The Seismic Structural System of a Long-Span Single Pylon Cable-Stayed Bridge

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SUMMARY

The combination of floating system and supplementary longitudinal restraining devices may be a good solution for single pylon long-span cable-stayed bridges. The investigation of structural system for the Huguang Road Bridge，which is a single pylon cable-stayed bridge with a main span of 300m, has provided a case study that can supply references to similar structures.

Four design strategies are investigated under ground motions and their seismic responses compared including half-floating system, fixed system, half-floating system with dampers and half-floating system with elastic links. In addition, parametric studies are carried out to choose the optimal parameters of the dampers and elastic links, respectively. The combination of half-floating system and 4 viscous dampers allowing 340mm longitudinal relative movement between girder and pylon is able to ensure the seismic safety of the bridge, and is selected as the optimal structural system.

Keywords: Seismic structural system, cable-stayed bridge, viscous damper, elastic link

1. INTRODUCTION

A number of catastrophic failures of bridges happened due to severe, impulsive seismic events such as the 1994 Northridge earthquake in California, the 1995 Kobe earthquake in Japan and 1999 Chi-Chi earthquake in Taiwan(Panchal & Jangid, 2008). Failure of bridges during such seismic events will seriously hamper the relief and rehabilitation work. In order to protect long-span bridges from earthquake damages, the seismic design pays special attention to the design procedure.

An important number of long span cable-stayed bridges have been constructed in the world, and about one fourth of the total amount is single pylon cable-stayed bridges. The structural seismic behavior of this type of bridge is highly dependent on its structural system，which can be classified in the following categories(Ito,1992; Li,2006):1) free floating system with no bearing placed between the girder and the pylon, the deck longitudinally free; 2) half-floating system where longitudinal movable bearings are placed between the girder and the pylon; 3) fixed system where the girder is fixed to the pylon; 4) floating system with supplementary longitudinal restraining device. The comparison of static responses(Lin & Chopra,2002) indicates that the floating system will result in large longitudinal displacement at the end of the girder and at the top of pylons, moreover, the bending moment at the bottom of pylons caused by longitudinal static wind and braking forces will be very large; adding vertical supports between the girder and the pylon only changes the bending moment of girder near the bearings; the fixed system can strongly reduce the longitudinal movements of the deck, consequently, most of single pylon cable-stayed bridge adopt this solution. On the other hand, the seismic response analysis indicates(Lin & Chopra,2002) that the floating system will result in smaller internal forces of the pylon and large longitudinal displacement at the end of the girder and at the top of the pylons; furthermore, the fixed system can significantly reduce longitudinal deck movements, but it will increase internal pylon forces, however, if supplementary longitudinal restraining devices are installed between the girder and the pylon, they can clearly improve the seismic performance of the bridge(Xu, Zhang etc.,2004).

Consequently，the key issue of seismic design is the selection and design of supplementary restraining devices. In term of operating principles, supplementary restraining devices which have been previously used on long span bridges worldwide may be classified under two types, namely, elastic links and dampers. The elastic link, such as large rubber bearings erected on Tatara Bridge in Japan or the steel cables erected on the second Shantou Bay Bridge(Xu,2004) in China, provides elastic stiffness to all loads, but small energy dissipation. Supplemental damping devices which provide additional damping dissipate part of the seismic input energy, thereby reducing seismic demands on the structure. Fluid viscous dampers (FVDs) are the most popular damping devices in long span bridges, and have been installed on large bridges such as the Golden Gate Bridge, Oakland Bay Bridge in USA(Seim,2003). Fluid viscous dampers allow slow movements caused by temperature changes, traffic loads, etc., but reduce stresses and deflections caused by the earthquake through for dissipation of energy from the bridge. In some remarkable bridges two restraining devices have been combined, e.g. dampers and fuse links control the seismic response of the Rion-Antirion Bridge in Greece.

The single pylon cable-stayed bridge under investigation is the main bridge of Huguang Road Bridge, which is an urban arterial bridge in ChaoHu city, AnHui province, China, and has a main span of 300m. Because of the long span, the structural seismic behavior of the bridge is complicated; in order to ensure the safety of the bridge under ground shaking, the seismic structural system is investigated carefully in the technical design of the bridge.

In order to limit the longitudinal seismic displacements of the Huguang Road Bridge, two supplementary restraining devices were proposed in the technical design stage, namely, elastic links and dampers with ultimate stops. This paper is focused on the investigation of both devices, including their effect on the structural seismic behavior, the optimization of macroscopic response, and the selection of the final structural system of the bridge.

2. BRIDGE DESCRIPTION

The Huguang Road bridge consists of 6 approach spans(3×30m+3×30m) on the north side, 11 approach spans(3×30m+(36+58+36)+ 3×30m) on the south, and 2 main spans(202.5m+300m) to complete an overall bridge length of 1052.5m, with two-way 6 road lanes and two sidewalks held by a 35m wide deck. Figure 2.1 shows the elevation of the main bridge, which is the longest hybrid girder cable-stayed bridge with a single pylon and double cable planes in China, the 62 couples cable are anchored in the pylon with fan-arrangement. The hybrid deck is consists of a double steel girder, as shown in figure 2.2, and a single box with 6 prestressed concrete cells, as shown in figure 2.3, the length of the former is 417.5m, and the latter is 85m. The reinforced concrete A-shaped pylon is 165.3m high, as shown in Figure 2.4, and supported on pile group foundation, which consist of 30 concrete piles, each pile is 2.6m diameter and 64.5m long. The curved double-column transitional piers and upright meno-column auxiliary piers, with rectangular cross section, are also located on pile group foundations.

The deck is supported on sliding bearings placed on the pylon corbels, and on the top of auxiliary and transition piers.

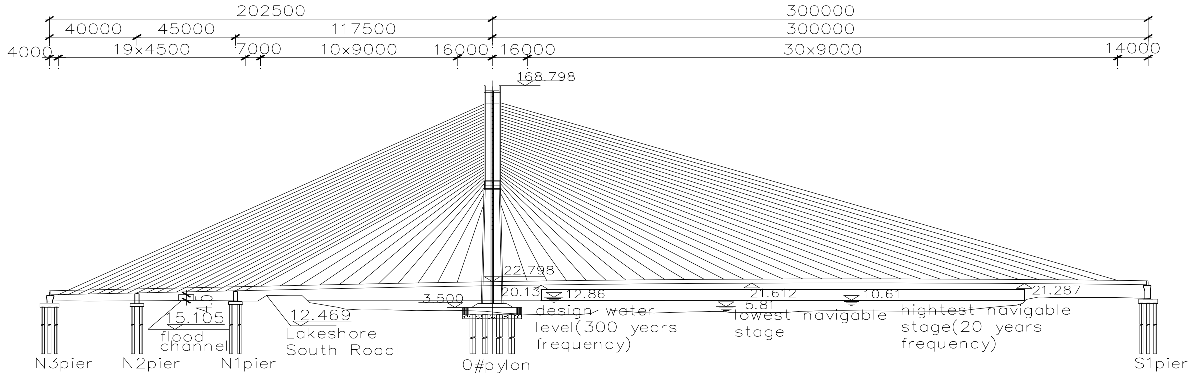


Fig.2.1 Elevation of the main bridge (elevation units: m, other units: mm)

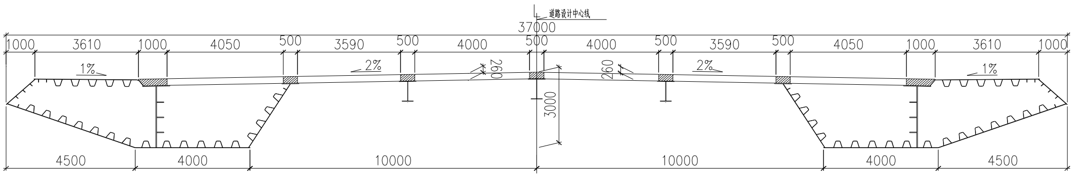


Fig.2.2 Cross-section of double steel girder (units: mm)

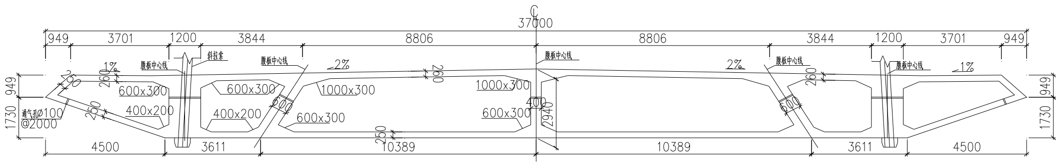


Fig.2.3 Cross-section of concrete girder (units: mm)

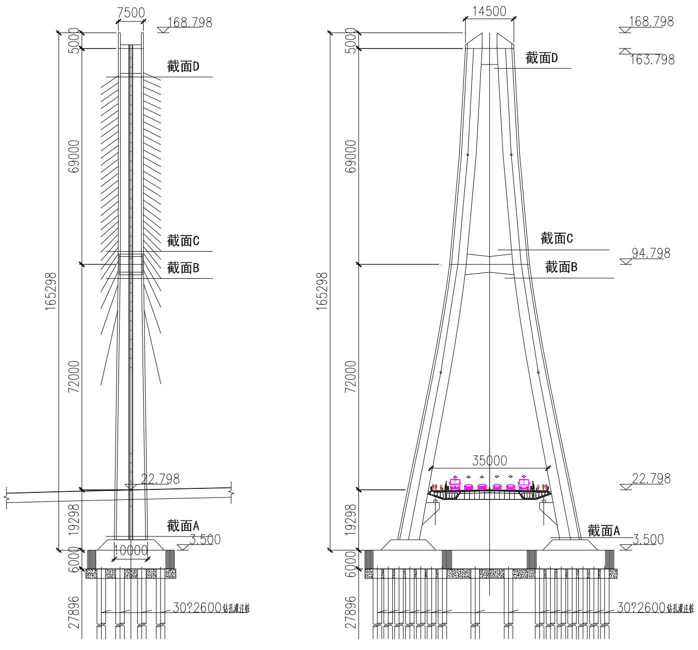


Fig.2.4 Pylon of the main Bridge (elevation units: m, other units: mm)

3. ANALYSIS MODELS AND EARTHQUAKE INPUT

3.1 Analysis model

The seismic analysis is based on a 3D finite element model, the approach spans are included at each side of the main bridge in the finite element model as boundary conditions, as shown in figure 3.1. In the model, the girder, the pylon, and the side piers are simulated by means of beam elements, the concrete girder and each steel girder of the main bridge is modeled as single beam, and the two steel girders are connected with transverse beams. Cables are represented with truss elements including the influence of cable sag. Each pile of the pile group foundation in the main bridge is described by six springs, each monolithic pile group of the transitional and auxiliary piers is described by six springs, the pile caps are included as mass points. The P-Delta effects of the pylon and cable are considered. Nodes of main girder and cable anchorages on deck are connected through a master-slave relationship.

The constraint condition of the model is as follows: in the longitudinal direction, the girder is connected to pylons with sliding bearings and restraining devices, and be connected to all the piers with sliding bearings; in the transverse direction, the girder is fixed with respect of all the piers and pylon.

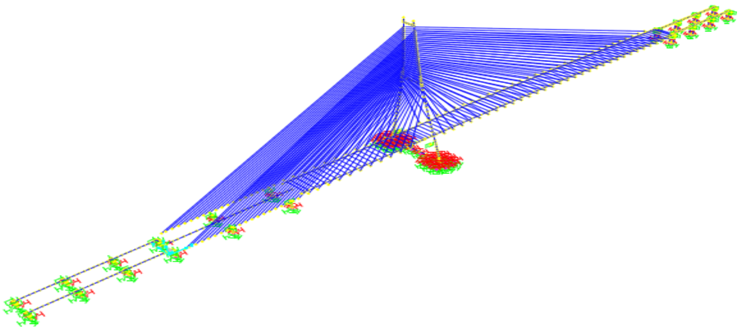


Fig.3.1 3D Finite Element Model

3.2 Input ground motions

The time history response method is employed to estimate the seismic response of this bridge, and the equations of motion are incrementally solved by employing step-by-step algorithm.

The seismic fortification intensity is 7; 2475-year return period is taken as earthquake action E2(MOT, 2008). Two-directional ground motions (H+V) are applied simultaneously to obtain the maximum forces and displacements. The vertical direction input ground motion is taken into account, its PGA is the two thirds of the one in the horizontal direction. The member forces and displacements are calculated by combining the respective response quantities obtained in each direction by the SRSS method.

A site-specific target response spectrum, which is representative of a 2475-year return period earthquake, was developed by the Earthquake Engineering Research Institute of Anhui Province, see figure 3.2, in which 3% damping was assumed. subsequently seven compatible ground motions were developed, Figure 3.3 shows one of the records obtained.

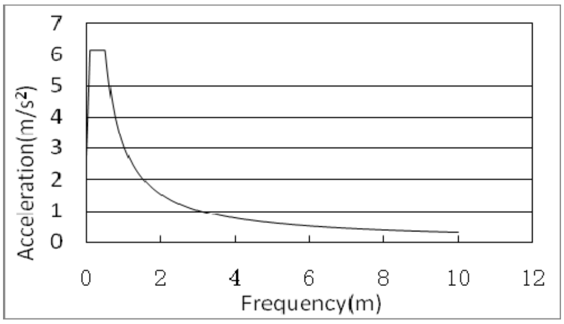


Fig.3.2 Target response spectrum

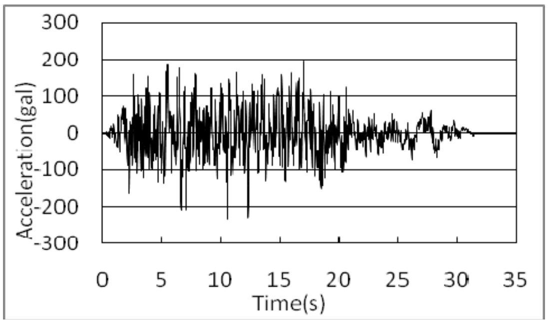


Fig.3.3 Acceleration time-history

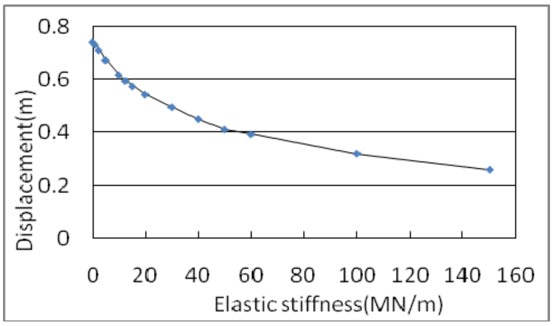
4. EFFECT OF ELASTIC LINKS ON THE STRUCTURAL BEHAVIOR

The effect of elastic links on the structural seismic behavior depends on the elastic stiffness K. In the following, the effect of elastic stiffness K on seismic response of the Huguang Road Bridge is analyzed, thereby, an appropriate stiffness K is determined.

4.1 Effect of elastic stiffness K on seismic response

In order to analyze the effect of elastic stiffness on seismic response, a total of 14 values of K are assumed, namely, 0, 1, 2.5, 5, 10, 12.5, 15, 20, 30, 40, 50, 60, 100, 150MN/m, and seven time-history analyses per value of K are executed using the above mentioned ground motions. The average responses are adopted.

Figure 4.1 illustrates the influence of the elastic stiffness on the relative displacement between girder and pylon, Figure 4.2 to 4.5 present the influence of the elastic stiffness K on the force of the elastic link, the relative deck displacement between the main bridge and the approach structures, the bending moment and shear force at the bottom of the pylon leg, respectively. These curves indicate that increasing of elastic stiffness, the displacement of link decreases and the force of link increases monotonously, the deck relative displacement of main and approach bridge decreases rapidly when the K is less than 15MN/m, decrease become slowly until K equal 100MN/m, then, it is slower as K value increase. The bending moment at the bottom of pylon decreases strongly when K is less than 20MN/m, the decrease is slower until K is beyond to 60MN/m, then, it is slower as K value increase, while shear force at the bottom of pylon leg increases until elastic stiffness reaches 60MN/m, beyond this level is not sensitive to K, Therefore, the movement of deck and the bending moment can be reduced without increasing the shear force at the bottom of the pylon leg using elastic links with appropriate stiffness.



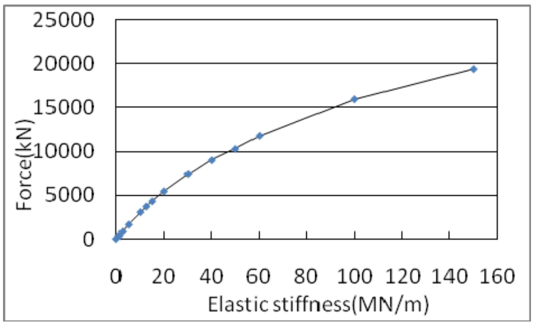
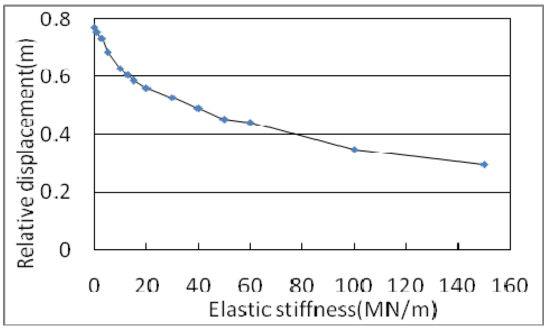


Fig.4.1 Deformation of the elastic link

Fig.4.2 Force of the elastic link



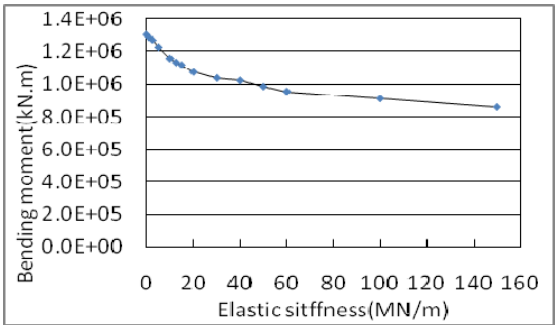


Fig.4.3 Relative displacement of deck

Fig.4.4 Bending moment at the base of pylon

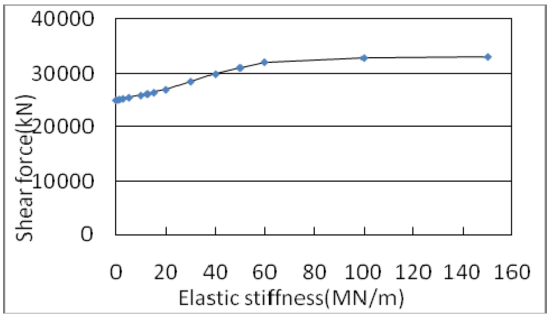


Fig.4.5 Shear force at the base of pylon

4.2 Determination of the elastic stiffness K

Based on the results, two elastic links between the girder and pylon are finally selected, the elastic stiffness of each elastic link is 30MN/m after balancing displacements and bridge forces.

5. EFFECT OF DAMPERS ON THE STRUCTURAL BEHAVIOR

Another alternative for controlling the longitudinal movements of the floating deck is addressed the combination of dampers and ultimate stops. The dampers will be especially active during a seismic event, but have no effect on the static load cases, namely, the girder will be acting as if it was unrestrained at the pylon. The ultimate stops will be activated by static wind and thereby reduce the movements of girder and forces of pylon.

It should be ensured that the dampers have adequate displacement capacity, they should not bottom out before the ultimate stop is active, so the displacement capacity need to meet the demand introduced by the live load, temperature variations and earthquake. On the other hand, in order to limit the structural response caused by longitudinal static wind, the displacement demand caused by the earthquake shall be reduced as much as possible.

Therefore, the damper parameters should be determined from seismic analyst, trying to limit the longitudinal movements to a given value， and also to reduce the forces of the pylon.

5.1 Effect of damper parameters on seismic response

It has been verified that the seismic behavior of a fluid viscous damper depends on two parameters, namely, damping coefficient C and exponent α. In order to determine appropriate damping coefficient C and exponent α for dampers which will be implemented on the Huguang Road Bridge, time-history analyst are carried out for the half-floating deck system model with longitudinal nonlinear damper installed. The value of α is assumed as 0.2, 0.3, 0.4 respectively, and value of C ranges from 0 to 20000. A total of seven time-history analyses per C and α values are executed using the above mentioned ground motions, and the average responses are adopted.

Among the numerous results, the deformation and aforementioned damper force, the girder end relative displacement of main and approach bridges, the bending moment and shear force at the bottom of pylon leg are especially monitored. The effects of damper parameters on response of the above components are illustrated in figures 5.1 to 5.5.

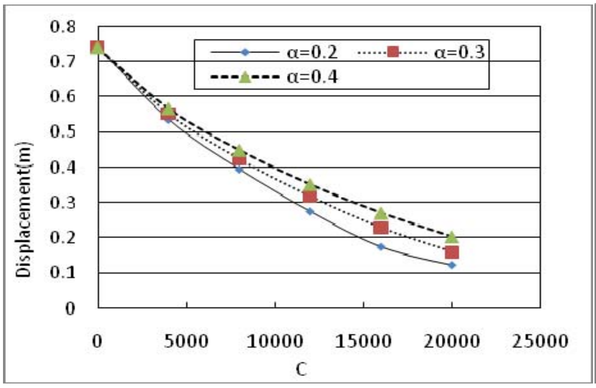


Fig.5.1 Displacement of the damper

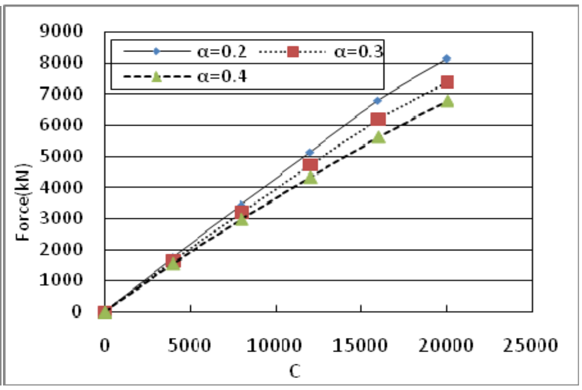


Fig.5.2 Force of the damper

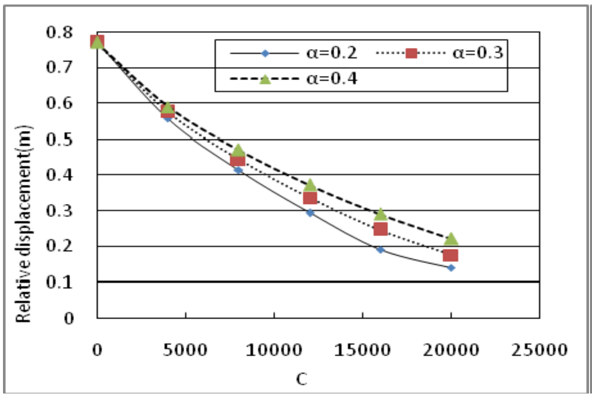


Fig.5.3 Relative displacement of the deck

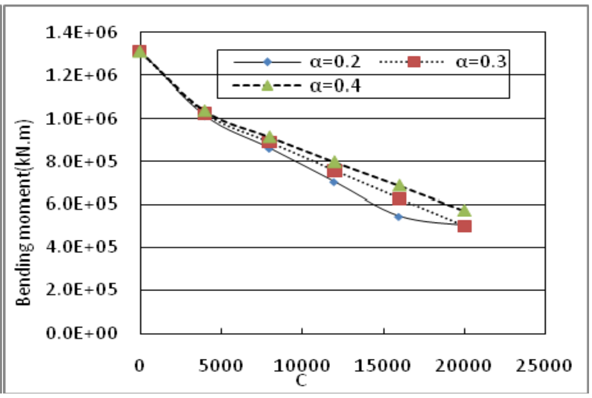


Fig.5.4 Bending moment at the bottom of the pylon

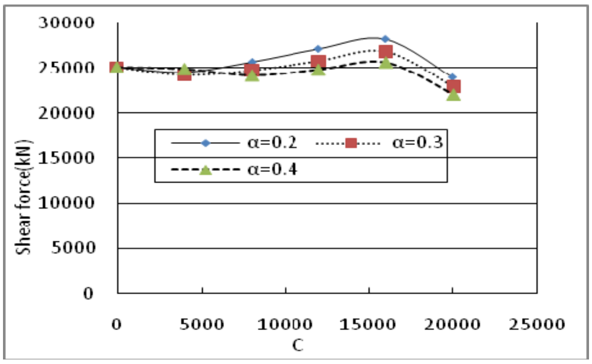


Fig.5.5 Shear force at the base of the pylon

Figures 5.1, 5.3 and 5.4 show that, for a certain exponent α, there is a significant reduction by increasing of damping coefficient C in the damper movement, pylon base bending moment and girder relative displacement of the main and approach bridges, but figure 5.2 reveals that the damper force is almost proportional to the damper coefficient. Figure 5.5 indicates that the pylon base shear force do not change significantly with the increment of C, and there is a peak value at C=15000. On the other hand, for a certain damping coefficients C, by increasing the exponent α, the damper displacement, besides the girder relative displacement of the main and approach bridges, increase, nevertheless the damper and pylon force decrease. The change of bending moment at the bottom of pylon depends on the damping coefficient C, as long as C is smaller, the bending moment increases with the increment of α, however the trend is contrary for larger C.

5.2 Determination of damper variables

From these results, it is clear that viscous dampers can reduce the displacement and bending moment notably. In order to limit the movements of deck and the damper within a target value of 40cm, and considering the construction features and installed of the damper, four viscous dampers are selected between the girder and the pylon, with a velocity exponent α of 0.3, and a damping coefficient C=10000, the maximum damper displacement 330mm, and the maximum damper force of each device is 2.02MN.

6. FINAL STRUCTURAL SYSTEM

In table 6.1, the seismic responses of the Huguang Road Bridge with four systems are compared: 1) the girder is connected to pylon with sliding bearings, 2) the girder is fixed on the corbel of the pylon, 3) the girder is connected to the pylon with sliding bearings and elastic links, and 4) the girder is connected to pylon with sliding bearings and dampers & ultimate stops.

The following results may be derived from table 6.1:

1) In contrast with half-floating system where the girder is connected to pylon with sliding bearings, dampers will reduce the deck displacement and girder relative displacement between the main and approach bridges to 45%, and the bending moment at the bottom of the pylon leg will be reduced to 58%. In contrast with the fixed system, where the girder is fixed to the corbel

of pylon, the damper will induce relative displacements between girder and pylon, but will reduce the pylon base shear and eliminate the large shear force between both elements.

2) Compared to half-floating system, the elastic links will reduce the deck displacement and girder relative displacement between the main and approach bridges to 55%, and the bending moment at the bottom of pylon leg will be reduced to 73%. In contrast with fixed system where the girder is fixed to the corbel of pylon, the elastic links also will induce the relative displacement between the girder and the pylon, reducing the pylon base shear and the shear force between girder and pylon.

3) Compared with the results of half-floating system with elastic links and dampers, the reader may observe that the effectiveness of dampers on reducing the seismic response is higher than the elastic links, and the seismic force of elastic links is larger than that of dampers, in addition, the former is better because that it can provide energy dissipation during an earthquake event.

Finally, the nonlinear dampers with ultimate stops (Figure 6.1) are proposed by the design group after the advantages and disadvantages of the four strategies are carefully balanced.

Table 6.1 Comparison of key variables for four proposed structural systems

Structure system	Half-floating system	Fixed system	With elastic links	With dampers
Disp. at girder end(m)	0.75	0.096	0.41	0.34
Disp. at pylon top(m)	0.94	0.17	0.54	0.44
Relative disp. of girders (m)	0.77	0.14	0.44	0.34
Axial force at pylon bottom (kN)	4.64E+04	4.61E+04	4.63E+04	4.60E+04
Shear force at pylon bottom(kN)	2.52E+04	5.33E+04	3.22E+04	2.25E+04
Moment at pylon bottom(kN.m)	1.31E+06	8.95E+05	9.61E+05	7.55E+05
Links force(kN)	33.3	4.56E+04	2.36E+04	8.08E+03
Links displacement(m)	0.72	0	0.39	0.33

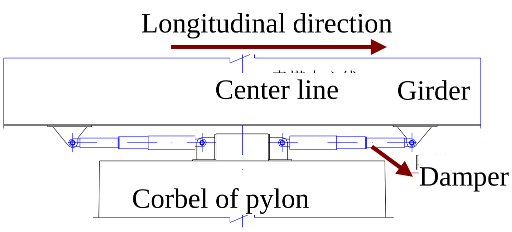


Fig.6.1 Location of dampers with ultimate stops of the selected design

7. CONCLUSIONS

Assessing the seismic design of a single pylon long-span cable-stayed bridge, both floating and fixed systems have serious disadvantages, the combination of half-floating system and supplementary longitudinal restraining devices may be a good solution. The investigation of structural systems for the Huguang Road Bridge has provided a case study that may supply references for other single pylon long-span cable-stayed bridges.

The responses of four structural systems are investigated under seismic loads, including two supplementary restraining devices, namely, elastic links and dampers with ultimate stops, although the fixed structural system can reduce the deck displacement and the bending moment at the pylon bottom, the response of the connection joint between girder and pylon is very large and complex. Both kinds of devices are effective solutions to reduce the seismic response. With appropriate parameters are previously determined based on sensitivity analysis, the damper effectiveness is much better than the elastic links. Furthermore they will notably reducing the seismic responses especially the deck movements of the bridge, dissipate the input earthquake energy.

The combination of dampers and ultimate stops is a good seismic structural solution that ensures the safety of the Huguang Road Bridge under strong ground shaking, and this structural system is adopted in the construction of the Huguang Road Bridge.

ACKNOWLEDGEMENTS

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REFERENCES

V.R.Panchal and R.S.Jangid(2008). Seismic isolation of bridge using variable curvature friction pendulum system. *Proceedings of the 14th WCEE*, Beijing, China.

Xiaoli Li(2006). Study for design theories of single pylon cable-stayed bridges (*A dissertation submitted to Tongji University in conformity with the requirements for the degree of Ph.D, in Chinese*). Tongji University, Shanghai, China.

Manabu Ito(1992). Supporting devices of long span cable-stayed bridge girder. *Innovative Large Span Structures[C]*. Toronto: IASSOCSCE, 1992, 25- 30.

Wen-Hsiung Lin and Anil K. Chopra(2002), Earthquake response of elastic SDF systems with non-linear fluid viscous dampers, *E.E.S.D.*, 31:9,1623-1642.

Liping Xu, Xigang Zhang etc.(2004), Investigation of structural system for the Sutong Bridge (in Chinese), *Proceedings of the Sutong Bridge,* Vol.1, Jiangsu Province Sutong Bridge Construction Commanding Department, P.R.C., Chinese Science and Technology Publishing House.

Liping Xu(2004), Analysis of structural systems for super long-span cable-stayed bridges (in Chinese), *Journal of Tongji University*,31:4,400-403.

Charles Seim(2003), The seismic retrofit of the Golden Gate Bridge, *Proceedings of the first PRC-US workshop on seismic analysis and design of special bridges*, Technical Report MCEER-03-0004.

Ministry of Transport of the People's Republic of China (2008), Guidelines for Seismic Design of Highway Bridges(JTG/T B02-01-2008), Beijing: China Communications Press.