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Passive control system for seismic protection of a multi-tower cable-stayed bridge

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Abstract. The performance of passive control system for the seismic protection of a multi-tower cable-stayed bridge with the application of partially longitudinal constraint system is investigated. The seismic responses of the Jiashao Bridge, a six-tower cable-stayed bridge using the partially longitudinal constraint system are studied under real earthquake ground motions. The effects of the passive control devices including the viscous fluid dampers and elastic cables on the seismic responses of the bridge are examined by taking different values of parameters of the devices. Further, the optimization design principle of passive control system using viscous fluid dampers is presented to determine the optimized parameters of the viscous fluid dampers. The results of the investigations show that the control objective of the multi-tower cable-stayed bridge with the partially longitudinal constraint system is to reduce the base shears and moments of bridge towers longitudinally restricted with the bridge deck. The viscous fluid dampers are found to be more effective than elastic cables in controlling the seismic responses. The optimized parameters for the viscous fluid dampers are determined following the principle that the peak displacement at the end of bridge deck reaches to the maximum value, which can yield maximum reductions in the base shears and moments of bridge towers longitudinally restricted with the bridge deck, with slight increases in the base shears and moments of bridge towers longitudinally unrestricted with the bridge deck.

Keywords: multi-tower cable-stayed bridge; seismic response; viscous fluid damper; elastic cable; passive control system

1. Introduction

The contemporary cable-stayed bridge is becoming more and more popular and being used where previously a suspension bridge might have been chosen. The increasing attention on cable-stayed bridges is not only due to their inherent beauty but also to the efficient utilization of structural materials and the increased stiffness over suspension bridges. For long-span cable-stayed bridges, the multi-tower cable-stayed bridges with three or more towers have been a recent design trend (Virlogeux 1999; Ni *et al*. 2005). Typical examples of this bridge type are the Millau Viaduct Bridge in France, the Maracaibo Bridge in Venezuela, the Rion-Antirion Bridge in Greece, the Mezcala Bridge in Mexico, the Dongting Lake Bridge in China, and the Ting Kau

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Bridge in Hong Kong (Virlogeux 1999; Barre *et al*. 1999; Papanikolas 2003; Ni *et al*. 2005). The longest multi-tower cable-stayed bridge in the world is Jiashao Bridge in China, which is a six-tower cable-stayed bridge with the total length 2680 m.

Compared with a conventional three-span cable-stayed bridge with two towers, large temperature-induced deformation in the long bridge deck is one of the major problems in the design of multi-tower cable-stayed bridges. The commonly used structural measure to reduce the temperature effects is the application of longitudinal constraints between the bridge deck and part of bridge towers such as the Millau Viaduct Bridge in France and the Jiashao Bridge in China. The application of the partially longitudinal constraint system can improve the static performance of the multi-tower cable-stayed bridge under temperature action. However, studies of the seismic performance of the multi-tower cable-stayed bridge using partially longitudinal constraint system under earthquake ground motions are meager. In addition, it is especially desirable to understand the performance of seismic control of the multi-tower cable-stayed bridge using partially longitudinal constraint system.

In the past, an amount of research work had been done on investigating the seismic performance of two-tower cable-stayed bridges using different longitudinal constraint systems between the bridge deck and towers (Camara *et al*. 2013). These studies had shown that the type of longitudinal constraint systems is one of the most important factors that affect the seismic responses of two-tower cable-stayed bridges. The fully constraint system with rigid connections between all bridge towers and the deck will reduce the displacements of the bridge deck and significantly increase the base shears and moments of towers. On the other hand, the displacements of the bridge deck will be excessive if the fully floating system with no connections between all towers and the deck is used. Considering the safety of bridge towers is vital to the cable-stayed bridges, the fully floating system is widely used in long-span two-tower cable-stayed bridges recently. In order to reduce the large displacements of the bridge deck in the fully floating system, various seismic control methods for the two-tower cable-stayed bridges had been investigated in detail by various researchers (Fujino and Siringoringo 2013). Especially, the benchmark seismic control problem for a two-tower cable-stayed bridge had been developed under the coordination of the ASCE Subcommittee on Benchmark Problems to investigate the effectiveness of various seismic control strategies, such as passive control (Domaneschi and Martinelli 2012), active control (Fallah and Taghikhany 2013), active and passive control (Bontempi *et al*. 2003), semi-active control (Domaneschi 2010), negative stiffness control (Iemura and Pradono 2009; Li *et al*. 2011) and hybrid control (He and Agrawal 2007). Among these control systems, passive control systems are of particular interests due to their reliability and ease of implementation. These investigations conducted into the application of passive control systems for two-tower cable-stayed bridges provide valuable references for the seismic protection of a multi-tower cable-stayed bridge using partially longitudinal constraint system.

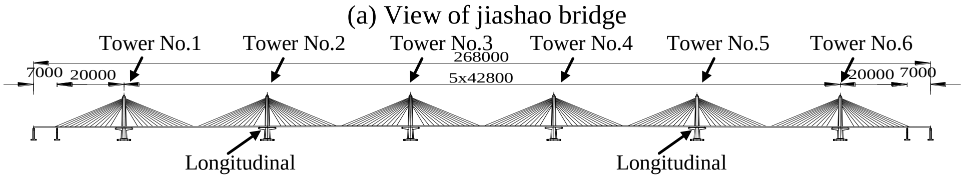
In the present study, the performance of passive control system for protecting a multi-tower cable-stayed bridge with the application of partially longitudinal constraint system under strong earthquake ground motions is investigated. The specific objectives of this study are to: (i) investigate the differences in the seismic responses of a multi-tower cable-stayed bridge using partially longitudinal constraint system and fully floating system; (ii) investigate the performance of elastic cables and viscous fluid dampers for the seismic control of a multi-tower cable-stayed bridge with the application of partially longitudinal constraint system; (iii) make a comparison of the seismic control effects using elastic cables and viscous fluid dampers; and (iv) to arrive at the values of optimal design parameters of the viscous fluid dampers for the seismic control of a multi-tower cable-stayed bridge with the application of partially longitudinal constraint system.

2. The multi-tower cable-stayed bridge model

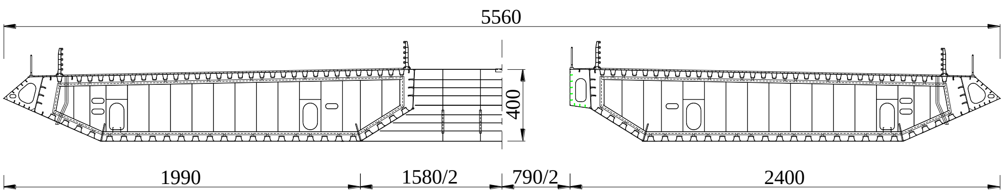
2.1 Bridge description

The subject of this study is Jiashao Bridge shown in Fig. 1(a), which is a six-tower cable-stayed bridge that crosses the Hangzhou Bay, along the highway between Jiaxing and Shaoxing in China. The total length of the bridge is 2680 m with the span arrangement of 70 m + 200 m + 5 × 428 m + 200 m + 70 m, which is the longest multi-span cable-stayed bridge in the world. Fig. 1(b) shows the design elevation view of the Jiashao Bridge. Its six single-leg towers are 172.174 m high supporting the bridge deck in conjunction with stay cables. There are 288 main stay cables in four planes anchored to the deck edge girders at 15 m intervals. The bridge deck is separated into two carriageways and each carriageway is flat steel box girder with 24 m wide and 4m high. Fig. 1(c) shows the typical deck cross-section of the bridge. In order to overcome the problem of large temperature deformation in the long bridge deck, the partially longitudinal constraint system is applied in the design of Jiashao Bridge. As shown in Fig. 1(b), the longitudinal constraints are applied to restrict the bridge deck from moving in the longitudinal direction at bridge towers No.2 and No.5, respectively. And there has no longitudinal restraints between the bridge deck and other bridge towers. The role of such partially longitudinal constraint system is to reduce the temperature-induced longitudinal deformation in the bridge deck.

(a) View of jiashao bridge



(b) Elevation of Jiashao bridge (unit: cm)



(c) Cross section of bridge deck (unit: cm)

Fig. 1 Jiashao bridge

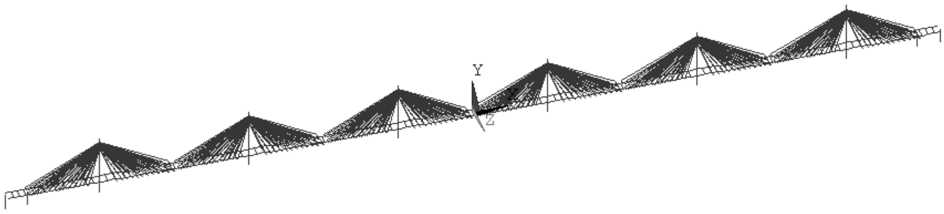


Fig. 2 Finite element model of Jiashao bridge

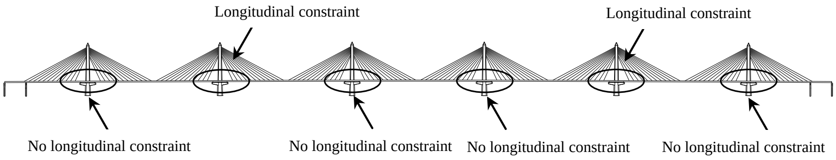
2.2 Finite element model

A three-dimensional finite element model of the Jiashao Bridge has been developed by use of the commercial software package ANSYS. The finite element model involves 1402 nodes and 1872 elements, as shown in Fig. 2. In this model, a double-girder model is used to simulate the bridge deck system when conducting dynamic analysis. The steel box girders, bridge towers and piers are all modeled as Timoshenko's beam elements with 6 degrees of freedom (DOFs) at each node, which account for transverse shear deformation, biaxial bending and axial strain. A 2-node truss element is used to simulate the stay cables, which accounts for only tension and no compression based on the real condition. Considering the geometric stiffness of stay cables under dead loadings, the equivalent elastic modulus for stay cables proposed by Ernst is adopted. Constraints are applied to restrict the bridge deck from moving in the lateral and vertical directions at all bridge towers and in the longitudinal direction at bridge towers No.2 and No.5. Boundary conditions restrict the motions of bridge deck at all bridge piers to allow only longitudinal displacement X and rotations about the Y and Z axes. Additionally, the bridge is assumed to be attached to bedrock, and the effects of soil-structure interactions are neglected.

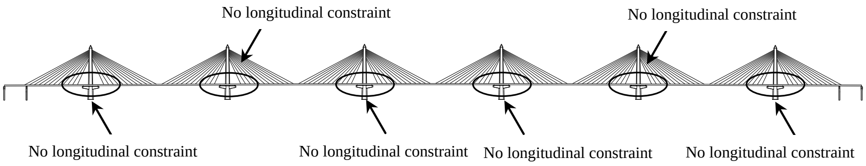
3. Seismic responses of the multi-tower cable-stayed bridge

3.1 Dynamic characteristics of the bridge

Considering the structural dynamic characteristics including modal frequencies and mode shapes form the basis of seismic analysis of the multi-tower cable-stayed bridges, it is especially desirable to understand the effect of aforementioned partially longitudinal constraint system on the dynamic characteristics of the bridge. Hence, the modal analysis of the Jiashao Bridge is conducted with the developed finite element model. The static equilibrium state of the bridge, which is the initial configuration for modal analysis, is achieved by geometrically nonlinear analysis of the bridge under dead loadings (Ni *et al*. 2005; He *et al*. 2009). The LANCZOS eigenvalue solver is adopted for modal analysis. Main vibration modes of finite element model are listed in Table 1. In order to investigate the effect of partially longitudinal constraints on the dynamic characteristics of the bridge, the contrast analytical model is developed based on the original finite element model of Jiashao Bridge. In the contrast model, the longitudinal constraints between the bridge deck and all six towers are released in the bridge, i.e., fully floating system. The illustrations of partially longitudinal constraint system and fully floating system are shown in Fig. 3. The modal analysis results of fully floating system are also shown in Table 1.



(a) Partially longitudinal constraint system



(b) Fully floating system

Fig. 3 Illustrations of partially longitudinal constraint system and fully floating system

Table 1 Vibration modes of the original model of Jiashao Bridge and contrast model

Partially longitudinal constraint system			Fully floating system		
Mode No.	Frequency /Hz	Description	Mode No.	Frequency /Hz	Description
1	0.2274	1st symmetric vertical bending of bridge deck + symmetric longitudinal bending of bridge tower	1	0.1704	1st symmetric vertical bending of bridge deck + symmetric longitudinal bending of bridge tower
2	0.2615	1st anti-symmetric vertical bending of bridge deck + anti-symmetric longitudinal bending of bridge tower	2	0.1725	Longitudinal floating + 1st anti-symmetric vertical bending of bridge deck + anti-symmetric longitudinal bending of bridge tower
3	0.2894	1st symmetric lateral bending of bridge tower	3	0.2304	2nd symmetric vertical bending of bridge deck + symmetric longitudinal bending of bridge tower
4	0.2907	1st anti-symmetric lateral bending of bridge tower	4	0.2617	2nd anti-symmetric vertical bending of bridge deck + anti-symmetric longitudinal bending of bridge tower
9	0.3085	2nd symmetric vertical bending of bridge deck + symmetric longitudinal bending of bridge tower	5	0.2894	1st symmetric lateral bending of bridge tower
10	0.3618	2nd anti-symmetric vertical bending of bridge deck + anti-symmetric longitudinal bending of bridge tower	6	0.2907	1st anti-symmetric lateral bending of bridge tower
21	0.7087	1st symmetric lateral bending of bridge deck + symmetric lateral bending of bridge tower	23	0.7071	1st symmetric lateral bending of bridge deck + symmetric lateral bending of bridge tower

Table 1 Continued

33	0.8956	1st anti-symmetric lateral bending of bridge deck + anti-symmetric lateral bending of bridge tower	31	0.8558	1st anti-symmetric lateral bending of bridge deck + anti-symmetric lateral bending of bridge tower
43	1.1361	1st symmetric torsion of bridge deck	43	1.1357	1st symmetric torsion of bridge deck
44	1.1389	2nd symmetric torsion of bridge deck	44	1.1384	2nd symmetric torsion of bridge deck

Comparing the modal analysis results between the original model and contrast model as shown in Table 1, it can be seen that:

(i) In the original model with partially constraint system, the longitudinal floating vibration mode doesn't occur due to the longitudinal constraints between the bridge deck and two bridge towers. However, the longitudinal floating vibration mode occurs in the contrast model with fully floating system.

(ii) The modal frequency of the first symmetric vertical bending mode of bridge deck of the original model with partially constraint system is 0.2274Hz, while the modal frequency of the contrast model with fully floating system is 0.1704Hz. The relative variation is about 25.07%. And the modal frequencies of the first anti-symmetric vertical bending of bridge deck of the original model and contrast model are 0.2615Hz and 0.1725Hz, respectively. The relative variation is about 34.03%. Hence, the application of the partially longitudinal constraints between the bridge deck and two towers significantly increases the vertical bending stiffness of the bridge deck.

(iii) The modal frequencies of the first symmetric lateral bending mode of bridge deck of the original model and contrast model are 0.7087Hz and 0.7071Hz, respectively. The relative variation is about 0.23%. And the modal frequencies of the first anti-symmetric lateral bending mode of bridge deck of the original model and contrast model are 0.8956Hz and 0.8558Hz, respectively. The relative variation is about 4.44%. Hence, the application of the partially longitudinal constraints has little effect on the modal frequencies of lateral bending modes of the bridge deck.

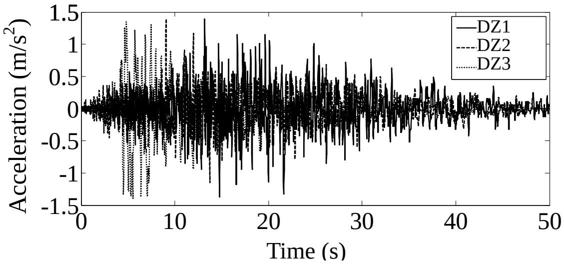
(iv) The modal frequencies of the first symmetric lateral bending mode and first anti-symmetric lateral bending mode of bridge tower are both 0.2894Hz and 0.2907Hz, respectively with regard to the original model and contrast model, which indicates that the application of the partially longitudinal constraints has no effect on the modal frequencies of lateral bending modes of bridge tower.

(v) The modal frequencies of the first symmetric torsional mode of bridge deck of the original model and contrast model are 1.1361Hz and 1.1357Hz, respectively. The relative variation is only about 0.04%, which indicates that the application of the partially longitudinal constraints has little effect on the modal frequencies of torsional modes of bridge deck.

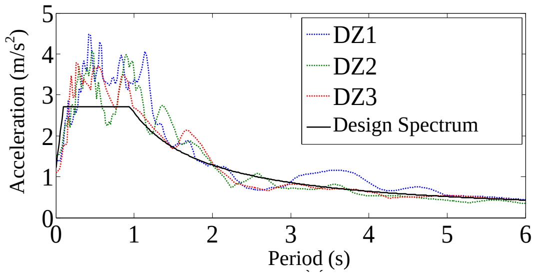
From the aforementioned analysis results, with the application of partially longitudinal constraint system in the multi-tower cable-stayed bridge, the longitudinal floating vibration mode disappears and the modal frequencies of vertical bending modes of bridge deck are significantly increased, which deserves special attention when conducting seismic analysis.

3.2 Seismic responses of the bridge

The seismic responses of the multi-tower cable-stayed bridge are investigated under three different real earthquake ground motions as shown in Table 2. The time history curves of three earthquake ground motions (DZ1, DZ2 and DZ3) are shown in Fig. 4(a), in which the peak ground acceleration of selected earthquake ground motions is adjusted to 0.1392g according to seismic risk analysis of the bridge site. The corresponding acceleration response spectra of the ground motions for a 2% damping ratio are shown in Fig. 4(b). The seismic design spectrum is also shown in Fig. 4(b), which is in accordance with the acceleration response spectra of the real earthquake ground motions. As damping in the bridge structure is generally very low, therefore 2% damping is assumed in the present study. One-dimensional ground acceleration is assumed to act uniformly at all the supports along the longitudinal direction of the bridge. The maximum results from calculation results of three earthquake ground motions are selected to evaluate the seismic performance of the multi-tower cable-stayed bridge.

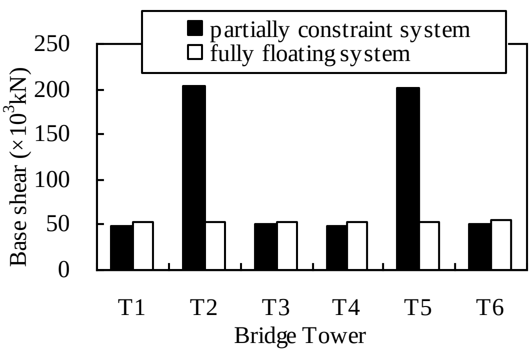


(a) Time-history curves

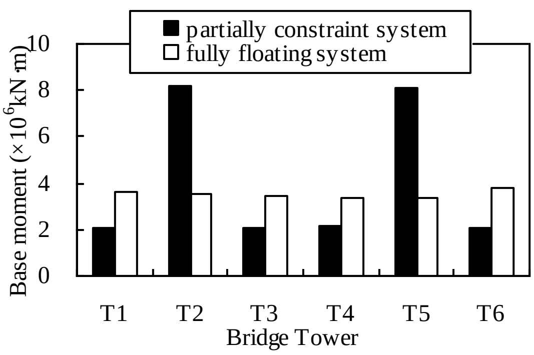


(b) Acceleration response spectra

Fig. 4 Time-history curves and acceleration response spectra of earthquake ground motions



(a) Peak base shear



(b) Peak base moment

Fig. 5 Peak base shears and peak base moments of bridge towers

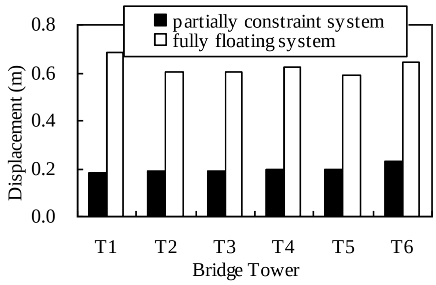


Fig. 6 Peak displacements on the top of bridge towers

Table 2 Selected earthquake ground motions

Ground motion No.	Earthquake name	Recording station	Effective duration (s)	Characteristic period (s)	PGA (g)
DZ1	AR-E	El Salvado-AR	46.38	0.93	0.289
DZ2	AR-N	El Salvado-AR	45.48	0.92	0.357
DZ3	BA-E	El Salvado-BA	37.70	0.89	1.098

Table 3 Peak displacements at two ends of the bridge deck

Peak displacement	Partially constraint system	Fully floating system
Left end (m)	0.1586	0.7023
Right end (m)	0.1589	0.7025

To evaluate the seismic performance of the multi-tower cable-stayed bridge with the application of partially longitudinal constraint system, the longitudinal response quantities selected are: the peak base shear of the bridge tower, the peak base moment of the bridge tower, the peak displacement at the end of the bridge deck, and peak displacement on the top of the bridge tower. Fig. 5 shows the peak base shears and moments of bridge towers. Fig. 6 shows peak displacements on the top of bridge towers. Table 3 shows the peak displacements at two ends of the bridge deck. In order to investigate the effect of partially longitudinal constraints on the seismic responses of the bridge, the seismic responses of the contrast model with fully floating system are also calculated and shown in Fig. 5, Fig. 6 and Table 3.

It can be seen from Fig. 5, Fig. 6 and Table 3 that: (i) The peak base shears and moments of the bridge towers No.2 and No.5 in the partially longitudinal constraint system are 4 times as those in the other towers. Thus, part of bridge towers longitudinally restricted with the bridge deck results in the concentration effects of base shear and moment. In contrast, the peak base shears and moments of all towers are uniformly distributed in the fully floating system.

(ii) With regard to the partially longitudinal constraint system and fully floating system, the peak base shear and moment of the bridge tower are found to be a maximum for the bridge towers No.2 and No.5 in the partially longitudinal constraint system due to the increases in the modal frequencies of vertical bending modes of bridge deck in combination of the longitudinal concentration effects of base shear and base moment.

(iii) The peak displacements on the top of bridge towers and the peak displacements at two ends of bridge deck in the fully floating system are around 3 times and 4.5 times as those in the partially longitudinal constraint system. This is because the longitudinal floating vibration mode disappears in the partially longitudinal constraint system, which leads to the small displacements of the bridge deck and towers.

Therefore, the advantages of the multi-tower cable-stayed bridge with the application of partially longitudinal constraint system are that the peak displacements of the bridge deck and towers are very small and the peak base shears and moments of those towers which are longitudinally unrestricted with the bridge deck are also small. However, the disadvantage is that the peak base shears and moments of those towers longitudinally restricted with the bridge deck are too large. Therefore, the control objective of the partially longitudinal constraint system is to reduce the peak base shears and moments of bridge towers longitudinally restricted with the bridge deck, which is very different from the fully floating system. In the fully floating system, the peak displacements of the bridge deck and towers are too large. In contrast, the peak base shears and moments of all towers are relatively small. Hence, the control objective of the fully floating system is to reduce the peak displacements of the bridge deck and towers.

4. Performance of passive control devices

4.1 Parametric study on viscous fluid damper

Viscous fluid dampers and elastic cables are typically used in the long-span cable-stayed bridges with fully floating system, in which the viscous fluid dampers and elastic cables provide longitudinal links between the bridge deck and towers, so as to effectively reduce the large displacements of the bridge deck when subjected to earthquake ground motions. In this section, a parametric study is performed to investigate the effects of viscous fluid dampers and elastic cables on the seismic control of the multi-tower cable-stayed bridge with the application of partially longitudinal constraint system.

In a viscous fluid damper, the damping force f is described as (Lang *et al*. 2013)

$$f = c|v|^{\alpha}\,\mathrm{sgn}(v) \tag{1}$$

Where c is the damping coefficient of the damper; α is the velocity exponent of the damper; v is the relative velocity across the damper. From Eq. (1), the damping coefficient and the velocity exponent are the two parameters that govern the selection of a viscous fluid damper. In the present study, the velocity exponent α is varied from 0.2 to 1.0 with the interval of 0.2. And the damping coefficient c is varied from 2000 to 16000 with the interval of 2000. Considering the configuration of the multi-tower cable-stayed bridge with the partially longitudinal constraint system, the viscous fluid dampers are placed at the bridge towers longitudinally unrestricted with the bridge deck, i.e. tower No.1, No.3, No.4 and No.6 in Jiashao Bridge as shown in Fig. 7.

A parametric study is performed to investigate the effects of variations in damping coefficient c and velocity exponent α of viscous fluid dampers on the seismic responses of the bridge. The results of the parametric study are shown in Figs. 8- 11. Figs. 8 and 9 show the peak base shears and moments of the bridge towers controlled by viscous fluid damper. It can be seen from Figs. 8 and 9 that:

(i) For all the velocity exponents α, the peak base shear and moment of the bridge tower No. 2 reduce reasonably with increasing damping coefficient c of the viscous fluid dampers. For a

specific damping coefficient c, the peak base shear and moment of the bridge tower No. 2 reduce with a decreasing in velocity exponents α. For the values of damping coefficient c = 16000 and velocity exponents α = 0.2, the reductions observed in the base shear and moment of tower No.2 are 53% and 47%, respectively.
(ii) For all the velocity exponents α, the peak base shears and moments of the bridge towers No.1 and No. 3 increase with an increasing in damping coefficient c. For a specific damping coefficient c, the peak base shears and moments of the bridge tower No. 1 and No.3 increase reasonably with a decreasing in velocity exponents α. For the values of damping coefficient c = 16000 and velocity exponents α = 0.2, the increases observed in the base shears of tower No.1 and No. 3 are 92% and 55%, respectively. And the increases observed in the base moments of tower No.1 and No. 3 are 90% and 75%, respectively. Therefore, for the partially longitudinal constraint system, the control effects for the base shears and moments of bridge towers are approximately the same due to the small peak displacements on the top of bridge towers.

Fig. 10 and Fig. 11 show the peak displacements on the top of bridge towers and peak displacements at two ends of bridge deck controlled by viscous fluid dampers. It can be observed from Fig. 10 and Fig. 11 that:

(i) With regard to the bridge tower No.1, the peak displacement on the top of the tower reduces with an increase in damping coefficient c up to a certain level for the velocity exponents α = 0.2 and 0.4. The maximum reduction in the peak displacement of bridge tower No.1 is around 6%. With regard to the bridge tower No.2, the peak displacement on the top of the tower reduces with an increase in damping coefficient c up to a certain level for the velocity exponents α = 0.2, 0.4, 0.6 and 0.8. The maximum reduction in the peak displacement of bridge tower No.1 is around 20%. With regard to the bridge tower No.3, the peak displacement on the top of the tower reduces with an increase in damping coefficient c. For the values of damping coefficient c = 16000 and velocity exponent α = 0.2, the reduction observed in the peak displacement of bridge tower No. 3 is around 16%.

(ii) For the velocity exponents α = 0.6, 0.8 and 1.0, the peak displacements at two ends of the bridge deck increase with an increasing in damping coefficient c. And for the velocity exponents α = 0.2 and 0.4, the peak displacements of bridge deck increase with an increase in damping coefficient c up to a certain level, giving maximum values for the peak displacements of bridge deck. The maximum increase in the peak displacements of bridge deck is around 22%, which corresponds to the parameters of damping coefficient c = 12000 and velocity exponents α = 0.4.

The analytical investigations for the seismic control of the multi-tower cable-stayed bridge with the partially longitudinal constraint system using viscous fluid dampers indicate that the large base shears and moments of bridge towers longitudinally restricted with the bridge deck are significantly reduced, with significant increases in the base shears and moments of bridge towers longitudinally unrestricted with the bridge deck. Furthermore, the displacements on the top of bridge towers are found to be slightly reduced, with slight increases in the displacements at two ends of bridge deck.

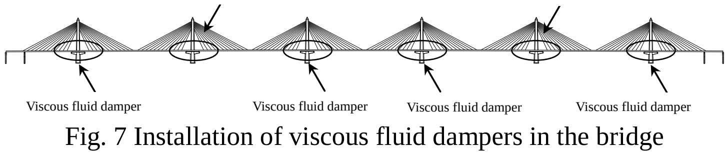
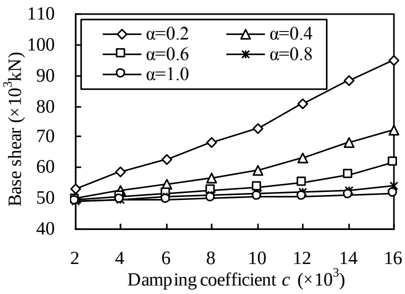
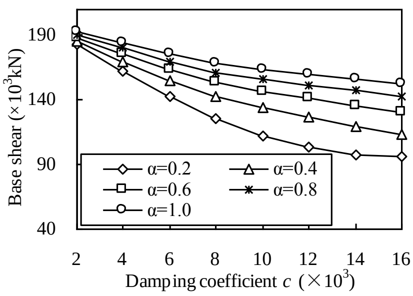


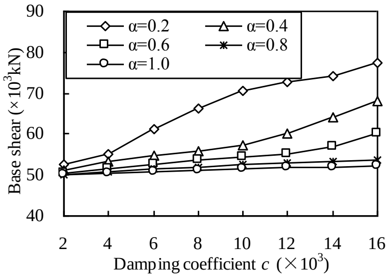
Fig. 7 Installation of viscous fluid dampers in the bridge



(a) Peak base shear of tower No.1

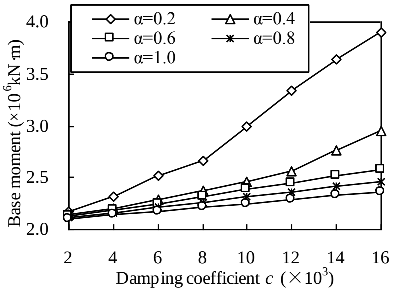


(b) Peak base shear of tower No.2

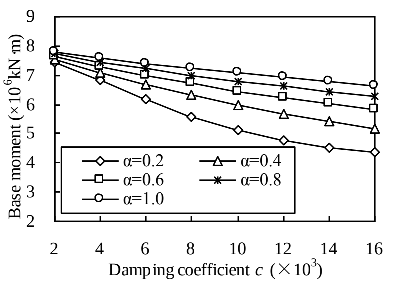


(c) Peak base shear of tower No.3

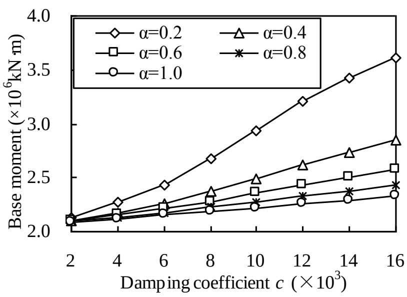
Fig. 8 Effects of variations in damping coefficient and velocity exponent of the viscous fluid dampers on the peak base shears of bridge towers



(a) Peak base moment of tower No.1

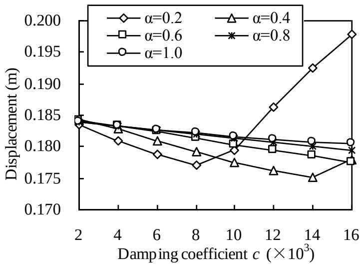


(b) Peak base moment of tower No.2

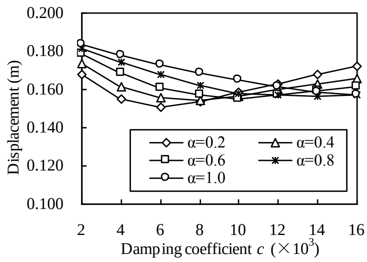


(c) Peak base moment of tower No.3

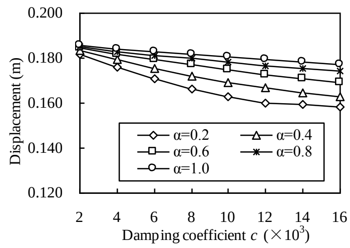
Fig. 9 Effects of variations in damping coefficient and velocity exponent of the viscous fluid dampers on the peak base moments of bridge towers



(a) Peak displacement of tower No.1

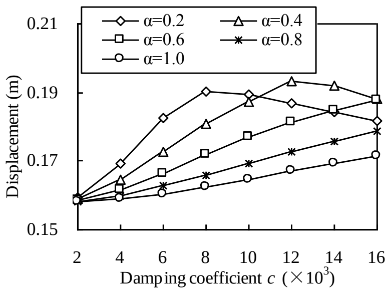


(b) Peak displacement of tower No.2

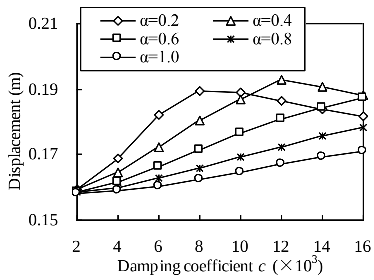


(c) Peak displacement of tower No.3

Fig. 10 Effects of variations in damping coefficient and velocity exponent of the viscous fluid dampers on the peak displacements on the top of bridge towers



(a) Peak displacement at the left end of bridge deck



(b) Peak displacement at the right end of bridge deck

Fig. 11 Effects of variations in damping coefficient and velocity exponent of the viscous fluid dampers on the peak displacements at two ends of bridge deck

4.2 Parametric study on elastic cable

In an elastic cable, the cable force F is described as

$$F = kd \tag{2}$$

where k is the elastic stiffness of the cable; d is the cable deformation. From Eq. (2), the elastic stiffness is the parameter that governs the selection of elastic cable. In the present study, the elastic stiffness k is varied from 0 to 10^8 kN/m. Considering the configuration of the multi-tower cable-stayed bridge with the partially longitudinal constraint system, the elastic cables are placed at the bridge towers longitudinally unrestricted with the bridge deck, i.e. tower No.1, No.3, No.4 and No.6 in Jiashao Bridge as shown in Fig. 12.

A parametric study is performed to investigate the effects of variations in elastic stiffness *k* of elastic cables on the seismic responses of the bridge. The results of the parametric study are shown in Fig. 13- Fig. 16. Fig. 13 and Fig. 14 show the peak base shears and moments of the bridge towers controlled by elastic cables. It can be seen from Fig. 13 and Fig. 14 that:

(i) When the elastic stiffness *k* is less than 10^4 kN/m, the peak base shear and moment of the bridge tower No. 2 remain almost the same. And when the elastic stiffness *k* is in the range of 10^4 kN/m~5×10^6 kN/m, the peak base shear and moment of the bridge tower No. 2 reduce reasonably with increasing elastic stiffness *k* of elastic cables. Finally when the elastic stiffness *k* is larger than 5×10^6 kN/m, the peak base shear and moment remain almost the same. For the value of elastic stiffness $k = 5 \times 10^6$ kN/m, the reductions observed in the base shear and moment of tower No.2 are both around 45%.

(ii) When the elastic stiffness *k* is less than 5×10^4 kN/m, the peak base shears and moments of the bridge tower No.1 and No.3 remain almost the same. And when the elastic stiffness *k* is larger than 5×10^4 kN/m, the peak base shears and moments of the bridge tower No. 1 and No.3 increase with an increasing in elastic stiffness *k*. For the value of elastic stiffness $k = 10^8$ kN/m, the increases observed in the base shears of tower No.1 and No.3 are 155% and 147%, respectively. And the increases observed in the base moments of tower No.1 and No.3 are 153% and 136%, respectively.

Fig. 15 and Fig. 16 show the peak displacements on the top of bridge towers and peak displacements at two ends of bridge deck controlled by elastic cables. It can be observed from Fig. 15 and Fig. 16 that:

(i) When the elastic stiffness *k* is less than 10^5 kN/m, the peak displacements on the top of the towers remain almost the same. And when the elastic stiffness *k* is larger than 10^5 kN/m, the peak displacements on the top of the towers increase with an increasing in the elastic stiffness *k*. For the value of elastic stiffness $k = 10^8$ kN/m, the increases observed in the peak displacements of tower No.1, No.2 and No.3 are 28%, 18% and 12%, respectively.

(ii) The peak displacements at two ends of bridge deck increase with an increase in elastic stiffness *k* up to a certain level, giving a maximum value for the peak displacement of bridge deck. The maximum increase in the peak displacement of bridge deck is found to be 20% with the elastic stiffness $k = 10^5$ kN/m. It should be noted that the longitudinal floating vibration mode disappears when the elastic stiffness *k* is larger than 10^5 kN/m. Hence, the longitudinal floating vibration mode has a significant effect on the peak displacement of bridge deck.

The analytical investigations for the seismic control of the multi-tower cable-stayed bridge with the partially longitudinal constraint system using elastic cables indicate that the large base shears and moments of bridge towers longitudinally restricted with the bridge deck are significantly reduced, with significant increases in the base shears and moments of bridge towers longitudinally unrestricted with the bridge deck. Furthermore, the displacements on the top of bridge towers and displacements at two ends of bridge deck are both found to be slightly increased.

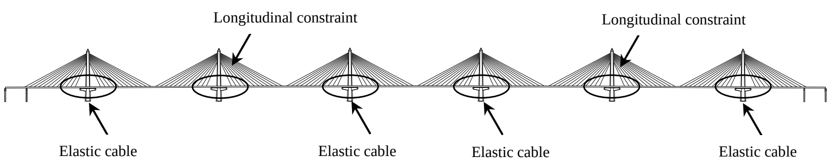
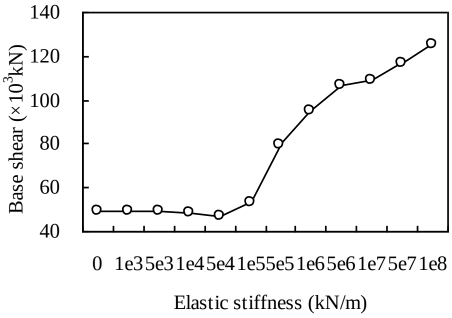
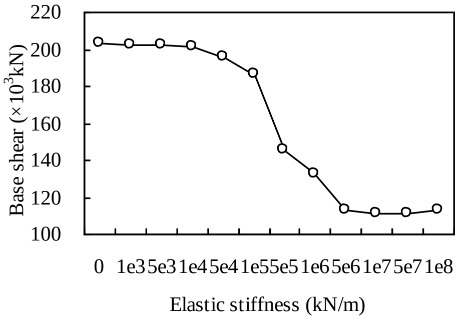


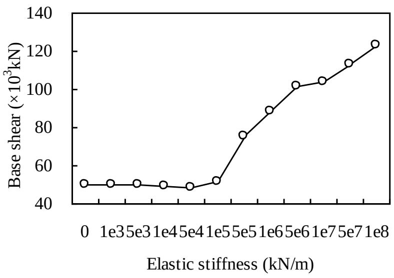
Fig. 12 Installation of elastic cables in the bridge



(a) Peak base shear of tower No.1

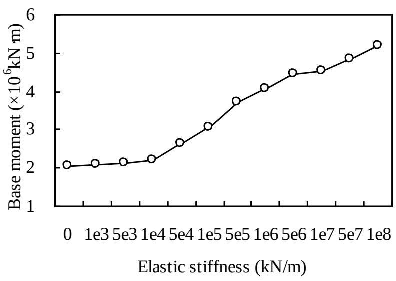


(b) Peak base shear of tower No.2

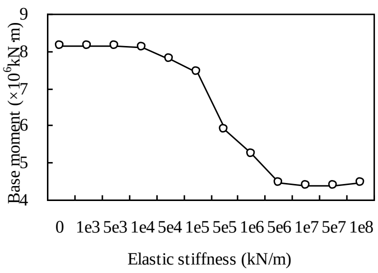


(c) Peak base shear of tower No.3

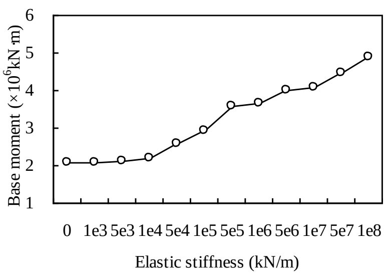
Fig. 13 Effects of variations in elastic stiffness of the elastic cables on the peak base shears of bridge towers



(a) Peak base shear of tower No.1

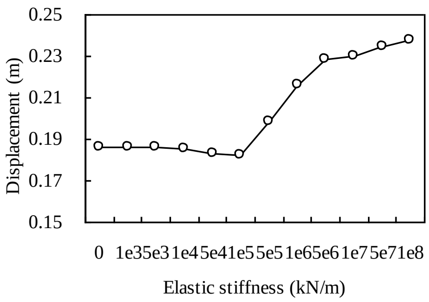


(b) Peak base shear of tower No.2

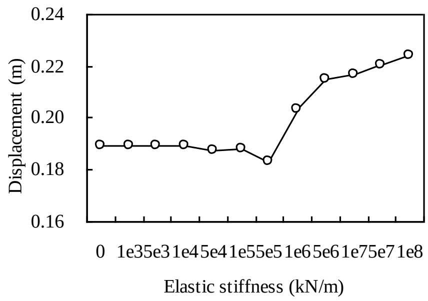


(c) Peak base moment of tower No.3

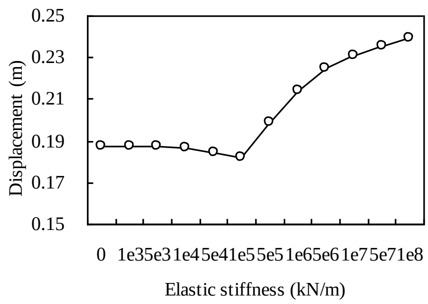
Fig. 14 Effects of variations in elastic stiffness of the elastic cables on the peak base moments of bridge towers bridge towers



(a) Peak base shear of tower No.1

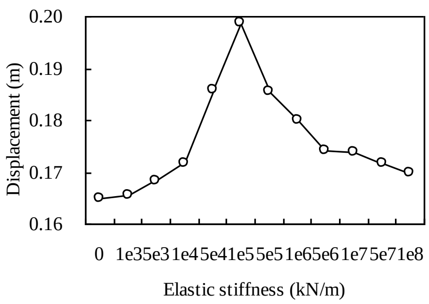


(b) Peak base shear of tower No.2

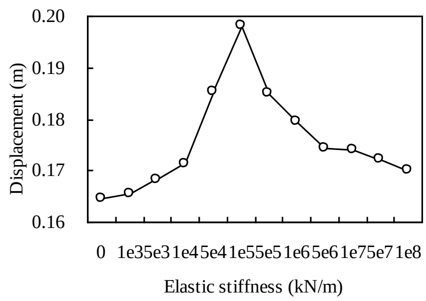


(c) Peak displacement of tower No.3

Fig. 15 Effects of variations in elastic stiffness of the elastic cables on the peak displacements on the top of bridge towers



(a) Peak displacement at the left end of bridge deck

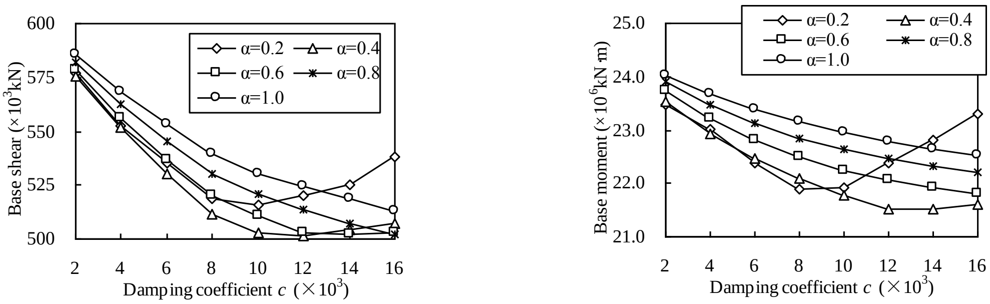


(b) Peak displacement at the right end of bridge deck

Fig. 16 Effects of variations in elastic stiffness of the elastic cables on the peak displacements at two ends of bridge deck

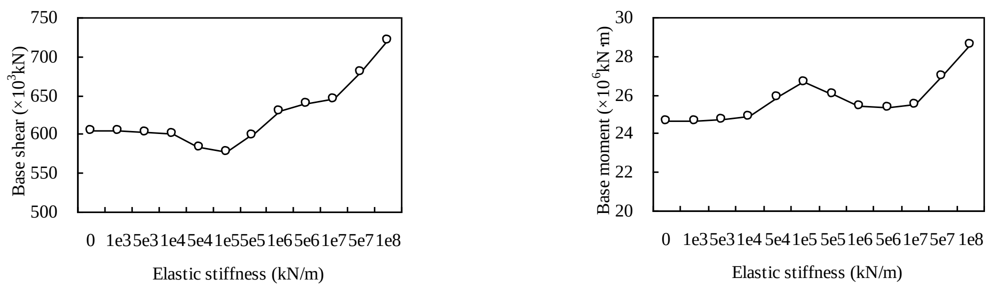
4.3 Discussion

The results of the parametric study reveal that the installations of viscous fluid dampers and elastic cables are beneficial for the reductions in base shears and moments of bridge towers longitudinally restricted with the bridge deck, with significant increases in the base shears and moments of bridge towers longitudinally unrestricted with the bridge deck and slight increases in the peak displacements at two ends of bridge deck, which is very different from the fully floating



(a) Total base shear (b) Total base moment

Fig. 17 Effects of variations in damping coefficient and velocity exponent of the viscous fluid dampers on the total base shear and moment of bridge towers



(a) Total base shear (b) Total base moment

Fig. 18 Effects of variations in elastic stiffness of the elastic cables on the total base shear and moment of bridge towers

system. In the fully floating system, the large peak displacements of the bridge deck can be significantly reduced using viscous fluid dampers and elastic cables, usually with slight increases in the base shears of bridge towers.

In order to compare the seismic control effects using viscous fluid dampers and elastic cables, Fig. 17 and Fig. 18 show the total base shear and moment of all bridge towers controlled by viscous fluid dampers and elastic cables, respectively. From Fig. 17, it is observed that total base shear and moment are reduced using the viscous fluid dampers with an increase in damping coefficient c up to a certain level, giving an optimum value of the damping coefficient c. Therefore, the total base shear and moment of all bridge towers obtain the minimum values in the terms of damping coefficient c = 12000 and velocity exponent α = 0.4. And it is observed in Fig. 18 that the total base shear and moment using elastic cables increase reasonably with an increase in elastic stiffness k. In addition, the displacements on the top of bridge towers are found to be slightly reduced using the viscous fluid dampers and slightly increased using elastic cables shown in Fig. 10 and Fig. 15, respectively.

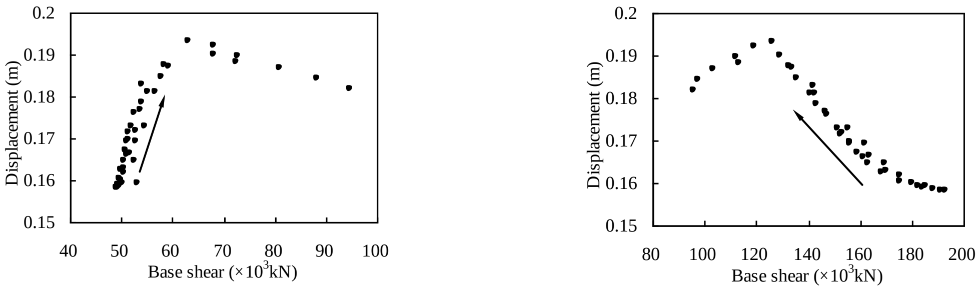
Therefore, the results of the investigations demonstrate that the installations of elastic cables are to increase the rigidity of the bridge so that the total base shear and moment of bridge towers are increased and seismic energies of the bridge towers longitudinally restricted with the bridge deck are transferred to other towers unrestricted with the bridge deck. However, the installations of viscous fluid dampers increase the energy dissipation capacities so that the total base shear and moment of bridge towers are reduced substantially while simultaneously limiting the displacements on the top of bridge towers. Therefore, the viscous fluid dampers are found to be more effective than elastic cables in controlling the seismic responses of the multi-tower cable-stayed bridge with the application of partially longitudinal constraint system.

5. Optimization design of passive control system

The parametric studies performed using viscous fluid dampers and elastic cables indicate that the passive control system using viscous fluid dampers is more effective in controlling the seismic responses of the multi-tower cable-stayed bridge with the partially longitudinal constraint system. Thus, the optimization design of passive control system using viscous fluid dampers is necessary for practical application (Takewaki 2009; Murakami *et al*. 2013). In this section, the optimization design principle is proposed to determine the optimized parameters c and α of the viscous fluid dampers.

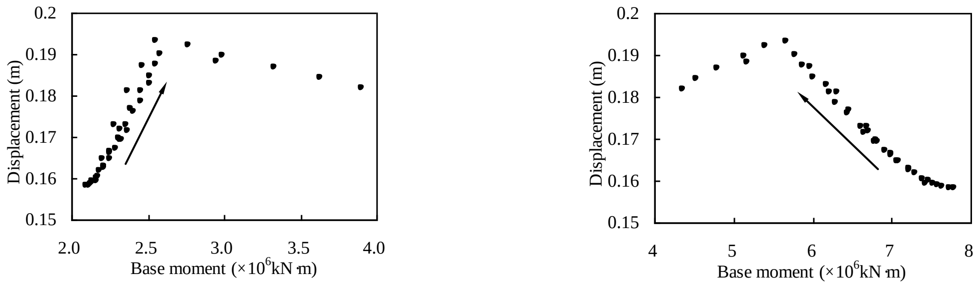
In the Section 4.1, the parametric study results show that the controlling effects between bridge towers longitudinally restricted with the bridge deck and those unrestricted with the bridge deck are contradictory. And the displacements at two ends of bridge deck are slightly increased. Therefore, the optimization design objective of passive control system is to yield maximum reductions in the base shears and moments of bridge towers longitudinally restricted with the bridge deck, with hampering the significant gain achieved in the base shears and moments of bridge towers longitudinally unrestricted with the bridge deck. Meantime, the unfavorable controlling effect on the displacements at two ends of bridge deck is also worthy of attention. Based on the parametric study results shown in Fig. 8, Fig. 9 and Fig. 11, the relationships between the base shears and moments of bridge towers and displacements of bridge deck under the controlling of viscous fluid dampers using different parameters of damping coefficient c and velocity exponent α are plotted in Fig. 19 and Fig. 20.

It is observed in Fig. 19(a) and Fig. 20(a) that, with the increases of base shear and moment of tower No. 1, the peak displacement at the left end of bridge deck increases up to the maximum value and then reduces very slowly. And in Fig. 19(b) and Fig. 20(b), it can be observed that with the decreases of base shear and moment of tower No.2, the peak displacement at the left end of bridge deck increases up to the maximum vale and then reduces very slowly. Therefore, with the installations of viscous fluid dampers, the base shear and moment of tower No.2 must be reduced, together with the increases in the base shear and moment of tower No.1 and the peak displacement at the left end of bridge deck. It can be also observed from Fig. 19 and Fig. 20 that, when the peak displacement at the left end of bridge deck reaches to the maximum value, the base shear and moment of tower No.2 can be reduced significantly, with the slight increases in the base shear and moment of tower No.1. And when the peak displacement reduces over the extreme point, the base shear and moment of tower No.2 reduce slowly, with the significant increases in the base shear and moment of tower No.1. Therefore, considering the efficiency of seismic control, the optimized parameters for the viscous fluid dampers are judiciously determined following the principle that the peak displacement at the end of bridge deck reaches to the maximum value. It should be noted that for the partially longitudinal constraint system, the displacement at the end of bridge deck is still small and in the controllable range even if it reaches to the maximum value, which is different from the seismic control of the cable-stayed bridges with the fully floating system.



(a) Base shear of tower No. 1 (b) Base shear of tower No. 2

Fig. 19 The relationship between the base shear of the bridge tower and displacement at the left end of bridge deck



(a) Base moment of tower No. 1 (b) Base moment of tower No. 2

Fig. 20 The relationship between the base moment of the bridge tower and displacement at the left end of bridge deck

Table 4 Optimized results for passive control system

Response quantity	Uncontrolled response f_0	Controlled response f_1	Variation (f_0- f_1)
Base shear of tower No.1 (×10^{3}kN)	49.13	63.06	-13.93
Base moment of tower No.1 (×10^{6}kN • m)	2.06	2.56	-0.50
Base shear of tower No.2 (×10^{3}kN)	202.85	126.23	76.62
Base moment of tower No.2 (×10^{6}kN • m)	8.16	5.67	2.49
Base shear of tower No.3 (×10^{3}kN)	49.92	60.12	-10.20
Base moment of tower No.3 (×10^{6}kN • m)	2.06	2.61	-0.55
Displacement on the top of tower No.1 (m)	0.186	0.176	0.010
Displacement on the top of tower No.2 (m)	0.190	0.160	0.030
Displacement on the top of tower No.3 (m)	0.187	0.167	0.020
Displacement at the end of bridge deck (m)	0.159	0.193	-0.034

As shown in Fig. 11, the peak displacement at the end of bridge deck reaches to the maximum value when the damping coefficient c is 12000 and velocity exponent α is 0.4. Table 4 shows the passive control results using the parameters of c = 12000 and α = 0.4. It can be observed that the reductions in the base shear and moment of tower No.2 are 76.62×10^{3}kN and 2.49 × 10^{6}kN·m, respectively. And the increases in base shear and moment of tower No.1 are 13.93 × 10^{3}kN and

0.50×10^6kN·m, respectively. It should be noted that the total base shear and moment of all bridge towers obtain the minimum values in the terms of damping coefficient c = 12000 and velocity exponent α = 0.4 as shown in Fig. 17, which indicates the selection principle for the optimized parameters of the viscous fluid dampers is reasonable.

6. Conclusions

The performance of passive control system in protecting a multi-tower cable-stayed bridge with the application of partially longitudinal constraint system subjected to strong earthquake ground motions is investigated. The seismic responses of the Jiashao Bridge, a six-tower cable-stayed bridge are studied under three real earthquake motions and the differences between the partially longitudinal constraint system and fully floating system are discussed. The seismic responses of the bridge using the passive control devices including viscous fluid dampers and elastic cables are evaluated and the comparisons between the viscous fluid dampers and elastic cables are made in order to verify their effectiveness. Finally, the optimization design principle of passive control system using viscous fluid dampers is presented to determine the optimized parameters of the viscous fluid dampers for the multi-tower cable-stayed bridge with the partially longitudinal constraint system. From the analytical results of the present study the following conclusions are drawn:

(1) The base shears and moments of bridge towers longitudinally unrestricted with the bridge deck are small for the multi-tower cable-stayed bridge with the application of partially longitudinal constraint system. The displacement responses of the bridge deck are also very small. However, the base shears and moments of bridge towers longitudinally restricted with the bridge deck are too large. Therefore, the control objective of the partially longitudinal constraint system is to reduce the base shears and moments of bridge towers longitudinally restricted with the bridge deck, which is very different from the fully floating system. The control objective of the fully floating system is to reduce the large peak displacements of the bridge deck.

(2) The installations of viscous fluid dampers and elastic cables are beneficial for the reductions in base shears and moments of bridge towers longitudinally restricted with the bridge deck, with significant increases in the base shears and moments of bridge towers longitudinally unrestricted with the bridge deck and slight increases in the peak displacements at two ends of bridge deck. Furthermore, the displacement responses on the top of bridge towers are found to be slightly reduced using viscous fluid dampers and slightly increased using elastic cables.

(3) The installations of elastic cables are to transfer the seismic energies of the bridge towers longitudinally restricted with the bridge deck to other towers unrestricted with the bridge deck. However, the installations of viscous fluid dampers increase the energy dissipation capacities so that the total base shear and moment of bridge towers are reduced substantially. Therefore, the viscous fluid dampers are found to be more effective than elastic cables in controlling the seismic responses of the multi-tower cable-stayed bridge with the application of partially longitudinal constraint system.

(4) Considering the efficiency of seismic control, the optimized parameters for the viscous fluid dampers are determined following the principle that the peak displacement at the end of bridge deck reaches to the maximum value, which can yield maximum reductions in the base shears and moments of bridge towers longitudinally restricted with the bridge deck, with slight increases in the base shears and moments of bridge towers longitudinally unrestricted with the bridge deck.

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