STUDY AND TREND ON CONCEPTUAL SEISMIC DESIGN FOR BRIDGES IN CHINA

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ABSTRACT :

This paper reviewed the research and prospect of bridge conceptual seismic design in China. Instead of doing seismic analyses for detail design, it is emphasized that the seismic design should be implemented early in the conceptual design phase. In this study, some bridge design schemes were proposed from the conceptual seismic design viewpoint, which included: i) bridge form selection method based on the dynamic characteristics; ii) seismic performance enhancement methods for a continuous girder bridge in the transverse direction; iii) design scheme of spatial pylon for a cable-stayed bridge to resist the maximum displacements and internal forces; and iv) seismic mitigation and isolation techniques and applications in China. Finally, the paper presented some research directions on the bridge conceptual seismic design.

KEYWORDS: Bridge, Conceptual seismic design, Seismic mitigation and isolation, Research direction

1. INTRODUCTION

Since most of the Chinese territory is located at the earthquake zone, researches on the bridge seismic design are highly correlated with the national security and economy. Structural engineers started to study the seismic design early in 1950s. Chinese Academy of Science Institute of Civil Engineering composed “Code of Building Design in Earthquake Zone” in 1964, which specified seismic design specifications for buildings, hydraulic projects, highways, and bridges. Furthermore, the “Interim Provisions for Seismic Design of Highways and Buildings in Beijing-Tianjin Area” was published after the Xingtai earthquake. The second wave of interest in the structural seismic design followed the Tangshan earthquake in 1976. Progress was made with the “Railway Engineering Anti-earthquake Design Specification” and “Highway Engineering Anti-earthquake Design Specification” published in 1977 and 1979, respectively. Interest has risen to an apex in 1990s as many infrastructures are constructed in China. With the developments of structural design concepts and analysis techniques, a lot of achievements have been gained on the aspects of seismic analysis for long-span bridges, ductile seismic design, seismic mitigation and isolation techniques.

Conceptual seismic design is developed based on the analyses of many earthquake hazards. Menn C. [Menn C. (1991)] proposed some conceptual design approaches for two bridges, one (Chandoline Bridge) with difficult technical constraints and the other (Poya Bridge) with complex constraints with regard to urban design. Several ideal bridge characteristics for earthquake resistance were presented by Priestley et al. [Priestley (1996)]. Through the developments in the last decades, engineers and scholars has paid attention to the conceptual design, and treated it as an important design phase. Their purpose is to design a fine bridge with good seismic performance without large increase of cost. However, there are still some problems in the bridge seismic design process. Firstly, seismic analysis was normally performed as checking calculation; secondly, the ductile design or mitigation and isolation techniques were usually utilized for component-level design; and finally, there was lack of systematic design code to guide the bridge conceptual seismic design. Therefore, it’s also necessary to further develop such an approach to satisfy the current engineering requirements.

From the conceptual seismic design viewpoint, it is important to select a proper bridge form, identify the most vulnerable bridge component, predict the potential progressive failure path and evaluate the bridge seismic performance. Also, designing a good bridge requires both component-level and structure-level conceptual designs.

2. BRIDGE FORM SELECTION

2.1 Conceptual Seismic Design for a Real-scale Continuous Girder Bridges in Transverse Direction

In the conceptual design phase, simplified calculation method is very important for its simplicity and reflecting the bridge essential properties. In the work of Yuan Wan-cheng, the simplified model of multi-span continuous girder bridge was applied on a real-scale bridge structure, and two types of site conditions were considered[Yan Dong andYuan Wan-cheng (2003)]. The influences of expansion joint locations and structural formation on the bridge seismic performance was illuminated, and the solutions which could improve the bridge seismic behavior were proposed as well.

The example shows a 25-span continuous girder bridge, and each span is 29 m long. The layout of the bridge is shown in Figure 1, which is composed of 5 continuous girders connected with 4 expansion joints. There are 24 piers in this bridge categorized into 3 types, including solid single-column pier, hollow single-column pier and solid twin-column pier, whose heights are ranged from 5.5 m to 48 m. Two soil categories are involved: rock and stiff soils (soil type I) and soft to medium clays and sands (soil type III) (JTJ 004-89 1999). The response spectrum curves are presented in Figure 2. For two kinds of soil types, the improvement strategies are respectively addressed as below:

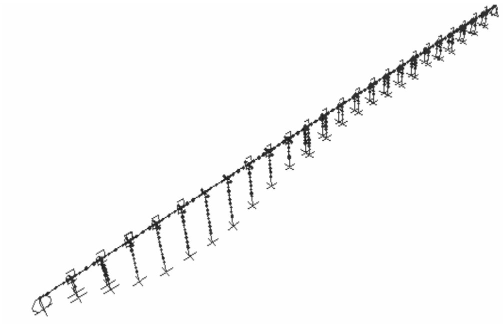

Figure 1 The finite element model of multi-span continuous girder bridge

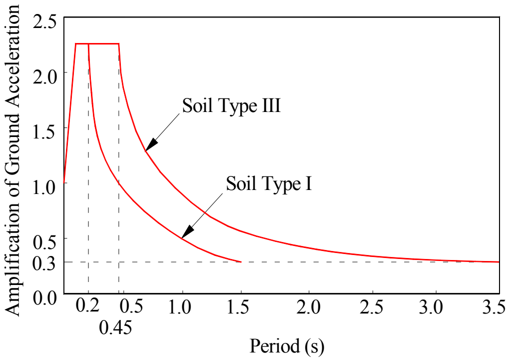

Figure 2 Response spectrum curves

2.1.1 Conceptual seismic design strategy for soil type I

The acceleration response spectrum is influenced by the soil types, especially in the range of short period. The specific period T_g for soil type I is relatively small ($T_g = 0.2\,\mathrm{s}$), beyond which the acceleration amplification decreases fast. Any further increasing of the structural period could make the internal forces to be decreased significantly. Therefore, reducing the lateral flexural stiffness (i.e. enlarging the fundamental vibration period) could efficiently enhance the bridge seismic performance in the transverse direction. Based on this consideration, a new pier type, named as close twin-column pier, is suggested in this study to upgrade some of the piers. The close twin-column pier is built by vertically dividing the solid single-column pier into two parts along the axial plane of symmetry, and making them to be close to each other (Figure 3). It could reduce the pier's transverse stiffness by 45-50%, but ensure its flexural stiffness in the longitudinal direction remaining constant. The piers selected to be replaced belong to the second part, those are pier No. 3, 8, 9 and 10. The purpose is to adjust the stiffness distribution of the piers linked to the second continuous girder (Figure 4) so as to reduce the rotational angle of the superstructure. The analysis results are shown in Figure 5 and 6.

2.1.2 Conceptual seismic design strategy for soil type III

Comparing with the condition of soil type I, the specific period T_g for soil type III is relatively large

($T_g = 0.45\,\mathrm{s}$). Since large deformation becomes the critical problem for this type of soft soils, the proposed countermeasures for stiff soils would not be applicable any more. Therefore, for this type problem, the conceptual design strategies are proposed as follows: i) move the expansion joints from the pier No. 10 to No. 8, whose purpose is to adjust the flexural stiffness distribution for some of the continuous girders; ii) separate the single-column pier No. 8-10 into twin-column pier (Figure 7) to enlarge the equivalent flexural stiffness and restrict the maximum displacements. The analysis results of original design and adjusted scheme are shown in Figure8 to 10. The results show that either the displacements or the shear and normal stresses are reduced to some extent by using the proposed methods. The bridge seismic performance in the transverse direction is improved.

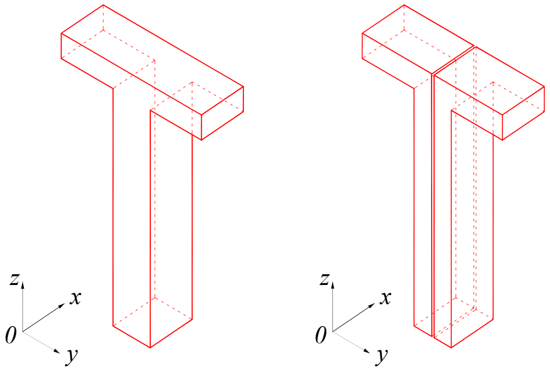

Figure 3 Suggested pier

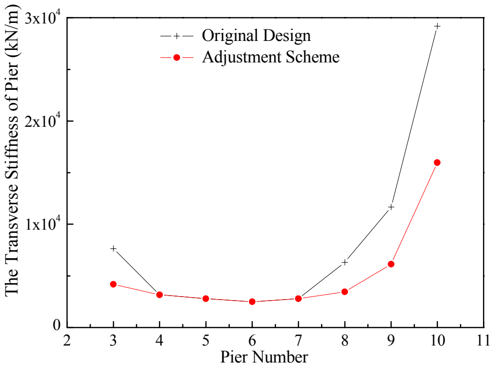

Figure 4 Stiffness distribution of piers

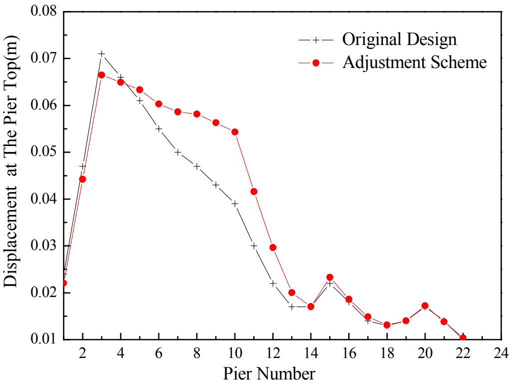

Figure 5 Comparing the displacement at the top of pier

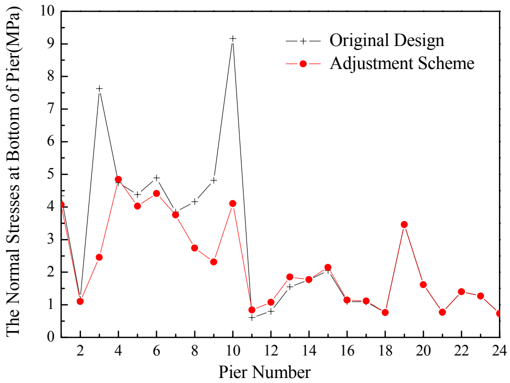

Figure 6 Comparing the normal stress at the bottom of pier

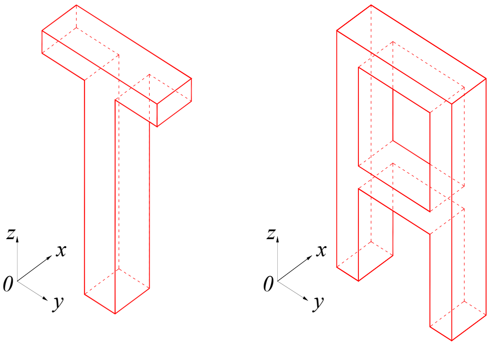

Figure 7 Suggested pier

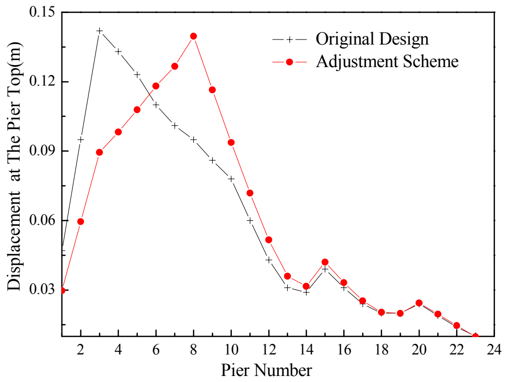

Figure 8 Comparing of the displacement at the top of pier

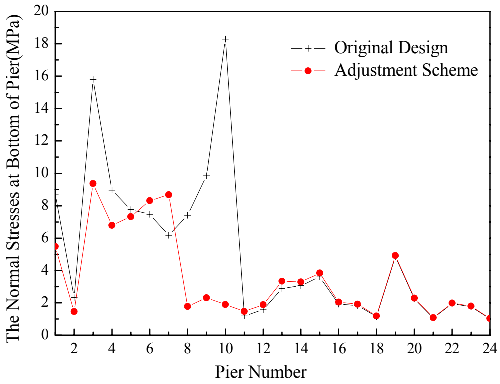

Figure 9 Comparing of normal stress at the bottom of pier

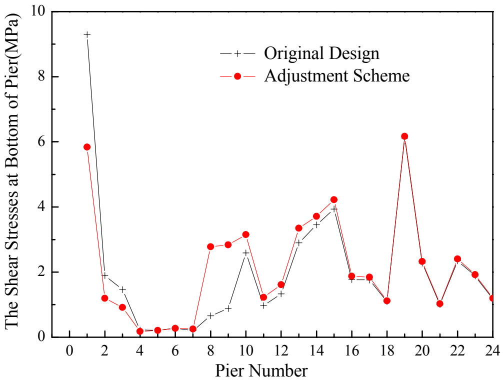

Figure 10 Comparing of shear stress at the bottom of pier

2.2. Conceptual Seismic Design of Long-span Floating Cable-stayed Bridge

The floating cable-stayed bridge is a typical flexible structure having a relatively long period. For instance, the basic period of Nan Pu Bridge is 9.24s and the basic period of Shanghai Yangtze River Bridge is 13s. In this case, increasing the structural period would not be efficient to reduce the internal forces but the displacements at tower-top and beam-end will be enlarged greatly. According to the acceleration and displacement response spectrums, the acceleration amplification is relatively small in the range of long period; however, the displacement response may be too large to be tolerated. Furthermore, within the long period region, the slope appears to be flat for the curve of acceleration spectrum, but sharp for the displacement one. Therefore, it is beneficial to make the bridge period within a proper range, in which the responses of internal forces and maximum displacements are both acceptable.

2.2.1 The simplified model of floating cable-stayed bridge

Li Guo-hao (1996) proposed the SDOF model for the floating cable-stayed bridge. Under the horizontal and longitudinal earthquake loads, the contribution of the basic mode is dominant for the floating cable-stayed bridge. The basic period can be determined by

$$T \approx 2\pi\sqrt{M_{sub}/K_T} \tag{2.1}$$

where M_{sub} is the equivalent mass of bridge; K_T is the stiffness of the tower.

2.2.2 Seismic Analysis of Cable-stayed Bridge with Spatial Tower

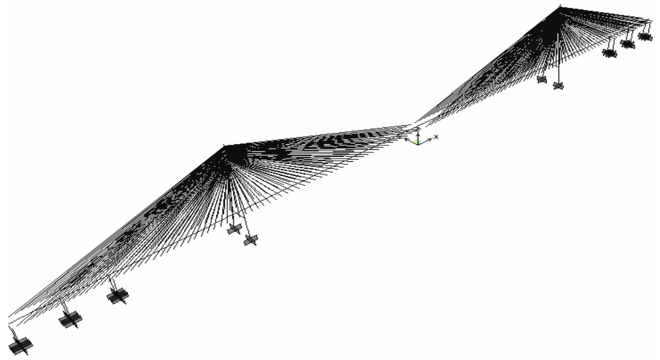

Figure 11 The FE model of cable-stayed bridge

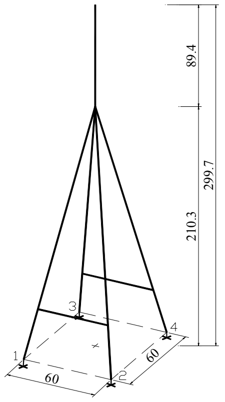

Figure 12 Spatial tower (Unit: m)

The main span of the example cable-stayed bridge is 1088 m long. Its layout of spans is 100+100+300+1088+300+100+100 m and total length is 2088 m. The bridge is designed as a floating structure, having long period of vibration. The bridge tower is inverted Y shape, and there are 2 subsidiary piers and 1 transitional pier on each side. The finite-element model is shown in Figure 11. As Eqn.2.1, the period of the anti-symmetric floating mode is in inverse proportion to $\sqrt{K_T}$. Thus, the spatial tower (Figure 12) is proposed to increase the flexural stiffness of the tower. By using the spatial tower, the bending stiffness of the spatial tower is about 9.66 times of the original one, but its weight is just 1.88 times of the original one. The first mode of vibration is lateral-symmetric bending, whose period is 7.316s. The maximum displacement at beam end is reduced by 57.3%. Since the towers' constraint to the beam becomes stronger, the mid-span displacement is reduced by 8.4% under transverse earthquake load condition. Additionally, under vertical and longitudinal seismic input, the bending moment of each tower column is 2.034E6 kN-m in spatial tower model and it is 88% of the original design. Under the vertical and transverse seismic load, the bending moment of each tower column is 1.299E6 kN-m which is 78% of the original design.

3. SEISMIC MITIGATION AND ISOLATION TECHNIAUES FOR BRIDGES

3.1. Research Background

Since 1990s, Chinese scholars began to research on seismic mitigation and isolation effect of rubber bearing. The achievements include: isolation bearing for highway bridges [Xu Feng-yun(1986)], experiments of static and dynamic behaviors of slab rubber bearing and PTFE slide plate rubber bearing [Fan Li-chu and Yuan Wan-cheng (1987)], rubber bearing for bridges [Fan Li-chu and Yuan Wan-cheng(1989)]. Fan Li-chu and Yuan Wan-cheng developed the first-generation isolation bearing, i.e. arc steel plate rubber bearing. During 1993-1996, they further exploited the second-generation one. Subsequently, Chinese researchers also studied the dynamic characteristic of lead-rubber bearing and its seismic reduction energy consumption behavior [Architectural Research Institute of Railway Science Academe(1995), Hu Zhao-tong and Liu Jian-xin (1998), Li Jian-zhong and Yuan Wan-cheng (1998)]. For the theory of seismic mitigation and isolation, Li Jian-zhong (1998) generated the optimum design formulas on the basis of isolation systems for continuous girder bridges. This approach could determine the key parameters of seismic absorption and isolation bearing for bridges. Wang Shu-bo(1997)studied the equivalent linearization method for seismic mitigation and isolation design and proposed an improvement scheme. Zhou Xi-yuan(2001)researched on the simplified analysis method for regular isolated bridges. Wang Zhi-qiang(2000) presented the method of studying the responses of isolated bridges, which combined the non-linear static analysis method (Push-over) with capacity spectrum method. Fan Jian and Tang Jia-xiang(2000) studied the dynamic characteristic and seismic responses for sliding isolation structure. Using the shaking table test, Zhang Jun-ping and Zhou Fu-lin(2002) summarized the design method and process for isolated bridges. They also discussed some critical problems in the conceptual design and detail design phases. Many other scholars processed the seismic isolation technique for the practical application on various bridge structures[Gong Yi-qiong et al.(1997), Wang Zhi-qiang et al. (2002), Ye Ai-jun et al. (2004), Hu Shi-de et al. (2002)]. Furthermore the applications of isolation design, analysis of seismic responses and damping effect on railway bridge can be seen in the literatures [Xi Qiao-ling et al. (1998), Wang Li and Yan Gui-ping(2003), Zhang Zhen-ge et al. (2003), Wang Li et al. (2002)].

3.2. Arrangement of the Seismic Mitigation and Isolation Devices

The seismic mitigation and isolation device can be placed either on the top or at the bottom of piers. If it is placed on pier top, ground motion could not be isolated. As a result, the pier vibrates independently constrained on the top. Thus, while calculating the earthquake force of pier, the mass and its vibration mode should be considered. For the tall and heavy pier, however, the seismic mitigation and isolation device should be placed at the bottom of it. In General, the seismic responses are controlled by using both the laminated rubber bearings and damping devices. By adopting the laminated rubber bearings, the horizontal stiffness distribution of the bridge substructure can be adjusted. Consequently, the internal forces in piers can be reduced correspondingly. In the transverse direction, the lateral responses also can be reduced by properly setting the seismic mitigation and isolation device. In China, seismic mitigation and isolation devices have been used in some bridges as listed in Table 3.1 and Table 3.2[Wang zhi-qiang(2002), Hu shi-de(2003)].

Table 3.1 Bridges adopting seismic mitigation and isolation devices in China

Bridge name	Bridge style	Layout (m)	Type of bearing
Tangjin expressway Yong Ding new river bridge	Prestressed concrete continuous box girder	82.75+110+82.75	Seismic mitigation and isolation ; energy absorption for sliding pot bearing and curved steel strip
South Xinjiang railway Buguzi bridge	Continuous box girder	9×32	The type of lead rubber bearing is VP500-L
Shi jing-qu bridge in Shi-Huang expressway	Prefabricated RC box hollow slab	3×16	The type of lead-rubber isolating bearing is GZY300-V4T(1)
Yichang Changjiang river bridge on Yichang-Wanzhou railway	Hybrid structure of continuous rigid-frame and concrete-filled steel tube flexible arch	130+2×275+130	The type of lead-rubber isolating bearing is EBP
Hengqin bridge in Zhuhai city	Single tower and double cable surface cable-stayed bridge	2×120	The type of aseismic spherical steel support is KQGZ
The south branch of the second nanjing yangtze river bridge	Double cable surface cable-stayed bridge	305+628+305	The type of aseismic spherical steel support is KQGZ
North approach span in Suzhou-Nantong yangtze river bridge	Continuous girder	Span length include:30m,50m,75m	The type of double spherical aseismic bearing is KZQZ

Table 3.2 Some bridges adopting viscous damper in China

Bridge name	Bridge style	Maximum damping force (kN)	Maximum stroke (mm)	Damping coefficient	Damping exponent
Main channel bridge of Donghai sea crossing project	Double-pylon single-plane and half floating cable-stayed bridge with composite girder	±2500 ±2000	±400 ±500	2500kN（s/mm）$^{0.3}$ 476 kN（s/mm）$^{0.21}$	0.3 0.21
Lupu bridge	Half through tied arch	±2000	±200	520 kN（s/mm）$^{0.21}$	0.21
Egongyan yangtze river bridge in Chongqing	Suspension bridge	±2000	±550	470 kN（s/mm）$^{0.21}$	0.21
Chongqing Caiyuanba bridge	Tied arch with rigid frame and truss	±1500	±220	2000kN（s/mm）$^{0.2}$	0.2
Chaobai river bridge in Jing-Cheng road	Partial cable-stayed bridge with three towers	±2000	±200	1200kN（s/mm）$^{0.12}$	0.12
Nachaokou bridge in Xiamen island ring road	Half-through tied basket handle arch bridge with steel box girder	±500 ±1000	±100 ±120	250kN（s/mm）$^{0.15}$ 500 kN（s/mm）$^{0.15}$	0.15 0.15

4. RESEARCH DIRECTIONS OF BRIDGE CONCEPTUAL SEISMIC DESIGN

In recent years, nonlinear viscous dampers were applied on some bridges in China, which could effectively restrict the seismic displacements. However, the theoretical development and experimental verification on the nonlinear properties of the viscous damper are still needed to be performed. To avoid excessive displacement is always a key problem to solve for long-span bridges. Setting allowable displacement as a design parameter could protect the bridge from some failure caused by the large deformation, e.g. instability caused by P-Delta effect, girder falling and collision between adjacent spans. Simplified, effective displacement-based analysis method and bridge seismic vulnerability are also important research directions.

As far as the theorem of structural seismic design is concerned, strength-based design scheme has some limitations. Therefore, the displacement-based approach plays an important role within the performance-based design philosophy. Chopra and Geol(2001)，Qiang Xue (2001) studied the displacement-based design for single degree-of-freedom (DOF) system. Calvi(1995) and Kowalsky(2002) set up displacement-based seismic design method for multi-DOF structure. Anderson and Mahin(1998) proposed the displacement-based design method for simple seismic isolation bridges. Y.Y.Lin (2003) studied the displacement-based seismic design method by using the substitute structure. However, the displacement-based seismic design method still has some problems, such as i) the target displacement are difficult to be determined; and ii) the process of design is too complex. Moreover, the method has good accuracy for the short-period structures; further study for long-period structures is also needed.

5. CONCLUSIONS

The paper gave a simple review on the main achievements of Chinese seismic researches and introduced the bridge conceptual seismic design idea according to the author's study experience. Meanwhile, the conceptual seismic design strategies for continuous girder bridge and cable-stayed bridge are respectively recommended. The paper also addressed the seismic mitigation and isolation techniques and applications in China. Finally, some research directions on the bridge conceptual seismic design were also presented.

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