}	0.788	0.666	0.600	1.174	0.971	0.880	1.954	1.234	1.257	1.954	1.234	1.257
J_{14}	2.70e-3	4.36e-3	–	1.75e-3	2.55e-3	–	7.38e-3	8.39e-3	–	7.38e-3	8.39e-3	–
J_{15}	4.29e-4	6.92e-4	–	2.33e-4	3.40e-4	–	6.95e-4	7.91e-4	–	6.95e-4	7.91e-4	–
J_{16}	24	24	24	24	24	24	24	24	24	24	24	24
J_{17}	9	33	33	9	33	33	9	33	33	9	33	33
J_{18}	30	32	32	30	32	32	30	32	32	30	32	32

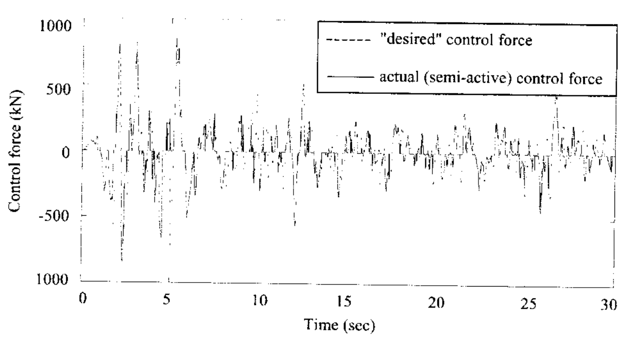


Fig. 8. "Desired" and Actual Control Force under the 1940 El Centro NS Earthquake

Table 4. Actuator Requirements for Control Strategies

Earthquake	Max.	Active Control	Semi-Active Control
1940 El Centro NS	Force (kN)	1000	1000
	Stroke (m)	0.0990	0.0891
	Velocity (m/s)	0.6140	0.5759
1985 Mexico City	Force (kN)	741.81	732.00
	Stroke (m)	0.0469	0.0425
	Velocity (m/s)	0.2826	0.2480
1990 Gebze NS	Force (kN)	1000	1000
	Stroke (m)	0.1618	0.1648
	Velocity (m/s)	0.4665	0.4893

since smart dampers have not only the potential to achieve the majority of the performance of fully active systems but also many attractive features such as bounded-input, bounded-output stability and small energy requirements the semi-active control strategies using smart dampers show significant promise for seismic protection of cable-stayed bridges.

To demonstrate the feasibility of these controllers, peak values of the force, stroke, and velocity are provided for all the three earthquakes in Table 4. The force, velocity, and stoke requirements presented by Dyke *et al.* (2003) are 1000 kN, 1 m/sec, and 0.2 m, respectively. As seen from Table 4, all the three maximum responses satisfy the actuator requirements in the active and semi-active control cases.

5. Concluding Remarks

A semi-active control strategy using smart dampers is proposed. To do this, the phase I benchmark control problem for seismic responses of cable-stayed bridges has been thoroughly investigated. To determine the control action for each smart damper, a clipped-optimal control algorithm is used. The appropriate combinations and optimal values of the weighting parameters for the proposed smart damping strategy have been obtained and the Kanai-Tajimi shaping filter has been incorporated to more effectively design the control system.

The numerical simulation results show that the performance of the proposed control design is nearly the same as that of the active control system. The proposed control system also significantly reduces all the peak and normed responses, with the exception of the shear at deck level and the deck displacement compared with the "as-built" uncontrolled bridge case (*i.e.*, including shock transmission devices). In addition, a semi-active control strategy using smart dampers has many attractive features, such as the bounded-input, bounded-output stability and small energy requirements. The results of this investigation indicate that smart dampers could effectively be used for the control of a seismically excited benchmark cable-stayed bridge.

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References

American Society of Civil Engineers (ASCE). (1997). "Session 7WB, structural control: a benchmark comparison." *Proc. ASCE Structures Congress XV*, Portland, Oregon, Vol. 2, pp. 1265-1289.

Dyke, S.J., Spencer, Jr., B.F., Quast, P., Kaspari, Jr., D.C., and Sain, M.K. (1995). "The role of control-structure interaction in protective system design." *ASCE Journal of Engineering Mechanics*, Vol. 121, No. 2, pp. 322-338.

Dyke, S.J., Spencer, Jr., B.F., Sain, M.K., and Carlson, J.D. (1996). "Modeling and control of magnetorheological dampers for seismic response." *Smart Materials and Structures*, Vol. 5, pp. 565-575.

Dyke, S.J. and Spencer, Jr., B.F. (1997). "A comparison of semi-active control strategies for the MR damper." *Proc. IASTED International Conference on Intelligent Information Systems*, The Bahamas.

Dyke, S.J., Turan, G., Caicedo, J.M., Bergman, L.A., and Hague, S. (2003). "Phase I benchmark control problem for seismic response of cable-stayed bridges." *Jounal of Structural Engineering*, ASCE, Vol. 129, pp. 873-883.

EESD (1998). "Special issue: benchmark problems." *Earthquake Engineering and Structural Dynamics*, Vol. 27, No. 11, pp. 1125-1397.

International Association on Structural Control (IASC). (1998). "Session 10 - benchmark tests of buildings." *Proc. Second World Conference on Structural Control*, Kyoto, Japan, Vol. 2, pp. 1349-1490.

Jung, H.-J., Spencer, Jr., B.F., and Lee, I.-W. (2001). "Benchmark control problem for seismically excited cable-stayed bridges using smart damping strategies." *IABSE Conference on Cable-Supported Bridges*, Seoul, Korea, Serial 84, 256-257.

Jung, H.-J., Park, K.-S., Spencer, Jr., B.F., and Lee, I.-W. (2002). "Semi-active control of a seismically excited cable-stayed bridge considering dynamic models of MR fluid damper." *Journal of Earthquake Engineering Society of Korea*, Vol. 6, No. 2, pp. 63-71.

Laub, A.J., Health, M.T., Paige, C.C., and Ward, R.C. (1987). "Computation of system balancing transformations and other applications of simultaneous diagonalization algorithms." *IEEE Transaction on Automatic Control*, Vol. AC-32, pp. 17-32.

MATLAB® (1997). The Math Works, Inc. Natick, Massachusetts.

Ohtori, Y., Christensen, R.E., Spencer, Jr., B.F., and Dyke, S.J. (2000). "Benchmark control problems for seismically excited nonlinear buildings." *<http://www.nd.edu/~quake/>*.

Ramallo, J.C., Johnson, E.A., Spencer, Jr., B.F., and Sain, M.K. (1999). "Semiactive Building Base Isolation." *Proceedings of the American Control Conference*, San Diego, USA, pp. 515-519.

SIMULINK® (1997). The Math Works, Inc. Natick, Massachusetts.

Soong, T.T. and Grigoriu, M. (1993). *Random Vibration of Mechanical and Structural Systems*, Prentice Hall, Englewood Cliffs, New Jersey.

Spencer, Jr., B.F., Suhardjo, J., and Sain, M.K. (1994). "Frequency domain optimal control strategies for aseismic protection." *ASCE Journal of Engineering Mechanics*, Vol. 120, No. 1, pp. 135-159.

Spencer, Jr., B.F., Dyke, S.J., and Deoskar, H.S. (1997). "Benchmark problem in structural control." *Proc. Structures Congress XV*, Portland, Oregon, Vol. 2, pp. 1265-1269.

Spencer, Jr., B.F., Dyke, S.J., and Deoskar, H.S. (1998a). "Benchmark problems in structural control: part I - active mass driver system." *Earthquake Engineering and Structural Dynamics*, Vol. 27, No. 11, pp. 1127-1139.

Spencer, Jr., B.F., Dyke, S.J., and Deoskar, H.S. (1998b). "Benchmark problems in structural control: part II - active tendon system." *Earthquake Engineering and Structural Dynamics*, Vol. 27, No. 11, pp. 1141-1147.

Wilson, J. and Gravelle, W. (1991). "Modelling of a cable-stayed bridge for dynamic analysis." *Earthquake Engineering and Structural Dynamics*, Vol. 20, pp. 707-721.

Zhou, K., Doyle, J.C., and Glover, K. (1996). *Robust and Optimal Control*, Prentice-Hall, New Jersey.