State-of-the-Art of Seismic Research and Practice on Major Bridges in China

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SUMMARY:
Since 1990s, the construction of long span bridges, such as cable-stayed bridges, suspension bridges and arch bridges has been developing very fast in China. Meanwhile, their seismic performances have attracted great attention in the fields of both bridge engineering and earthquake engineering. This paper first introduces the seismic design methods and seismic mitigation measures of these bridges, and then points out problems that are still unsolved at the current stage. In addition, the future seismic research emphases, especially about performance-based seismic design theory of long span bridges, seismic mitigation technology and test technology for bridges, are also presented.

Keywords: long span bridge, seismic performance, performance based seismic design, seismic test technology

1. INTRODUCTIONS

It is well known that many long span bridges, such as Su-tong Changjiang Highway Bridge (cable-stayed bridge with a main span of 1080m）, Xihoumen Bridge（suspension bridge with a main span of 1650m）, Shanghai Changjiang Bridge（cable-stayed bridge with a main span of 730m）, Lu-Pu Bridge（steel arch bridge with a main span of 550m）, have been built in China during the past two decades. Some of those are major bridges only built within the last five years. The major bridges are of different types and location dependent, their seismic responses could be quite different from those of short to medium span bridges. Therefore, the seismic design of these bridges is actually case studies for each specific bridge with site-specific ground motions. Achievements have been made with many years of practice and experience in earthquake engineering, though it is understandable that so far there are no specifications and codes to guide the seismic design of these long span bridges and major bridges either at home or abroad.

In this paper, the seismic design methods and mitigation measures for long span bridges are first introduced and then further research concerning these aspects are proposed.

2. PERFORMANCE OBJECTIVES AND DESIGN CRITERIA

During the design life cycle of a bridge, the probability of the occurrence of a large earthquake is generally very low; hence the idea of designing a bridge that can resist a severe earthquake without damage is uneconomical and unnecessary. A long span bridge consists of superstructures (i.e. girder and deck), substructures (i.e. piers and abutments), foundation and connecting components (i.e. expansion joint and bearings). All these components can be classified into key components and non-key components. The importance and performance objectives of different components in a bridge are different. Bridge foundation (mostly pile groups) is widely recognized as a key component because once foundation is damaged under a large earthquake, it is very difficult to inspect, repair and also impossible to replace. On the contrary, if damage occurs in an auxiliary pier, the pier can be easily repaired. It is same for connecting components, such as bearings and expansion joints, provided that the damage caused by the earthquake can be estimated. Even if a bearing is not damaged during an earthquake, it still needs to be replaced considering its own life cycle. Therefore, there is no need to require the non-key components to meet the same seismic design level as those key components. In accordance with this conception, multiple seismic design levels should be adopted for major bridges, and the performance objectives of each design level should be based on the inspectability, replaceability and retrofitability of the components composed of a bridge. In other words, for performance-based seismic design of major bridges, the inspectability, replaceability and retrofitability of every component during the life cycle should be indicated.

2.1 Performance Objectives

Based on the classification of each component, different levels of seismic criteria and expected performance objectives should be given. In China, two levels of ground motions are used in the design. For the lower level earthquake (E1 earthquake), corresponding to an event with a mean return period of 475 years to 950 years, the targeted post earthquake level of service is full serviceability. The bridge must resist this earthquake with no damage or permanent offset of any structural components. For the upper level earthquake (E2 earthquake), corresponding to a mean return period of 2,500 years, the desirable post earthquake level of service is different for key components and non-key components. The Taizhou Changjiang Highway Bridge (the Taizhou Bridge for short) is employed to show the seismic design levels and performance objectives for major bridges in China.

The Taizhou Bridge spans the Yangtze River in Jiangsu Province in China, connecting the Taizhou City on the north side with Zhengjiang City on the south side. The structure is a three-tower and two-span suspension bridge with two main spans of 1,080 m and two side spans of 390 m each. The overall layout of the Taizhou Bridge is shown in Fig.2.1.

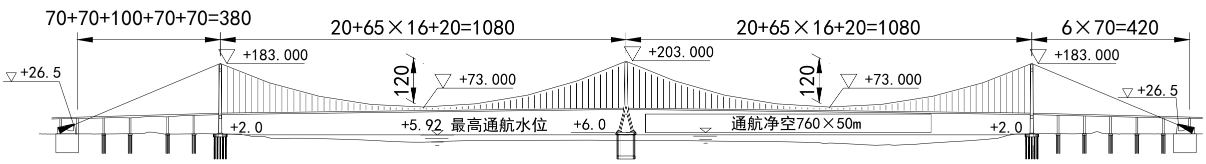


Figure 2.1. The overall layout of the Taizhou Bridge

The structure of the Taizhou Bridge mainly consists of superstructure, piers, towers, foundations and connecting components such as bearings with different performance and importance requirements. As a consequence, according to the importance and repairability of different components of the Taizhou Bridge as well as the difficulty to recover the bridge structure after earthquake, the proposed performance-based design criteria are set in terms of four-level performance objectives and two-level ground motion as follows:

1. For the lower level earthquake motion (labeled as E1 earthquake), corresponding to an event with a mean return period of 950 years, all structural elements are required to remain in the elastic range with no damage. Level of service is full serviceability (Performance Level 1).
2. While for the upper lever earthquake motion (labeled as E2 earthquake), corresponding to an event with a mean return period of 2,500 years, minor inelastic deformation (e.g. narrow flexural cracking in concrete) is permitted for the critical structural elements, e.g. towers, anchorages, foundations, girder and cables (Performance Level 2). Minimal Damage is defined as minor inelastic response with post-earthquake damage limited to narrow cracking in concrete and consequential yielding of secondary steel members.
3. With respect to components, such as connecting or auxiliary piers, they may sustain repairable damage (Performance Level 3) when suffered E2 earthquake, meanwhile repair or replacement

after earthquake must not require closure of traffic. The repairable Damage is defined as inelastic response resulting in concrete cracking, reinforcement yielding and minor spalling of cover concrete.

4. Easily replaceable components, such as bearings and expansion joint, may sustain significant damage (Performance Level 4) when suffered E2 earthquake.

2.2 Design Criteria

Design criteria are established corresponding to the desired performance objectives for the two ground motion levels. The application of design criteria is demonstrated by taking bridge towers, piers and piles as examples. For these components, the criteria are set in terms of limited values of curvatures, as stated below.

First of all, sections are discretized into fiber elements (Fig.2.2) and the stress-strain relationships of materials are used to model reinforcement and concrete. Moment-Curvature analysis (axial force included) is conducted to obtain the moment-curvature relationship of the section (Fig.2.3). In Figure.2.3, M_y stands for the moment capacity corresponding to the first reinforcing bar yielding; M_u is the ultimate moment of the section; M_{eq} is the equivalent yield moment obtained by idealizing the actual moment-curvature curve with an elastic perfectly plastic model.

When subjected to lower level earthquake (E1 earthquake), the seismic moment demand of cross sections in bridge towers, piers and piles should not be greater than the first yield moment M_y (axial force included). Since M_y stands for the moment capacity corresponding to the first reinforcing bar yielding, the whole section will be elastic when the seismic moment demand is less than the first yield moment. Research indicates that the width of the crack will not exceed the permissible value and there is no damage in the structure, satisfying Performance Level 1.

During upper level earthquake (E2 earthquake), the seismic moment demand of cross sections in bridge towers and piles should not be greater than the equivalent yield moment M_{eq} (axial force included). M_{eq} is obtained by idealizing the actual moment-curvature curve with an elastic perfectly plastic response, as indicated in Fig.2.3. According to the elastic perfectly plastic model, when the seismic moment demand is less than the equivalent yield moment, the overall response of the structure remains elastic. In fact, corresponding to M_{eq}, some of the reinforcements do yield in a section. Research indicates that the width of the crack may exceed the permissible value, but the concrete cover is in minimal damage. As the duration of earthquakes is short, the cracks developed during earthquakes tends to close due to gravity after seismic excitation ceases, which will not affect the normal traffic, satisfying Performance Level 2.

For components which are easy to repair, such as connecting piers and piers of approach bridges, ductility design is adopted under upper level earthquake, satisfying Performance Level 3.

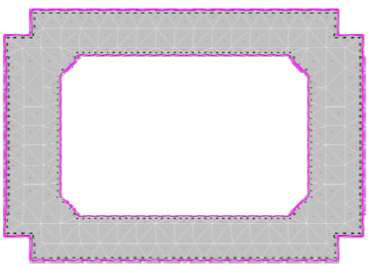


Fig 2.2. Section discretization

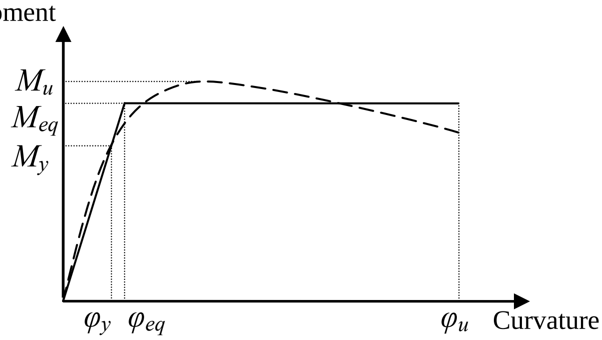


Fig 2.3. Moment-Curvature curve

3. THE IMPLEMENTATION OF DAMPERS ON LONG SPAN BRIDGES

Energy dissipation devices have been widely used in the world since 1970s for the seismic protection of bridges. Viscous damping is a way to add energy dissipation to a structure, and viscous damper has lately emerged as one of the alternative technology devices that are available for seismic design of bridge structures. Up to now, many applications of viscous dampers have been reported for the seismic protection of bridges around the world. In China, many long-span bridges installed viscous dampers to control the seismic response of the bridge. This paper introduces seismic applications of viscous dampers on three long-span bridges in China, they are:

1. Lu-Pu Bridge in Shanghai, a tied half-through arch bridge with a main span of 550m. Viscous dampers were installed at expansion joints to reduce the relative displacements between the adjacent decks.
2. Su-Tong Bridge over Yangtze River in Jiangsu Province, a cable-stayed bridge with a main span of 1088m. The viscous dampers were located between the box girder and the towers.
3. Taizhou Changjiang Highway Bridge. The viscous dampers will be located at the side towers.

3.1 Application in Lu-Pu Bridge

3.1.1. Bridge description

Lu-Pu bridge, one of the largest steel arch bridges in the world at present, is a half through tied arch bridge with a 550m main span and 2×100m side spans. The major components of the arch bridge are steel arch ribs, and orthogonal anisotropic steel deck with separate steel boxes, as shown in Figure 3.1. The width of the bridge deck is 37m.

Figure 3.1. Lu-Pu Bridge

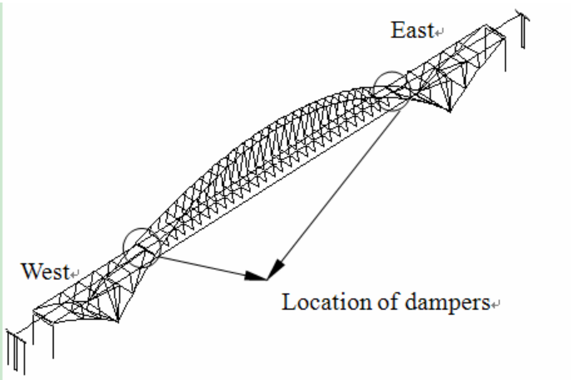


Figure 3.2. Location of dampers

3.1.2. Setting of viscous dampers

At the intersections of the arch rib and deck, crossbeams are designed, and the deck is supported by longitudinal sliding pot rubber bearings on the crossbeam. Investigations on seismic response of Lu-Pu Bridge reveal that relative displacements at expansion joints are large. Impact might occur under earthquakes. Therefore, longitudinal viscous dampers are installed at expansion joints. Locations of longitudinal dampers installed are shown in Figure 3.2. Two viscous dampers were installed at each of the expansion joints between the main span deck and transverse girder connecting the two ribs. The main purpose is to reduce the relative displacements at the expansion joints, thus to eliminate the possibility of impact due to longitudinal movements. At the same time, viscous damper can accommodate slow temperature displacements without developing forces in the dampers.

3.1.3. Damper parameters

The properties of the dampers were optimized to achieve an appropriate reduction of the relative displacements and stresses, keeping the damper force within reasonable limit. Different values of the exponent ξ were evaluated. Exponent ξ from 0.15 to 1.0 were considered. For each of these exponents, several values of C were examined in a parametric study aimed to identify the optimum dampers. This study was carried out by calculating the seismic response subjected to the site ground motions with three-dimensional elastic models of the bridge. The same damper properties were assumed for all dampers. Cases of parameters analysis are listed in Table 3.1.

Table 3.1. Cases of parameters analysis

C	230	330	460	560	660
ξ	0.15	0.15	0.15	0.15	0.15
	0.21	0.21	0.21	0.21	0.21
	0.3	0.3	0.3	0.3	0.3
	0.5	0.5	0.5	0.5	0.5
	0.7	0.7	0.7	0.7	0.7
	1.0	1.0	1.0	1.0	1.0

The parametric study shows that the velocity exponent and damping coefficient have an effect on the optimum seismic design, including the forces, relative displacements, and the damping forces. At last exponent ξ was selected as 0.21 and damping coefficient 520kN.mm/s for Lu-Pu Bridge. The effect of viscous dampers (with C =520, ξ =0.21) is shown in Table 3.2.

Table 3.2. Effect of viscous dampers

Section Position	Axial force （kN×10^4）		Bending moment （kN.m×10^4）	
	west	east	west	east
side arch base	3.248 (3.949)	3.605 (4.266)	18.57 (25.32)	19.96 (20.61)
main arch base	2.487 (2.963)	2.965 (2.960)	17.42 (17.61)	25.09 (27.04)
deck joint disp.(mm)	107.7 (160.7)	133.5 (169.1)		

Note: values in brackets are corresponding to responses without damper.

3.1.4. Damper tests

In order to investigate the dynamic performance of the damper, a comprehensive testing program was designed and undertaken at State Key Laboratory for Disaster Reduction in Civil Engineering of Tongji University, specifically to validate the assumed mechanical characteristics of reduced-scale viscous damper (see Figure 3.3).

Figure 3.3. Testing damper

The damper tested is designed for a force-velocity relationship of $F = 92 \cdot V^{0.21}$. The tested damper is designed to produce approximately 200kN at a velocity of 200mm/s and have a displacement range of ± 70 mm. These values represent scale factors of 1:10 for force, 1:2.857 for displacement, and 1:3.2 for velocity.

A typical damper force-displacement relationship for a constant-velocity test is shown in Figure 3.4. The plot is for a five-cycle test with a target constant velocity of 35.2mm/s. It can be seen that the damper force output was very stable and repeatable in this test. Note that the damper force is a function of velocity and that the applied velocity was approximately constant, the damper force is therefore also approximately constant across the test displacement range. For each of the constant velocity tests, an "average" value of damper force as a function of velocity was determined, and then compared against the target force-velocity relationship. Figure 3.5 summarizes all of the constant-velocity tests. The solid line shown in the figure is the target force-velocity law. It can be seen that in general, there is a good consistency between the actual and target damper behavior.

Other damper characteristics that were evaluated in the test program included the predictability of the damper behavior under seismic loading, sinusoidal Tests.

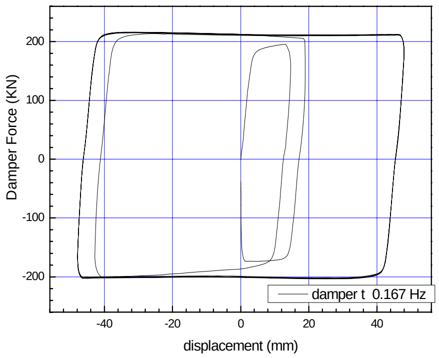


Figure 3.4. Typical damper force versus displacement plot for a cyclic constant-velocity test

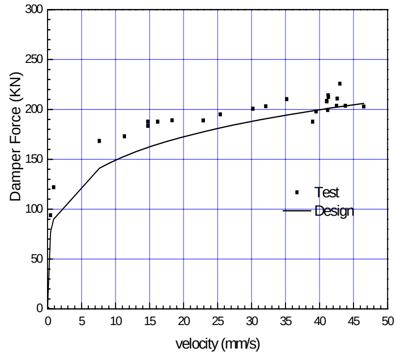


Figure 3.5. Damper force versus velocity for all cyclic constant-velocity tests

3.2 Application in Su-tong Bridge

3.2.1. Bridge description

The Su-Tong Bridge is the longest span cable-stayed bridge in the world with its completion. It has a steel box girder deck of 40.6m wide and 4.0m high. The layout of spans is 100+100+300+1088+300+100+100m (see Figure 3.6). The height of the inverted Y shape reinforced concrete tower is 300m. The deck is supported by sliding bearings sitting on the top of each auxiliary pier and anchored pier, and there is no bearing between deck and crossbeam of each tower.

3.2.2. Setting of viscous dampers

The investigation on seismic response using response spectrum method reveals that the maximum displacement of the girder might exceed 1.0m, therefore efficient devices should be adopted to restrain the movements of the deck. Viscous damper is one of the devices under investigation. It is proposed to set viscous dampers between the girder and towers, as shown in Figure 3.7.

Figure 3.6. Su-Tong Bridge

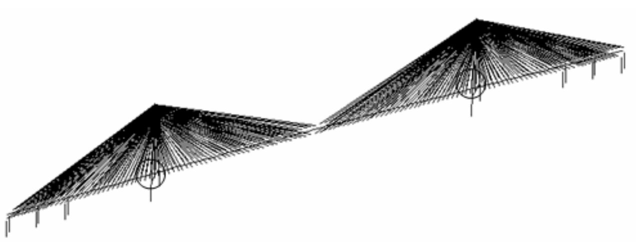


Figure 3.7. Locations of viscous dampers

3.1.3. Parametric analysis of dampers

Key parameters of a viscous damper are damping coefficient C and velocity exponent ξ, which determine the damper's dynamic behavior under earthquake. In order to choose optimum values for C and ξ, parametric study was carried out using nonlinear time-history analysis method. The value of ξ is 0.3, 0.4, 0.5, 0.7, 1.0 respectively, and value of C ranges from 0 to 25000.

The study was carried out based on ten site specific ground motions and three-dimensional elastic models considering the energy dissipation of sliding bearing sitting on the top of each side pier. Among the voluminous results from a transient dynamic analysis, the displacement of bridge girder, the bending moment at the base of tower, the damper force, the relative displacement between girder and tower are monitored. The effects of damper parameters on the response of the above components are illustrated in Figure 3.8 to Figure 3.11.

From Figure 3.8 to Figure 3.11, one can see that viscous dampers can reduce the earthquake response notably, especially for displacement. In a view to get balance between force and displacement, a velocity exponent ξ of 0.4 and a damping coefficient of 15000 were proposed.

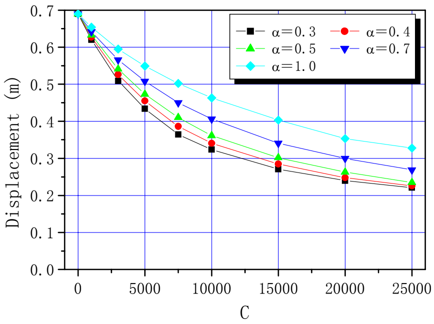


Figure 3.8. Displacement of deck

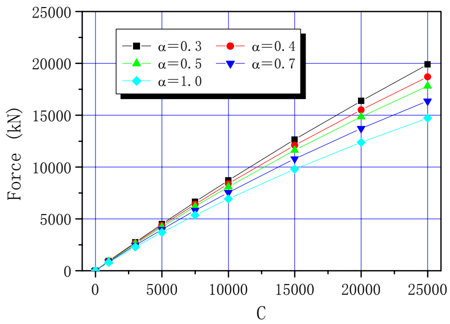


Figure 3.9. Force of the damper

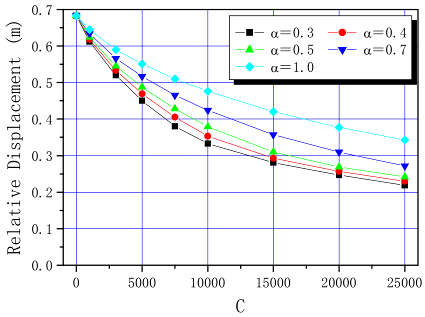


Figure 3.10. Relative displacement between girder and tower

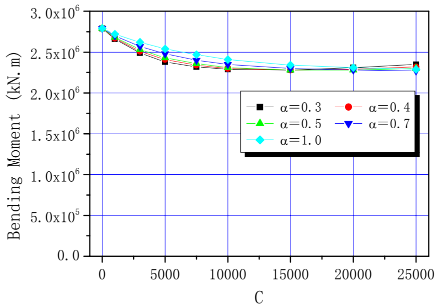


Figure 3.11. Bending moment at the base of tower

3.3 Application in Taizhou Changjiang Bridge

As shown in Figure 2.1, Taizhou Changjiang Bridge is a three-tower and two-span suspension bridge with two main spans of 1,080 m and two side spans of 390 m each. The viscous dampers were installed between girder and two side towers. The main objective of this case study is to investigate the influence of parameters of viscous dampers on the seismic effect of bridge structure.

Parametric analysis was implemented in order to investigate the influence of parameters of viscous dampers on the seismic effect of bridge structure. Fig.3.12 to Fig.3.14 depict the variation of seismic effect of bridge structure with the variation of damping coefficient C and velocity exponent ξ.

It can be seen from these figures that the deck displacement, moment and shear demand at the middle tower base monotonically decrease with the increase of damping coefficient C but begin to vary within a minor range after damping coefficient C larger than 10,000. According to the results of parametric analysis, it can be concluded that viscous dampers involving a damping coefficient C between 7,500 and 10,000 and a velocity exponent ξ between 0.3 and 0.4 would be the most effective values in reducing the deck displacement and seismic internal forces at the middle tower base to 37% and 25%, respectively. As for side towers, the larger the value of damping coefficient C, the more effectively viscous dampers reduce the seismic internal forces. Eventually, a rational range of damping coefficient

C and velocity exponent *ξ* value was suggested to be from 7,500 to 10,000 and 0.3 to 0.4, respectively.

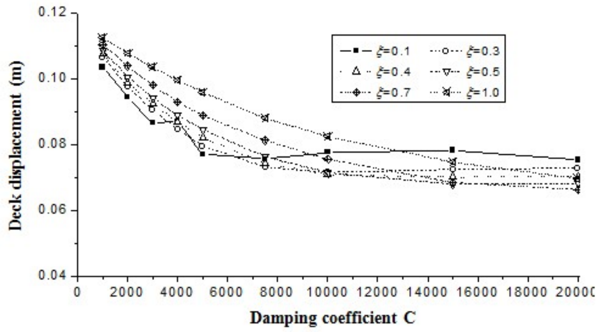
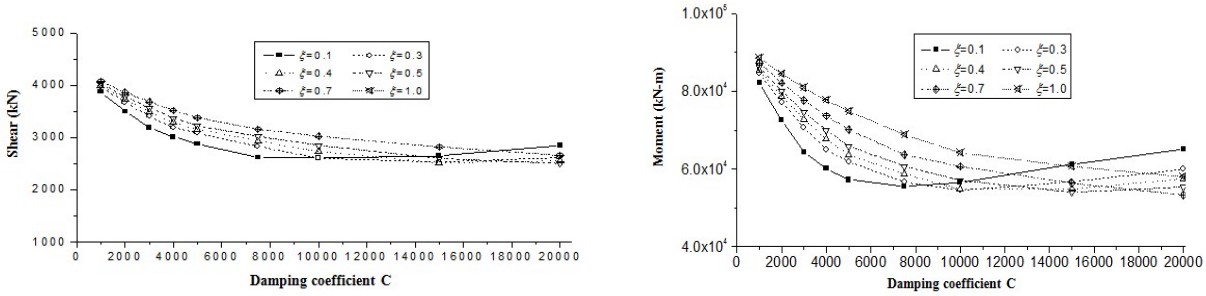
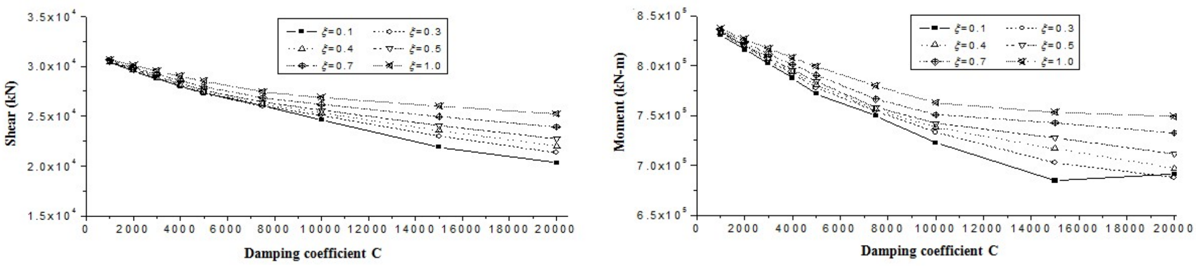


Fig.3.12. Influence of damping coefficient *C* and velocity exponent *ξ* on deck displacement on the north side



（a）Shear （b）Moment

Fig.3.13. Influence of damping coefficient *C* and velocity exponent *ξ* on internal forces at the middle tower base



（a）Shear （b）Moment

Fig.3.14. Influence of *C* and *ξ* on internal forces at the north side tower base

4. FURTHER RESEACHES

Different from general engineering structures, major bridges are long-period structures with distinct spatial characteristics and composed of various kinds of components. Compared to ordinary bridges that has clearly specification in their seismic design, the seismic research of these major long span bridges is less, existing problems need to be further studied are included but not limited to as follows:

1. Quantitative relationship between damage and performance objectives for major structural components of long span bridges subjected to earthquakes.

   Bridge structures should have clear performance objectives for different levels of seismic criteria, which can be realized in performance-based seismic design. Performance objectives are directly related with the damage state of structures under earthquakes. Quantitative definition of structural damage states to determine the performance objectives for different levels of earthquakes and connect the performance objectives with the damage state is one of the critical problems in performance-based seismic design.

2. Seismic vulnerability analysis as well as seismic damage and risk assessment of long span bridges.

   As a result of the inherent randomness and uncertainty in ground motions and structural performances, on the basis of study concerning structures damage and failure process using incremental dynamic analysis method, seismic vulnerability analysis with probability method is also a significant topic in theoretical research about performance-based seismic design of long span bridges.

3. Shake table test of long span bridges.

   In the past decades, due to the limitation in the dimensions and bearing capacity of shake tables, there is few large scale shake table array test of long span bridges using actual materials either at home or abroad.

   Multi-functional shake table test system, with a total testing payload of 200ton, composed of A (side table 30ton payload), B (main table 70ton payload), C (main table 70ton payload), D (side table 30ton payload) four shake tables, two trenches (70m and 30m in length, respectively) and one reaction wall, will be among the largest and most capable multiple shake tables systems in the world, which is now under the final preparation by Tongji University.

   All four tables are moveable within the first 70 meter trench and work as a large linear shake table array. Tables can work in same way or with relative motion.Two or more tables can be combined into a large linear shake table array (using another 30m parallel trench) as shown in fig.4.1.

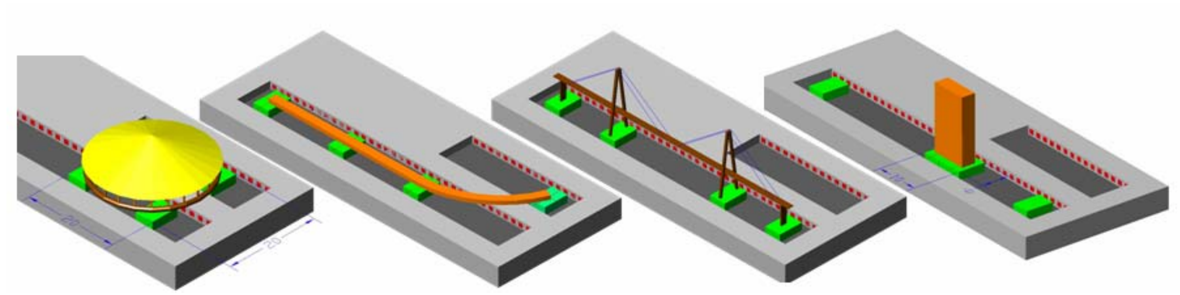


Fig. 4.1 Working modes of the Tongji shake table array

With the completion of the system, a world-class multi-purpose earthquake simulation platform for the vibration and seismic testing research will be developed for bridge engineering, especially for long span bridges and also for spatial structure engineering, underground structure engineering and lifeline engineering.

5. CONCLUSION

Based on the consideration of the inspectability, replaceability and retrofitability of the key components and non-key components in a bridge, different seismic design levels and expected performance objectives are suggested for the major bridges in China by taking one of each type of major bridge engineering project as examples. The application of viscous dampers and their effects on reducing seismic responses in practical long-span bridges in China are presented. In addition, the vulnerability analysis and progressive collapse analysis as well as the risk assessment are proposed to be important issues to further study in order to guide the seismic design of major bridges in the future.

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