Research on strengthening suspended deck system for half-through CFST arch bridge by setting longitudinal steel-tubular trusses

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ABSTRACT: The crossbeams are the main members for suspended deck system of many existing half-through CFST arch bridges. And the suspended longitudinal RC T-shaped floor beams in the through part of the bridge are supported on the PC cross beams which is suspended by high tensile steel cable hangers to the arch ribs. Such a deck system without a longitudinal stiffening girder will cause large deflection and vibration because of its weak integrity as well as vertical stiffness. Therefore, it is necessary to carry out research on strengthening of such kind of deck system to improve the risk-resistance capacity. Taking Shitanxi Bridge as an example, the strengthening project is proposed by setting longitudinal steel tubular trusses between the crossbeams. The static and dynamic behaviors of this bridge before and after strengthening were analyzed and field tests for both static and dynamic behaviors after strengthening were also carried out. Analysis and test results show that setting steel tubular truss beams between the crossbeams is effective on improving the dynamic performance and risk-resistance capacity for the suspended deck system of half-through or through CFST arch bridges without longitudinal stiffening beams. This strengthening method is not only economic and applicable, but also has little influence on traffic flow during construction.

1 INTRODUCTION

Concrete filled steel tubular (CFST) arch bridges have been building in China since 1990, in which half-through arch and through arch are the main types (Chen 2009). The deck systems in CFST arch bridges are generally reinforced or prestressted concrete structures for their economy. For a half-through arch bridge, the suspended longitudinal RC slabs or small T-shaped floor beams in the through part of the bridge, are supported on the RC or PC cross beams which are suspended by high tensile steel cable hangers to the arch ribs. For half-through CFST arch bridges built in 1990s, generally there is no longitudinal connection between the reinforced concrete cross beams. Thus the deck system will behave large deflection, vibration and low risk resistance capacity because of its bad integrity as well as vertical stiffness. Once a hanger is broken, cross beams and deck slabs will easily fall into the river and result a serious accident. Therefore, how to strengthening suspended deck system for early half-through or through CFST arch bridges is an issue worth of research (Chen 2007). Taking Shitanxi Bridge as an example, a strengthening project is proposed by setting longitudinal steel tubular trusses between the crossbeams in this paper.

Shitanxi Bridge situated in No.316 national highway, Fuzhou city, Fujian province, China, links Ming Xikou and Xiongjiang, and runs over the Shitanxi River, the branch Ming Jiang. The bridge is about 250m away from Shuikou power station. The main bridge is half-through CFST bridge with a clear span of 136m and rise-to-span ratio is 1/3. It adopts centenary curve shape with parameter value m of 1.167 as its arch axis. The lane of the bridge is 9m and each of the two sidewalks is 1.5m wide. The design load of the bridge is vehicle-over 20, trailer-100 by the old China Highway Bridge Design Code JTJ 021-85 and the pedestrian load is 3.0 kN/m^2 (Chen 2002).

An arch rib with a width of 1.6m and height of 3.0m consists of four CFST chords with 550mm diameter and 8mm thickness, filled with C50 concrete. Two of them in both upper and lower levels are welded together by two steel tubes with 400mm diameter and 8mm thickness.

The vertical and diagonal members are steel tubes with 219mm diameter, thick of 8mm. Three steel tubular truss bracings above the deck and two K-shape bracings under the deck are provided as lateral bracing systems for the main arch structure. The longitudinal distance of hanger is 8.1m. The hangers are high tensile steel wire. Each cable contains 110ф5mm high-strength wire.

The deck system is composed of RC cross beams, deck slabs and concrete pavement, as shown in Fig.1. The PC cross beams are suspended by hangers, and the T-shaped RC deck slabs are placed on the crossbeams. The crossbeams suspended by hangers or supported on the spandrel columns are all concrete structural members with I-shape section. The flange of upper and bottom slab is 0.6m in width and 0.27m in thickness. The web plate is 0.2m in thickness. The longitudinal laps between adjacent T-shaped RC deck slabs and transverse laps between slabs and cross beams are cast concrete in-situ to form whole deck slab. The total section of deck slab is 0.5m in height, 1m in width, and about 8m in length.

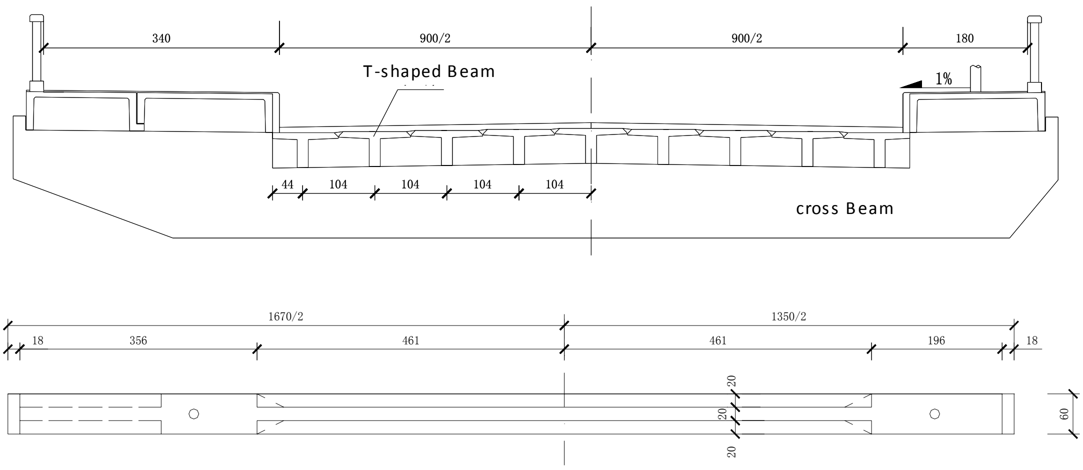


Figure 1 : Deck system arrangement diagram (unit: cm)

Shitanxi Bridge was constructed from October 1996 to the end of 1997. During more than ten years in service, some expansion joints and deck pavement were replaced and maintained at one time. Field investigations and analyses carried out by the highway maintenance management indicate that its main structures of the bridge are in good condition, the bridge can meet the requirements of design loads, and the efficient coefficient η of the test is equal or slightly lower than the allowable value(0.8~1.0). However, the vibration of the bridge could make passengers feel uncomfortable when the vehicles run through the bridge, especially heavy vehicles. In order to reduce the vibration and improve the service quality and durability of the bridge, a project to strengthening the deck system was proposed.

2 STRENGTHENING DESIGN

2.1 Design Principle

Based on an overall consideration of various factors, including actual performance of bridge structure, site condition and project budget, the main principles for strengthening design are as follows:

(1) After the strengthening, the integrity of deck system will be improved and the dynamic response to traffic will be reduced;

(2) Not only because no obvious problem is investigated for the hanger and it is difficult to replace it, but also because budget is limited, hanger replacement is not considered in this strengthening project. Therefore the strengthening should enhance the structure risk resistance capacity and a serious accident can be prevented once a hanger is broken. In other words, when a hanger is broken, the added stiffening longitudinal beams supported by the two nearby hangers can carry dead loads and a heavy vehicle of three span deck slabs.

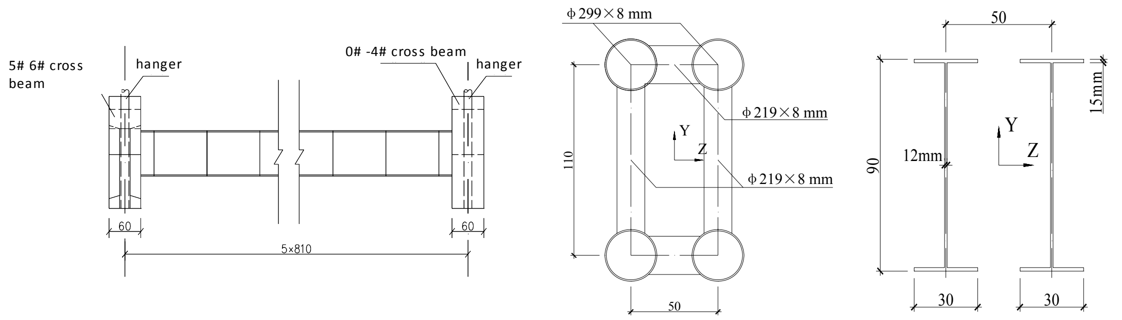
(3) The strengthening project is not only economic and applicable, but also has little influence on traffic and the original structure during strengthening construction.

2.2 *Strengthening and rebuilding scheme*

Following the above mentioned design principles, two strengthening schemes were proposed to add two longitudinal stiffening beams between the crossbeams in their two ends under the sidewalks, as follows:

(1) Each beam is composed of Q235 I-shape steel plate, as shown in Fig.2 (a) (b). The section properties are as follows: $A=0.0388m^2$, $Iz=0.0048m^4$, $Iy=0.026m^4$;

(2) Each longitudinal beam is composed of four circle steel tubes with the diameter of 299mm and thickness of 8mm, as shown in Fig.2 (c). The section properties are as follows: $A=0.0293m^2$, $Iz=0.0092m^4$, $Iy=0.021m^4$.



(a) (b) (c)

Figure 2 : Strengthening and rebuilding schemes (unit: cm): (a) longitudinal arrangement diagram of scheme1, (b) cross-section of scheme1, (c) cross-section of scheme2

2.3 *Comparison of schemes*

A three-dimensional finite element model has been developed to analyze the bridge. Arch rib is simulated by beam elements. Hangers are simulated with truss elements. The concrete deck slab is also modeled by two-node beam elements. The pavement layers did not have their own geometrical and inertial properties, only masses. The arch springs are assumed to be fixed. As a result, the model has a total of 2582 elements, 1302 nodes before strengthening, and the model has a total of 2612 elements, 1302 nodes after strengthening. The FE model is shown in Fig.3. In this FE model, the rear axle of design vehicle (total weight of 55t) directly acts on the centre line of one short and broken hanger.Table 1 and 2 indicate the static analyses results. From these two tables we can find that in both of the two schemes, the longitudinal beams can all bear dead and vehicle load in a short time when a hanger is not in work.

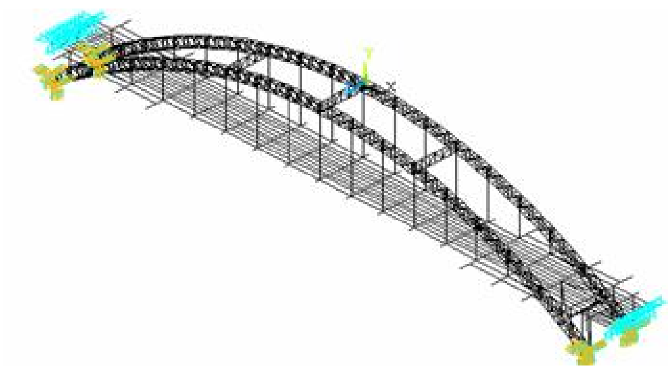


Figure 3 : Finite element model of Shitanxi Bridge

Table 1 : Internal force of stiffen longitudinal beams

Number of scheme	Internal force	dead load	live load	dead load + live load
1	moment（kN•m）	972.6	494.1	1466.7
	shear（kN）	115.8	139.6	255.4
	axial tension force（kN）	971.2	486.1	1457.3
2	moment（kN•m）	943.1	473.3	1416.4
	shear（kN）	136.6	101.3	237.9
	axial tension force（kN）	1063.5	534.5	1598.0

Table 2 : Stress of stiffen longitudinal beams

Stress	scheme 1（MPa）	scheme 2（MPa）	allowable stress（MPa）
tension stress（MPa）	175	162	215
Shear stress（MPa）	6.6	8	215

From the change of the natural frequencies shown in the Tab.3, it can be seen that the Mode 1 has no change because the deck system has no influence to the out-of-plane vibration of arch rib, while Mode 2 and 3 will increase after the strengthening, in which Mode 3 will give a better result than Mode 2.

Table 3 : Natural frequency(unit: Hz）

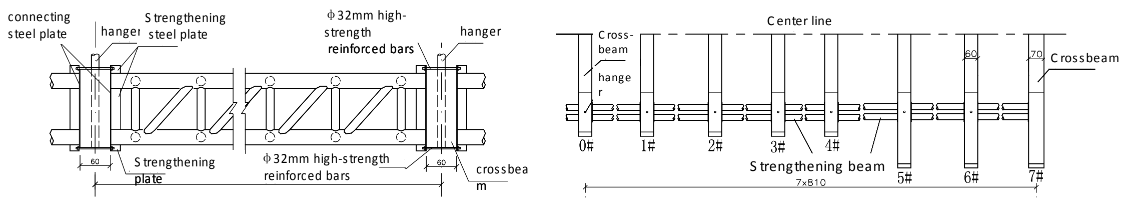
	mode	existing bridge	scheme 1	scheme 2
1	First bending mode of arch rib out of plane	0.395	0.395	0.395
2	First bending mode of deck in plane	0.707	0.744	0.767
3	First asymmetric bending of arch rib and deck in plane	0.939	0.936	0.948

Analysis on coupling vibration of vehicle-bridge is carried out using tested road roughness and vehicle speed of 30km/h. Results show that the dynamic deflections of the deck in the middle span are significantly reduced 7.5％ in scheme 1 and 12.6％ in scheme 2 respectively.

2.4 Strengthening design

By comparison the strengthening effects and the economic and construction feasibility, Scheme 2 was adopted as the design scheme at last.

Steel tube truss longitudinal beams are arranged between the crossbeams under the sidewalks, which are symmetry for center line of deck and their cross-sections are perpendicular to the axial line of hangers. The connecting steel plates welded at the two ends of each longitudinal beam are fixed at the crossbeams by the φ32mm high-strength reinforced bars, as shown in Fig.4. There are 15 crossbeams in Shitanxi Bridge, therefore 28 longitudinal beams (14 on each side) are set.



(a) elevation view (b) plan view

Figure 4 : Layout of longitudinal stiffening beam (unit: cm)

The longitudinal beam is composed of four steel tubes with the diameter of 299mm and thickness of 8mm, Two of them in both upper and lower levels are welded together by a steel tubes with 219mm diameter and 8mm thickness. The vertical and diagonal members are steel tubes with 160mm diameter, thick of 8mm. The cross section of the longitudinal beam is

1.399m in height and 0.799m in width, as shown in Fig.5.

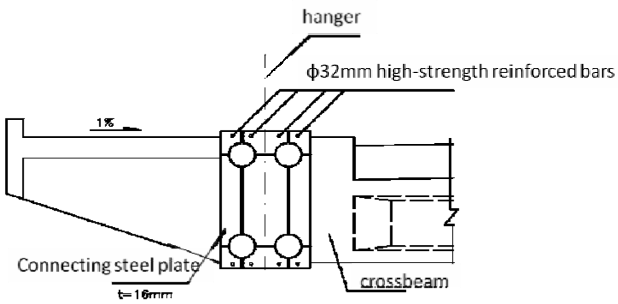


Figure 5 : Cross section of stiffen longitudinal beam

2.5 Construction

In construction, the longitudinal beams are set from one side to the other side, thus the traffic will not be disrupted by the construction. Construction sequence is listed bellow:

(1) Move pedestrian slabs away, and measure actual distance between the crossbeams;

(2) Weld and assemble the steel tube truss longitudinal beams in the workshop, and paint the surface of the steel structure with electric arc aluminum coating primer (120um) and epoxy micaceous iron antirust intermediate (80um) successively;

(3) Transport the longitudinal beams to the site, take it in position. After they are fixed at the crossbeams, polyurethane coating (50um) is applied to the surface of steel structure;

(4) To ensure the sealing performance of longitudinal and cross beams connections, the laps between the connecting steel plates and the crossbeams are filled with epoxy mortar;

(5) Finally, recover the pedestrian slabs.

Shitanxi Bridge after strengthening is shown in Fig.6.

Figure 6 : Shitanxi Bridge (after strenghtening)

3 FIELD TESTS AFTER STRENGTHENING

In order to inspect the construction quality and have a thorough knowledge of working performance and actual loading capacity of the structure, static and dynamic tests were carried out after the strengthening on August, 2008.

Static test results (shown in Tab.4 and Tab.5) show that the effective coefficient η of the deflection and strain can all meet code demand and the test results were accorded with the results from FEM analysis.

The axial forces of hangers increase slightly by the added dead load of the longitudinal beams after strengthening, as shown in Tab.6 and Tab.7, but still meet the design requirement. And the axial forces of hangers under live loads were evenly distributed; the fatigue property of hangers was improved.

Maximum deflection of arch rib and deck are reduced under live loads after strengthening, as shown in Tab.8, smaller than the allowable value of 13.6 cm.

Table 4 : Deflection and check coefficient of control section of arch rib

case	deflection of arch rib(mm)		effective coefficient	position
	test result	calculated value		
1-1	-21.45	-20.13	1.07	arch crown near the upstream of the river
1-2	-21.43	-20.03	1.07	arch crown near the downstream of the river
1-3	-17.96	-16.89	1.06	arch crown near the upstream of the river
2-1	-28.60	-27.70	1.03	3/4L section of arch rib near the upstream of the river
2-2	-28.36	-26.47	1.07	3/4L section of arch rib near the downstream of the river
2-3	-24.63	-23.34	1.06	3/4L section of arch rib near the upstream of the river
3-3	-19.88	-18.68	1.06	arch spring near the upstream of the river

Table 5 : Strain and check coefficient of control section of arch rib

case	strain of arch rib (mm)		effective coefficient	position
	test result	calculated value		
1-1	-134	-145	0.92	arch crown near the upstream of the river
	-128	-142	0.90	
1-2	-137	-144	0.95	arch crown near the downstream of the river
	-148	-141	1.04	
1-3	-119	-123	0.97	arch crown near the upstream of the river
	-130	-123	1.05	
2-1	-134	-138	0.97	3/4L section of arch rib near the upstream of the river
	-138	-135	1.02	
2-2	-130	-134	0.97	3/4L section of arch rib near the downstream of the river
	-135	-131	1.03	
2-3	-102	-115	0.89	3/4L section of arch rib near the upstream of the river
	-108	-115	0.94	
3-3	-107	-104	1.03	arch spring near the upstream of the river
	-103	-104	0.99	

Table 6 : Internal force of hangers under dead load (unit: kN)

No.	0	1	2	3	4	5	6
before consolidation	465	484	478	476	476	549	556
after consolidation	481	503	497	493	495	566	574

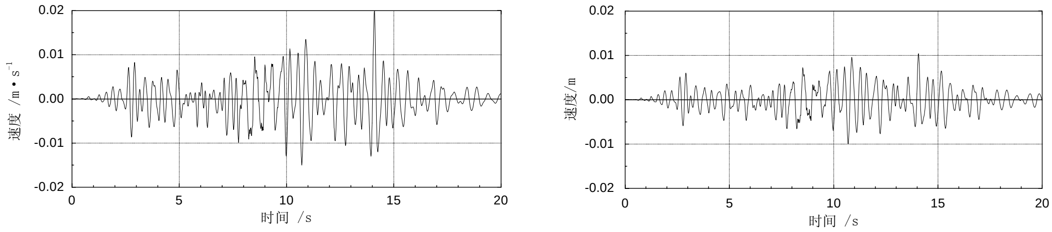
Table 7 : Internal force of hangers under vehicle load (unit: kN)

No.	0	1	2	3	4	5	6
before consolidation	0.0	34	69	69	61	97	298
after consolidation	3.3	34	64	67	62	106	253

Table 8 : Maximum deflection of deck and arch rib (unit: cm)

	maximum deflection of arch rib	maximum deflection of deck
before consolidation	5.61	5.87
after consolidation	5.57	5.82

The response speed time-history curve of deck at the span central is shown in Fig.7. It can be seen from the graph that response speed after strengthening is 1.3cm./s, smaller than the value before strengthening (2.0cm/s). The response speed can be converted into vibration sensation index by utilizing the relationship between them (Wu Qingxiong et al. 2008a, b, Kobori T. Kajikawa Y 1974). The vibration sensation index after strengthening is 0.81, reduced by 20% than before strengthening. By the analysis of coupling vibration of vehicle-bridge, we can find that strengthening makes dynamic response of deck system decrease.



(a) (b)

Figure 7 : Speed time-history curves of deck at the span central: (a) Before strengthening, (b) After strengthening

3 CONCLUSIONS

When vehicles run over the bridge, the deflection and vibration of deck system of Shitanxi Bridge were large because of the weak longitudinal integrity of the structure. So the strengthening schemes were studied. Based on the numerical analysis and site condition investigation, the scheme to adding longitudinal steel tubular truss beams between the crossbeams was selected as the solution to the problem. After-strengthening field tests show that the rigidity of the structure and the vehicle-bridge vibration performance are siginificanly improved. At the same time, the risk-resistance capacity of structure is also enhanced after strengthening. Once a hanger is broken, the longitudinal beams suspended by hangers can still bear temporary load in a short time and thus avoid the occurrence of a serious accident. Therefore, this strengthening method is not only economic and applicable, but also has little influence on traffic flow during construction.

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