LRB-based hybrid base isolation systems for cable-stayed bridges

사장교를 위한 LRB-기반 복합 기초격리 시스템

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국문요약

사장교에 발생하는 지진에 의한 진동을 감소시키기 위해 추가적인 능동/반능동 제어장치를 부착한 LRB-기반 복합 기초격리 시스템에 대한 논문이다. 복합 기초격리 시스템은 제어장치가 다중으로 작동하기 때문에 LRB가 설치된 교량 시스템과 같은 수동형 기초격리 시스템에 비해 제어 성능이 뛰어나다. 본 논문에서는, LQG 알고리듬에 의해 제어되는 능동형 유압식 가력기와 clipped 최적제어에 의해 제어되는 반능동형 자기유변 유체 (MR) 감쇠기를 추가적인 제어장치로 고려하여 추가적인 응답 감소 효과를 검토하였다. 이를 위해, 미국토목학회의 1단계 벤치마크 사장교에 LRB를 설치한 교량을 고려하였다. 수치해석 결과를 통해, 모든 LRB-기반 복합 기초격리시스템이 구조물의 응답을 효과적으로 감소시킴을 확인하였다. 또한, MR 감쇠기를 채택한 복합 기초격리 시스템은 구조물 강성의 불확실성에 대해 강인성을 보였지만 유압식 가력기를 채택한 경우에는 강인성이 부족함을 알 수 있었다. 따라서, 반능동형 추가 제어장치를 채택한 복합 기초격리 시스템의 대형 토목구조물에 대한 적용가능성이 제어 성능 및 강인성 면에서 분명하게 검증되었다.

주요어 : 복합 기초격리 시스템, LRB(납 - 고무 받침), 능동/반능동 제어장치, 사장교, 자기유변유체 감쇠기, 유압식 가력기

ABSTRACT

This paper presents LRB-based hybrid base isolation systems employing additional active/semiactive control devices for mitigating earthquake-induced vibration of a cable-stayed bridge. Hybrid base isolation systems could improve the control performance compared with the passive type-base isolation system such as LRB-installed bridge system due to multiple control devices are operating. In this paper, the additional response reduction by the two typical additional control devices, such as active type hydraulic actuators controlled by LQG algorithm and semiactive-type magnetorheological dampers controlled by clipped-optimal algorithm, have been evaluated bypreliminarily investigating the slightly modified version of the ASCE phase I benchmark cable-stayed bridge problem (i.e., the installation of LRBs to the nominal cable-stayed bridge model of the problem). It shows from the numerical simulation results that all the LRB based hybrid seismic isolation systems considered are quite effective to mitigate the structural responses. In addition, the numerical results demonstrate that the LRB based hybrid seismic isolation systems employing MR dampers have the robustness to some degree of the stiffness uncertainty of in the structure, whereas the hybrid system employing hydraulic actuators does not. Therefore, the feasibility of the hybrid base isolation systems employing semiactive additional control devices could be more appropriate in realfor full-scale civil infrastructure applications is clearly verified due to their efficacy and robustness.

Key words : hybrid base isolation system, LRB (Lead-Rubber Bearing), active/semiactive control devices, cable-stayed bridge, magnetorheological damper, hydraulic actuators

1. INTRODUCTION

Base isolation, which is a well-established technique that mitigates the responses of a structure subjected to an earthquake by essentially decoupling the structure and its contents from potentially damaging earthquake-induced ground motions, is one of the most widely accepted seismic protection systems.[1],[2] A variety of seismic base isolation devices, such as pure-friction, laminated rubber bearing, lead-rubber bearing, resilient-friction base isolator and friction pendulum bearing, have been developed and implemented on civil engineering structures worldwide for a number of years owing to their simplicity, reliability and effectiveness.

Because of the growing number of cable-stayed bridges that are vulnerable to dynamic loadings such as an earthquake due to large flexibility and low damping ratios, more research on the seismic protection of such structures is needed. Studies on the application of seismic base isolation systems to cable-stayed bridges have been carried out since mid 1990s. Ali and Abdel-Ghaffar[3],[4] accomplished a pioneering work on this subject. They comprehensively investigated the applicability of a base isolation system using rubber bearings with/without lead plugs to the seismic protection of cable-stayed bridge based on the theoretical formulation, experimental verification and numerical applications. They showed that a significant reduction in earthquake-induced forces could

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본 논문에 대한 토의를 2004년 8월 31일까지 학회로 보내 주시면 그 결과를 게재하겠습니다. (논문접수일 : 2004. 3. 9 / 심사종료일 : 2004. 6. 1)

be achieved along the bridge by proper choice of properties and locations of the devices. However, the base isolation system using rubber bearings is one of the passive control systems, which does not require an external power source, and therefore is limited in their ability to adapt to changing demands for structural response reduction.[5]

To solve the limitations of passive-type base isolation systems, a new strategy combining a base-isolated structure with active/semiactive control devices has been developed. Such an integrated system is called a hybrid base isolation system that has a higher level of performance without a substantial increase in the cost, which was very appealing from a practical point of view.[6] Moreover, hybrid base isolation systems have a benefit that, in the case of a power failure, the passive base isolation components still offer some degree of protection, unlike a fully active control system.[7] Iemura et al.[8] and Iemura and Pradono[9] investigated the feasibility of additional semiactive-type variable dampers in the rubber bearing-installed seismic isolation system for seismic retrofit of a cable-stayed bridge. They verified from numerical simulation of an in-service bridge in Japan that the application of the base isolation system additionally employing variable dampers was effective in absorbing the large seismic energy and reducing the response amplitudes, consequently seismic demand itself for design. Park et al.[10],[11] accomplished the preliminary study of the hybrid base isolation system considering active-type hydraulic actuators for seismic protection of a cable-stayed bridge. They demonstrated the efficacy of the hybrid base isolation system combining lead-rubber bearings (LRBs) and active control devices with respect to control performance as well as robustness to uncertainty in stiffness. However, the systematic approach to the applicability of various additional control devices, such as active-type hydraulic actuators and semiactive-type smart dampers, to LRB-installed cable-stayed bridges has not been reported yet.

This paper presents the comprehensive investigation of the effectiveness of hybrid base isolation systems employing various additional control devices, such as hydraulic actuators and smart dampers, for seismic protection of the phase I benchmark cable stayed bridge provided by Dyke et al.[12] under the coordination of the ASCE Task Committee on Structural Control Benchmarks. In this study, LRBs, which consist of low damping laminated rubber bearings and lead plugs to increase energy dissipation through hysteretic damping as the lead plugs shear during large deformation motion and is one of the most popular base isolation devices in recent years, are considered as fundamental base isolation devices. And then, an active type hydraulic actuator (HA) controlled by the LQG algorithm and a semiactive type magnetorheological damper (MRD) controlled by the clipped optimal algorithm are employed as additional active and semiactive control devices for the hybrid base isolation system, respectively.

In this study, the extensive sensitivity analysis is first carried out to obtain the appropriate parameters for each control system (e.g., the weighting parameters for the HA and MRD) for fair comparison of the performances of the various LRB based hybrid base isolation systems. A set of nVarious types of dynamic models for MR dampers are considered. umerical simulations with the appropriate parameters in each case are then presented to demonstrate the efficacy of each hybrid base isolation system by evaluating the control performance as well as the robustness to the stiffness uncertainty of the structure.

2. LRB-installed cable stayed bridge model

2.1. Nominal bridge model

The nominal bridge considered in this study is that of a phase I benchmark control problem.[12] This benchmark bridge is composed of two towers, 128 cables, and 12 additional piers in the approach bridge from the Illinois side. Because the Illinois approach has a negligible effect on the dynamics of the cable-stayed portion of the bridge, only the cable-stayed portion of the bridge is considered. The schematic of this bridge is shown in Figure 1(a).

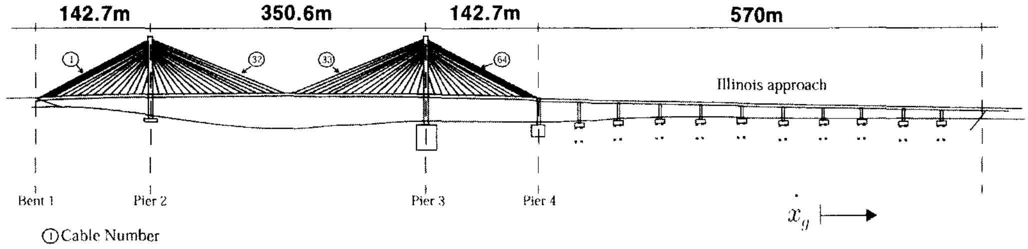


Fig 1 Schematic of the Bill Emerson Memorial Bridge

Each mode of this evaluation model has 3 % of critical damping, which is consistent with assumptions made during the design of bridge. The lowest ten undamped frequencies of the evaluation model for the original structural system (i.e., 16 shock transmission devices are present in the deck-tower connection) are 0.2899, 0.3699, 0.4683, 0.5158, 0.5812, 0.6490, 0.6687, 0.6970, 0.7102, and 0.7203 Hz. This original structural model can be considered as the uncontrolled system and also used as a basis of comparison for the controlled systems.

2.2 Installation of LRBs to the bridge model

In this study, LRBs are first installed in the nominal bridge model without shock transmission devices explained in the previous section as shown in Fig 2a. LRBs are laminated rubber bearings but contain one or more lead plugs that are inserted into holes, as shown in Fig 2b. Also, the typical hysteretic behavior of an LRB is represented in Fig 2c.

The installed LRBs could be considered as a passive control part for the hybrid base isolation systems. The main objective of LRBs is to increase the natural period of the isolated structures (for buildings and short-span bridges). Although the natural period of cable-stayed bridges is long enough to avoid the destructive seismic energy, a significant reduction in earthquake-induced forces could be achieved by the energy dissipation capacity of the lead plug in LRBs. However, the deck displacement is somewhat large due to the flexibility of LRBs after yielding of the lead plug. These increased displacements (i.e., deformations of LRBs) could be reduced by additional control devices.

The design of LRBs follows a recommended procedure provided by Ali and Abdel-Ghaffar.[3] In the design procedure, the design shear force level for the yielding of lead plugs is taken to be 0.10M$_b$, where M$_b$ is the part of the deck weight carried by LRBs. Then, the plastic stiffness ratio of LRBs at the bent and tower is assumed to be 1.0 (i.e., same properties of LRBs are used in the deck and bent/pier connections). As the results of the design procedure, 6 LRBs (3 in one part and 3 in the other part) are installed at the each deck-bent/pier connection (see Fig 3).

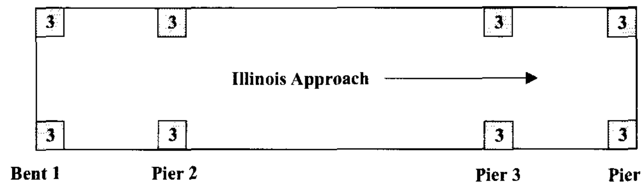


Fig 3. Configuration of LRBs in the LRB-installed bridge model

The properties of LRBs are shown in Table 1, and their nonlinear behavior is described by using the Bouc-Wen model (Wen, 1976).

Table 1 The properties of the LRB

Property	Value
Elastic stiffness, k_e(N/m)	3.571×10^7
Plastic stiffness, k_p(N/m)	3.139×10^6
Yield displacement of lead plugs, D_y(cm)	0.765
Design shear force level for the yielding of lead plugs, Q_d(kg)	2.540×10^4

The restoring force of the LRB is composed of the linear and nonlinear terms as

$$f_{LRB}(x_r, \dot{x}_r) = ak_e x_r + (1-a)k_e D_y \quad (1)$$

where K_e and α are the elastic stiffness and its contribution to restoring force, x_r and $\dot{x}_r$ are the relative displacement and velocity of nodes which LRBs are installed, respectively. And D_y and y are the yield displacement of the LRB and the variable, respectively, satisfying the following equation.

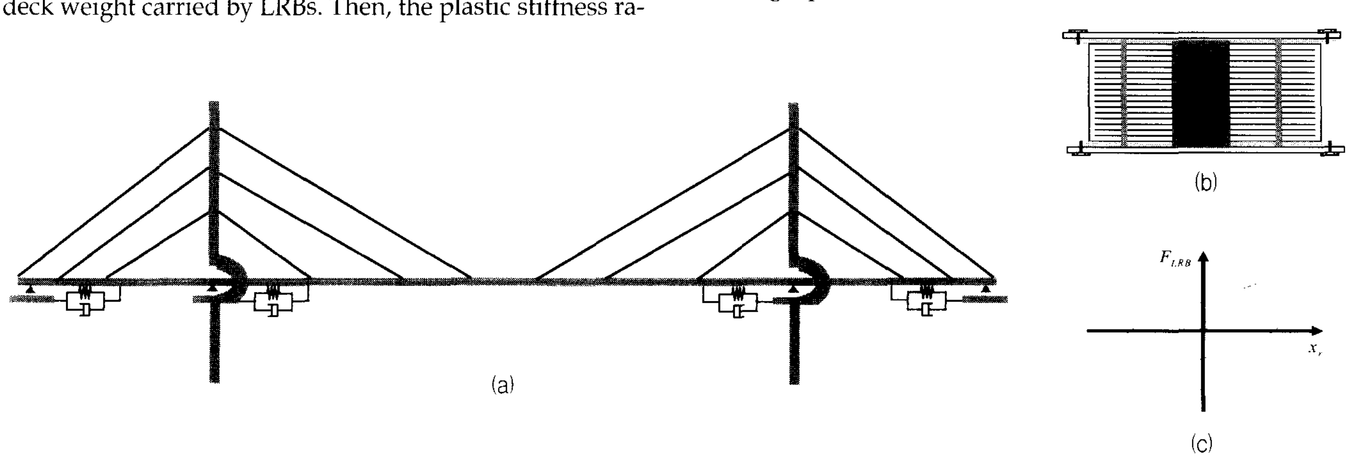


Fig 2 Schematic of the LRB installed bridge model

$$\dot{y} = \frac{1}{D_y}(A_i \dot{x}_r - \gamma|\dot{x}_r||y|^{n-1} - \beta\dot{x}_r|y|^n) \qquad (2)$$

where A_i, γ, β and n are the constant that affect the hysteretic behavior. The values of $A_i = n = 1$ and $\gamma = \beta = 0.5$ are used to simulate the characteristic curve of the LRB in this study. Finally, the equation describing the forces produced by LRBs is as follows

$$\mathbf{f}_{passive} = \mathbf{G}_{LRB} f_{LRB} = 3\mathbf{I}_{8\times8} f_{LRB} \qquad (3)$$

where $\mathbf{G}_{LRB}$ is the gain matrix to account for the number of LRBs. The block diagram of the base isolation system using LRB are shown in Fig 4.

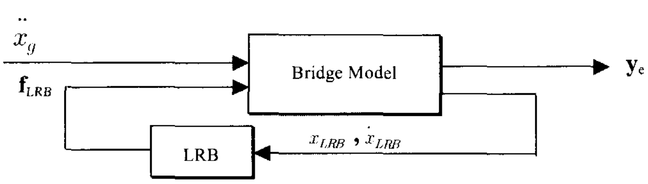


Fig 4. Block diagram of the LRB-installed base isolation system

3. Hybrid base isolation systems employing active/semiactive additional control devices

In LRB-based hybrid base isolation systems, various control devices can be used to additionally reduce the structural responses, especially the deck displacement (i.e., deformations of LRBs). In this section, two typical types of supplemental control devices such as active-type hydraulic actuators (HAs) and semiactive-type magnetorheological dampers (MRDs) are considered in combination with LRBs.

3.1. Active control device: hydraulic actuator(HA)

The first LRB-based hybrid seismic isolation system uses HAs. Active control devices such as HAs can enhance the effectiveness in structural response control. Furthermore, they have the relative insensitivity to site conditions and ground motions, the applicability to multi-hazard mitigation situations (i.e., for motion control against both strong wind and earthquakes), and the selectivity of control objectives (i.e., between the serviceability and safety of structures).

A total of 24 HAs, which are the same number and placement of devices as the sample control system in the benchmark problem[12], are placed at the deck-bent/pier connections (see Figs. 5 and 6). The actuator is assumed to have a capacity of 1000 kN without its dynamics. The active control forces produced by HAs are

$$\mathbf{f}_{active} = \mathbf{G}_{HA}\mathbf{f}_{HA} = \begin{bmatrix} 2\mathbf{I}_{2\times2} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & 4\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & 2\mathbf{I}_{2\times2} \end{bmatrix} \mathbf{f}_{HA} \qquad (4)$$

$$\mathbf{f}_{HA} = \mathbf{D}_{HA}\mathbf{u} = D_{HA}\mathbf{I}_{8\times8}\mathbf{u} \qquad (5)$$

where $\mathbf{G}_{HA}$ is the gain matrix to account for the number of HAs, D_{HA} is the gain of the relationship between the input voltage and the desired control force, and $\mathbf{u}$ is the control command input that is determined by control algorithm in Volts. The D/A is assumed to have a range of ±10 Volts, therefore the value of the D_{HA} is 100 kN/V (i.e., 10 Volts=1000 kN).

For feedback in the control algorithm, five accelerometers and four displacement sensors are used[12], as shown in Fig 5. Four accelerometers are located on top of the tower legs, and one is located on the deck at mid-span. Two displacement sensors are located at deck-pier 2 and deck-pier 3 connections, respectively. All sensor measurements are obtained in the longitudinal direction to the bridge.

This study employs a linear quadratic regulator (LQR) for state feedback gain, and a Kalman-Bucy filter estimator with process noise feed-through with the assumption that

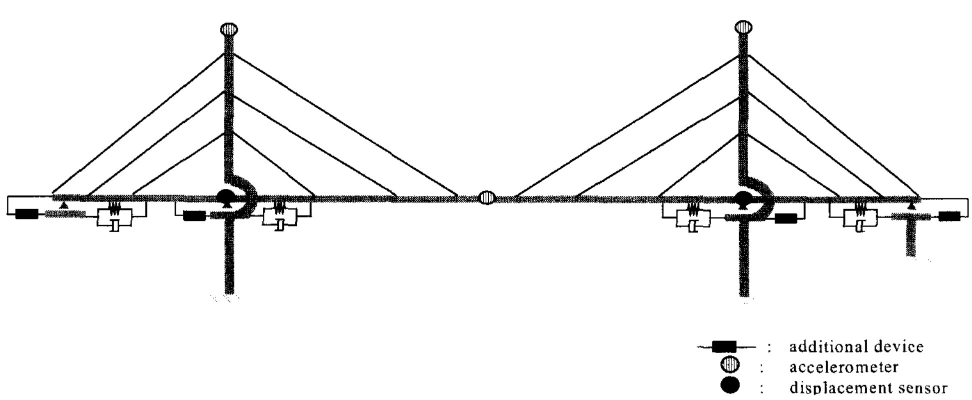


Fig 5 Schematic of the LRB-installed bridge model employing additional active/semiactive control devices and locations of devices and sensors

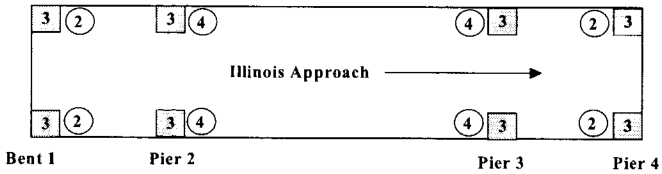


Fig 6 Configuration of additional devices in the hybrid base isolation system (□ LRBs; ○ HAs/MRDs)

the earthquake excitation, $\ddot{x}_g$, and sensor noise, $\mathbf{v}$, are stationary white noises. The control and observer gains are evaluated separately based on the separation principle.(13),(14) An infinite horizontal cost function is chosen as

$$J = \lim_{\tau\to\infty}\frac{1}{\tau}E\left[\int_0^\tau \left\{\left(\mathbf{C}_d^z\mathbf{x}_d + \mathbf{D}_d^z\mathbf{u}\right)^T\mathbf{Q}\left(\mathbf{C}_d^z\mathbf{x}_d + \mathbf{D}_d^z\mathbf{u}\right) + \mathbf{u}^T\mathbf{R}\mathbf{u}\right\}dt\right] \quad (6)$$

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 $S_{\ddot{x}_g\cdot\ddot{x}_g}/S_{v_iv_i} = \gamma = 25$, where $S_{\ddot{x}_g\cdot\ddot{x}_g}$ and $S_{v_iv_i}$ are the autospectral density function of the ground acceleration and measurement noise.

In the optimal control such as a LQG, obtaining the appropriate weighting parameters is very important to get well-performed controllers. In this study, the maximum response approach(10)-(11) is used to determine the optimal weighting matrix. The following combination and values of weighting parameters, which are used in Eq. (6), are obtained through the maximum response approach for the hybrid control systems.

- $\mathbf{Q}_{om\_dd} = \begin{bmatrix} q_{om}\mathbf{I}_{4\times4} & 0 \\ 0 & q_{dd}\mathbf{I}_{4\times4}\end{bmatrix}$, $q_{om} = 5\times10^{-9}, q_{dd} = 1\times10^{3}$.

The block diagram of the hybrid base isolation system employing active control devices such as hydraulic actuators (HA) are shown in Fig 7.

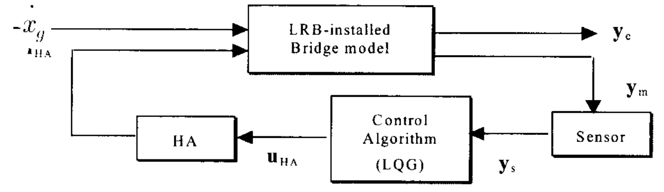


Fig 7 Block diagram of the hybrid base isolation system employing active control devices

3.2. Semiactive control device: magnetorheological damper (MRD)

The current level of active control devices was not ready to immediately apply to disaster mitigation strategies for severe earthquakes.(15) To enhance the safety of structures against severe earthquake, more advanced active control strategies with the principle of less energy and better performance should be urgently developed. On the other hand, semiactive control devices (e.g. variable orifice dampers, variable friction dampers, controllable fluid dampers, etc.) only require small power and do not have the potential to destabilize the structural system in the bounded-input, bounded-output sense. Therefore, the second hybrid seismic isolation system employs MRDs instead of HAs.

A total of 24 MRDs are considered in this section. The configuration and capacity of MRD are the same as those of HA. Similar to HA, the dynamics of MRD are neglected. In addition to 18 accelerometers and displacement sensors, 24 force transducers are installed in the integral parts of the damper unit to measure the damper forces applied to the structure for the clipped optimal algorithm.

The control scheme of a clipped-optimal control algorithm(16),(17) for seismic protection of bridges using MRD 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 MRD to generate the desired active control force, so long as this force is dissipative.

For the primary controller, a LQG control algorithm explained in 3.1 is adopted, and for the general smart damping device, the secondary control strategy is given by

$$f_{sa,i} = \begin{cases} f_{sa,i}, & f_{a,i}\cdot\dot{x}_{dev} \\ 0, & otherwise\end{cases} \quad (7)$$

where $f_{sa,i}$ is the control force of the ith semiactive damper, $f_{a,i}$ is the "desired" control force of the ith device, and $\dot{x}_{dev}$ is the velocity across the ith damper. Since the device is assumed to be "ideal" in this study, the control force given by Equation (7) can be replaced as follows:

$$u_{sa,i} = \begin{cases} u_{sa,i}, & u_{a,i}\cdot\dot{x}_{dev} \\ 0, & otherwise\end{cases} \quad (8)$$

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

The appropriate optimal weighting matrices of the semiactive control and hybrid control (LRB+MRD) systems are obtained by the maximum response approach similar to the previous hybrid seismic isolation (LRB+HA) system.

The appropriate response-weighting matrix in the semi-active control system is the same as that in the active control system, because the primary controller of the clipped-optimal control algorithm is the LQG control algorithm.

$$\mathbf{Q}_{om,dd} = \begin{bmatrix} q_{om}\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & q_{dd}\mathbf{I}_{4\times4} \end{bmatrix}, \quad q_{om} = 5\times10^{-9}, q_{dd} = 1\times10^{3}.$$

The block diagram of the hybrid base isolation system employing semiactive control devices such as magnetorheological dampers (MRDs) are shown in Fig 8.

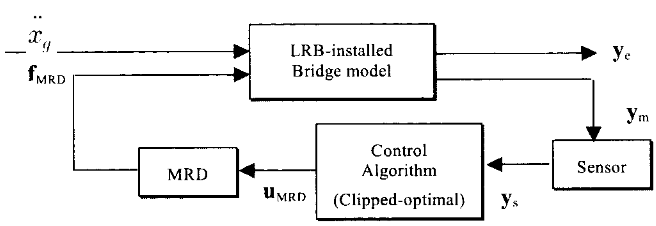
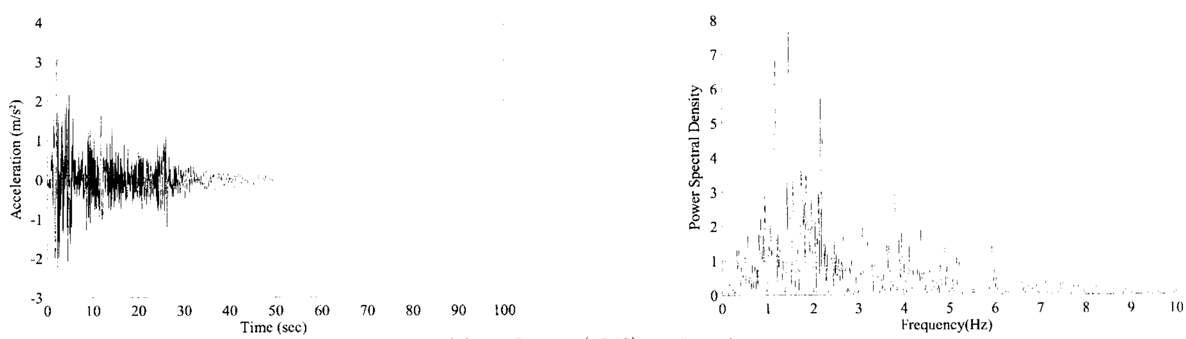


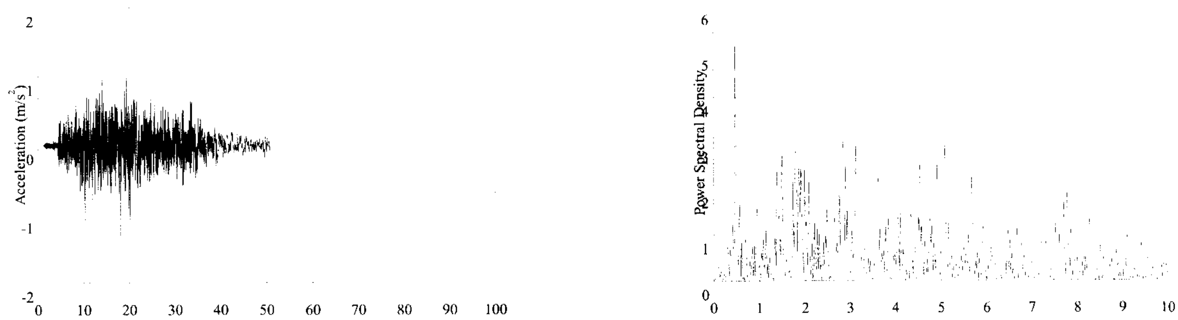
Fig 8 Block diagram of the hybrid base isolation system employing semiactive control devices

4. Numerical simulations

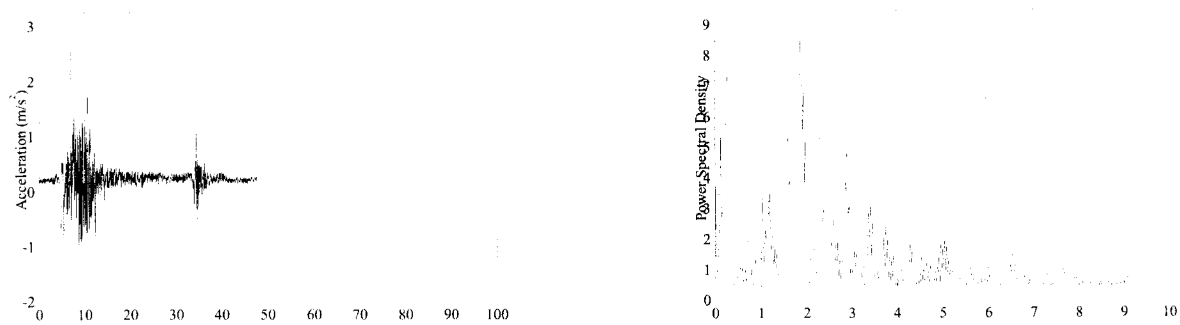
A set of numerical simulations is performed in MATLAB[(R)] to verify the effectiveness and robustness of the two LRB-based hybrid base isolation systems using active/semiactive control devices. Simulation results of the proposed hybrid systems are compared with the basic base isolation system employing LRB. To do this, the following three historical earthquake records are considered as ground excitations. First, the Mexico City earthquake (1985, peak ground acceleration (PGA): 0.14g) is selected because geological studies have indicated that the Cape Girardeau region, in which bridge is constructed, is similar to Mexico City. The El Centro (1940, PGA: 0.35g) and Turkey Gebze (1999, PGA: 0.27g) earthquakes are selected to test proposed control strategies on earthquakes with different characteristics. These three earthquakes are each at or below the design PGA level of 0.36g for the bridge. The time-history of the ground acceleration and power spectral density in each earthquake are shown in Fig 9.



(a) El Centro (1940) earthquake



(b) Mexico City (1985) earthquake



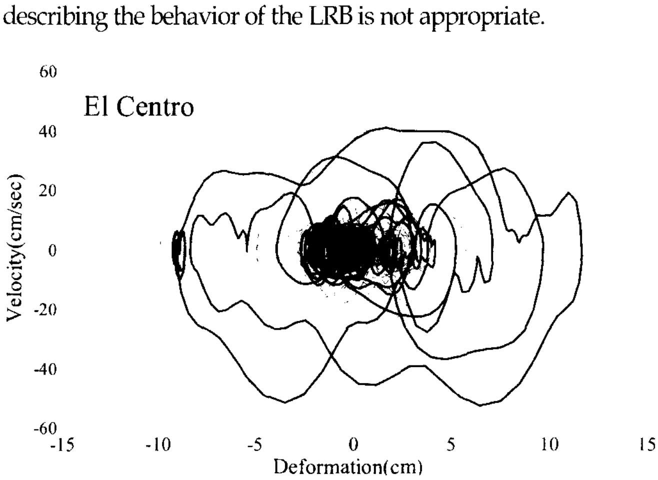
(c) Gebze (1999) earthquake

Fig 9. Time history and power spectral density of earthquakes

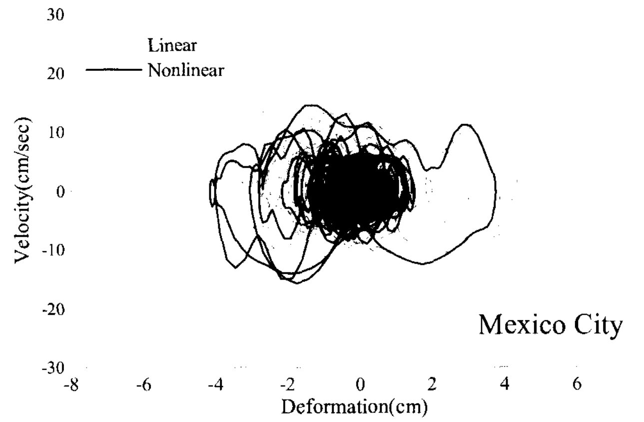
For cable-stayed bridges subjected to seismic excitation, critical responses are related to the structural integrity of the bridge rather than to serviceability issues. Among the responses, the following are defined as most critical: i) shears and bending moments at the deck level of tower, and ii) overturning moments at the tower supports. The vertical displacements of the bridges are not important in general, however it should be noted that based on design considerations, the deck should not move more than 30 cm relative to bent 1 or pier 4 in the longitudinal direction in order to ensure that the deck will not disintegrate from its end connections.[18] Therefore, 18 criteria have been defined[12] to evaluate the capabilities of each proposed control system. Among these 18 evaluation criteria, only the first six evaluation criteria related maximum structural responses are considered in this study (i.e., the peak base shear (J_1), the peak shear at deck level (J_2), the peak overturning moment (J_3), the peak moment at deck level (J_4), the peak cable tension (J_5), and the peak deck displacement at bent 1 and pier 4 (J_6)). A detailed description of the benchmark control problem for cable-stayed bridges including the bridge model and evaluation criteria can be found in Dyke et al. [12]

4.1. Results in the case of the passive base isolation system (i.e., LRB installed bridge)

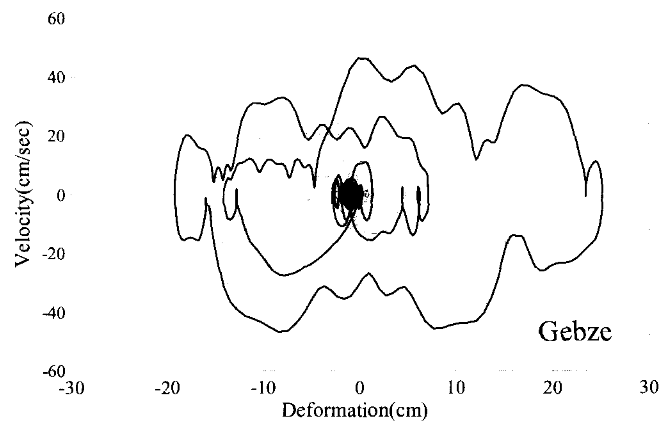
In this study, before the analyses in the cases of the hybrid base isolation systems employing active/semiactive control devices are carried out, the analysis in the case of the passive base isolation system are performed. The numerical simulation results from the linearized model of the LRB (i.e., by using the effective stiffness of the LRB) are compared with those from the nonlinear model (i.e., by using Bouc-Wen hysteresis model) to verify the necessity of the nonlinear model, as shown in Fig 10 and Table 2. Fig 10 shows the deformation of the LRB as well as the velocity in the linear model is quite different from that in the nonlinear model. This means that the linearized model for describing the behavior of the LRB is not appropriate.



(a) El Centro



(b) Mexico City



(c) Gebze

Fig 10 Velocity vs. deformation of the LRB at pier 2 with by linear and nonlinear models

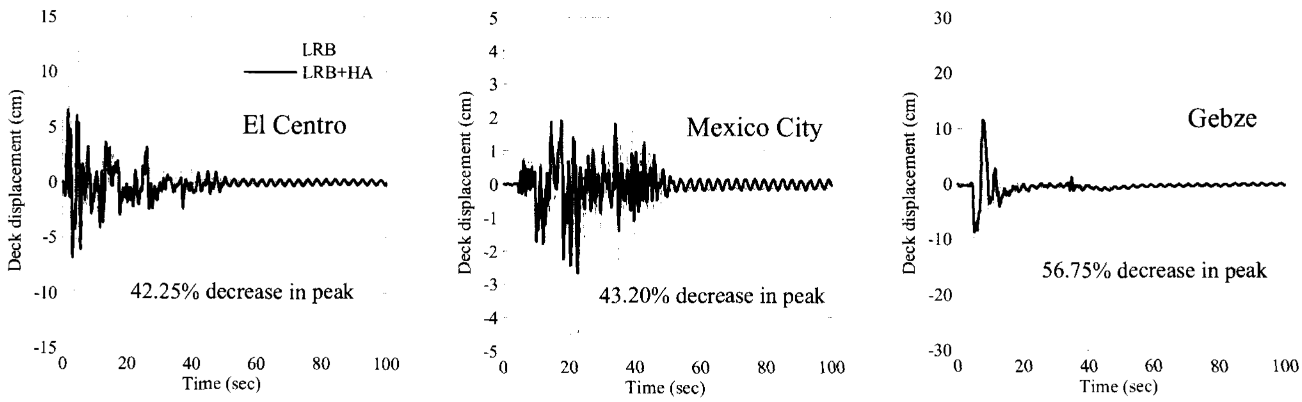
Table 2 also shows the evaluation criteria with linear and nonlinear LRB models. As seen from the table, most of the values in the linear case are slightly larger than those in the nonlinear case, especially in the case of the Mexico City earthquake. In other words, if the linear model is used for the LRB-installed system, the results could be overestimated up to 53% .

4.2. Control performances

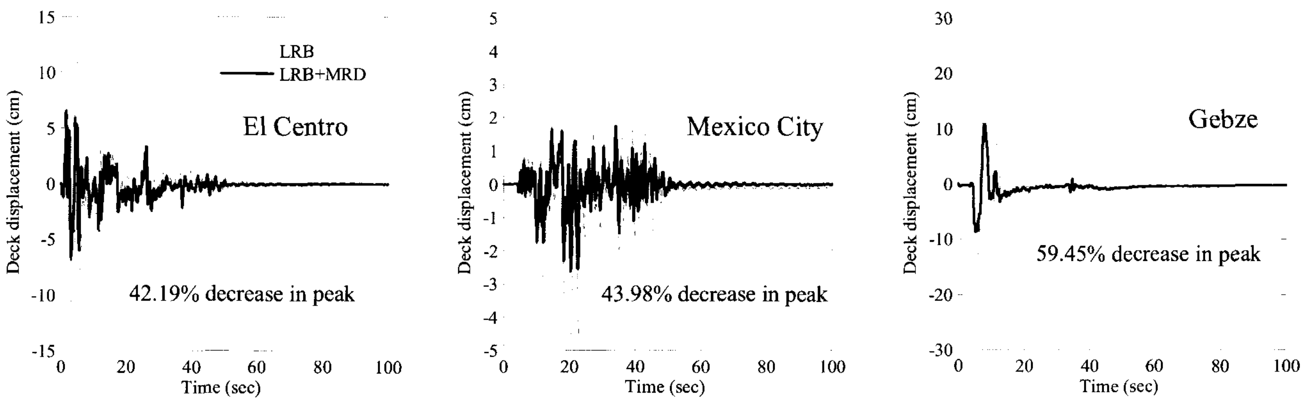
Figs 11 and 12 show the deck displacement and base shear force records at pier 2 in the LRB case and the LRB+HA and LRB+MRD cases, respectively. As shown in Fig 11, the additionally controlled systems (i.e., the LRB-based hybrid cases) significantly reduce the deck displacement than the basic isolation system (i.e., the LRB case) (i.e., 42% ~ 77% reduction in peak responses). On the other hand, Fig 12 indicates that the increase of the base shear force due to the additional control device is not significant in all the hybrid control systems. These figures clearly show the efficacy of the additional control devices in the LRB-based isolation system.

Table 2 Evaluation criteria with linear and nonlinear LRB models

Criterion	Earthquake	Linear	Nonlinear	Deviation (%)
J_1 peak base shear	El Centro	0.4187	0.3967	5.26
	Mexico	0.4895	0.5459	11.53
	Gebze	0.4746	0.4230	10.88
J_2 peak shear at deck level	El Centro	1.1640	1.1846	1.77
	Mexico	1.3545	1.1097	18.07
	Gebze	1.5291	1.4616	4.41
J_3 peak overturning mom.	El Centro	0.3393	0.3054	10.00
	Mexico	0.6593	0.6188	6.15
	Gebze	0.5550	0.5012	9.69
J_4 peak mom. at deck level	El Centro	0.6613	0.6077	8.11
	Mexico	0.7117	0.4468	37.22
	Gebze	1.4425	1.2656	12.26
J_5 peak dev. of cable tension	El Centro	0.2085	0.2077	0.36
	Mexico	8.735e-2	4.877e-2	44.17
	Gebze	0.1693	0.1589	6.17
J_6 peak deck displacement	El Centro	1.7361	1.4250	17.92
	Mexico	3.1738	2.0197	36.36
	Gebze	4.1946	3.8289	8.72
J_7 normed base shear	El Centro	0.2305	0.2304	0.03
	Mexico	0.3922	0.4211	7.39
	Gebze	0.3580	0.3340	6.71
J_8 normed shear at deck level	El Centro	1.1801	1.0909	7.56
	Mexico	1.2059	0.9634	20.11
	Gebze	1.4992	1.5502	3.41
J_9 normed overturning mom.	El Centro	0.2892	0.2473	14.49
	Mexico	0.4870	0.3989	18.08
	Gebze	0.5704	0.4815	15.60
J_{10} normed mom. at deck level	El Centro	0.9077	0.7128	21.47
	Mexico	1.2085	0.6536	45.91
	Gebze	1.6499	1.4429	12.55
J_{11} normed dev. of cable tension	El Centro	2.910e-2	2.233e-2	23.27
	Mexico	1.105e-2	5.180e-3	53.13
	Gebze	1.959e-2	1.713e-2	12.56
J_{12} peak control force	El Centro	1.523e-3	1.344e-3	11.80
	Mexico	6.792e-4	7.763e-4	14.30
	Gebze	2.470e-3	2.161e-3	12.52
J_{13} peak stroke	El Centro	1.1399	0.9356	17.92
	Mexico	1.5983	1.0171	36.36
	Gebze	2.2998	2.0993	8.72

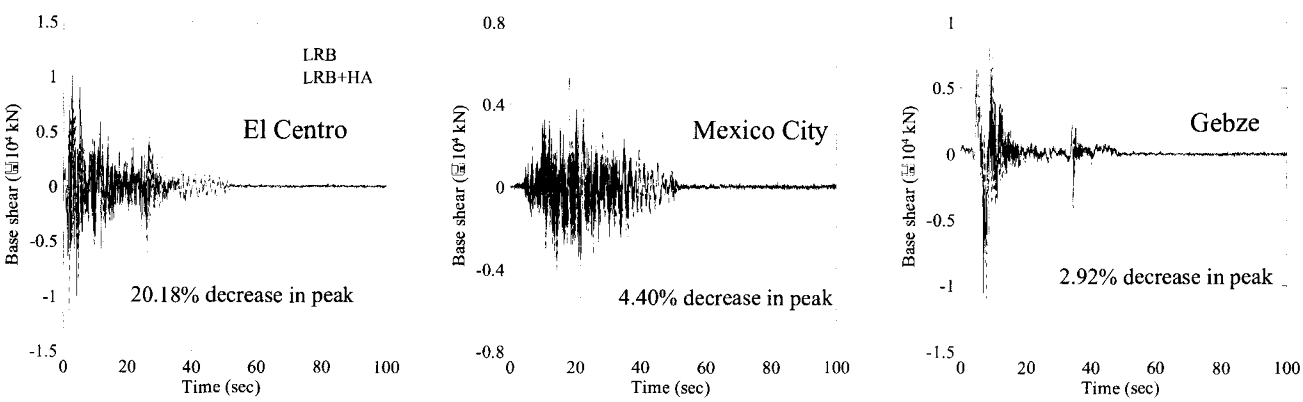


(a) LRB+HA

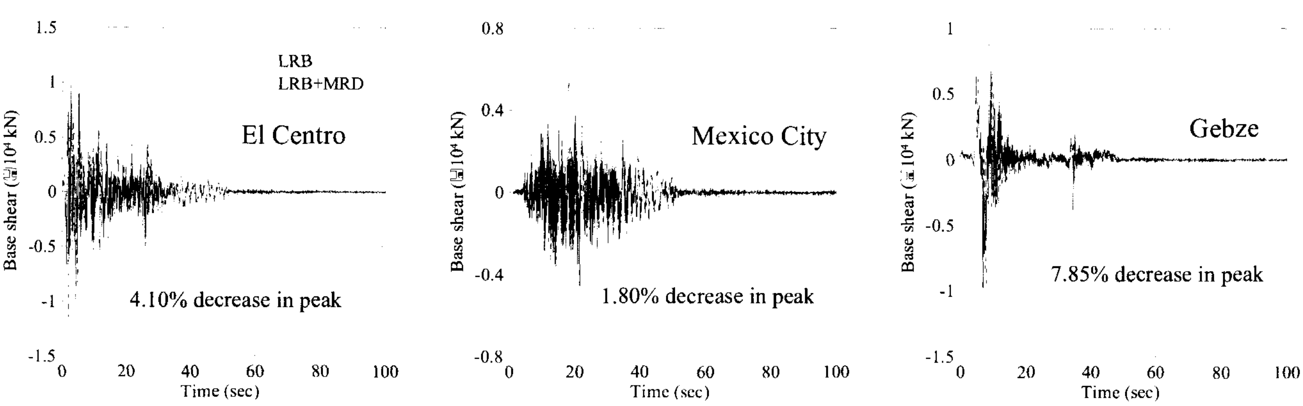


(b) LRB+MRD

Fig 11 Deck displacement records of pier 2 with LRB and hybrid control system

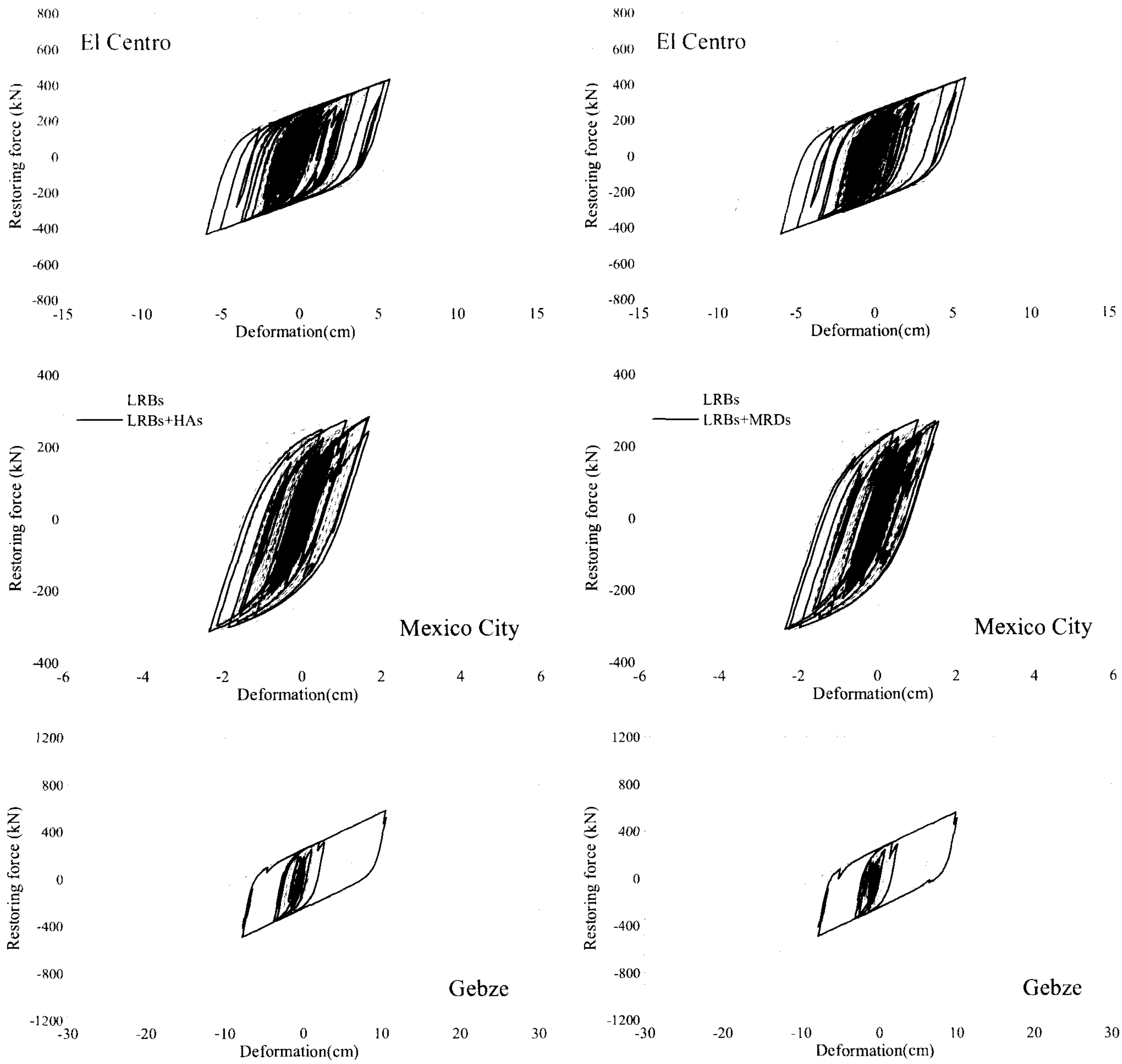


(a) LRB+HA



(b) LRB+MRD

Fig 12. Base shear records of pier 2 with LRB and hybrid control system

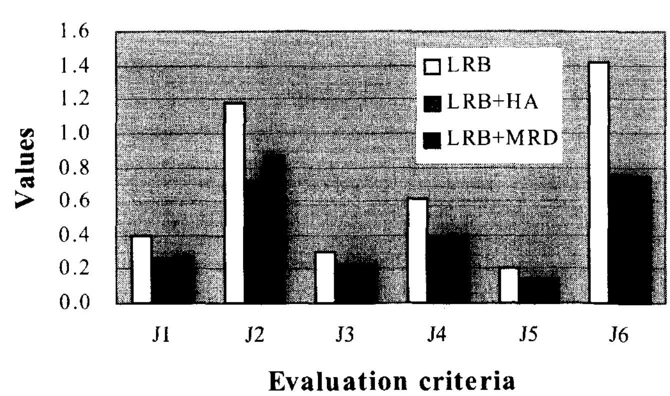


(a) additional active devices (b) additional semiactive devices

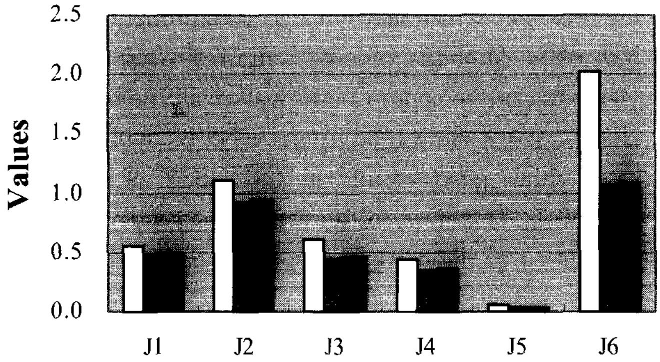
Fig 13. Restoring force vs. deformation of the LRB at pier 2 in hybrid control systems

The deck displacements of the structure with LRBs are larger than the other control systems. However, the increased deck displacements are still less than the allowable displacement (30cm) and are decreased by the additional active/semiactive devices in the hybrid base isolation systems, as shown in Fig 13. The figure also shows that the additional active/semiactive control devices reduce the deformation of the LRB significantly.

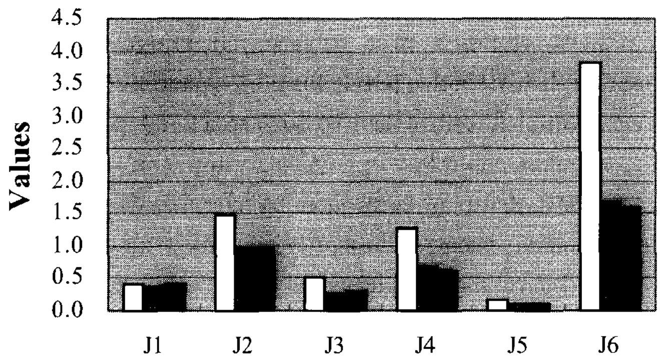
Fig 14 shows the values of six evaluation criteria related to maximum structural responses for each earthquake and Table 3 represents the maximum values of six evaluation criteria for all the three earthquakes. Tension in the stay cables remains within a recommended range of allowable values[12] for all the considered control systems.



(a) El Centro Earthquake



(b) Mexico City Earthquake



(c) Turkey Gebze earthquake

Fig 14 Evaluation criteria related to maximum structural responses for each earthquake

Table 3 Maximum evaluation criteria for all the three earthquakes

Criterion	LRB	LRB+HA	LRB+MRD
J_1 peak base shear	0.5459	0.4841	0.4991
J_2 peak shear at deck level	1.4616	0.9476	0.9545
J_3 peak overturning mom.	0.6188	0.4444	0.4592
J_4 peak mom. at deck level	1.2656	0.6750	0.6131
J_5 peak dev. of cable tension	0.2077	0.1468	0.1501
J_6 peak deck displacement	3.8289	1.6702	1.5814

In the figure and the table, it is demonstrated that the overall performances of LRB-based hybrid seismic isolation systems are better than that of passive seismic isolation system employing LRB only, especially, the responses at the deck level (i.e., J_2 and J_4) and the deck displacement (J_6). These results are because of the multiple control action of the LRB and other supplementary control devices (i.e., HA, and MRD). Moreover, it is verified from the figure and the table that all the three LRB-based hybrid control systems show the similar overall performance.

The actuator requirements, i.e., maximum control force, stroke and velocity, of all the considered control systems satisfy the criteria provided by Dyke et al.[12] as shown in Table 4.

Table 4 Additional control device requirements for control systems

Earthquake	Max.	LRB+LD	LRB+HA	LRB+MRD
El Centro	Force (kN)	1000	1000	1000
	Stroke (m)	0.526	0.0735	0.0723
	Vel. (m/s)	0.4818	0.5332	0.5339
Mexico City	Force (kN)	509	398	408
	Stroke (m)	0.0192	0.0262	0.0266
	Vel. (m/s)	0.0925	0.2096	0.1702
Gebze	Force (kN)	1000	920	901
	Stroke (m)	0.0615	0.1201	0.1137
	Vel. (m/s)	0.4034	0.4219	0.4577

4.3. Controller robustness

The evaluation model with the hybrid seismic isolation system produces desirable results based on the performance criteria set by Dyke et al.[12] It is expected that the same controller should also have good performance when it will be connected to the real bridge. However, the dynamics of the real bridge may not be expected to be identical to the evaluation model. Even if the proposed control system shows good performance in the evaluation model, it does not necessarily mean that it yields good performance in the actual bridge, too. Therefore, the robustness of the proposed hybrid seismic isolation systems is investigated with respect to the uncertainties of the stiffness parameter.

The stiffness matrix is perturbed by a small amount, and the resulting bridge model is simulated with the controller designed for the nominal system. The resulting perturbed stiffness is calculated as

$$\mathbf{K}_{pert} = \mathbf{K}(1+\delta) \tag{11}$$

where $\mathbf{K}$ is the nominal stiffness of the bridge, which is used in the formulation of the evaluation model and for which the controller is designed, δ is the perturbation amount, and $\mathbf{K}_{pert}$ is the perturbed stiffness matrix. The stiffness matrix is perturbed ±5, ±10, ±15 and ±20% in this study. The maximum value of variations of evaluation criteria related to the maximum structural responses (i.e., J_1 ~J_6) for the ±5, ±10, ±15 and ±20 % stiffness perturbed systems for all three earthquakes are shown in Fig 15.

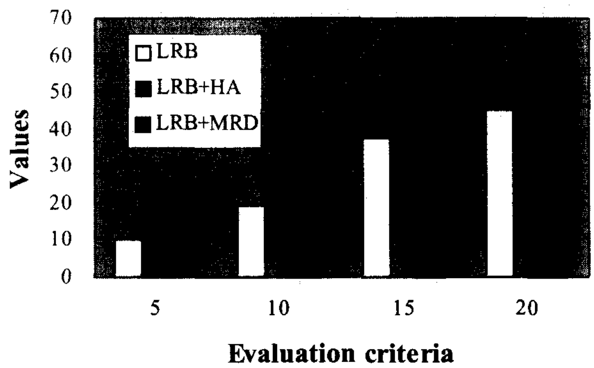


Fig 15 Maximum value of variation for ±5, ±10, ±15 and ±20 % stiffness perturbed systems for all the three earthquakes (If the maximum value is greater than 100 %, then the results are not presented.)

The control performance of the active additional control device (i.e., HA) is good as explained in 4.2, however it may cause the controller robustness problem as shown in Fig 15. The maximum value of variation is greater than 100% even for ±10% stiffness perturbed system. This indicates that the LRB-based hybrid control system employing HA may not work in the real applications. On the other hand, passive and semiactive additional control devices (i.e., MRD) have the good controller robustness. Although the maximum value of variation of the hybrid control systems employing MRD is relatively large for small amount of stiffness perturbations (i.e., ±5 and ±10%) compared with the LRB case, these values are generally maintained to large amount of stiffness perturbations (i.e., ±15 and ±20%). For ±20% stiffness perturbed system, the value is somewhat increased in the LRB+MRD. Table 5 shows the maximum variation of evaluation criteria related to maximum structural responses for all three earthquakes with ±5% stiffness perturbation.

Table 5 Maximum variation of evaluation criteria related to structural responses for a all three earthquakes (±5% stiffness perturbed case, %)

Criterion		LRB	LRB+HA	LRB+MRD
J_1	peak base shear	7.98	9.75	8.66
J_2	peak shear at deck level	2.54	16.62	14.65
J_3	peak overturning mom.	5.97	4.46	14.83
J_4	peak mom. at deck level	5.70	13.08	2.49
J_5	peak dev. of cable tension	10.07	7.51	9.68
J_6	peak deck displacement	1.59	50.00	1.42

As shown in Table 5, the controller robustness of all the hybrid seismic isolation systems is quite good except for J_6 -peak deck displacement in the LRB+HA case. Furthermore, the LRB+MRD case shows the similar robustness to the LRB case, which may have good controller robustness because it combines passive control devices. From the viewpoint of the control performance, all the hybrid isolation systems show good results, whereas the LRB+MRD cases show good results in the aspect of controller robustness. Therefore, the semiactive control device can be considered as the more appropriate additional one than the active device.

5. Conclusions

The extensive comparative study of the LRB-based hybrid seismic isolation systems for mitigating earthquake-induced vibration of a cable-stayed bridge has been accomplished. In this paper, the performances of two typical additional control devices, such as active-type hydraulic actuators controlled by LQG algorithm and semiactive-type MR dampers controlled by clipped-optimal algorithm, have been preliminarily evaluated for the ASCE phase I benchmark cable-stayed bridge problem. It shows from the numerical simulation results that all the LRB-based hybrid seismic isolation systems considered are quite effective to mitigate the structural responses. In addition, the numerical results demonstrate that the LRB-based hybrid seismic isolation systems employing MRDs have the robustness to some degree of the stiffness uncertainty of in the structure, whereas the hybrid system employing HAs does not. Therefore, the feasibility of the hybrid base isolation systems employing passive or semiactive additional control devices could be more appropriate in realfor full-scale civil infrastructure applications is clearly verified due to their efficacy and robustness.

Acknowledgements

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