Application of HDR Dampers in Seismic Protection of LRB-Controlled Cable-Stayed Bridges

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Cable-stayed bridges have become increasingly popular in the past decade due to their remarkable economic efficiency and aesthetic appearance.

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, high damping rubber (HDR) dampers are prominent systems as supplemental dissipating devices for seismic protection of LRB-controlled cable-stayed bridges.


**Objectives**

- To investigate the use of HDR as dissipating device for seismic control of LRB-controlled cable-stayed bridges.
- To determine the effect of variation in damping of HDR dampers on the seismic responses of the controlled cable-stayed bridge.
- To compare the seismic responses of the LRB-controlled and hybrid-controlled cable-stayed bridge.
The Tatarabridge in Japan with a total length of 1480 m with 890 m central span is considered for numerical study.

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 rigidly connected to the towers.

1st Transverse mode (0.1326 Hz)
The experimental tests and analytical studies confirm that the force-displacement hysteretic relation of LRB devices can be reasonably described by equivalent bilinear models. The initial elastic stiffness, the post-yield stiffness, the characteristic strength, and the yield displacement are required parameters to describe the equivalent stiffness and damping of LRB in bilinear model:

$$K_{eff} = K_d + \frac{Q_d}{u} \quad \xi_{eff} = \frac{2Q_d(u - u_y)}{\pi K_{eff}u^2}$$

Post-yielding stiffness is as one tenth of the initial elastic stiffness ($\alpha = 0.1$). Six isolators are considered in each deck-to-pier and deck-to-tower connections of the main span (20% damping ratio is considered for LRBs).
Characterize the behaviour of HDR dampers

The equivalent linear model is considered to model the behaviour of HDR dampers. The 18% damping is considered for HDRs.

The restoring force of the bearing in the equivalent linear model is defined as:

\[ F_b = k_b x_b + c_b \dot{x}_b \]

\[ k_b = \frac{F^+ - F^-}{\Delta^+ - \Delta^-} \]

Based on the weight of the structure and the designed time period (T=3s), six dampers are considered in each deck-to-tower connection.
Overview of the hybrid control system

Plan view of deck-to-tower connection

Elevation view

Transverse view
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 = 0.821 g) and the 1940 Imperial Valley earthquake (GPA = 0.341 g) records.

In the numerical study, 30 (sec) of each earthquake record is considered to investigate the seismic performance of the bridge.

Ground acceleration time-history curve of Kobe, 1995, earthquake in longitudinal direction

Ground acceleration time-history curve of Imperial Valley, 1940, earthquake in longitudinal direction
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.
Findings

- The results of the study from the presented time-history responses of the controlled bridge under Kobe earthquake loading show that:

✓ The application of supplemental HDR dampers is an efficient strategy to further control the seismic-induced responses of LRB-controlled cable-stayed bridges.

✓ In the case of Kobe earthquake loading, the maximum tower base shear of the LRB-controlled bridge is reduced about 26%. Similarly, the maximum tower base moment is reduced around 30%. The maximum deck displacement of the LRB-controlled bridge is reduced by using the HDRs around 58%.
Simulation results

- 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 Imperial Valley earthquake.
Findings

- The results of the study from the presented time-history responses of the controlled bridge under Imperial Valley earthquake loading show that:

  ✓ The application of supplemental HDR dampers is an efficient strategy to further control the seismic-induced responses of LRB-controlled cable-stayed bridges.

  ✓ In the case of Imperial Valley loading, the maximum tower base shear of the controlled bridge with HDRs is reduced around 19%. Similarly, the maximum tower base moment is reduced about 35%. Moreover, the maximum deck displacement of the LRB-controlled bridges is reduced 25% when using HDRs.
Effect of variation in damping of the HDR dampers on the peak resultant base shear response of the controlled bridge with LRB (T = 2.5 sec)

\[ J_1 = \max \left( \frac{\max_{t} \left| F_{br}(t) \right|}{F_{ob}} \right) \]

By increasing the damping of HDR dampers, the base shear response of the controlled bridge reduces up to a certain level, giving an optimum value of around 15% for damping ratio of HDRs.
Effect of variation in damping of the HDR dampers on the peak resultant base moment response of the controlled bridge with LRB (T = 2.5 sec)

$$I_2 = \max \left( \frac{\max_{t} |M_{21}(t)|}{M_{op,max}} \right)$$
Effect of variation in damping of the HDR dampers on the peak resultant deck displacement response of the controlled bridge with LRB (T = 2.5 sec)

\[ I_o = \max \left( \max_{i=1} \left| \frac{x_i(t)}{x_{0d}} \right| \right) \]

✓ The displacement of the controlled bridge deck reduces reasonably, with an increase in damping of HDR dampers from 5% to 30% in the case of both earthquake records.
Effect of designed time period of HDR dampers on peak base shear, and peak base moment responses of the controlled bridge ($\xi = 0.18$, $\alpha = 10$)

- The HDR devices with less designed time period control the earthquake responses of the bridge more effective compared with HDR dampers with higher designed time period.
Effect of designed time period of HDR dampers on peak deck displacement response of the controlled bridge ($\xi = 0.18$, $\alpha = 10$)

- The peak deck displacement response of the controlled bridge increases significantly by increasing the designed time period ($T$) of the HDR dampers from 2 (sec) to 2.5 (sec), while it is kept approximately unchanged with more increase in $T$. 
**Conclusions**

- The results of the analytical study under two earthquake records (Kobe earthquake and Imperial Valley earthquake) show that the HDR dampers significantly control the earthquake-induced forces and displacements of LRB-controlled cable-stayed bridges.

- The parametric study indicates that increasing the damping ratio of HDR dampers has not significant effect on seismic responses of the controlled cable-stayed bridge.

- The results of the parametric study also show that the hybrid control system in which the post-yielding stiffness of LRBs is designed to be as one sixth of the initial elastic stiffness ($\alpha=6$) and the designed period of HDR is considered 2.5 (sec) is the most efficient system.
Thank you for your attention.