Study on structural system of Sutong Bridge

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Abstract: Sutong Bridge, whose layout is [(100 + 100 + 300) + 1 088 + (300 + 100 + 100)] m, marks the largest span of cable-stayed bridges in the world. The complex natural condition at the bridge site and the strict requirements for resistance of wind and seismic action make it crucial to choose a favorable structural system to assure the function and safety of the bridge. The comparison among several optional structural systems for Sutong Bridge is illustrated. After detailed analysis is carried out for viscous damper and hydraulic buffer, super liquid viscous damper with additional displacement limitation is designed for the first application in bridge engineering. The parameters for the damper is analyzed and studied and the dampers are installed successfully after quality tests.

Key words: cable-stayed bridge; structural system; damper; damper parameter; displacement restraint

1 Introduction

In the past decades, the span record of cable-stayed bridges has been growing rapidly. From 602 m of Yangpu Bridge in Shanghai in 1993, to 856 m of Normandie Bridge in France in 1995, to 890 m of Tatara Bridge in Japan in 1998, the just finished Sutong Bridge pushes the spanrecord to 1 088 m. The continuous breaking of the span record of cable-stayed bridge is built upon the foundation of appropriate structural system. Generally, there are 3 types of structural systems for cable-stayed bridge: floating system, restrained system and fixed system[1-3].

In a floating system, there is no other vertical support for the girder besides supports at two ends or at the pylons and elastic supports of cables. The girder becomes a system that can slightly move longitudinally.

Restrained system refers to one or more rigid or flexible restraints between a girder and a pylon. The restraints are longitudinal or both longitudinal and vertical. Flexible restraint can be further divided into elastic restraint and damping restraint. The former acts upon both static and dynamic actions, but the latter only responds to fast loads, such as braking, turbulent wind and seismic load. Popular damping restraints are viscous damper and hydraulic buffer.

The feature of fixed system is the fixing between a girder and a pylon. It can be the fixing between the girder and the upper pylon, which is supported on the piers. It can also be the fixing of the girder, the pylon and the piers. Such fixing results are not only in strong stiffness and small displacements, but also in worse dynamic performance and bigger internal forces caused by temperatures.

This paper compares floating system, viscous damper system, hydraulic buffer system and fixed system based on the natural conditions of Sutong Bridge and proposes the appropriate structural system for super-long span cable stayed bridge.

2 Objectives of structural system of Sutong Bridge

The site of Sutong Yangtze River Bridge (short as Sutong Bridge) features in 4 aspects, i. e., bad climate, complex hydrologic condition, deep bed rock and high navigation requirement. The main bridge, which is discussed comprehensively about the structural system, is the most important structure in the whole Sutong Bridge, which is a two-pylon and two-cable plane cable-stayed bridge with the main span of 1 088 m. The layout of span is (100 + 100 + 300) + 1 088 + (300 + 100 + 100) = 2 088 m. The main girder is flat streamline steel box girder, with a total width of 41 m (including wind nose) and the height of 4 m. The concrete pylons are 300 m high with an inverted Y-shape. 131 bored piles with variable diameters (2.8 m for upper pile and 2.5 m for the rest) are adopted for the foundations of main pylons[4,5].

For long-span bridges, appropriate structural system is a key point to achieve structural function and safety. With the increasing of the span, the bridge tends to be higher, longer and more flexible; the struc-

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tures also show less stiffness and damping. Since the 1 088 m Sutong Bridge is located in a region with high requirement upon wind and earthquake, the following objectives of structural system should be achieved [6,7]:

1) To reduce seismic responses;

2) To reduce girder vibration induced by vehicle braking and fluctuating wind;

3) To reduce internal forces induced by temperature load;

4) To reduce girder end displacement induced by strong wind load and to minimize the requirements for expansion joint;

5) To reduce the pylon top displacements and the internal forces of pylons.

To achieve the above objectives, it is necessary to increase the stiffness and damping of the bridge. The displacements and internal forces upon static and dynamic loads can be optimized as the stiffness increases. The dynamic response to fast loads can be reduced and more energy can be dissipated as the damping increases. Therefore, the designers select three structural systems to compare, as shown in Table 1.

Table 1 Comparison of three structural systems for Sutong Bridge

Item	Floating system	Restrained system	Fixed system
Advantage	Long vibration period, low seismic response, forces by temperatures releasable	No restraints to slow load, but actions upon fast loads	Large stiffness, easy for erection of the girder
Disadvantage	Large displacements at ends of the girder, large expansion joints required, large displacements and internal forces are caused	Large displacements at ends of the girder and large moments at the bottom of pylons by static wind load	Large internal forces caused by temperature and seismic loads
Conclusion	Not acceptable	Further study required on restrained system	Not acceptable

From the qualitative comparison in Table 1, floating system and fixed system probably bring risks over acceptable level, but the application of damping equipment is a proper way to ease the responses of fast load. Popular equipments (viscous damper and hydraulic buffer) provide additional damping to dissipate energy and to reduce dynamic response. For viscous damper, damping force has a nonlinear exponential relation with velocity ($F = Cv^{\alpha}$, where, C is damping coefficient, α is velocity exponential) and limited duration and displacement of girder vibration is allowed and general damping ratio is 20 % ~ 60 %; for hydraulic buffer, damping force has a linear relation with velocity ($F = Cv$) and the vibration is stopped within a very short duration and a small displacement and general damping ratio is over 100 %. Therefore, with different damping parameters, viscous damper and hydraulic buffer show different damping properties and different requirements for bridge dynamic response and damping devices.

Although dynamic responses can be restrained by viscous damper or hydraulic buffer, static wind load still produces large displacements at ends of the girder and large internal forces at the bottom of pylons. Therefore, designers consider bringing displacement limitations into damping equipment to reduce such displacements and internal forces. In the following part, detailed discussion and comparison are described about viscous damper and hydraulic buffer with displacement lock-ups.

3 Comparison between viscous damper and hydraulic buffer with displacement lockups

The comparison bases on the cable-stayed bridge model of Sutong Bridge with the main span of 1 088 m. With the finite element analysis, responses of different structural systems are studied subjected to live load, temperature load, longitudinal wind load, braking and seismic load.

3.1 Analysis of parameters of viscous damper with displacement limitation

Viscous damper with displacement limitation needs two sets of parameters, one is damping parameter and the other is displacement limitation.

The object of the damper between the girder and the pylon is to keep the displacement of the girder and internal forces of the structure within the requirements. The damping coefficient C and velocity exponential α are studied and determined by the above object with considering displacement of the damper, damping force, displacement at the top of a pylon and bending moment at the bottom of a pylon. The damping coefficient C is taken as 0, 1 000, 3 000, 5 000, 7 500, 10 000, 15 000, 20 000 and 25 000 kN/(m• s^{-1})$^{\alpha}$, and velocity exponential α is taken as 0.3, 0.4, 0.5, 0.7 and 1.0, where $C = 0$ corresponds to floating system. Average seismic response upon ten histories of seismic accelerations is calculated for each set of total 45 sets of C and α. The seismic inputs include both longitudinal direction and transversal direction. In addition, the seismic responses with $\alpha = 0.15$ and C = 10 000 and 15 000 are calculated to study the damper with small velocity exponential.

Fig. 1 ~ Fig. 4 plot displacements of the damper, damping forces, displacements at the top of a pylon and bending moments at the bottom of a pylon corresponding to different damping parameters respectively. From the curves, the following conclusions can be drawn.

1) When velocity exponential α keeps constant, as damping coefficient C increases, displacement of the damper, displacement at the top of a pylon and bending moment at the bottom of a pylon decrease, while damping force keeps rising. In a wide range of damping parameters, bending moment at the bottom of a pylon is substantially less than that of floating system.

2) When damping coefficient C keeps constant, as velocity exponential α increases, displacement of the damper and displacement at the top of a pylon increase while damping force decreases. When damping coefficient C is small, as velocity exponential α increases, bending moment at the bottom of a pylon increases. But it reverses when damping coefficient C is big enough.

The seismic responses with $\alpha = 0.15$ and C = 10 000 and 15 000 prove similar conclusion to the above.

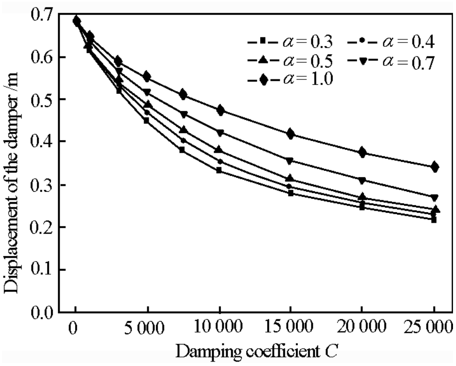

Fig. 1 Effects on dampers' displacements of different parameters

After the evaluation of structural responses of dampers with different parameters, the final parameters are chosen as $C = 15\ 000\ \mathrm{kN/(m \cdot s^{-1})^{0.4}}$ and $\alpha = 0.4$ to achieve the relatively low response. The maximum deformation velocity is 0.58 m/s.

Displacement limitation, as a key parameter for load combinations, should follow the following rules.

1) Enough gap should be provided for normal loads (vehicles, temperature) at service, and no restraint is triggered.

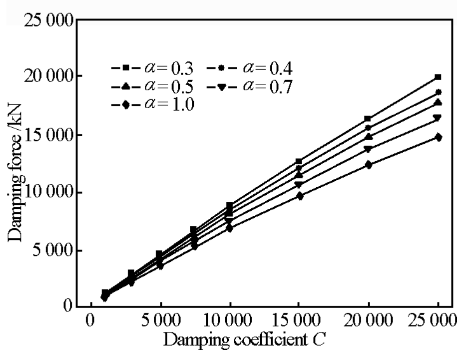

Fig. 2 Effects on damping force of different parameters

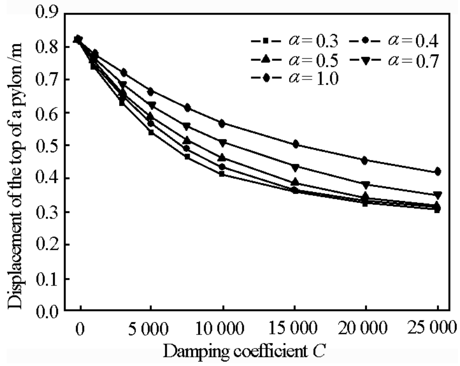

Fig. 3 Effects on pylon top displacement of different parameters

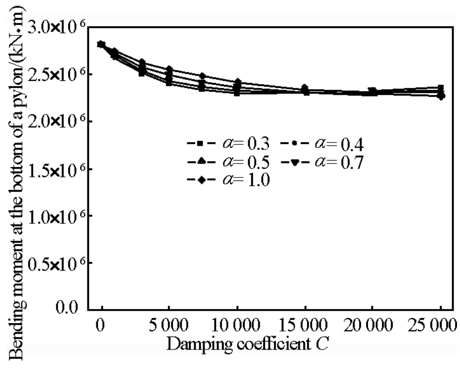

Fig. 4 Effects on pylon bottom moment of different parameters

2) Enough gap should be provided for normal loads (vehicles, temperature) at seismic strike, and no restraint is triggered.

3) Smaller displacement should be designed for the dampers to restrain the response subjected to longitudinal wind and to minimize the expansion joints.

Three most favorable load combinations for possible large displacements at ends of the girder are considered for the displacement limitations in Fig. 5. Load combination 1 is live load and temperature load. Load combination 2 is seismic load and temperature load.

Load combination 3 is seismic load, live load of 4 lanes, uniform temperature load and maximal average day wind load. The maximal value of all three load combinations is ±745 mm. Based on the above three rules, the displacement limitation is set to ±750 mm.

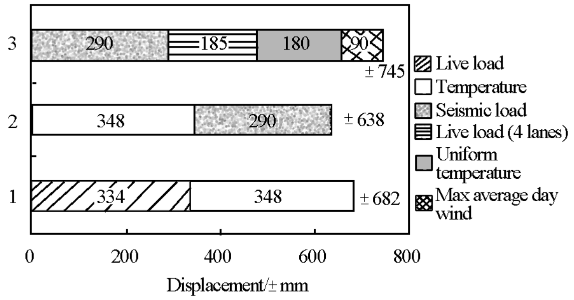

Fig. 5 Determination of limit displacement of dampers

By the above analysis, the parameters for the damper with displacement limitations are as follows:

Viscous damper: $F = Cv^{\alpha}$, $\alpha = 0.4$, $C = 15\ 000$ kN/$(\mathrm{m}\cdot \mathrm{s}^{-1})^{0.4}$ at one pylon, damping force is 12.1 MN at one pylon, maximal velocity is 0.58 m/s.

Displacement limitation: the gap is ±750 mm, restraining force is 20.8 MN.

3.2 Analysis of parameters of hydraulic buffer with displacement limitation

In a hydraulic buffer with displacement limitation, the function of damping force and velocity is $F = Cv$. To output great damping force to stop the vibration, damping coefficient C should be large enough.

In a seismic analysis, a rigid connection of pylons and the girder can be applied for an approximate simulation. The boundary and initial conditions are the same as that of 3.1.

Table 2, Table 3 and Table 4 show the seismic responses of the bridge. By the hydraulic buffer, the displacements at the seismic load are effectively controlled. However, the force acting on hydraulic buffer is as large as 76.2 MN, i.e., each 19 MN for a set of 4 equipments.

Table 2 Maximum of internal forces of towers

Section	Longitudinal shear force/kN	Transversal bending moment/(kN· m)
Bottom of pylon north	4.69E+04	3.16E+06
Bottom of pier cap north	3.32E+05	7.12E+06

Table 3 Maximum of reactions of supports

Position	Hydraulic buffer system	
	Force /kN	Displacement/m
Pylon north	6.42E+04	0
1st pier north	1.38E+02	0.474
2nd pier north	9.00E+01	0.385
3rd pier north	5.00E+01	0.328

Table 4 Maximal longitudinal displacements of keypoints

Position	Displacement/m
Top of pylon north	0.237
End of girder north	0.190

By the above analysis and similar analysis for displacement limitation, the parameters for the hydraulic buffer with displacement limitations are as follows:

Hydraulic buffer: total buffer force is 76.2 MN;

Displacement limitation: gap is ±750 mm.

3.3 Comparison of viscous damper and hydraulic buffer

The viscous damper in 3.1, the hydraulic buffer in 3.2 and floating system are studied for several typical responses shown in Fig. 6 ~ Fig. 9.

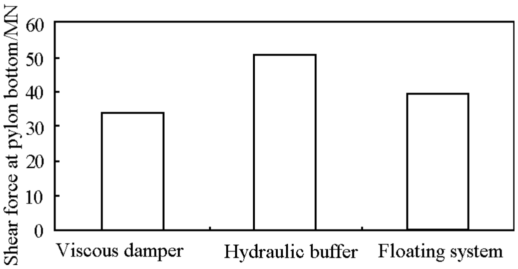

Fig. 6 Shears at the bottom of the pylon

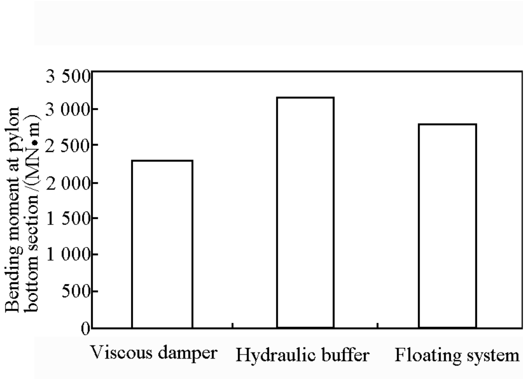

Fig. 7 Moments at the bottom of the pylon

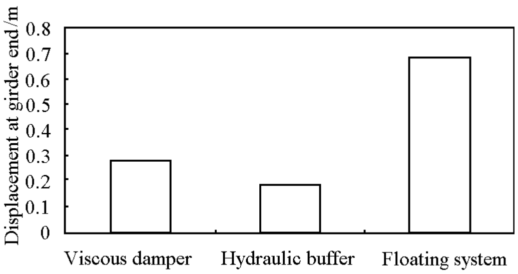

Fig. 8 Displacements at one end of the girder

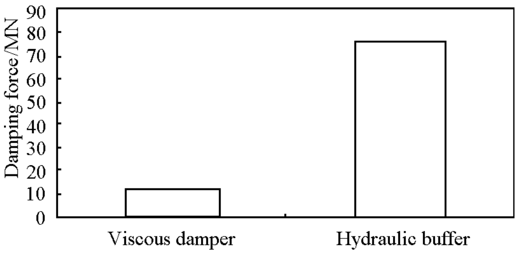

Fig. 9 Damping force required

Several points can be drawn from Fig. 6 ~ Fig. 9:

1) The seismic response with a viscous damper is slightly bigger than a hydraulic buffer and is only 40 % of the floating system.

2) Shear and bending moment of the bottom of a pylon with a viscous damper is the smallest, while a hydraulic buffer is the biggest.

The above results show that the case of viscous damper produces smaller seismic response including internal force and displacement than the case of hydraulic buffer, and the required damping force for viscous damper is only 1/6 of hydraulic buffer's, which lowers the requirement of design and fabrication of damping device. Therefore, the viscous damper ($C = 15\ 000$ kN/(m·s^{-1})$^{0.4}$, $\alpha = 0.4$) with the limit (gap = ± 750 mm, $F = 40$ MN) is finally selected for Sutong Bridge.

4 Recommended parameters

Based on the above parameter for viscous damper, designers place 8 viscous dampers on the bridge, 4 for each pylon-girder connection. The detailed design parameters for each viscous damper are listed in Table 5. Anti-wind bearings are installed along transversal direction to restrain the transverse displacement of girder at pylons. The longitudinal sliding bearings are installed on piers, and relative transverse movement is restricted.

Table 5 Design parameters for single viscous damper

Item	Name	Damper device with travel limit
Dynamic damping parameters	Function of force and velocity	$F = Cv^{\alpha}$
	Velocity exponent α	0.4
	Damping coefficient C /(kN·(m·s^{-1})$^{-0.4}$)	3 750
	Maximum response velocity/(m·s^{-1})	0.58
	Damping force/kN	3 025
	Seismic displacement/mm	±290
	Maximum clearance/mm	±750
Static displacement limitation parameters	Static displacement restraining force/kN	9 870
	Displacement restraining stiffness/(MN·m^{-1})	100
	Maximal displacement/mm	100
	Temperature deformation rate	232 mm/10 h
	Maximum resistance for temperature deformation(kN)	<3 025 × 5 % = 151.25
Horizontal rotation /(°)		2

5 Test requirements

There are about a dozen of applications of damping equipments in bridge engineering in the recent several years. However, there's still no regulation or code for the design and test of damping equipment.

According to the requirements and conditions of Sutong Bridge, designers propose the test specification for the damper for the first time in China and integrate the damper with operational monitoring system. The test includes workshop test and prototype test. The former includes shape test, pressure test, displacement test, friction test, limitation test, dynamic test and ultimate test. The latter includes performance tests in different velocities and different temperatures and abrasion tests in different velocities[8].

6 Realization of the damper

Based on design parameters and testing requirements of damper proposed by designers, the owner selects American Taylor Corporation as damper producer **by public bidding**. **Fig.** 10 shows the damper of Sutong Bridge after installation. Besides, the interface with bridge health monitoring system is also installed to the damper, which helps to monitor the working state of damper at any moment. In addition to the innovative combination of displacement limit function with damp-

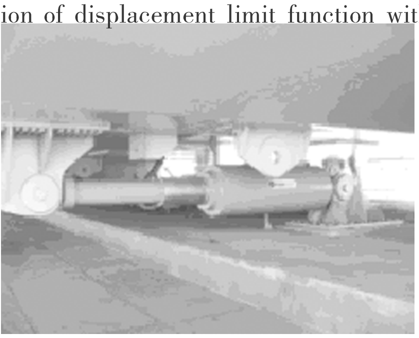

Fig. 10 Site pictures of dampers in Sutong Bridge

ing function in the fluid viscous damper, this is the first time in the world that a damper is connected with bridge health monitoring system.

7 Conclusions

1) Based on comparison and selection of structural system of Sutong Bridge, for the first time in the world the designers introduce viscous damper with combined function of displacement limit and damping into the project of Sutong Bridge, which effectively increases the bridge stiffness, improves the structural damping and resolves key technical problems in the design of long-span bridges.

2) The application of super fluid viscous damper with displacement limit function to the bridge engineering enriches the function of dampers, which in turn promotes the development of research and fabrication technology of dampers.

3) Viscous damper and hydraulic buffer have different damping properties, which should be selected, based on detailed requirement of bridges and calculated results of parametric optimization.

4) Test of damping equipments should be determined according to conditions of specific bridges.

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