RESEARCH ON THE ASEISMIC BEHAVIOR OF LONG-SPAN CABLE-STAYED BRIDGE WITH DAMPING EFFECT

WU Fangwen, Zhang Qingkai, Feng Binglong,Qiu Jiantao

School of Highway, Chang’an University, Xi’an, Shaanxi, 710064, P.R.China; ibridge2014@163.com

ABSTRACT

The main beam of a cable-stayed bridge with a floating system may have a larger longitudinal displacement subject to earthquake effect. Thus, seismic control and isolation are crucial to bridge safety. This paper takes Huai’an Bridge, which has elastic coupling devices and viscous dampers set at the joint of the tower and the beam, as the research background. Its finite element model is established, and the elastic stiffness of elastic coupling devices and damper parameters are analyzed. Viscous damper and elastic coupling devices are simulated using Maxwell model and spring elements, and their damping effects are analyzed and compared through structural dynamic time-history analysis. Results show that viscous damper and elastic coupling device furnished at the joint of tower and beam of a cable-stayed bridge tower beam can effectively reduce the longitudinal displacement of the key part of the construction subject to earthquake effect, perfect the internal force distribution, and improve the aseismic performance. Between the two, viscous damper has better damping effects.

KEYWORDS

cable-stayed bridge, viscous damper, elastic coupling devices, seismic response

1. INTRODUCTION

China is one of the countries with the world's strongest seismic activities. Large parts of the country are located in highly seismic areas. Wenchuan earthquake which was 8 degree intensity happened in 2008 and caused 6,140 bridges to suffer varying degrees of damage and destruction, and even collapse. The loss of such bridges seriously delayed the rescue process, increased the number and extent of injuries, seriously exacerbated economic losses, and triggered larger secondary disasters. The Qinghai Yushu earthquake in 2010, 7.1 degree intensity, also caused varying degrees of damage to bridges within the county, mainly because the seismic intensity that occurred exceeded the seismic fortification criteria and the bridge construction inadequacies in earthquake resistance. The Ya'an Lushan earthquake in 2013, 7.0 degree intensity, brought different degrees of damage to highways totaling 2986 km, and caused 327 bridges to suffer varying degrees of damage and destruction. In those earthquake disasters, bridges are the most vulnerable to seismic damages in the highway traffic system. Once they collapse, they will lead to greater secondary disasters and indirect economic losses, especially in No. 213 National Highway and Duwen Expressway, which are close to the epicenter and are seriously damaged or destructed in the Wenchuan earthquake. Indeed, the current research on the damping of bridge constructions is necessary and urgent.

After the period of bridge with damper exceeds a certain limit, the overall seismic response will

DOI 10.14311/CEJ.2016.02.0008

decrease with the increasing period, and the seismic response of the same period will reduce with the increasing damping. The seismic reduction design utilizes the seismic response and achieves the damping purpose by increasing the natural vibration period and the damping factor. Therefore, the basic principle of seismic reduction design is as follows[1]: flexible supports are adopted to extend the natural vibration period of the whole structure and to reduce the structural seismic response. Energy dissipation devices are then adopted to dissipate energy and to limit the structural displacement. The main function of elastic cable devices is to provide the appropriate elastic stiffness, rather than energy dissipation. These devices, which have relatively simple construction, convenient installation, moderate price, and ability to provide greater elastic stiffness, have already been widely applied to bridge seismic reduction in Japan and many other countries. The No. 2 Shantou Bay Bridge in Guangdong Province, which is a hybrid beam cable-stayed bridge with main span of 518m, also adopts elastic cable devices at the joint of the tower and beam to reduce the seismic response, with a 54m long 55×75 steel strand on each side of the tower. One end of the steel strand is anchored to the bottom end rail of the tower, whereas the other end is anchored to the stiffening girder [2]. Energy dissipating dampers refer to dampers installed between the tower and the stiffening girder as shown in Fig.1. When the bridge is suffering earthquake, the piston and the cylinder will move in relation to each other because the difference in pressure before and after the piston leads the damping fluid to flow through the damping hole, produce a damping force, and minimize the structural response by converting part of the energy from structural vibration into thermal energy via the viscous damping fluid. Many researchers have conducted thorough studies on dampers applied in bridge seismic reduction. For example, Feng (1993)[3], Yang (1995)[4], and Tsopelas (1990)[5] successively studied the damping effects of variable dampers on the seismic response of bridges. They unanimously agreed that variable dampers could effectively reduce the absolute acceleration of superstructure and the relative displacement between stiffening girder and pier. Tsai (1996)[6] proposed to adopt viscoelastic dampers for minimizing the seismic response of bridge. Yang Menggang (2004)[7] considered that the application of MR dampers in bridge construction had a good damping effects. The viscous fluid damper in bridge construction has been widely used in bridge damping without affecting the original structural vibration period and mode before being added. It is characterized by elliptical hysteresis curve, reusability under earthquake effect, and other evident advantages. The famous American Golden Gate Bridge also successfully adopted viscous dampers to retrofit the structure resistance ability.

In this paper, seismic reduction performance of one cable-stayed bridge is analyzed. In order to study the features of the seismic reduction devices, the applications of viscous dampers and elastic cable device in the bridge were analyzed from the aspects of structural damping or longitudinal structural stiffness. Moreover, a finite element model is established based on FEM software, by which time-history method is used to analyze the seismic responses of the two damping measures and explore their damping effects to provide a scientific basis for the damping design of cable-stayed bridge.

2. Mechanical properties of elastic and viscous dampers

(1) Elastic cable

The working principle of damping about elastic cable devices mainly involves two aspects: (1) by adopting the flexible coupling between the tower and stiffening girder to change the force propagation passage, the stress situation of the structure is relieved; (2) Seismic displacement at girder end is reduced by increasing the structural stiffness. After elastic connection devices are installed, the force *F,* the device stiffness K_e and relative displacement d between tower and stiffening girder can be expressed in the following linear equation:

$$F = K_e d \tag{1}$$

The controlling effects of coupling devices between tower and stiffening girder on seismic displacement depend upon the device parameters. Therefore, reasonable parameter settings are very critical, and the parameters of elastic coupling devices should be set according to the requirements of such devices in beam-end displacement, bending moment at the bottom of the tower.

(2) Viscous damper

The main construction of liquid viscous damper is shown in Fig. 1, which consists of cylinder block, piston, liquid, etc. The working principle of viscous damper [8] states that the piston under the influence of an external force may slide inside the cylinder block, then a pressure difference produces and that lead the damping fluid to flow through the damping hole, bringing a relatively large damping force. The flow of such viscous damping fluid will convert most of the energy from the vibrating structure into thermal energy that will disperse soon, thus achieving the purpose of energy dissipation and damping.

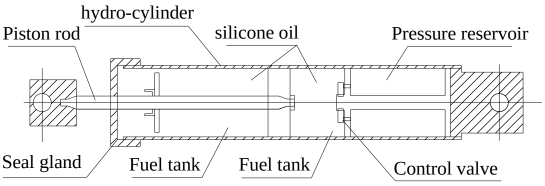


Fig. 1 - Viscous Damper

Given that the viscous damper is related to the structural vibration velocity [9], its mechanical properties can be described by an equation about the relation between force and velocity:

$$\mathrm{F} = \mathrm{CV}^{\alpha} \tag{2}$$

where F, C, V, and α represent the damping force, damping coefficient, relative motion velocity of piston, and damping exponent (also called the velocity exponent), respectively. When α=1, the damping force of damper is linear with velocity (V), and the damper is a linear damper. When α<1, the damper is into the nonlinear operation and is a non-linear viscous damper.Moreover,when α>1,the damper is an ultra-linear damper, and the F-V relation of viscous damper is shown in Fig. 2.

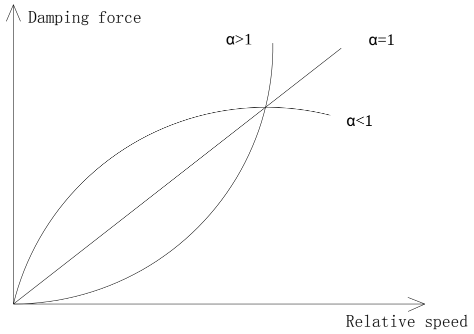
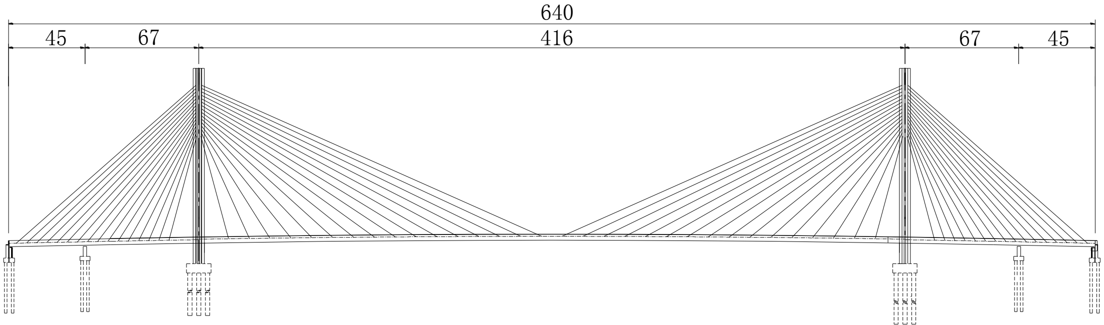


Fig. 2 - Relation between Damping Force and Relative Velocity

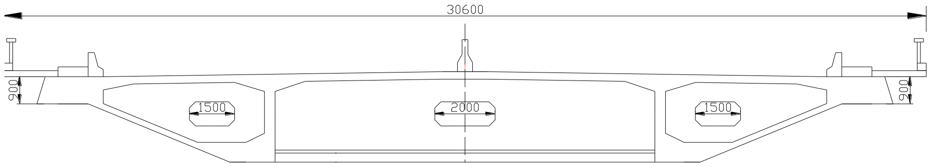
As shown in Fig. 2, when the velocities of linear and ultra-linear dampers are lower, the output damping forces are far less than those of non-linear viscous damper. However, when the velocities are higher, the output damping forces are much greater than those of non-linear viscous damper. Therefore, although the aseismic performance of the structure can be improved when α≧1, it may still be invalid due to low damper connection strength in any devastating earthquake. However, the non-linear viscous damper can output a large damping force at very low relative velocity, and a damping force increases slightly at a higher relative velocity. Thus, better damping effects are produced in small earthquakes, and the support systems and connection points in devastating earthquakes are effectively protected from any structural failure caused by an excessively large damping force. Therefore, the damping range of damper is wider and the structural design is relatively simpler. Moreover, when α becomes smaller, the relative velocity is higher, and the damping force will increase more slowly with the increasing higher relative velocity.

3. Finite element model and dynamic characteristic analysis

Huai’an Bridge is a steel-concrete cable-stayed bridge with dual tower and dual cables, which is a floating support system. A combination of spans (45+67+416+67+45 m) is shown in Fig. 3. The box girder for main span is an all-welded steel beam, wherein the top, middle chamber, side chamber, and cantilever board widths are 40 m, 15.2 m, 8.95 m, and 3.45 m, respectively. The tower is A-shaped, with a height of 115 m. The spatial arrangement of 64 cables is fan-shaped[9].



(a) Structure Arrangement (Unit: m)



(b) Cross Section (Unit:cm)

Fig. 3 Arrangement of Huai’an cable-stayed bridge. (Unit: m)

The motion equation of an SDOF structure under seismic load is as follows:

$$m\ddot{u} + c\dot{u} + ku = -m\ddot{u}_g \tag{3}$$

In Equation (3), $u = u(t)$ represents the relative displacement and $\ddot{u}_g(t)$ represents the seismic acceleration time history. For seismic problems of linear elastic structure, an analytical expression in integral calculus form is given using Duhamel's integral. The equivalent seismic load is $p_{eq}(t) = -m\ddot{u}_g(t)$, and using Duhamel's integral, the displacement in response to the structural seismic response is:

$$u(t) = \frac{-1}{\omega_D}\int_0^t \ddot{u}_g(\tau)e^{-\xi\omega_n(t-\tau)}\sin\left[\omega_D(t-\tau)\right]d\tau \tag{4}$$

In Equation (4), $\omega_D = \omega_n\sqrt{1-\xi^2}$ represents natural frequency of the damping system. When the damping coefficient is very small, Equation (4) can be simplified into:

$$u(t)=\frac{-1}{\omega_n}\int_0^t \ddot{u}_g(\tau)e^{-\xi\omega_n(t-\tau)}\sin\omega_n(t-\tau)d\tau \qquad (5)$$

The linear dynamic finite element equation for MDOF structure is:

$$M\ddot{u}+C\dot{u}+Ku=0 \qquad (6)$$

In Equation (6), M, C, K respectively represent the total mass matrix, total damping matrix, and total stiffness matrix respectively, while $\ddot{u}, \dot{u}, u$ respectively represent the acceleration vector, velocity vector, and displacement vector.

The structural vibration characteristics of cable-stayed bridge at complete stage can be obtained from the following eigenvalue equation:

$$\left|K-\omega^2 M\right|=0 \qquad (7)$$

where ω represents the natural frequency of bridge construction with different orders. According to the finite element analysis, the first 10-order frequencies of the three models are shown in Table 1.

Tab. 1. - The first 10-Order frequencies of the three models (Unit: Hz)

Order	Model Without damping	Model with elastic cable	Model with viscous damper
1	0.212026	0.335724	0.212012
2	0.214013	0.217458	0.214006
3	0.270279	0.273572	0.270256
4	0.326126	0.328326	0.326104
5	0.337853	0.340738	0.337831
6	0.350522	0.354683	0.350501
7	0.357491	0.359747	0.357462
8	0.392650	0.396538	0.392629
9	0.465068	0.468574	0.465036
10	0.503615	0.507945	0.503693

As Table 1 shows, after viscous dampers are considered, the natural frequency of the structure is slightly reduced. The longitudinal damping effect of bridge construction is increased, and the natural vibration period of construction is extended, thereby reducing the structural internal force response. After the elastic cable damping devices are installed, the longitudinal stiffness of the main bridge is changed, and the first-order vibration mode is greatly affected, while the rest are less affected. However, the vibration mode is still in small value part of the response spectrum, characterized by the vertical drift of the main beam and the longer period.

4. Seismic reduction analysis of cable-stayed bridge

4.1 *Construction of damping device*

The finite element dynamic analysis of the main bridge of Huai'an Bridge is carried out by Midas Civil software to build up a finite element model, as shown in Fig. 4. The backbone, beam-element, truss-element, spring element, and Maxwell damping models are adopted by main beam, main tower, piers, and foundation, stayed cable, elastic cable, and viscous damper, respectively.

DOI 10.14311/CEJ.2016.02.0008

To study the damping effect of the cable-stayed bridge with viscous damper and elastic cable, the following three cases are analyzed:

(1) Semi-floating system model without damping device.

(2) Four elastic cables between the stiffening girder and the tower shown in Fig. 5, with elastic stiffness K＝3000 kN/m.

(3) Four viscous dampers between the tower and the beam shown in Fig. 6, with damping coefficient C＝7000kN.S/m.

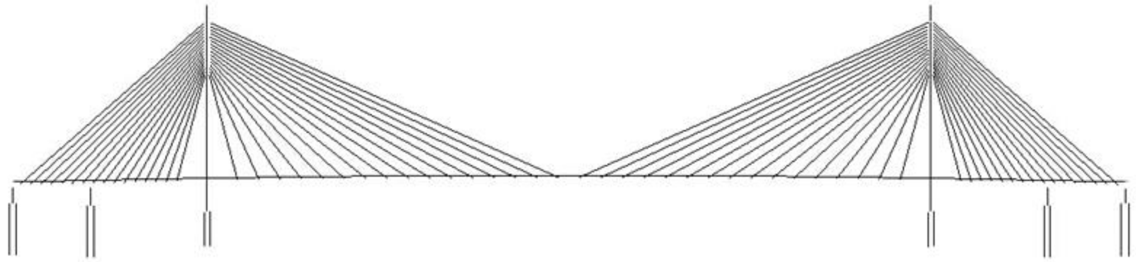


Fig. 4 - Finite Element Model of Huai'an Bridge

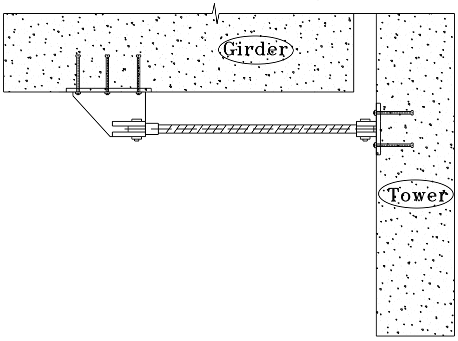


Fig. 5 - Damping Diagram of Elastic Cable

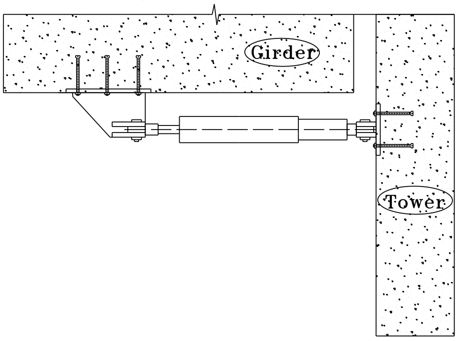


Fig.6 - Damping Diagram of Viscous Damper

4.2 Seismic input

The Huai'an Bridge, which belongs to Seismic Group I and Site Category II, has the designed seismic intensity of 7° and the designed basic seismic acceleration equal to 0.1 g. Combined with the actual situation of the bridge and the above-mentioned requirements, this paper chooses the seismic waves of Wenchuan earthquake, with the correction factor of $\frac{a'_{\max}}{a_{\max}} = \frac{0.10}{0.9772} = 0.1023$. The seismic travel time curve of this earthquake after amplitude modulation is shown in Fig. 7.

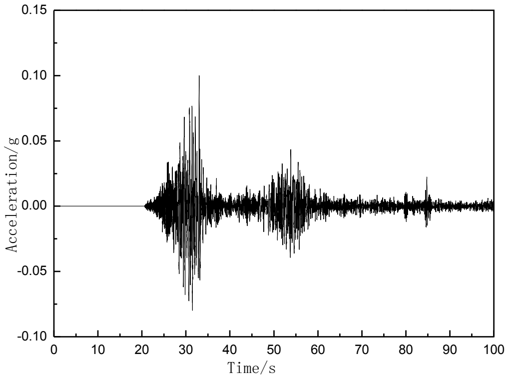


Fig. 7 - Seismic Travel Time Curve of Wenchuan Earthquake

Through finite element analysis, the displacement of each control node of Huai'an Bridge under the longitudinal seismic action and the peak internal force response of the control section are shown in Table 2. After the elastic cable device or viscous damper is mounted, the structural internal force is significantly reduced to provide the effective aseismic level of the structure.

Tab. 2. - Peak Internal Force Displacement of Huai'an Bridge

Item	Tower top displacement(cm)	Beam-end displacement(cm)	Bending moment of the tower bottom (kN•m)	Tower bottom shearing force (kN)
Model without damper	18.52	16.37	58860	2630
Model with elastic cable	10.8	9.87	54360	2400
Model with viscous damper	9.06	7.54	46410	2200

After the viscous damper is longitudinally mounted at the junction of the tower and beam, the bending moment of the tower bottom is reduced by 21%, and the tower top longitudinal displacement is reduced by 52%. After the elastic cable is mounted, the longitudinal displacement damping rate of the tower top is up to 41%, and the bending moment of the tower bottom is 8%. Thus, it is clear that both viscous damper and elastic cable have good damping effects, and the peak dynamic response subject to earthquake effect, is reduced to the utmost extent. As shown in Figs. 8 to 11, after the viscous damper and the elastic cable are adopted, Huai'an Bridge has the internal force response of the control section and the displacement of each control node rapidly attenuated. This indicates that both viscous damper and elastic cable play very good roles in damping, especially the viscous damper which has the more obvious effect in controlling the displacement.

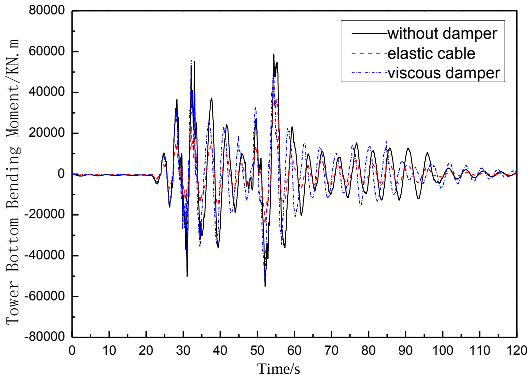


Fig. 8 - Tower Bottom Bending Moment

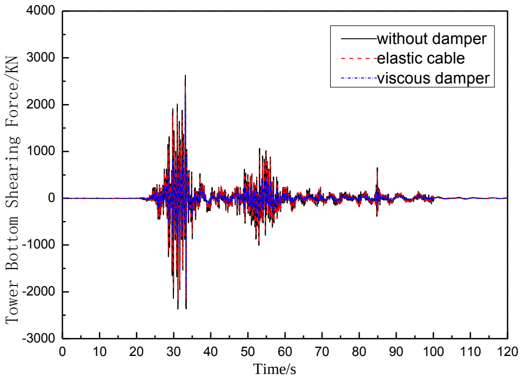


Fig. 9 - Tower Bottom Shearing Force

DOI 10.14311/CEJ.2016.02.0008

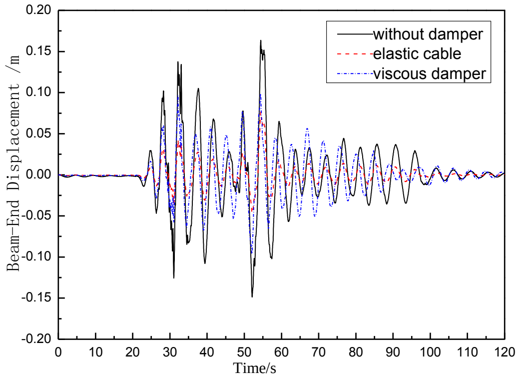


Fig. 10 - Beam-End Horizontal Displacement

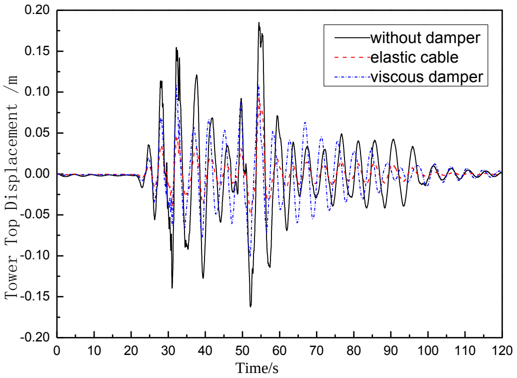


Fig. 11 - Tower Top Horizontal Displacement

5. Conclusions

As shown in the seismic response analysis, the cable-stayed bridge has the larger tower top longitudinal displacement, larger beam-end longitudinal displacement, and larger bending moment of the tower bottom. Through a comparative analysis on the damping effects of elastic cable limiter and viscous damper on the cable-stayed bridge with floating system, it is found that both seismic isolation and control means can effectively control the structural internal force and displacement, especially the viscous damper which has certain superiorities in controlling the internal force. The main results include: (1) the viscous damper will not change the natural vibration characteristics of the structure, but the elastic cable will increase the natural frequency; and (2) both viscous damper and elastic cable can cut down the bending moment at the bottom of the main tower, while greatly reducing the longitudinal displacement of the main tower and main beam of cable-stayed bridge and diminishing the displacement and internal force at the same time.

Due to the uncertainty of seismic oscillation, and through the optimization analysis and comparison of elastic cable and viscous damper parameters, the appropriate parameters can be selected to achieve the desired damping effects. The two damping methods that use viscous damper and elastic cable, respectively have sound damping effects, with the former having better displacement-controlling effect.

ACKNOWLEDGMENT

This study was supported by the National Natural Science Funds (No. 51408040) and the Fundamental Research Funds for Central Universities (No. 2013G1211012).

REFERENCE

[1] FAN Li-chu,HU Shi-de,YE Ai-jun. 2001. Seismic Design of large span Bridges. People’s communications press ,102-117.

[2] WANG Di,HUANG Ping-ming.2008. Research on Deck-tower Connection of Super Long-span Cable-stayed Bridge. Journal of Zheng Zhou University(Engineering Science),56-61

[3] Q.Feng,M.Shinozuka.Control of seismic 1993. response of bridge struetores using variable dampers.Journal of Intelligent Materials Systems and Struetures, vol. 4, pp. 117-122.

[4] J.N.Yang, J.C.Wu, K.Kawashima.Hybrid 1995.control of seismic-exeited bridge struetures. E.E.S.D, vol. 24, No. 11, pp. 1437-1451.

[5] P.Tsopelas, M.C.Constantinou, S.Okamoto.1993. Experimental study of bridge seismic sliding isolati -on.Engineering Structures. vol. 18(4):301-310.

[6] C.S.Tsai, H.H.Lee.1993. Seismic mitigation of bridges by using viseoelastic dampers. Computers &St-ruetures, vol. 48, no. 4, pp. 719-727.

[7] YANG Meng-gang,2004.Study on Theory of Using Magnetorheological Damper to Control Seismic Response for Long-span Bridge. Chang sha,Central South University, pp.110-112.

[8] Priestley, M.J.N. 1997. Seismic and Strengthening Design of Bridges.Bei jing,People's communications press ,pp 105-128

[9] Shijun. 2015.The seismic respond analysis and earthquake reduction design of long span cable-stayed bridge.Chang'an University,XI'an..