International Journal of Structural Analysis & Design – IJSAD
Volume 1 : Issue 1
Publication Date : 09 January 2014

Seismic Isolation of Cable-stayed Bridges with HDR control devices

B. Asgari, S. A. Osman

Department of Civil & Structural Engineering
Universiti Kebangsaan Malaysia (UKM)
Bangi, 43600 Selangor, Malaysia

A. Adnan

Department of Civil & Structural Engineering
Universiti Teknology Malaysia (UTM)
81310 Johor, Malaysia

***Abstract*— With the growing construction of long-span bridges, the seismic response analysis of cable-stayed bridges have become a critical issue in engineering communities. Application of seismic isolation systems is a prominent way to improve the seismic performance of cable-stayed bridges. This paper investigates the performance of high damping rubber (HDR) bearings as seismic control systems for cable-stayed bridges. The design information of Tatara Bridge in Japan is considered for finite element (FE) modeling procedure. The time history method is applied for the seismic analysis. The seismic behavior of uncontrolled bridge is compared with the corresponding responses of isolated bridge to find out the efficiency of the control system. The results of investigations show that the addition of HDR bearings improve the seismic forces in cable-stayed bridges; however, the application of the isolation system increase the displacement response of the isolated bridge during the earthquake.**

***Keywords*—**seismic response, cable-stayed bridge, isolation system , high damping rubber (HDR) bearing

I. *Introduction*

Cable-stayed bridges have been developing rapidly since World War II, and become one of the most popular types of bridges for long spans length to 1000 m or even longer. The increasing popularity of cable-stayed bridges, where previously a suspension bridge might have been chosen, are attributed to the pleasing aesthetics, efficient utilization of structural materials, the increased stiffness over suspension bridges and the relatively small size of the bridge elements. Despite all the advantages, there have been several concerns over the use of cable-stayed bridges. Cable-stayed bridges are complex structures consisting of various structural components with different stiffness and damping characteristics. They are normally sensitive to dynamic loadings such as earthquakes, winds and vehicles.

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. This fact introduces new challenges to the earthquake engineering community in terms of seeking and developing new damping and isolation technologies that could improve the seismic performance of cable-stayed bridges.

Seismic isolation aims mainly at the isolation of structure from the supporting ground, generally in the horizontal direction, in order to reduce the transmission of the earth quake motion to the structure. A variety of research works had been done on investigating the effectiveness of seismic isolation for cable-stayed bridges. The first studies began with Ali and Abdel-Ghaffar [1] that proposed lead rubber bearing (LRB) devices as passive control systems. In recent years, many passive, semi-active and active protection devices have been proposed to reduce the seismically induced forces and displacements of cable-stayed bridges [2-6].

In the field of seismic engineering, the use of high damping rubbers (HDR) ,with good load-bearing ability and damping characteristics, have been applied successfully to mitigate seismic effects on bridges and buildings. The rubber bearings with high damping were developed by Malaysian Rubber Producers, an Association (MRPRA) of United Kingdom in 1982. The high damping of HDR is provided by addition of the chemical compounds (generally carbon black in seismic control systems, which improves the stiffness, the relaxation characteristics, the creep, and the fatigue life of the rubber) that may also affect the other mechanical properties of the rubber. The flexibility and energy absorption capability of HDR-based isolation systems result in the absorption of the earthquake input energy before transmission to the structure and enhance the serviceability of the structure. Despite all of the advantages of utilizing HDR materials and their cost efficiency in comparison with other control devices, few studies have investigated the performance of HDR-based seismic control systems for cable-stayed bridges. It is essential that more research be conducted to characterize and model rubber-based isolation and damper systems for the earthquake protection of cable-stayed bridges. This study investigates the seismic response of a long-span cable stayed bridges which is isolated with HDR bearings. The design information of Tatara Bridge in Japan ,with 890m main span, are considered for numerical studies conducted in ANSYS software through Finite Element (FE) method. A comparative study is applied to compare the seismic response of the original bridge and isolated bridge with HDR bearings.

II. The cable-stayed bridge model

The Tatara cable-stayed bridge is located at the centre of the Honshu-Shikoku Bridge on the Nishiseto Expressway. The bridge has a total length of 1480 m, with a centre span of 890 m. The inverted Y-shaped steel towers with a height of 220 m have slits in the upper tower for aesthetic purposes and to enhance the aerodynamic effects of the structure. The main girder is a 3-cell steel box section consists of three spans, which are 270 m, 890 m, and 320 m long and 2.70 m deep. The pre-stressed concrete (PC) girders are used in the side spans to balance the weight of the main span. The stay cables are arranged in 21 levels and two planes with indented surfaces in the polyethylene cable coating to enhance their aerodynamic stability. Fig. 1 shows the general arrangement of the Tatara Bridge.

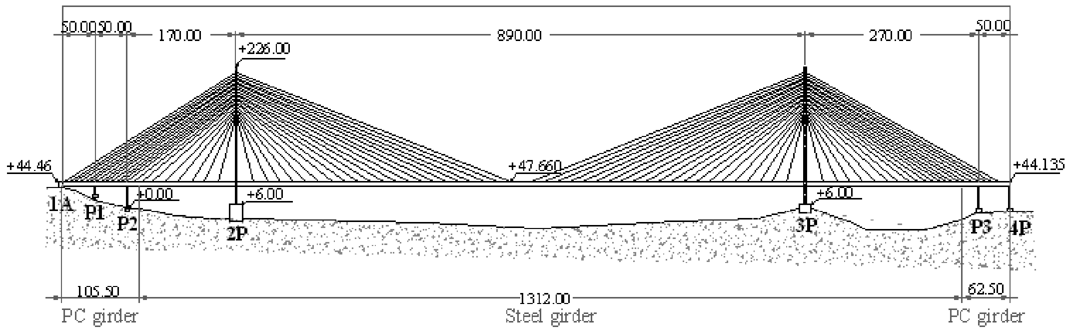


Fig. 1. General arrangement of the Tatara cable-stayed bridge

A detailed three-dimensional FE model is developed in the ANSYS program. The geometry and details of the model are based on the design information of the Tatara Bridge. To reduce the degrees of freedom, a simplified three-dimensional finite element model of the bridge is developed using elastic beam elements and link elements. The bridge deck is modelled using a single central spine with offset rigid links to accommodate cable anchor points (fishbone model). The BEAM4 elements from the ANSYS element library are used to model the central spine. The MPC184 elements are applied to model the rigid links, and 50 concentrated mass elements (MASS21) are used to include the mass of the equilibrium blocks, parapet and anchors that are non-structural members. The steel towers, heads and struts of the towers are also modelled as three-dimensional (3-D) elastic BEAM4 elements.

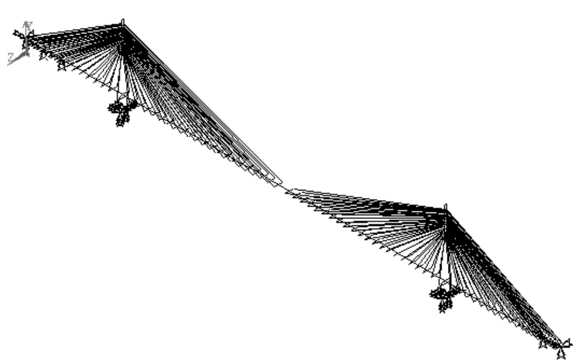
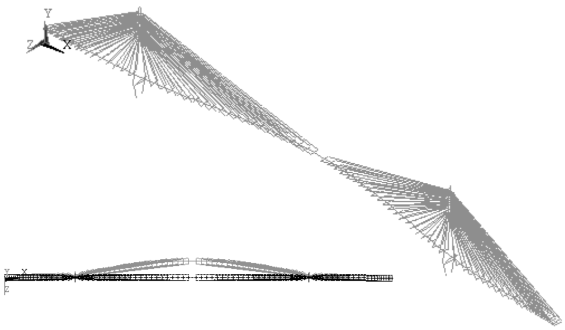


Fig. 2. Three-dimensional FE model of the Tatara cable-stayed bridge

The rigid links (MPC184 elements) are extended from the axial centre of the tower to the cable anchor points. The cables of the bridge are parallel stranded cables made of 7-mm steel wires with a tensile strength of 1,569 MPa, forming a non-grouted cable covered with polyethylene tube. The cables are modelled in ANSYS by employing 3-D nonlinear tension-only truss elements (LINK10) and utilizing the stress-stiffening capability to consider the sag effect. The FE model of the Tatara cable-stayed bridge is shown in Fig.2. The natural frequencies and mode shapes of the bridge are first calculated starting from deformed configuration under dead loads. The deck-to-tower connections of uncontrolled bridge can be assumed as two different models: (a) a configuration in which the deck is 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. In this case, the bridge shows limited deck displacement (maximum 0.206 m) but a high shear at the base of the towers as well as unacceptable variations of tension in the cables: (b) a configuration in which the deck is not restrained longitudinally to the piers and the tie in this direction is supplied only by the cable stays. The first ten natural frequencies of this second configuration are 0.0510, 0.0530, 0.1170, 0.2135, 0.2176, 0.2669, 0.3290, 0.3587, 0.3703 and 0.4175 Hz. In this model, even though maximum values of base shear and moment respectively equal to 39.2 and 48.5% of those of model (a), there is an unacceptable sliding of the deck, with a maximum displacement equal to 1.271 m. To evaluate the seismic response of the uncontrolled bridge, he bridge deck is assumed to be rigidly connected to the towers. Fig. 3 represents the first mode shape of the bridge with dead load included. For implementing isolation system, the isolators are replaced with conventional bearings.



1st Transverse bending mode (0.1326 Hz)

Fig. 3. First mode shape of the FE model with fixed connections

The inherent damping of the structure is assumed 2% in present study.

III. Seismic isolation system

A. *Characterize the behavior of HDR bearings*

The nonlinear force-displacement relation of rubber-based control systems are generally modeled by equivalent linear elastic-viscous and bilinear hysteretic behaviors in recent studies and specifications [7-13].

The equivalent linear model is applied extensively in the numerical studies of natural rubber (NR) bearings. The linear restoring force of the bearing (F_b) in the equivalent linear model is defined as [11]

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

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

The isolation time-period (T_b) and the damping ratio (ξ_b) can be defined as

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

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

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

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

where F^+ and F^- are the positive and negative forces of the test displacements Δ^+ and Δ^-, respectively. The model presented is applied to model high damping rubber bearings (HDRB) in different studies [7, 14, 15]. The equivalent linear model is considered in this study to model the behavior of HDR bearings. The 15% damping is considered for the present study for HDRs.

B. *Equations of motion*

The equations of motion of the isolated cable-stayed bridge subjected to seismic loads are expressed in the following matrix form [4]:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} + [D]\{F_b\} = -[M][r]\{\ddot{u}_g\} \quad (5)$$

$$\{u\} = \{x_1, y_1, z_1, \ldots, x_N, y_N, z_N\}T \quad (6)$$

$$\{\ddot{u}_g\} = \{\ddot{x}_g, \ddot{y}_g, 0\}T \quad (7)$$

where [M], [K] and [C] are the mass, stiffness and damping matrices of the structure, respectively; $\{\ddot{u}\}$, $\{\dot{u}\}$, and $\{u\}$ represent structural acceleration, structural velocity and structural displacement vectors, respectively; [D] is the location matrix for the restoring forces of isolators; $\{F_b\}$ is the vector containing the restoring forces of isolators; [r] is the influence coefficient matrix; $\{\ddot{u}_g\}$ is the seismic acceleration vector; $\ddot{x}_g$, $\ddot{y}_g$ represent the earthquake ground accelerations in the longitudinal and transverse directions, respectively; and x_i , $y_{1i}$and z_i are the displacements of the ith node of the bridge in the longitudinal, transverse and vertical directions, respectively.

IV. Numerical studies

The seismic response of bridge is investigated under Kobe, 1995, earthquake which has been used widely by researchers in the past. The peak ground acceleration (PGA) of Kobe earthquake in longitudinal direction is 0.821g. The ground acceleration of Kobe, 1995, earthquake is shown in Fig. 4. In the numerical studies of the seismic responses, 30 s is used in the analysis. The 0.02 s time step is used for Kobe record.

HDR bearings are applied in deck-to-tower connections to reduce seismic forces and to absorb large seismic energy. For avoiding large bearing force, which makes the energy-absorbing device do not work efficiently, bearing stiffness with 1.7 times the original main period (T) is chosen (based on

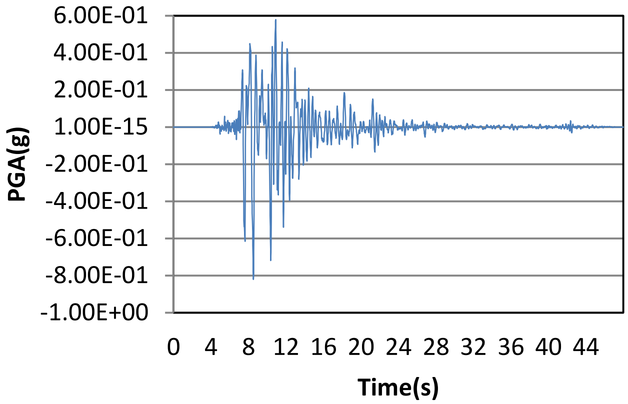


Fig. 4. Ground acceleration time-history curve of Kobe, 1995, earthquake in(longitudinal direction (N-S)

the study on a simplified model of the bridge under seismic motion). The mentioned bearing stiffness makes HDR bearings work well in reducing seismic induced forces and displacements. Isolation bearings are applied as can be seen in Fig.5. The FE model is analysed in ANSYS commercial program through time-history analysis, Using Newmark's constant average acceleration (β=1/4) integration of the equations of motion as shown in Fig. 6. The response of the nonlinear structure to the base excitation is investigated.

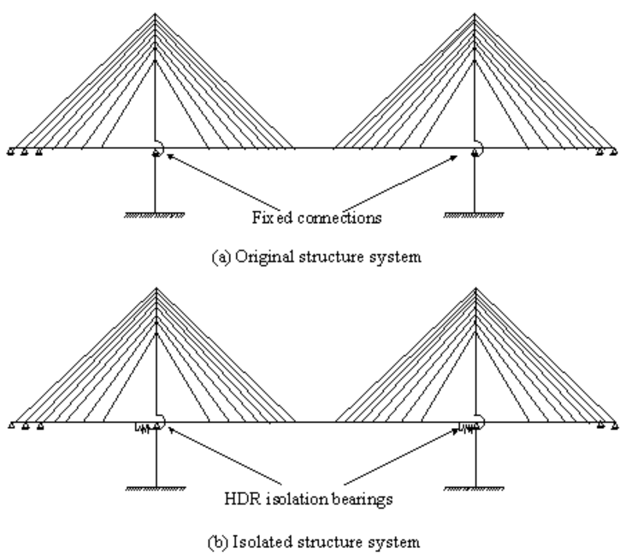


Fig. 5. Isolated system of a cable-stayed bridge model

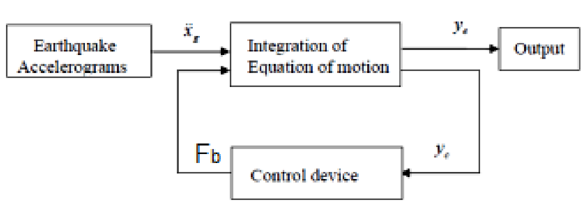


Fig. 6. The schematic process of seismic analysis of the isolation system [14]

A. *Evaluation of results*

For cable-stayed bridges subjected to seismic loads, critical responses are related to the structural integrity of the bridge rather than to serviceability issues. Thus, in evaluating the performance of each control point, the shear forces and moments in the towers at key locations must be considered. Additionally, the tension in the cables should never approach zero, and should remain close to the nominal pretension [16].

There are 18 evaluation criteria mentioned in the benchmark problem [16]. The first six evaluation criteria (J_1 to J_6) are considered as peak responses of the bridge with respect to uncontrolled bridge (model (a)), where J_1 is the ratio of peak base shear of the towers, J_2 is the ratio of peak shear force at deck level of the towers, J_3 is the ratio of peak overturning moment of the towers, J_4 is the ratio of peak moment at deck level of the towers, J_5 is the ratio of peak deviation in the cable tension and J_6 is the ratio of peak displacement of the deck at abutment. The next five evaluation criteria (J_7 to J_{11}) are considered as norm responses of the bridge with respect to uncontrolled bridge, and The last seven evaluation criteria (J_{12} to J_{18}) are related to the requirement of the control device. The first 6 evaluation criteria are considered in this study to investigate the performance of HDR bearings as seismic control devices of the modeled bridge (TABLE. I).

TABLE I. SUMMERY OF 6 EVALUATION CRITERIA

$J_1 = \max \left\{ \frac{\max_{i,t} \lvert F_{bi}(t) \rvert}{F_{0b}^{\max}} \right\}$	$J_4 = \max \left\{ \frac{\max_{i,t} \lvert M_{di}(t) \rvert}{M_{0d}^{\max}} \right\}$
$J_2 = \max \left\{ \frac{\max_{i,t} \lvert F_{di}(t) \rvert}{F_{0d}^{\max}} \right\}$	$J_5 = \max \left\{ \max_{i,t} \left\lvert \frac{T_{ai}(t) - T_{0i}}{T_{0i}} \right\rvert \right\}$
$J_3 = \max \left\{ \frac{\max_{i,t} \lvert M_{bi}(t) \rvert}{M_{0b}^{\max}} \right\}$	$J_6 = \max \left\{ \max_{i,t} \left\lvert \frac{x_{bi}(t)}{x_{0b}} \right\rvert \right\}$

0: uncontrolled condition; i: i th tower; d: deck level; t: tower

The Evaluation criteria for damping ratio of 15% for HDR bearings under Kobe earthquake loads are shown in TABLE. II. It can be found from results of investigations that applying HDR bearings is effective to decrease the tower base shear and moments, as well as deck moments and cable tensions. However, the displacement response of the deck will increase by applying HDR control devices significantly.

To investigate the effect of damping ratio of the HDR isolators on seismic responses of the bridge (deck displacement, base moment and base shear), a comparative study is conducted by varying the parameter ξ_b from 5 to 30%. The variation of bearing displacement, for different damping ratio of HDRB is shown in Fig. 7.

TABLE II. EVALUATION CRITERIA FOR KOBE, 1995, EARTHQUAKE

Criteria	Controlled bridge with HDR bearings
J_1 -Peak base shear	0.517
J_2 -Peak shear at deck level	1.209
J_3 -Peak base moment	0.418
J_4 -Peak moments at deck level	0.753
J_5 -Peak development of cable tension	0.316
J_6-Peak deck displacement	3.89

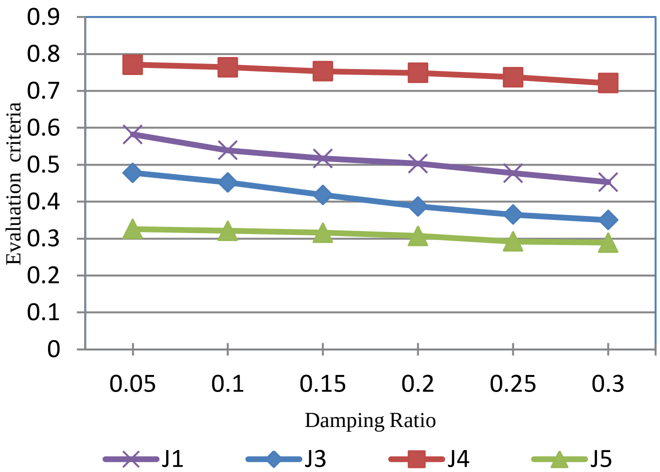


Fig. 7. Effect of damping ratio of HDR bearings on seismic response of the bridge

Fig.7 represents that base shear as well as base moment response is decreasing with increase in damping ratio of HDR bearings significantly for Kobe earthquake considered. However, it seems that damping ratio has not any significant effect on deck moment and cable tensions.

V. Conclusions

The performance of HDR control devices on seismic response of a long-span cable-stayed bridge is investigated in this paper. The results of investigations show that HDR bearings are efficient devices in decreasing seismic forces of cable-stayed bridges. However, the application of HDR bearings increases the displacement response of the deck. Applying energy dissipating devices in parallel with HDR bearings would be an effective solution to overcome the mentioned problem which can be considered in future studies. It can also be found from the results of this study that increasing the damping ratio of HDR bearings would improve their efficiency to control the seismic forces in cable-stayed bridges. This fact would be helpful in manufacturing process of HDR bearings for cable-stayed bridges.

Acknowledgment

The authors would like to thank all previous researchers that their studies have been reviewed in this paper. The research reported in this paper is sponsored by remarked GRA research grants (UKM-HEJIM-INDUSTRI-07-2010) funded by the National University of Malaysia (UKM) and (FRGS/1/2011/TK/UKM/02/13) founded by Ministry of Higher Education, Malaysia.

References

[1] AM. Abdel-Ghaffar, AS. "Nazmy, 3-D non-linear seismic behaviour of cable-stayed bridges," Structurul Engineering, Vol.117, 1991, pp.3456-3476.

[2] B. Andrawes, R. DesRoches, "Comparison between shape memory alloy seismic restrainers and other bridge retrofit devices," Bridge Engineering, Vol.12, 2007, pp.700-709.

[3] Alaa M. Sharabash, B. O. Andrawes, "Application of shape memory alloy dampers in the seismic control of cable-stayed bridges," Journal of Engineering Structures, Vol.31, 2009, pp. 607-616.

[4] B.B. Soneji and R.S. Jangid, "Passive hybrid systems for earthquake protection of cable-stayed bridge," Engineering Structures , Vol.29, 2007, pp. 57–70.

[5] Dong-Ho Ha, Jang Ho Park, Kwan-Soon Park, Wonsuk Park, Jinkyo F. Choo, "Optimization of Complex Dampers for the Improvement of Seismic Performance of Long-span Bridges," KSCE Journal of Civil Engineering, Vol.14, 2010, pp.33-40.

[6] H. Jung, K. Park, BF. Spencer and I. Lee, "Hybrid seismic protection of cable-stayed bridges," Earthquake Engng Struct Dynam, Vol.33, 2004, pp.795–820.

[7] H. Iemura, , A. Igarashi, and A. Toyooka, "Development of an innovative seismic damper for large-scale bridges and sub-structured hybrid earthquake loading tests." 4th Int. Conf. on Bridge Maintenance, Safety and Management (IABMAS08), Session TuM-8, 2008, Seoul, Korea.

[8] M. N. Haque, A. R. Bhuiyan, and M. J. Alam, "Seismic response analysis of base isolated highway bridge: Effectiveness of using laminated rubber bearings." IABSE-JSCE Joint Conference on Advances in Bridge Engineering-II, 2010, Dhaka, Bangladesh.

[9] O.P. Gomase and S.V. Bakre, "Performance of Non-Linear Elastomeric Base-Isolated building structure." International Journal of Civil and Structural Engineering, 2 (1), 2011,pp. 280-291.

[10] M. K.Razzaq, A. R. Bhuiyan, Y. Okui, H. Mitamura, and T. Imai, "Effect of rubber bearing's modeling on seismic response of base isolated highway bridge" Joint conference proceedings, 7CUEE, 5ICEE, 2010, Tokyo, Japan.

[11] Japan Road Association, (JRA 2002). Specifications for highway bridges, Part V: Seismic design, Tokyo, Japan.

[12] Japan Road Association, (JRA 2004). A manual of support bearings for highway bridges, Marizen, Tokyo (in Japanese).

[13] American Association of State Highways and Transportation Officials (AASHTO), 2000. Guide Specification for Seismic Isolation Design, 2/e.

[14] P.Saha, and R. S. Jangid, "Comparative Performance of Isolation Systems for Benchmark Cable-stayed Bridge." International Journal of Applied Science and Engineering, 6(2), 2008,p p.111-139.

[15] P. R. Soti, and p. Saha, "Review of various passive control devices for seismic control of benchmark cable stayed bridge." International Journal of Earth Sciences and Engineering, 4(6), 2011,pp. 726-731.

[16] S. J. Dyke, J. M. Caicedo, G. Turan, L. A. Bergman, and S. Hague, "Phase I benchmark control problem for seismic response of cable-stayed bridges." Journal of Structural Engineering, ASCE, 129, 2003, pp. 857-872.