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APPLICATION OF HDR DAMPERS IN SEISMIC PROTECTION OF LRB-CONTROLLED CABLE-STAYED BRIDGES

B. Asgari[1], S. A. Osman[2], and A. Azlan[3]

ABSTRACT

Cable-stayed bridges have been developing rapidly in recent years, and become one of the most popular types of bridges for long spans length to 1000 m or even longer. Despite all the advantages, there have been several concerns over the use of cable-stayed bridges. Cable-stayed bridges are normally sensitive to dynamic loadings such as earthquakes. Moreover, cable-stayed bridges possess very low inherent damping (usually less than 5% of critical) that may not always be enough to help alleviate vibration under severe ground motions. The results of previous studies show that the application of lead rubber bearings (LRBs) is an effective solution in controlling earthquake-induced forces of cable-stayed bridges. However, the application of LRBs increase the seismic responses of the deck, notably deck displacements. Regarding the cost efficiency and high damping properties of high damping rubber (HDR) materials, this study investigates the performance of HDR dampers as supplemental seismic control devices for LRB-controlled cable-stayed bridges. The results of time history analysis show that the HDR dampers successfully improve the seismic responses in LRB-controlled cable-stayed bridges.

[1]Research assistant, Dept. of Civil & Structural Engineering, Universiti Kebangsaan Malaysia, Bangi, 43000
[2]Assoc. Professor, Dept. of Civil & Structural Engineering, Universiti Kebangsaan Malaysia, Bangi, 43000
[3]Professor, Dept. of Civil & Structural Engineering, Technology University of Malaysia, Johor, 46300

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Cable-stayed bridges have been developing rapidly in recent years, and become one of the most popular types of bridges for long spans length to 1000 m or even longer. Despite all the advantages, there have been several concerns over the use of cable-stayed bridges. Cable-stayed bridges are normally sensitive to dynamic loadings such as earthquakes. Moreover, cable-stayed bridges possess very low inherent damping (usually less than 5% of critical) that may not always be enough to help alleviate vibration under severe ground motions. The results of previous studies show that the application of lead rubber bearings (LRBs) is an effective solution in controlling earthquake-induced forces of cable-stayed bridges. However, the application of LRBs increases the seismic responses of the deck, notably deck displacements. Regarding the cost efficiency and high damping properties of high damping rubber (HDR) materials, this study investigates the performance of HDR dampers as supplemental seismic control devices for LRB-controlled cable-stayed bridges. The design data of Tatara Bridge in Japan is considered for numerical studies. The results of time history analysis show that the HDR dampers successfully improve the seismic responses in LRB-controlled cable-stayed bridges.

Introduction

For many years, engineering communities have made an effort to control the earthquake input energy in structures and thus to mitigate their structural response to the ground motions. Innovative isolation systems and supplemental energy dissipation devices have been developed as seismic control techniques, and they are economical alternatives to traditional earthquake control methods. The effectiveness of the control devices and their applications to structures have been investigated in past research works [1-5]. Several types of isolation and supplemental damping systems, including passive, semi-active and active control devices, have been developed widely for the seismic design of buildings and bridges in recent decades [6-11].

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[1]Research assistant, Dept. of Civil & Structural Engineering, National University of Malaysia, Bangi, 43000
[2]Assoc. Professor, Dept. of Civil & Structural Engineering, National University of Malaysia, Bangi, 43000
[3]Proffesor, Dept. of Civil & Structural Engineering, Technology University of Malaysia, Johor, 46300

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Cable-stayed bridges are highly vulnerable to strong seismic excitations due to their low damping and flexibility. This fact introduces new challenges to the engineering community in terms of seeking and developing new technologies to improve the performance of cable-stayed bridges under strong earthquakes. Due to the sensitivity of cable-stayed bridges to the dynamic loading, the application of control devices is a promising way to mitigate the vibration caused by natural disasters such as earthquakes.

The lead rubber bearings (LRBs) with high inherent damping properties were invented by Robinson [12] in New Zealand and have been widely used as isolation systems for bridges throughout the world. Ali and Abdel-Ghaffar [13, 14] were among the first to propose LRBs as seismic control systems for cable-stayed bridges. Their studies showed that the application of LRBs significantly reduces the moments at the pier-foundation and deck-cable connections while transmitting less force to the abutment. More recently, different studies have discussed the effect of LRB devices on the seismic response of cable-stayed bridges [15-18]. A comparison of the seismic isolation systems indicates that LRBs have more consistent performance and are more effective compared to other isolators in controlling earthquake-induced forces on cable-stayed bridges [19]. However, the application of LRBs increases the seismic responses of the deck, particularly the deck displacement [19-21]. The application of LRB-based hybrid control systems is an effective strategy to control the seismic-induced responses of cable-stayed bridges [21, 22].

The high damping rubbers (HDR) with good load-bearing ability and damping characteristics, in which the rubber composition is changed to provide high damping properties, have been applied successfully to mitigate seismic effects on structures [23]. The HDR dampers are investigated in this study as supplemental dissipating devices for seismic control of LRB-controlled cable-stayed bridges. A comparative study is applied to compare the seismic responses of the LRB-controlled and hybrid-controlled cable-stayed bridge. The design data of Tatara Bridge in Japan, with 890m main span, is considered for numerical studies conducted in ANSYS software through Finite Element (FE) method. The parametric study is applied to investigate the effect of variation in damping of HDR dampers on the seismic responses of the controlled cable-stayed bridge.

The proposed hybrid control strategy offers significant potential for future application of seismic control systems. The results of the study are beneficial for the seismic control design and retrofitting of cable-stayed bridges.

Numerical Study

A detailed FE model of a long-span cable-stayed bridge is developed in this study for numerical studies. The geometry and details of the modeled bridge are based on the design data of the Tatara Bridge in Japan. The bridge has a total length of 1480 m, with a centre span of 890 m. Figure 1 shows the general arrangement of the Tatara Bridge.

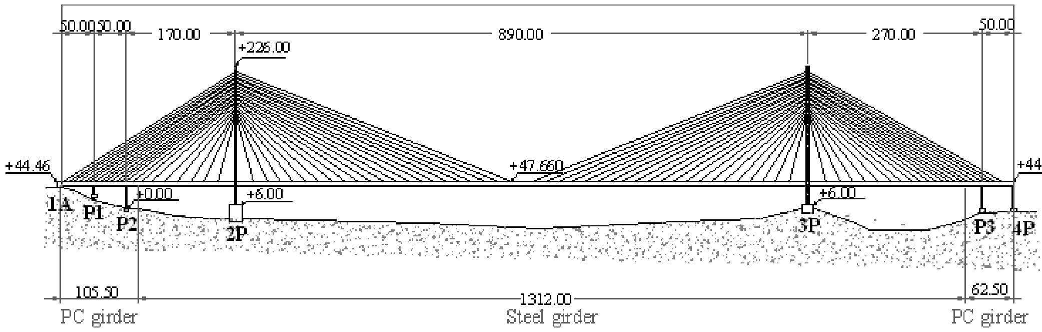


Figure. 1. General arrangement of the Tatara cable-stayed bridge

To establish an accurate FE model, a full 3-D model of the cable-stayed bridge in ANSYS [24] is implemented using elastic beam elements and link elements. Table 1 shows the applied properties of the Tatara Bridge's structural members in FE model.

Table 1
Structural Properties of the simulated bridge

Structural members	Element type	Material	E(MPa)
Tower	BEAM4, BEAM44	Steel	2.10×10^5
Girder	BEAM4	Steel Concrete	2.10×10^5 3.00×10^4
Cable	Link10	Steel	2.00×10^5

The natural frequencies and mode shapes of the bridge are first calculated starting from deformed configuration under dead loads. To evaluate the seismic response of the uncontrolled bridge, the bridge deck is assumed to be restrained longitudinally to the main piers. The first ten natural frequencies of this configuration are 0.1326, 0.2186, 0.2780, 0.3204, 0.3650, 0.3728, 0.4217, 0.4337, 0.5090 and 0.5429 Hz.

Modeling the LRB Isolators

The equivalent bilinear model [25] is applied to model the dynamic behavior of LRB bearings. The equivalent viscous damping of the system is determined to be 20% in primary study (ξ=0.2). The 3 sec isolation time period is considered for design of LRBs. To avoid the introduction of artificial viscous damping in the isolation system, Rayleigh damping is not included in the modeling of the LRBs. The post-yielding stiffness of the LRBs is considered to be one tenth of the initial elastic stiffness (α=10). Six LRB bearings are applied in each connection of the main span (P2, 2P, 3P, and P3 in Figure. 1, to reduce seismic forces and to absorb large amounts of seismic energy. The LRB isolators are modeled using COMBIN39 and COMBIN40 spring elements [24]. The COMBIN40 spring elements are used to model the isolator behavior in the vertical direction, and the equivalent bilinear behavior of the LRBs in the two longitudinal directions is modeled using COMBIN39 elements, which simulate the hysteresis effects in LRB isolators.

Modeling the HDR Dampers

The analytical model of the HDR dampers is not described in existing codes and regulations. However, the nonlinear force-displacement relationship of HDR control systems is generally modeled using equivalent linear behavior in technical codes and specifications [25-27]. The linear restoring force of the control system (F_b) in the equivalent linear model is defined as Eq. 1 [25]:

$$F_b = k_b x_b + c_b \dot{x}_b \qquad (1)$$

where c_b and k_b are the effective damping and stiffness of the isolation system, respectively; and x_b and $\dot{x}_b$ are the displacement and the velocity of the device, respectively.

The isolation time-period (T_b) and damping ratio (ξ_b) can be defined as Eq. 2 and Eq. 3:

$$T_b = 2\pi\sqrt{\frac{M}{k_b}} \qquad (2)$$

$$\xi_b = \frac{c_b}{2M\omega_b} \qquad (3)$$

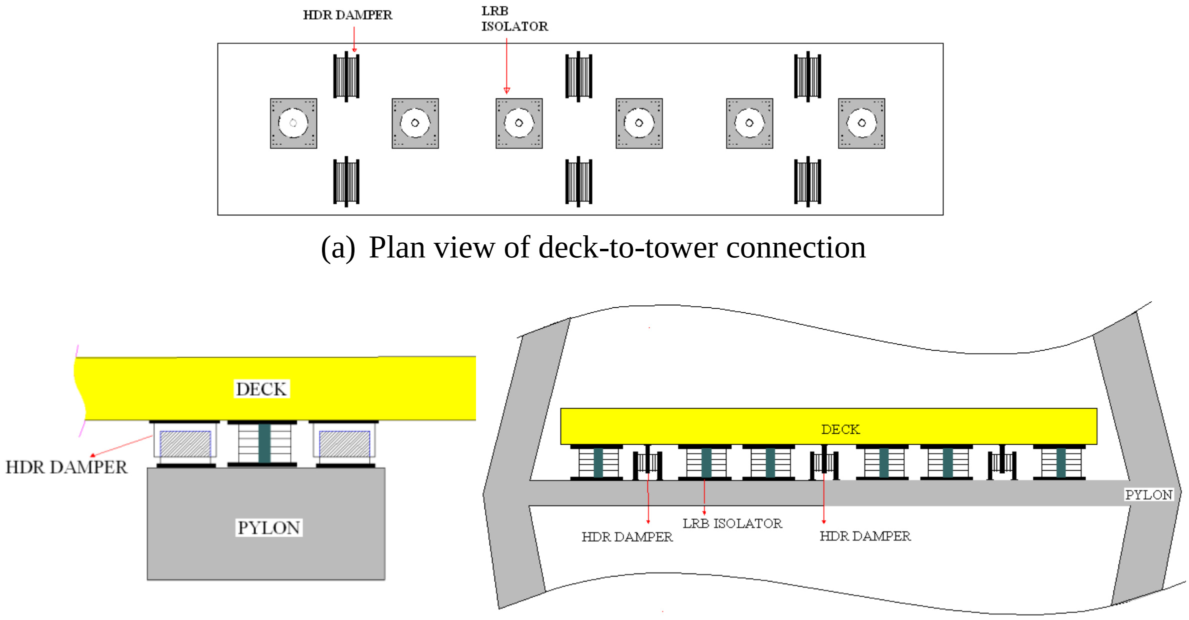
where M is the mass of the structure, and ω_b is the isolation natural frequency. The equivalent linear elastic stiffness of each loading cycle (k) can be calculated from the force-displacement curve of the isolator as Eq. 4:

$$k = \frac{F^{+} - F^{-}}{\Delta^{+} - \Delta^{-}} \quad (4)$$

where F^{+} and F^{-} are the positive and negative forces of the test displacements Δ^{+} and Δ^{-}, respectively. The equivalent linear model has been applied to model HDR bearings in several studies [19, 29, and 30].

An equivalent linear model 18% damping ratio (ξ) as the maximum practical amount of damping and 3 (sec) designed time period (T) are used to model the behavior of the HDR dampers.

The HDR dampers are applied in the deck-to-tower connections to further mitigate the seismic responses of the bridge, especially for deck displacement. Six HDR dampers are applied in each deck-to-tower connection (2P and 3P in Fig. 1) to provide stiffness and damping. The COMBIN14 spring-damper elements are used to model the equivalent stiffness and damping of the HDR dampers. A schematic of the hybrid control system is provided in Fig. 2.



(a) Plan view of deck-to-tower connection

(b) Elevation view

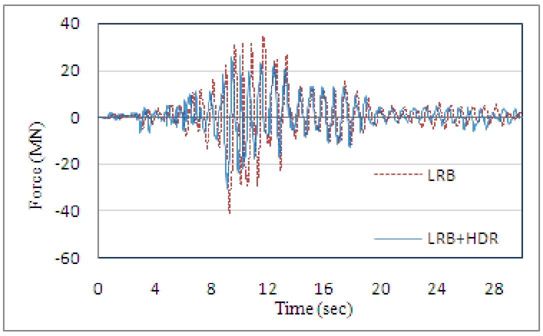
(c) Transverse view

Figure. 2. Overview of the hybrid control system applied in deck-to-tower connection

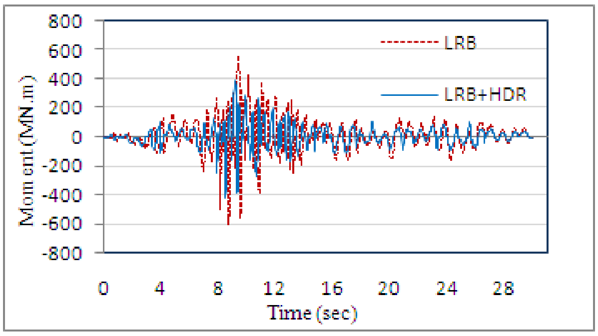
Seismic analysis of the controlled bridge

The seismic response of the simulated cable-stayed bridge is investigated through a time history analysis in the longitudinal direction using the 1995 Kobe earthquake (GPA=0.821g) and the 1940 Imperial Valley earthquake (GPA=0.341g) records. In the numerical study, 30 (sec) of each earthquake record is considered to investigate the seismic performance of the bridge. A 0.02 sec of time step is used for the Kobe earthquake, and a 0.01 sec of time step is used for the Imperial Valley earthquake [31]. The Newmark's constant average acceleration (β=1/4) integration of the equations of motion is used in numerical study using the ANSYS commercial program.

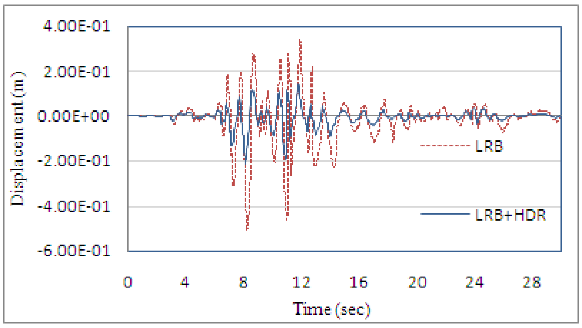
Fig. 3 provide the comparison between the time histories of the tower base shear, tower base moment, and deck displacement responses for the LRB-controlled bridge and the controlled bridge with the hybrid system (LRB+HDR) under the longitudinal components of the Kobe earthquake. It can be observed from Fig. 3 that the maximum tower base shear of the LRB-controlled bridge with HDR dampers is reduced to 30.60 MN compared to 41.05 MN without HDRs, which represents a reduction of 25.4%. Similarly, the maximum tower base moment is reduced to 421.08 MN.m compared to 600.01 MN.m without HDRs, which represents a reduction of 29.82%. Moreover, applying HDR dampers in addition to LRB devices significantly controls the deck displacement response of the bridge. The maximum deck displacement of the LRB-controlled bridge was reduced from 512 mm to 217 mm when using the HDR dampers, which represents a reduction of 57.6%.



(a)



(b)



(c)

Figure. 3. (a) Base shear force, (b) Base moment and (c) Deck displacement time history responses of the controlled cable-stayed bridge using LRB+HDR compared to the controlled bridge using LRB (Kobe 1995) (ξ=0.18)

Similar results can be found in the responses of the controlled bridge under the Imperial Valley excitation conditions. The maximum tower base shear of the LRB-controlled bridge with HDRs is reduced to 20.80 MN compared to 25.46 MN without HDRs, which represents a reduction of 18.3%. Similarly, the maximum tower base moment is reduced to 294.20 MN.m compared to 447.86 MN.m without HDRs, which represents a reduction of 34.30%. Moreover, the deck displacement response of the bridge is significantly controlled by applying HDR dampers in addition to LRB devices. The maximum deck displacement of the LRB-controlled bridge was reduced from 260 mm to 194 mm when using HDRs, which represents a reduction of 25%.

The results of the study confirm the efficiency of the HDR dampers in controlling the earthquake-induced forces and displacements of LRB-controlled cable-stayed bridges. A parametric study is presented below to better understand the performance of the HDR dampers in the hybrid control system.

Parametric study

Different parametric studies on structural parameters of LRBs and HDR dampers have been conducted extensively. However, for the purpose of this paper the parametric study on the effect of variation in damping ratio of HDR dampers on seismic responses of LRB-controlled cable-stayed bridge is presented. Fourteen evaluation criteria based on Dyke [32] are defined to evaluate the effectiveness of the control systems. The ratio of hybrid-controlled to uncontrolled responses (bridge with rigid deck-to-pier connections) is considered in the evaluation criteria. The details of the applied method are described in the literature [32]. The first six evaluation criteria (J_1 to J_6) consider the ability of the controller to reduce peak responses, and the second five evaluation criteria (J_7 to J_{11}) consider normed (i.e., r.m.s) responses over the entire simulation time. The final two evaluation criteria (J_{13} and J_{16}) consider the requirements of each control system. The results of the parametric study under Kobe and Imperial Valley earthquake records are presented in Table 2 and Table 3. The results of the parametric study as summarized in Table 2 and Table 3) show that increasing the damping ratio of HDR dampers from 12% to 18% does not necessarily improve the shear force and moment of the controlled bridge. However, the deck displacement response of the bridge is significantly reduced by increasing the damping ratio of HDR dampers under both earthquake records. Increasing the damping ratio of HDR dampers requires larger control force and stroke demands. The peak damping forces and strokes of the HDR dampers are derived separately from the analytical results (as observed from Table 2 and Table 3).

Table 2
Evaluation criteria for Kobe, 1995 Earthquake

Criterion	LRB α=10	LRB+HDR (ξ=0.12)	LRB+HDR (ξ=0.18)
J_1-Peak base shear	0.491	0.360	0.364
J_2-Peak shear at deck level	1.526	1.078	1.075
J_3-Peak base moment	0.383	0.257	0.269
J_4-Peak moment at deck level	0.723	0.446	0.440
J_5-Peak development of cable tension	0.251	0.241	0.237
J_6-Peak deck displacement	3.20	1.437	1.349
J_7-Normed base shear	0.279	0.242	0.239
J_8-Normed shear at deck level	1.623	1.137	1.127
J_9-Normed base moment	0.395	0.313	0.325
J_{10}-Normed moment at deck level	0.887	0.536	0.521
J_{11}-Normed development of cable tension	0.0305	0.266	0.0245
J_{12}-Peak control force	3.05×10^{-3}	4.13×10^{-3} HDR: 3.81×10^{-3}	4.33×10^{-3} HDR: 4.13×10^{-3}
J_{13}-Peak stroke	1.535	0.503	0.525
J_{16}-number of control devices	24	24+12	24+12

Table 3
Evaluation criteria for Imperial Valley, 1940 Earthquake

Criterion	LRB α=10	LRB+HDR (ξ=0.12)	LRB+HDR (ξ=0.18)
J_1-Peak base shear	0.491	0.418	0.456
J_2-Peak shear at deck level	1.526	0.971	0.965
J_3-Peak base moment	0.383	0.267	0.253
J_4-Peak moment at deck level	0.723	0.449	0.431
J_5-Peak development of cable tension	0.251	0.192	0.185
J_6-Peak deck displacement	3.20	1.421	1.231
J_7-Normed base shear	0.279	0.275	0.297
J_8-Normed shear at deck level	1.623	1.082	1.073
J_9-Normed base moment	0.395	0.241	0.221
J_{10}-Normed moment at deck level	0.887	0.360	0.344
J_{11}-Normed development of cable tension	0.0305	0.0175	0.0169
J_{12}-Peak control force	3.05×10^{-3}	3.12×10^{-3} HDR:	3.22×10^{-3} HDR:

		3.08×10^{-3}	3.19×10^{-3}
J_{13}-Peak stroke	1.535	0.370	0.415
J_{16}-number of control devices	24	24+12	24+12

Conclusions

The performance of the HDR dampers in controlling the seismic responses of a LRB-controlled cable-stayed bridge is investigated in this study. The seismic behavior of the controlled bridge with hybrid control system (LRB+HDR dampers) is compared with the LRB-controlled cable-stayed bridge. The results of the analytical study under two earthquake conditions (Kobe and Imperial Valley earthquakes) indicate that the HDR dampers are able to control the base shear, base moment, and deck displacement of the simulated LRB-controlled cable-stayed bridge by up to 25.4%, 34.3%, and 57.6%, respectively. A parametric study is conducted to investigate the effects of variation on the damping ratio of HDR dampers on the seismic responses of the cable-stayed bridge. The parametric study indicates that increasing the damping ratio of the HDR dampers from 12% to 18% does not affect the shear and moment responses of the cable-stayed bridge. However, increasing the damping ratio of the HDR dampers has a significant effect on the deck displacement response of the bridge.

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