HYBRID CONTROL STRATEGIES FOR SEISMIC PROTECTION OF BENCHMARK CABLE-STAYED BRIDGES

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ABSTRACT

This paper presents a hybrid control strategy for seismic protection of a benchmark cable-stayed bridge, which is provided as a *testbed* structure for the development of strategies for the control of cable-stayed bridges. In this study, a hybrid control system is composed of a passive control system to reduce the earthquake-induced forces in the structure and an active control system to further reduce the bridge responses, especially deck displacements. Conventional passive isolation devices such as rubber bearings and lead rubber bearings are used for the passive control design. Numerical simulation results show that the performance of the proposed hybrid control strategy is quite effective compared to that of the passive control strategy and slightly better than that of the active control strategy. The hybrid control method is also more reliable than the active control method due to the passive control part. Therefore, the proposed control strategy can effectively be used to seismically excited cable-stayed bridges.

Introduction

In recent years benchmark control problems have been developed as a *testbed* structure to compare and contrast various structural control strategies (Caughey, 1998). Benchmark control problems allow researchers to apply various algorithms, devices, and sensors to a specified problem and make direct comparisons of the results in terms of a specified set of performance objectives. Until recently, however, all of the benchmark problems have focused on the control of buildings (Spencer *et al.* 1997; EESD 1998; Ohtori *et al.* 2000).

Since there are a growing number of cable-stayed bridges throughout the world, more research on the control for seismic response of such structures is needed. The control of very flexible and large structures such as cable-stayed bridges is a unique and challenging problem. For these reasons, the first generation benchmark control problem for cable-stayed bridges under seismic loads has been developed (Dyke *et al.* 2000). The benchmark problem is based on the cable-stayed bridge currently under construction in Cape Girardeau, Missouri, USA. Based on detailed drawings of the Cape Girardeau Bridge, a three dimensional evaluation model was developed to represent the complex behavior of the full scale benchmark bridge. To evaluate the proposed control strategies in terms that are meaningful for cable-stayed bridges, appropriate

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evaluation criteria are briefly specified within the problem statement.

In this study, a hybrid control strategy for the seismic protection of a cable-stayed bridge is investigated by using the benchmark bridge model provided by Dyke *et al.* (2000). The hybrid control strategy is composed of a passive control system to reduce the earthquake-induced forces in the structure and an active control system to further reduce the bridge responses, especially deck displacements, are employed. Following a summary of the benchmark problem statement, a seismic control design using the hybrid control strategies is proposed. Then, numerical simulation results are presented to demonstrate the effectiveness of the proposed control strategy.

Benchmark Problem Statement

The bridge considered in this study is composed of two towers, 128 cables, and 12 additional piers in the approach bridge from the Illinois side, as shown in Fig. 1. Because the bearing at pier 4 does not restrict longitudinal motion and rotation about the longitudinal axis of the bridge, the Illinois approach has a negligible effect on the dynamics of the cable-stayed portion of the bridge. In the benchmark study, therefore, the Illinois approach is not included. Based on the description of the Cape Girardeau Bridge, a three dimensional finite element model of the bridge was developed in MATLAB®.

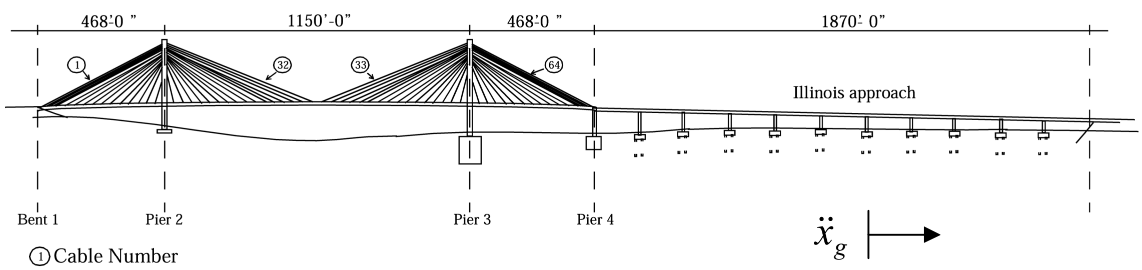

Figure 1. Drawing of the Cape Girardeau Bridge

A linear evaluation model is used in the benchmark study. However, the stiffness matrices used in the 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). The effects of soil-structure interaction are neglected, because the bridge assumed to be attached to bedrock. The most destructive direction is the longitudinal one in cable-stayed bridges. So, a one dimensional ground acceleration is applied in this direction. The finite element model employs beam elements, cable elements and rigid links. The nonlinear static analysis is performed in ABAQUS®, and the element mass and stiffness matrices are output to MATLAB® for assembly. Then, the constraints are applied, and static condensation is performed to reduce the full model to a 419 DOF reduced-order model. The modal damping matrix was developed by assigning 3% of critical damping to each mode, which is consistent with assumptions made during the design of the bridges.

A set of eighteen evaluation criteria have been developed to evaluate the capabilities of each control strategy (Dyke *et al.* 2000). The first six evaluation criteria are peak responses of the bridge to consider the ability of the controller. The second five evaluation criteria consider normed responses over the entire simulation time. The last seven evaluation criteria consider the requirements of each control system itself. More details are shown in Dyke *et al.* (2000).

Seismic Control System Using Hybrid Control Strategies

In this section, a description of the proposed control strategies is provided. For this preliminary study, simple passive and active control strategies are combined to examine the effectiveness of the hybrid control strategy. Accelerometers, displacement transducers are employed as sensors. Conventional base isolation systems are used as passive control devices. An H_2/LQG control algorithm (Spencer *et al.* 1994), which was used for sample controller in the benchmark study, is employed for the active control part of the hybrid control strategies.

Sensors

Five accelerometers and four displacement sensors are employed. Four accelerometers are located on top of the tower legs, and one is located on the deck at mid span. Two displacement sensors are positioned between the deck and pier 2 and two displacement sensors are located between the deck and pier 3. All sensor measurements are obtained in the longitudinal direction to the bridge and are assumed to be ideal, having a constant magnitude and phase (Dyke *et al.* 2000). The sensors can be modeled as

$$\mathbf{y}_s = \mathbf{D}_s \mathbf{y}_m + \mathbf{v} \quad (1)$$

where $\mathbf{y}_s$ is a vector of the measured absolute accelerations and device displacements in Volts, $\mathbf{y}_m$ is the vector of measured continuous-time absolute accelerations and device displacement in physical units, and $\mathbf{v}$ is the measurement noise, which has an *rms* value of 0.003 V. Sensor gain matrix $\mathbf{D}_s$ is

$$\mathbf{D}_s = \begin{bmatrix} \mathbf{I}_{5\times5} G_a & \mathbf{0} \\ \mathbf{0} & \mathbf{I}_{4\times4} G_d \end{bmatrix} \quad (2)$$

where $G_a = 0.714\,\mathrm{V/(m/sec^2)}$ is the sensor gain for acceleration and $G_d = 30\mathrm{V/m}$ is the displacement sensor gain.

Control Devices

Passive Control Devices

In the hybrid control strategies, passive control devices have a great role for the performance of the control method. In this study, conventional base isolation devices such as rubber bearings and lead rubber bearings are used. The bearings fabricated using rubber and lead offer a simple method of passive control and are relatively easy and inexpensive to manufacture. The design of passive control devices follows a general and recommended procedure (Ali and Abdel-Ghaffar, 2000). In the design procedure, the combined plastic or elastic stiffness of the bearings at the piers and bent are assumed to be 1.15W per meter, where W is the part of the deck weight carried by bearings. The elastic stiffness of a lead rubber bearing is assumed to be 10 times the plastic stiffness. This assumption seems to enjoy broad acceptance among bearing designers (Robinson, 1982; Mayes *et al.* 1984). The design shear force level for the yielding of lead plugs is taken to be 0.07W. Finally, eight lead rubber bearings and twelve rubber bearings are employed in this study. Four lead rubber bearings are used between the deck and bent 1 and four are used between the deck and pier 4. Six rubber bearings are employed between the deck and pier 2 and Six are employed between the deck and pier 3. The properties of the bearings are shown in Table 1.

Table 1. The Properties of the Passive Control Devices

	Rubber Bearing	**Lead Rubber Bearing**
k_e (N/m)[1)]	7.9853×10^{6}	6.5005×10^{7}
k_p (N/m)[2)]	-	7.5311×10^{6}
k_{eff} (N/m)[3)]	-	1.1685×10^{7}
k_v (N/m)[4)]	4.6170×10^{9}	6.6457×10^{10}
ξ(%)[5)]	10	20.99
Q_d (ton)[6)]	-	25.4

1) elastic stiffness; 2) plastic stiffness; 3) effective stiffness; 4) vertical stiffness
5) damping ratio; 6) design shear force level for the yielding of lead plugs

Active Control Devices

In this study, a total of 24 hydraulic actuators, which are used in the benchmark problem, are employed (Dyke *et al.* 2000). Eight 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 actuators have a capacity of 1000 kN. Actuator dynamics are neglected and the actuator is considered to be ideal. The equation describing the forces produced by the actuators are

$$\mathbf{f} = \mathbf{K}_f\mathbf{u} = \mathbf{G}_{dev}\mathbf{D}_d\mathbf{u} = \begin{bmatrix} 2\mathbf{I}_{2\times2} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & 4\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & 2\mathbf{I}_{2\times2} \end{bmatrix}\mathbf{D}_d\mathbf{u} \quad (3)$$

$$\mathbf{y}_f = \mathbf{D}_d\mathbf{u} = D_d\mathbf{I}_{8\times8}\mathbf{u} \quad (4)$$

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, $D_d = 100\,\text{kN/V}$ is the device gain, and $\mathbf{K}_f$ is a matrix that accounts for the gain of the relationship between the input voltage and the desired control force, as well as the fact that multiple actuators are used at each actuator location, as shown in Eq. 3.

Control Design Model

A reduced order model of the system is developed for control design, which is formed from the evaluation model and has 30 states. This model obtained by forming a balanced realization of the system and condensing out the states with relatively small controllability and observability grammians (Laub *et al.* 1987). The resulting state space system is represented as follows

$$\dot{\mathbf{x}}_d = \mathbf{A}_d \mathbf{x}_d + \mathbf{B}_d \mathbf{u} + \mathbf{E}_d \ddot{x}_g \tag{5}$$

$$\mathbf{z} = \mathbf{C}_d^z \mathbf{x}_d + \mathbf{D}_d^z \mathbf{u} + \mathbf{F}_d^z \ddot{x}_g \tag{6}$$

$$\mathbf{y}_s = \mathbf{C}_d^y \mathbf{x}_d + \mathbf{D}_d^y \mathbf{u} + \mathbf{F}_d^y \ddot{x}_g + \mathbf{v} \tag{7}$$

where $\mathbf{x}_d$ is the design state vector, $\ddot{x}_g$ is the ground acceleration, $\mathbf{u}$ is the control command input, and $\mathbf{z}$ is the regulated output vector including evaluation outputs.

Control Algorithm for the Hybrid Control Strategies

In this study, an H_2/LQG control design is adopted for the active control part. For this design, $\ddot{x}_g$ is taken to be a stationary white noise, and an infinite horizontal cost function is chosen as

$$J = \lim_{\tau \to \infty} \frac{1}{\tau} \mathrm{E}\left[\int_0^\tau \left\{ \mathbf{z}^\mathrm{T} \mathbf{Q} \mathbf{z} + \mathbf{u}^\mathrm{T} \mathbf{R} \mathbf{u} \right\} dt \right] \tag{8}$$

where $\mathbf{R}$ is an identity matrix of order 8, and $\mathbf{Q}$ is the response weighting matrix. Further, the measurement noise is assumed to be identically distributed, statistically independent Gaussian white noise process, and $S_{\ddot{x}_g \ddot{x}_g} / S_{v_i v_i} = \gamma = 25$.

Herein, the Lyapunov equation approach is used to select the optimal response weighting matrix $\mathbf{Q}$, because the *rms* responses can generally be computed by solving the Lyapunov equation for a linear system such as the bridge model employing active control devices. Eqs. 5 and 6 can be rewritten as

$$\dot{\mathbf{x}}_d = (\mathbf{A}_d - \mathbf{B}_d \mathbf{K}_u)\mathbf{x}_d + \mathbf{E}_d \ddot{x}_g = \mathbf{A}_c \mathbf{x}_d + \mathbf{E}_d \ddot{x}_g \tag{9}$$

$$\mathbf{z} = (\mathbf{C}_d^z - \mathbf{D}_d^z \mathbf{K}_u)\mathbf{x}_d + \mathbf{F}_d^z \ddot{x}_g = \mathbf{C}_c \mathbf{x}_d + \mathbf{F}_d^z \ddot{x}_g \tag{10}$$

where $\mathbf{K}_u$ is the feedback gain matrix for the deterministic regulator problem. Assuming the vector $\mathbf{x}_d$ is a stationary process, the Lyapunov equation is

$$\mathbf{A}_c \mathbf{G}_{\mathbf{x}_d \mathbf{x}_d} + \mathbf{G}_{\mathbf{x}_d \mathbf{x}_d} \mathbf{A}_c^{\mathrm{T}} + 2\pi S_o \mathbf{E}_d \mathbf{E}_d^{\mathrm{T}} = 0 \tag{11}$$

where $E\left[\ddot{x}_g(t_2) \ddot{x}_g(t_1) \right] \equiv 2\pi S_0 \delta(t_2 - t_1)$. This equation can be solved for in MATLAB® using the function *lyap* to determine the value of $\mathbf{G}_{\mathbf{x}_d \mathbf{x}_d}$, the covariance of the state vector $\mathbf{x}_d$. The covariance of the output can be determined from the covariance of the state, using Eq. 10 with

$\mathbf{F}_d^z = \mathbf{0}$ as

$$\mathbf{G_{zz}} = E\left[\mathbf{zz}^T\right] = E\left[\mathbf{C}_c\mathbf{x}_d\mathbf{x}_d^T\mathbf{C}_c^T\right] = \mathbf{C}_c E\left[\mathbf{x}_d\mathbf{x}_d^T\right]C_c^T = \mathbf{C}_c\mathbf{G}_{\mathbf{x}_d\mathbf{x}_d}\mathbf{C}_c^T \tag{12}$$

The *rms* responses are the square root of the covariance of the responses, the diagonal terms of $\mathbf{G_{zz}}$ determined as

$$\mathbf{z}^{rms} = \sqrt{\mathrm{diag}(\mathbf{G_{zz}})} \tag{13}$$

In this study, the responses to find optimal weighting parameters are selected as shown in Table 2.

Table 2. The Selected Responses for Optimal Weighting Parameters

Responses	Corresponding Weighting Parameters
base shears at piers 2and 3	q_{bs}
shears at deck level at piers 2 and 3	q_{sd}
overturning moments at base of piers 2 and 3	q_{om}
moments at deck level at piers 2 and 3	q_{md}
deck displacements at bent 1 and pier 4	q_{dd}
top displacements at towers 1 and 2	q_{td}

For the extensive parametric study, first the *rms* responses as increasing each weighing parameter are calculated to determine the optimal values of each weighting parameter. In the active control case, the shear deck level-weighted, the overturning moment-weighted, and the deck displacement-weighted cases give better reduction of the *rms* responses than the other cases. Simulations by using the historical earthquake records have been performed to choose more reliably the combinations of the weighting parameters. Therefore, the following two combinations of weighting parameters are considered for the active control strategies: (1) q_{om} and q_{dd}, (2) q_{sd} and q_{dd}. On the other hand, the overturning moment-weighted, the moment at deck level-weighted, and the top displacement-weighted cases give better reduction of the *rms* responses than the other cases in the hybrid control case. Similar to the active control case, the following approximate two combinations of weighting parameters are considered for the hybrid control strategies: (1) q_{om} and q_{td}, (2) q_{md} and q_{td}. Following this extensive parametric study, two cases are considered:

For Active Control Case

- *Case* 1: overturning moments and deck displacements

$$\mathbf{Q}_{om\_dd} = \begin{bmatrix} q_{om}\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & q_{dd}\mathbf{I}_{4\times4} \end{bmatrix} \tag{14}$$

• *Case* 2: shears at deck level and deck displacements

$$\mathbf{Q}_{sd\_dd} = \begin{bmatrix} q_{sd}\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & q_{dd}\mathbf{I}_{4\times4} \end{bmatrix} \quad (15)$$

For Hybrid Control Case

• *Case* 1: overturning moments and top displacement

$$\mathbf{Q}_{om\_td} = \begin{bmatrix} q_{om}\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & q_{td}\mathbf{I}_{4\times4} \end{bmatrix} \quad (16)$$

• *Case* 2: moments at deck level and top displacements

$$\mathbf{Q}_{md\_td} = \begin{bmatrix} q_{md}\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & q_{td}\mathbf{I}_{4\times4} \end{bmatrix} \quad (17)$$

Numerical Simulation Results

A set of simulations is performed for the three historical earthquakes to verify the effectiveness of the proposed control strategies. Simulation results of the proposed control design are compared to those of a passive and an active control designs. In this preliminary study, the appropriate values of weighting parameters for the active control design and the proposed control design are chosen as

For Active Control Design

***Case* 1:** $q_{om} = 6\times10^{-9}, q_{dd} = 6\times10^{3}$

***Case* 2:** $q_{sd} = 2\times10^{-5}, q_{dd} = 6\times10^{3}$

For Hybrid Control Design

***Case* 1:** $q_{om} = 1\times10^{-8}, q_{td} = 1\times10^{4}$

***Case* 2:** $q_{md} = 1\times10^{-7}, q_{td} = 6\times10^{3}$

Tables 3 to 5 show the values of eighteen evaluation criteria. While the controller presented in Dyke *et al.* (2000) is not intended to be competitive control design, the associated performance indices are given in these tables for the readers' reference. As can be seen from the tables, the passive control design itself is effective to reduce the responses of bridge. The bridge responses are further reduces in the proposed control design (*i.e.,* hybrid control design) due to the additional active control devices. As a whole, the performance of the proposed control design is quite effective compared to that of the passive control strategy and slightly better than that of the active control strategy. In the case of the 1940 El Centro NS earthquake, the performance of both case 1 and case 2 control methods are effective in active control design. In hybrid control design, the results of case 2 are slightly better than those of case 1. For the 1985 Mexico City and 1999 Gebze NS earthquakes, the deck displacements in all control strategies are increased as compared to those in the uncontrolled case. However, the proposed control design shows the smallest deck displacements among the control methods due to the additional active control devices.

Table 3. Evaluation Criteria for the 1940 El Centro NS Earthquake

Criterion	**Dyke *et al.* (2000)**	**Passive Control**	**Active Control (H_2/LQG)**		**Hybrid Control**	
			***Case* 1**	***Case* 2**	***Case* 1**	***Case* 2**
J_1	0.3868	0.3565	0.2816	0.2888	0.2831	0.2745
J_2	1.0681	1.0638	0.8446	0.7890	0.7970	0.7085
J_3	0.2944	0.3162	0.2605	0.2610	0.2331	0.3001
J_4	0.6252	0.5475	0.5898	0.6209	0.4113	0.3279
J_5	0.1861	0.1865	0.1571	0.1572	0.1446	0.1224
J_6	1.2006	1.3665	0.9793	1.0932	0.8469	0.9236
J_7	0.2257	0.2427	0.1999	0.2169	0.1972	0.2203
J_8	1.1778	0.8872	0.7754	0.6841	0.6845	0.6477
J_9	0.2665	0.2786	0.1849	0.2165	0.1767	0.2222
J_{10}	0.8813	0.4956	0.5056	0.5230	0.3415	0.2929
J_{11}	2.2968e-2	1.4208e-2	1.5465e-2	1.3627e-2	1.3009e-2	1.1414e-2
J_{12}	1.5887e-3	-	1.9608e-3	1.9608e-3	1.9608e-3	1.9608e-3
J_{13}	0.7883	-	0.6430	0.7178	0.5561	0.6064
J_{14}	2.7011e-3	-	4.6249e-3	4.8703e-3	3.4416e-3	3.6139e-3
J_{15}	4.2871e-4	-	7.3406e-4	7.7301e-4	5.4624e-4	5.7360e-4
J_{16}	24	-	24	24	24	24
J_{17}	9	-	9	9	9	9
J_{18}	30	-	30	30	30	30

Table 4. Evaluation Criteria for the 1985 Mexico City Earthquake

Criterion	**Dyke *et al.* (2000)**	**Passive Control**	**Active Control (H_2/LQG)**		**Hybrid Control**	
			***Case* 1**	***Case* 2**	***Case* 1**	***Case* 2**
J_1	0.4582	0.5873	0.4992	0.5596	0.4799	0.5260
J_2	1.3693	1.3448	1.0568	0.9463	0.8884	0.9079
J_3	0.5836	0.8524	0.4461	0.5137	0.4449	0.5090
J_4	0.6140	0.5090	0.4505	0.4780	0.3836	0.3203
J_5	7.7483e-2	4.8254e-2	5.3797e-2	4.9921e-2	4.1773e-2	3.3667e-2
J_6	2.3317	2.9094	1.7978	1.9661	1.4267	1.5267
J_7	0.3983	0.4930	0.3519	0.4048	0.3521	0.4197
J_8	1.2118	1.0372	0.8481	0.7607	0.7530	0.7336
J_9	0.4192	0.6196	0.3158	0.3926	0.3214	0.4186
J_{10}	1.1067	0.8527	0.6958	0.7514	0.4883	0.4141
J_{11}	1.0276e-2	5.3606e-3	5.9250e-3	5.6224e-3	4.2993e-3	3.9147e-3
J_{12}	5.7440e-4	-	1.6967e-3	1.2472e-3	1.0275e-3	1.1079e-3
J_{13}	1.1742	-	0.9053	0.9901	0.7185	0.7688
J_{14}	1.7523e-3	-	2.5804e-3	2.6346e-3	1.3485e-3	1.5031e-3
J_{15}	2.3343e-4	-	3.4374e-4	3.5096e-4	1.7963e-4	2.0023e-4
J_{16}	24	-	24	24	24	24
J_{17}	9	-	9	9	9	9
J_{18}	30	-	30	30	30	30

Table 5. Evaluation Criteria for the 1990 Gebze Earthquake

Criterion	**Dyke *et al.* (2000)**	**Passive Control**	**Active Control (H_2/LQG)**		**Hybrid Control**	
			***Case* 1**	***Case* 2**	***Case* 1**	***Case* 2**
J_1	0.4540	0.4245	0.4277	0.4074	0.4035	0.3865
J_2	1.3784	1.0810	1.1988	1.0970	0.9127	0.8462
J_3	0.4434	0.3661	0.3341	0.3755	0.3038	0.3381
J_4	1.2246	0.5963	0.8692	0.9026	0.5518	0.5038
J_5	0.1481	0.1114	0.1001	9.5069e-2	8.9272e-2	6.9691e-2
J_6	3.5640	1.2724	2.0181	1.9572	1.0724	0.9433
J_7	0.3231	0.2970	0.2834	0.3248	0.2511	0.2928
J_8	1.4271	1.0282	1.0118	0.9308	0.8178	0.7922
J_9	0.4552	0.3285	0.3304	0.3865	0.2638	0.3059
J_{10}	1.4569	0.5660	0.8598	0.8461	0.4843	0.4085
J_{11}	1.7052e-2	7.3401e-3	1.0352e-2	1.0671e-2	5.5649e-3	6.3538e-3
J_{12}	1.7145e-3	-	1.9608e-3	1.9608e-3	1.9608e-3	1.9608e-3
J_{13}	1.9540	-	1.1065	1.0731	0.5880	0.5172
J_{14}	7.3689e-3	-	9.2050e-3	8.6695e-3	3.8293e-3	5.4193e-3
J_{15}	6.9492e-4	-	8.6807e-4	8.1757e-4	3.6112e-4	5.1106e-4
J_{16}	24	-	24	24	24	24
J_{17}	9	-	9	9	9	9
J_{18}	30	-	30	30	30	30

To demonstrate the feasibility of these controllers, peak values of the force, stroke, and velocity are provided for each earthquake in Table 6. The force, stroke, and velocity requirements presented by Dyke *et al.* (2000) are 1000 kN, 0.2m, and 1 m/sec. As seen from Table 6, all the three maximum responses satisfy the actuator requirements in the active and hybrid control cases.

Table 6. Actuator Requirements for Control Strategies

Earthquake	**Max.**	**Dyke *et al.* (2000)**	**Active Control (H_2/LQG)**		**Hybrid Control**	
			***Case* 1**	***Case* 2**	***Case* 1**	***Case* 2**
1940 El Centro NS	Force(kN)	810.26	1000	1000	1000	1000
	Stroke(m)	0.1172	0.0956	0.1067	0.0826	0.0901
	Vel. (m/s)	0.6846	0.6301	0.6322	0.4813	0.4973
1985 Mexico City	Force(kN)	292.94	865.31	636.06	524.03	565.04
	Stroke(m)	0.0567	0.0437	0.0478	0.0347	0.0371
	Vel. (m/s)	0.3243	0.2766	0.3082	0.1519	0.1636
1990 Gebze NS	Force(kN)	874.41	1000	1000	1000	1000
	Stroke(m)	0.2563	0.1451	0.1408	0.0771	0.0678
	Vel. (m/s)	0.5620	0.4324	0.4453	0.3388	0.3341

While the fully active control system may fail under severe earthquakes, the hybrid control system can operate well due to the passive control part even if the active control part may not work. Therefore, the proposed control design is more reliable and effective than the passive or active control method alone.

Conclusions

In this paper, a hybrid control strategy, which is composed of a passive control system to reduce the earthquake-induced forces in the structure and an active control system to further reduce the bridge responses, especially deck displacements, has been proposed by investigating the benchmark control problem for seismic responses of cable-stayed bridges. The proposed control design employs the conventional passive control devices for passive control part and adopts an H_2/LQG control algorithm for the active control part. The numerical results demonstrate that the performance of the proposed control design is quite effective compared to that of the passive control strategy and slightly better than that of the active control strategy. The hybrid control strategy is also more reliable than the active control method due to the passive control part. Therefore, the proposed control strategy can effectively be used to seismically excited cable-stayed bridges.

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