Seismic Design of Nanchang Chao-yang Bridge

Wang Fengming[1], Yuan Wancheng[1], Dang Xinzhi[1], Lin Zeng[1]
1. State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, China
E-mail: 77wilbur@tongji.edu.cn; yuan@tongji.edu.cn; leodangxz@163.com; 13linzengjx@tongji.edu.cn

Abstract: Based on the Chao-yang bridge seismic risk studies, the seismic standards and performance targets were analyzed, and the ground motion input was determined. A full-bridge finite element model was established and nonlinear seismic response of the bridge was analyzed by time history analysis method. Key sections of the main tower and transition piers were checked. Based on the above results, a seismic isolation measure with the cable-sliding friction aseismic bearing (CSFAB) was putted forward, and the results show that this measure can significantly reduce the seismic forces demand of key components and ensure the seismic safety of the structure. Meanwhile, the relative displacement between piers and decks can be controlled by using cables. Furthermore, a 1/20 scale model was tested on shaking table to certify the safety of the bridge seismic isolation design.

Keywords: Six-pylon cable-stayed bridge, Cable-sliding friction aseismic bearing, Seismic performance evaluation

1. Introduction

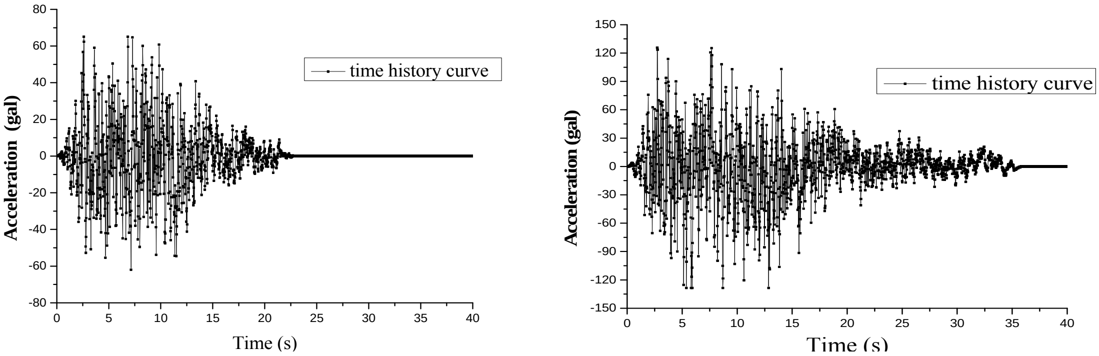
The Chao-yang bridge is composed of one main bridge across the Ganjiang River and two approach bridges, and the whole span length is 1.6km. The main bridge is a cable-stayed bridge with six tower and single-cable-plan, and with span arrangement of 79m+5×150m+79m=908m. The beam belongs to the composite box girder with corrugated steel webs with deck width of 40.5m, and it takes the form of the tower and beam consolidated and the pier and beam separated. The bridge approaches are multi-span continuous bridges. The span arrangement of east bank approach is 2×(49+50+49)m and that of west bank approach is 2×(4×49)m. The foundation of this bridge is grouped pile foundation with borehole cast-in-place concrete pile, and the pile diameter of main tower is 2m and of side pier is 1.5m.

The main bridge of Chao-yang bridge belongs to the multi-tower cable-stayed bridge, and its structure formation is novel. There are no existing criteria and technic standards to follow in the seismic design of this kind. Therefore, studying the seismic performance of this bridge is not only of great significance to ensure the seismic safety, but also has important guiding significance for the seismic study of multi-tower cable-stayed bridge structure [1]. This paper focuses on the main bridge of Chao-yang bridge, and the seismic standards and performance targets were analyzed, and the ground motion input was determined based on the Chao-yang bridge seismic risk studies. Nonlinear seismic response of the bridge was analyzed by time history analysis method and Key sections of the main tower and transition piers were checked. On the basis of the above results, the seismic isolation measure with CSFAB [2] was putted forward, and its effect isolate the seismic forces was evaluated by simulation and model experiment.

2. Ground motion inputs

Currently, two seismic fortification levels and two-stage design method is adopted for the seismic design of most large-span bridges, and this design method is also more mature. So this bridge also uses the two seismic fortification levels and two-stage design method. Based on the importance of each part of Chao-yang bridge project, the seismic fortification criterion has been made during multiple discussions, and E1 horizontal ground motions correspond to a 10% probability of exceedance in 50 years and E2 horizontal ground motions correspond to a 2% probability of exceedance in 50 years.

According to the “Nanchang Chao-yang Bridge Seismic Safety Evaluation Report” provided by Earthquake Engineering Research Institute in Jiangxi Province, China, two suite of synthetic horizontal acceleration time history curves of each seismic fortification criterion have been given, and each suite included 7 curves. Two representative accelerograms were illustrated in Fig. 1.



(a) 10% probability of exceedance in 50 years (b) 2% probability of exceedance in 50 years

Figure. 1. Representative horizontal acceleration time history curves

The horizontal ground motions were applied in the longitudinal direction and transversal direction of the bridge, while vertical motions were taken to be two thirds of the horizontal value [3].

3 Numerical modeling

In this paper, the spatial finite element model of the full-bridge was established and implemented by using the SAP2000 software, as shown in Fig.2. Beam elements were chosen to simulate the beams, towers and piers, and secondary dead load was added to the corresponding beams with distributed mass, in the same manner, spatial truss elements simulated cables, and spring elements simulated group piles to consider the interaction between soil and pile. All bearings were simulated by three-dimensional bearing elements, and sliding bearings were simulated by nonlinear element to consider the friction energy dissipation.

The dynamic performance of substructure of Chao-yang Bridge was focused in this paper. The seismic safety of towers and piers and the flexural capacity of all piles under the main towers and transition piers were checked. The shear strength checking of fixed bearing for one-way direction was also made.

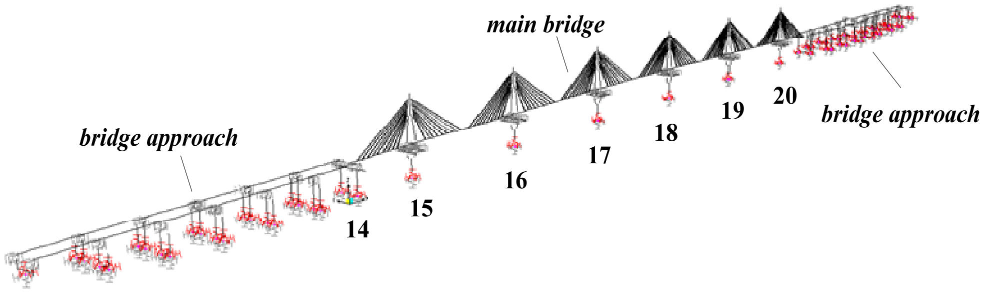


Figure. 2. Finite element model of Chao-yang bridge

4 Key section checking results

The seismic forces were got using nonlinear time history analysis method, and then combined with the permanent load internal force. Dead load axial force minus seismic axial force got the axial load combination and dead load bending moment plus seismic bending moment got the bending moment combination. The moment capacity checking of key components was made using the above force combinations with UcFyber software Because Chao-yang bridge is an almost symmetrical structure, the checking results of only half structure were listed in this paper. And all towers and piers could meet the E1 and E2 level earthquake requirements, the seismic performance checking results of them were not listed in this part because of space cause.

4.1 Longitudinal + vertical direction ground motion

The checking results with longitudinal + vertical direction ground motion inputs were shown in Table 1~ Table 2.

Table 1 Comparison of seismic demand and capacity of pile foundations

Condition	Location	Axial force combination (kN)	Moment combination (kN·m)	Moment capacity (kN·m)	Capacity/ demand	Safety check (√ or ×)
E1	P14	2.92E+03	8.54E+02	5.10E+03	5.97	√
	T15	1.87E+04	5.04E+03	2.07E+04	4.09	√
	T16	2.00E+04	4.30E+03	2.15E+04	5.01	√
	T17*	9.37E+03	5.78E+03	1.45E+04	2.51	√
E2	P14	1.25E+03	1.71E+03	5.97E+03	3.49	√
	T15	1.19E+04	8.62E+03	2.02E+04	2.34	√
	T16	1.25E+04	6.98E+03	2.06E+04	2.95	√
	T17*	-1.74E+04	1.23E+04	0	0	×

Notes: * indicates the fixed pier.

The results in Table 1 indicate that all piles could meet the seismic demand under E1 seismic action. Under E2 seismic action, the piles under T17 could not meet the seismic performance requirements, while other components could keep elastic.

Under the condition of longitudinal + vertical direction ground motion input, only the fixed bearing of T17 could withstand seismic shear force, so shear capacity checking should be made for this bearing. The checking results were shown in Table 2.

Table 2 Comparison of shear force demand of bearing

Condition	Location	Shear force (kN)	One bearing tonnage (kN)	Shear capacity (kN)	Capacity/ demand	Safety check (√ or ×)
E1	T17	14533	100000	10000	0.69	×
E2		25563	100000	10000	0.39	×

Notes: The shear capacity takes 10 percent of the bearing tonnage.

The results in Table 2 show that the seismic shear forces are both greater than the shear capacity of the fixed bearing under E1 and E2 seismic action, so the fixed bearing would be cut off.

4.2 Transversal + vertical direction ground motion

The checking results of key components with transversal + vertical direction ground motion inputs were shown in Table 3~ Table 4.

From the results of Table 3, it can be seen that all piles could meet the seismic demand under E1 seismic action. Under E2 seismic action, the seismic capacity of all piles was inadequate so that they would be yielded.

Under the condition of transversal + vertical direction ground motion input, the fixed bearings on this way of each towers could withstand seismic shear force, so transversal shear capacity checking should be made to all these bearings. The checking results were shown in Table 4.

Like the results under longitudinal ground motion input, the seismic shear forces of the fixed bearings are all greater than the shear capacity under E1 and E2 transversal seismic action. But the capacity to demand ratio of E1 seismic action is close to 1, and much better than that of E2. So the following seismic isolation measures were aimed to E2 level seismic action.

Table 3 Comparison of seismic demand and capacity of pile foundations

Condition	Location	Axial force combination (kN)	Moment combination (kN·m)	Moment capacity (kN·m)	Capacity/ demand	Safety check (√ or ×)
E1	P14	2.12E+03	2.71E+03	4.73E+03	1.74	√
	T15	1.37E+04	6.71E+03	1.70E+04	2.53	√
	T16	1.43E+04	6.77E+03	1.74E+04	2.56	√
	T17	1.36E+04	5.71E+03	1.70E+04	2.97	√
E2	P14	-6.06E+02	5.82E+03	4.90E+03	0.84	×
	T15	-5.14E+03	1.33E+04	7.64E+03	0.57	×
	T16	-5.37E+03	1.43E+04	7.44E+03	0.52	×
	T17	-6.36E+03	1.21E+04	6.58E+03	0.54	×

Table 4 Comparison of shear force demand of bearing

Condition	Location	Shear force (kN)	One bearing tonnage (kN)	Shear capacity (kN)	Capacity/ demand	Safety check (√ or ×)
E1	P14	4815	30000	4500	0.93.	×
	T15	11479	100000	10000	0.87	×
	T16	11715	100000	10000	0.85	×
	T17	12608	100000	10000	0.79	×
E2	P14	9184	30000	4500	0.49	×
	T15	23110	100000	10000	0.43	×
	T16	25754	100000	10000	0.39	×
	T17	25128	100000	10000	0.39	×

Notes: The shear capacity of bearings on the towers takes 10 percent of the bearing tonnage, and the shear capacity of bearings on the transition piers takes 15 percent of the bearing tonnage.

5 Seismic isolation design

5.1 Introduction of the CSFAB measure

The seismic isolation design measure of this bridge is the cable-sliding friction aseismic bearing design, which has been used on several bridges in use [4]. This new bearing is a combination of the plane sliding-type pot bearing or spherical bearing and restrainer cables with a shear bolt installed in the center of the bearing vertically while it is a sliding-type bearing without a shear bolt, which takes advantage of both the friction sliding resistance and the restraint capability of the cables. Under minor and moderate earthquakes, the shear bolt in a fixed-type bearing should not break, normal operations of the bridge could be carried out. And under a severe earthquake that causes the shear bolt to break, the fixed-type bearing functions as a sliding-type bearing to mitigate the transmission of seismic forces and dissipate seismic energy, while the excessive relative displacement between the superstructure and the pier can be restrained by the cable components.

In order to get the basic performance parameters, the quasi-static test of a CSFAB which design carrying capacity is 8MN has been done, and the hysteretic curve has got as shown in Fig. 3. Fig. 4 shows the photo of the test bearing.

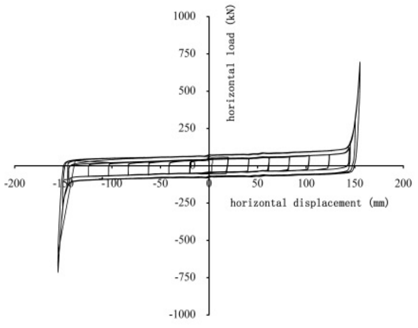


Figure. 3. Hysteretic curve of CSFAB

Figure. 4. Photo of the test CSFAB

In this seismic isolation project, sliding CSFAB was set on tower T15 and T19, which are distributed symmetrically taking the fixed tower, as shown in Fig. 5, and the shear bolts were set in the fixed bearings of T17. The free displacement of cables was selected as 0.15 m, and the elastic stiffness value was 1.02×10^6 kN/m, and the friction coefficient was 0.02, and the shear strength of the shear bolt was 10% of the single bearing tonnage. The layout of bearings on the other piers was as same as conventional project.

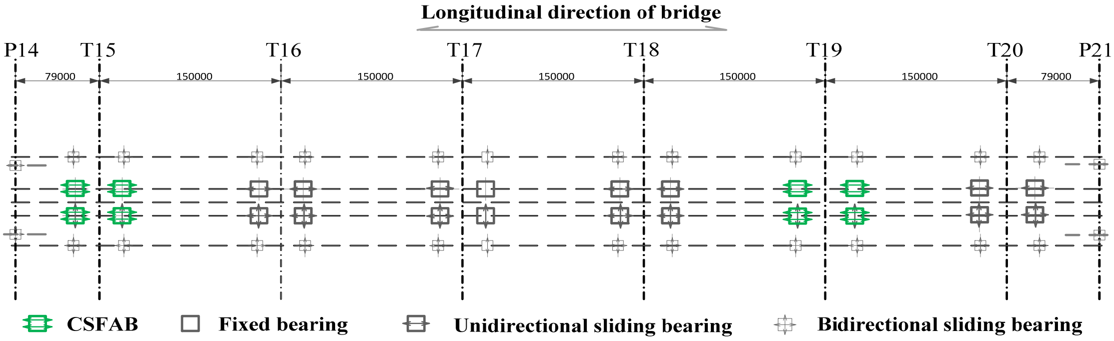


Figure. 5. Layout of bearings

In the finite element model, the CSFAB was simulated by combination of the Wen Plastic and polyline elastic element [5]. The pot bearing was simulated as a Wen plastic element, and the cables as multi-linear link elements. The shear bolt was not simulated in the bearing model, as the bolt is designed to be already sheared off under severe earthquakes, and also the shear bolt was deliberately sheared off under E2 seismic action discussed above.

5.2 Key section checking results

As before, the key components could almost meet the seismic demand under E1 earthquake action, so E1 seismic checking results using the isolation measures would not be made in this part. Under E2 seismic action, the shear bolt of fixed bearing was sheared off and the cables controlled the relative displacement between piers and beams. The following Table 5 ~ Table 8 show the seismic checking results of key components including the cable with the CSFAB isolation measure.

5.2.1 Longitudinal + vertical direction ground motion

Table 5 Comparison of seismic demand and capacity of pile foundations

Condition	Location	Axial force combination (kN)	Moment combination (kN·m)	Moment capacity (kN·m)	Capacity/ demand	Safety check (√ or ×)
E2	P14	1.32E+03	1.68E+03	5.97E+03	3.55	√

T15	8.68E+03	9.38E+03	1.79E+04	1.91	√
T16	1.40E+04	7.74E+03	2.16E+04	2.79	√
T17	1.41E+04	7.12E+03	2.17E+04	3.04	√

Table 6 Comparison of seismic demand and capacity of cables

Condition	Location	Cable force (kN)	One bearing tonnage (kN)	Cable ultimate strength (kN)	Capacity/ demand	Safety check (√ or ×)
E2	T15	3299	100000	32000	9.70	√

Notes: The ultimate strength of cables takes 32 percent of the bearing tonnage.

5.2.2 Transversal +vertical direction ground motion

Table 7 Comparison of seismic demand and capacity of pile foundations

Condition	Location	Axial force combination (kN)	Moment combination (kN·m)	Moment capacity (kN·m)	Capacity/ demand	Safety check (√ or ×)
E2	P14	1.43E+03	3.35E+03	6.02E+03	1.80	√
	T15	1.36E+04	9.32E+03	2.11E+04	2.26	√
	T16	1.62E+04	8.52E+03	2.28E+04	2.68	√
	T17	1.58E+04	7.61E+03	2.26E+04	2.97	√

Table 8 Comparison of seismic demand and capacity of cables

Condition	Location	Cable force (kN)	One bearing tonnage (kN)	Cable ultimate strength (kN)	Capacity/ demand	Safety check (√ or ×)
E2	T15	1954.5	100000	32000	16.4	√

Notes: The ultimate strength of cables takes 32 percent of the bearing tonnage.

The checking results in Table 5 ~ Table 8 indicated that the seismic isolation measure could reduce the seismic force of fixed tower significantly. Though the seismic force of other towers and piers increased to a certain extent, they were all under control and could meet the earthquake requirements.

In the meantime, the deck-pier relative displacement caused by the break of bearings could be effectively limited in case of girder falling. The relative displacement between deck and tower was listed in Table 9.

Table 9 Deck-tower relative displacement

Condition	Location	No cables (m)	Set cables (m)
E2 (longitudinal＋vertical ground motion)	P14	0.194	0.134
	T15	0.190	0.126
	T16	0.189	0.132
	T17	0.188	0.132
E2 (transversal＋vertical ground motion)	P14	0.156	0.119
	T15	0.149	0.110
	T16	0.149	0.133
	T17	0.149	0.140

The CSFAB was also set on the piers of approach bridges correspondingly, and all piers and piles could meet E1 and E2 level seismic requirements through seismic checking.

Above all, the simulation results demonstrated that the Chao-yang bridge could meet the expected E1 and E2 level earthquake requirements using CSFAB isolation measures. At the same time, a 1/20 scale model was tested on shaking table to certify the safety of the bridge seismic isolation design [6], as shown in Fig. 6. The experiment results also validated the effectiveness and safety of the CSFAB isolation design.

Figure. 6. Shaking table experiment model of Chao-yang bridge

6. Conclusions

Under moderate or strong earthquakes, the fixed towers of the bridge and piles under them are vulnerable components. Through adopting the seismic isolation design, the seismic force can be reduced significantly. The simulation and shaking table experiment results both indicated that when the CSFAB was set on the towers distributed symmetrically taking the fixed tower, the seismic force of the fixed tower reduced, and the force of the towers that set CSFAB increased at an acceptable range, while the relative displacement between tower and beam could be limit in a manageable level.

Acknowledgements

This research is supported by the National Natural Science Foundation of China under Grants No. 51278376 and 51478339, and by the Ministry of Science and Technology of China under Grant No. SLDRCE14-B-14. This support is gratefully acknowledged.

References

[1] Fang Yuan, Deng Yulin, Li Jianzhong. Discussion on dynamic characteristic and seismic responses of a long- span multi-tower cable stayed bridge. Structural Engineers. 2009, 25(5): 72-77.

[2] Yuan Wancheng, Cao Xinjian, Rong Zhaojun. Development and experimental study on cable-sliding friction aseismic bearing. Journal of Harbin Engineering University. 2010, 31: 1593-1600.

[3] Ministry of Housing and Urban-Rural Development of the People’s Republic of China, Code for seismic design of urban bridges (CJJ 166-2011). Beijing: China Building Industry Press, 2011.

[4] Cao Xinjian, Xiong Yongguang, Fu Yi, et al. Seismic Design of Hangzhou Jiu-bao Bridge．CECAR 5 & ASEC 2010 Conference，Sydney，Australia，Aug. 8~11, 2010.

[5] Yuan Wancheng, Wang Binbin, Cheung Pakchiu, et al. Seismic performance of cable-sliding friction bearing system for isolated bridges. Earthquake Engineering and Engineering Vibration. 2012, 11: 173-183.

[6] Zhou Ying, Lv Xilin. Method and Technology for Shaking Table Model Test of Building Structures. Beijing: Science press, 2012.06.