SMAR 2019 – Fifth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

SMAR 2019

Damage control, repair and strengthening of concrete arch bridges in China

Baochun CHEN [1]

[1] College of Civil Engineering, Fuzhou University, Fuzhou, China

Contact e-mail: baochunchen@fzu.edu.cn

ABSTRACT: Concrete arch bridge is one of the main type of bridges in China. In this paper, after a brief introduction of its develope history and maintanance, the damage control, repair and strengthening are presented, focusing on their special characteristics. There are many light concrete arch bridges in the Chinese road systems, including double-curved arch bridge, disc arch bridges and prestressed truss arch bridges, which were very economic and favored structures in the period between 1960s-1980s when construction materials and equipment have been rare. Now they have severe defects, such as deficient stiffness, low load bearing capacity or poor connections. Main problems and how to repair and strengthen them are presented with some case studies. Another big problem of Chinese concrete arch bridges is the deck failure caused by broken suspension cables. Some accidents are presented, and the causes of their collapse are analyzed. Finally, appropriate strengthening measures are proposed to improve the structural robustness and to prevent an extent disproportional failure to the original cause.

1 INTRODUCTION

China is a country with wide mountain areas that cover 69 % of the country's land area. Arch bridges are an appropriate bridge type to cross valleys. Ancient arch bridges have achieved high prestige in China since they first appeared in 230 B.C according the archaeological exploration (Chen 2005).

Thanks to its relatively high compressive strength, concrete can be used economically in an arch bridge, which is primarily subjected to compressive forces. It is well known that reinforced concrete (RC) can be used economically in arch bridges ranging from 35 to 200 m (Chen 2013) .

First Chinese RC bridges were constructed in railway applications in the 1940s. In 1965, the longest span of the Hong-du bridge in Du-an county (Guangxi province) reached the 100 m (Chen and Ye, 2008).

In 1960s-1970s, great efforts have been made in China to reduce the structural self-weight, to save materials and to facilitate construction by simple equipments. Some light arch bridges, such as double curved arch, disc arch and prestressed truss arch, were proposed and developed from the solid-ribbed arch.

After the 1980s, normal reinforced concrete rib or box arch bridges have been building with increase of the construction materials and improvement of the the construction equipments in the country. Until February 2016, a total of 253 concrete arch bridges were built with a span of no less than 100 m by an investigation. Currently, among 44 bridges with a span of 200 m or longer in the world, 11 of them are in China, which is 25%. All three arch bridges with a span longer than 400 m are in China (Chen, etc, 2017). The current long-span record is 445 m of the

Beipanjiang Bridge, which was opened to traffic on December 28, 2016, is shown in Fig. 1 (Xu, etc., 2011).

Fig. 1 Beipanjiang Bridge

Concrete arch bridges play a very important role in Chinese infrastructure with their great variety and large span. Their damage control, repair and strengthening are very important topics and will be presented in this paper.

2 GENERAL MAINTENANCE OF CONCRETE ARCH BRIDGES

Like other bridges, concrete arch bridges need service management and maintenance after completion. In China, the China Bridge Management System (CBMS) has been studied and developed since 1986 and is widely used for highway and city RC arch bridges.

The concrete arch bridges shall be inspected regularly and periodically, and especially when in case of doubts. Condition rating may be applied according to the *Code for Maintenance of Highway bridges and culverts (JTG H11-2004)*, in which a bridge structure is divided into 3 parts (superstructure, substructure and deck system), including 17 segments, the deficiency of all of them are considered according to a specified list of deficiency ratings. Such a condition rating method seems easy but is hard to implement for most engineers. In many times, it depends on the engineer's experience, education and subjective judgment to assess the third grade and the fourth-grade damages. Different people may draw different conclusions, which often causes dispute.

Based on years of practical experience, Hanwan Jiang et al. [8] conducted field investigation on arch bridges in Guangxi, then established a rating system and detailed inspection guidance based on 3D benchmark graphics. The guidance provides qualitative description, quantitative description, and 3D benchmark graphics description for the condition rating of arch bridges. It helps to reduce the mistakes and unexpected events during the arch bridge maintenance and management procedure. It can be proposed as a useful supplement to the current bridge maintenance code in China.

As basis for the condition rating, visual inspection is the most common method. If necessary, further inspection including field dynamic and static testing can be carried out. Finally, finite element method is employed to analyse and give the rating or assessment results.

Performance assessment of a RC arch bridge with a main span of 120 m was conducted through field visual inspection, ambient vibration testing, vehicle load (static and dynamic) testing, as well as finite element analysis by Zong and Xia (2008). The inspection, testing and analysis revealed deterioration and damage in bridge deck, rails, spandrel columns and arch-ring (box-section), while the bridge still has the capacity to carry the design load. Maintenance and strengthen are really necessary to guarantee the service quality and safety as well as the durability in future.

3 REPAIR AND STRENGTHEN OF LIGHT CONCRETE ARCH BRIDGES

For the existing concrete arch bridges, the main problems appeared in light arch bridges built before 1990s. They do not only have experienced many years in service, but the construction type itself has sometimes defects.

The main structure of a light concrete arch bridge has relatively small cross sections and is reinforced by few rebars for saving material. Therefore, the load-carrying capacity is low and the stiffness is small. The precast components are wet joined together by concrete with low strength. Thus, the integral and whole stiffness of the bridge is poor and it is easy to cause cracking in the joints. Moreover, the live load in 1960s was Vehicle-13 (the total weight of the vehicle is 13 tons), which was increased to Vehicle-20 or Vehicle-over 20 in 1980s. Now, both lane load and truck load much heavier than before are used in design (Chen, Yu and Li, etc., 2011).

The technical condition of the majority of these light arch bridges is very poor. Even it is encouraged to build and renew the infrastructures, it is not possible to rebuilt all of them. In order to allow them to serve under the increased traffic load safety, it is important to repair and strengthen them in time.

The typical damages include material degradation due to ageing, differential settlement of foundations, longitudinal and transverse cracks in the arch ribs, cracks in joints between precast members and in lateral connections, etc.

For double curved arch bridges, the main strengthening methods for the superstructures are as below:

(1) Strengthening arch ribs: employing steel plates or carbon fiber reinforced plastics (CFRP) layers to be attached in the arch ribs to improve the carrying capacity; encasing RC to the original arch ribs to enlarge their cross section areas; adding a bottom flange to the arch ribs to change the arch cross section from double curved into box.

(2) Improving lateral connection: Enlarging the lateral beams by encasing RC layer; adding new lateral beams; changing the lateral beams section from I-shape into rectangular.

(3) Others: Replacing the slight curved deck structure into normal solid slabs or integral cast-in-situ deck slab; changing the neutral axis line or compression line of an arch bridge; etc.

The double curved arch bridge, Wuli Bridge in Fuzhou, built in 1970 with spans of 7.9+8×22+6.1 m, was taken as a typical example by Shanggun and Zhou (2007). From investigation, it was found that some steel bars in most arch ribs were corroded. The transverse beams were damaged in some sections, and longitudinal cracks appeared in arch ribs, as shown in Fig. 2. After investigation and analysis, repair and strengthening measures were proposed and carried out, as shown in Fig. 3. The arch ring in springing and in crown were both enlarged, the former was enlarged by encasing RC to form a solid section, while the latter was enlarged by adding concrete in saddling to increase the section depth, the soffit of the crown section was reinforced by CFRP.

Fig.2 Damages of Wuli Bridge

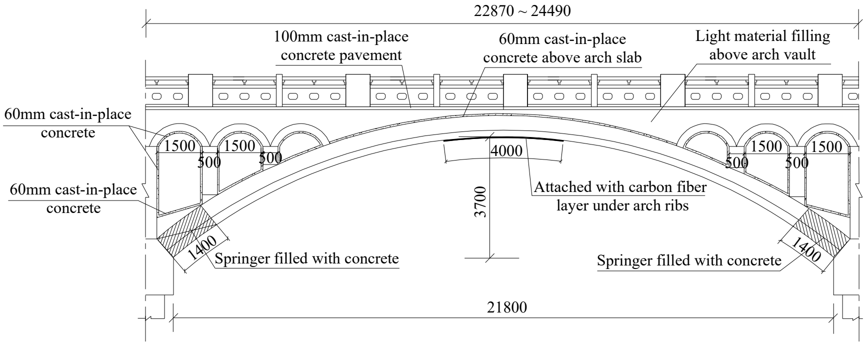

Fig. 3 Repair methods of Wuli Bridge (mm).

As in the rigid-frame arch bridge, the main problems are cracks in arch ribs, in cross beams, as well as in the micro curved deck slabs. The typical crack distribution in the bridge is shown in Fig. 4 (Ren, etc., 2008). Their repair and strengthening methods are similar to those mentioned for double-curve arch bridges, such as strengthening arch ribs, improving lateral connection and so on.

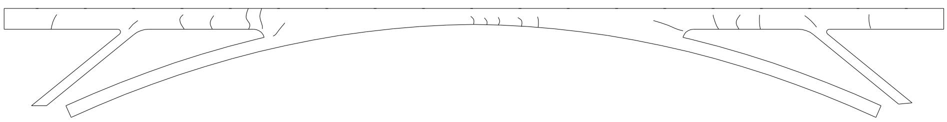

Fig. 4 Typical crack formation in a rigid-frame arch

4 SUSPENDER BROKEN AND DECK COLLAPSE OF THROUGH AND HALF-THROUGH CONCRETE ARCH BRIDGES

Formerly, most of the concrete arch bridges in China were deck bridges. After 1990, more and more through and half-through arch bridge are built. In these bridges, the dead-load of the deck and live loads on deck are transferred to the arch rib by suspenders. These suspenders are made of high strength cables, in which many problems were detected in existing bridges, such as corrosion, fatigue failure, and insufficient protection, as shown in Fig. 5 (Gao, etc., 2013).

(a) Corrosion in Anchorage (b) PE Cracking on Suspender Cable

Fig. 5 Distress of suspender

To improve their safety margin, we may use large safety factor for suspenders, enhance the waterproof and anti-corrosion design, employ bolts for the anchor head shields instead of welding for facilitating more easy inspection.

From present engineering practices, the suspender cables do not have the same design life as that of the main structure. Therefore, they must be designated as replaceable components. Moreover, measures for easy replacement should be considered in design, *e.g.*, the old one should be easily dismantled and the new one should be easily installed with a temporary support.

In recent years, suspender fracture happened in some Chinese concrete arch bridges. Some accidents are reported and investigated by chronological order in the follows.

Xiaonanmen Bridge in Yibin City, Sichuan Province, built in 1990, is a half-through RC arch bridge with a clear span of 240 m. There are two arch ribs with a clear rise of 48 m, resulting in a rise-to-span ratio of 1/5. The suspenders are made of steel strands of 21-7Φ5 mm, covered by seamless steel tube, filled with cement mortar for protection against corrosion. The suspenders carry the prestressed concrete transverse beams, which support the RC deck slabs. At 4:00 a.m. on November 7, 2001, some suspenders close to the arch springing were ruptured, causeing the the transverse beams and deck slabs as well as the passenger car on it fell into the river, as shown in Fig. 6. Four people were killed in this accident.

Fig. 6 Deck system collapse of Xiaonanmen Bridge

Yupingshan bridge in Nanping, Fujian Province, was built in 1995. Its central span is a half-through arch of two RC box ribs with a clear span of 100 m and a rise-span ratio of 1/3.73. A suspender is made of 61Φ5mm high-strength steel strand, protected by a steel tube filled with cement mortar. The bridge deck is RC slabs simply supported on transverse beams. A long suspender close to the midspan failed suddenly on January 11, 2010. It was good luck that the cross beam, carried by the failed suspender, did not fall into the river but interrupted by a water pipe with 500 mm diameter hanged under the deck. In addition, the accident occurred at 6 a.m. when there was no traffic and passengers on the bridge.

Gongguan Bridge of Wuyishan, Fujian Province is a three-span RC arch bridge built in 1999. The span arrangement is 80 m+100 m+80 m. The rise-to-span ratio of the arch ribs of the side span and the central span are 1/3.67 and 1/3.45, respectively. Each suspender is made of 61Φ5mm high-strength steel wires, protected by steel tubes filled with cement mortar. The bridge deck consisted of RC continuous slabs with a thickness of 25cm, which were supported by the transverse beams.

On July 14, 2011, a pair of shortest suspenders in one span was broken when an overloaded dump truck and a passenger bus drove in opposite direction on the bridge. The truck was running towards the midspan and escaped from the bridge, resulting ruptures of total of 7 pair suspenders one after the other, followed by falling off the transverse beams and deck slabs to the river. The bus drove in the direction to the springing, fell into the river (about 8.8 m from the bridge deck to the river bed) together with the bridge deck and transverse beam after they lost the support from the suspenders, resulting 1 passenger killed and 22 injured, as shown in Fig. 7.

Fig. 7 Gongguan Bridge of Wuyishan, Fujian Province

Luoguo Bridge is located in Panzhihua, Sichuan Province, crosses over the Jinsha River. The bridge is a half-through RC arch bridge, built in 1995, with a span of 160 m and a rise-to-span ratio of 1/4. Both of the transverse beams and the deck slabs are prestressed concrete structures. The suspenders are made of 22-7Φ5 mm strands. The deck slab sections were simply supported during erection and closed by wet joints on site.

At 6:15 pm of December 10, 2012, a pair suspender slipped out from the bottom anchors due to the anchorage head failure. At that time there were pedestrians and cars on the bridge, but no heavy truck. The failure of the suspenders caused support loss of the transverse beam, and the continuous deck slabs tied to the transverse beam deformed in V-shape but not falling into the river, as shown in Fig. 8.

Fig. 8 Luoguo bridge of Panzhihua, Sichuan

In the five bridges above mentioned, the suspenders were protected by steel tubes filled with cement mortar, which are not effective in protection and result the cable vulnerable to corrosion. The suspenders ruptured due to heavy corrosion are the original causes of these accidents.

In the five bridges, the cross beams are the main structure of the deck, which are carried by suspenders of high-strength steel cables. Deck slabs are simply supported on them without stiffened longitudinal girders. This type deck structure is widely applied in through or half-through arch bridges in China, due to the economic advantages, clear force-bearing behavior and simplicity in construction. However, it has no redundant constraint, has only one load path, and has weak structural robustness.

Structural robustness mainly refers to ability of a structure to withstand exteme events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportional to the original cause.

If the deck systems have string robustness, *e.g.*, they are integral structures or have stiffened longitudinal girders, tie connections would be provided for the transverse beams after they lost the support from the ruptured suspenders, thus they would not fall to the river. In other words, the accidents were limited to suspender rupters but not disproportional results of deck failures. However, for the deck structures in the five bridges, the suspenders are the only load path of the structure, the rupture of the suspender directly result the falling of the deck strcuture to the river, induce an extent disproportional to the original cause. When there are heavy trucks on the bridge, the stresses of the suspenders are high, which shortened the loss duration and caused large dynamic response to residual structures, and result in other suspenders' failure, thus a zipper-type collapse happen, such as the case of Gongguan Bridge.

Therefore, for through or half-through Concrete-filled Steel Tube (CFST) arch bridges, there is a mandatory provision (Clause 7.5.1) in China *Specifications for Concrete-filled Steel Tube Arch Bridges (GB 50923-2013)*. It stipulates that deck systems shall adopt the scheme of integrated structures. Deck systems that are mainly supported by transverse beams must be provided with stiffening longitudinal girders and shall have the redundancy to avoid collapse of the transverse beam due to the failure of the supporting suspenders at its two ends.

In the present *Specifications for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG 3362-2018),* it is stipulated that continouse longitudinal girders should be designed in deck system if the flexible suspenders are used in the concrete arch bridges. This requirement is similar as that in the *GB 50923-2013* but not so strictly.

For CFST arch bridges, Clause 14.3.21 of *GB 50923-2013* stipulates that "*for a half-through or through CFST arch bridge, if its deck systems consist of only cross beams and no longitudinal stiffening girders, the deck system should be strengthened and retrofitted according to their service status. The strengthened and retrofitted bridge structures shall have the redundancy to avoid collapse of the transverse beam due to the failure of the supporting suspenders at its two ends*." This requirement of the robustness is the same as that for the suspended deck structure of a new bridge. The strengthening methods are mainly included in longitudinally adding steel tube trussed girders or steel box girder, etc, which can be a reference for strengthening the similar deck systems in concrete arch bridges.

Shitanxi Bridge in Fujian Province is an example (Chen and Peng, 2010). The bridge is a half-through CFST trussed arch bridge with a net span of 136 m. The deck system consists of I-shaped RC crossbeams and ribbed RC deck slabs. In strengthening, two steel tube trusses were added as stiffening longitudinal girders (Fig. 9) to increase the structural robustness.

（a）Upward view （b）Local view

Fig. 9 Stiffening Longitudinal Girder in Shitanxi Bridge

5 LAST REMARKS

There are many concrete arch bridges serving in the road system in China. Besides the causes deteriorating all bridges, such as normal aging, increased traffic loading, construction quality as well as poor maintenance, there have been some congenital defects in this special Chinese concrete arch bridge type due to design and construction. For the light concrete arch bridges, the main problems are deficient stiffness, low bearing capacity and poorly protected connections. Special attention shall be paid during their repair and strengthening. For the through and half-through bridges, the suspender shall be checked regularly, maintenance measures should be carried out, and in case of insufficient result suspenders shall be replaced in time. None the less, deck systems weak in robustness shall be rehabilitated and strengthened if possible.

References

Baochun Chen，2005. State-of-the-art of the development of arch bridges in China *Proceedings of the 4th International Conference on New Dimensions of Bridge*, Fuzhou, China, 13-24

Bao-chun Chen, Lin Ye, 2008, An Overview of Long Span Concrete Arch Bridges in China, *Proceedings of Chinese-Croatian Joint Colloquium on Long Span Arch Bridges*, Brijuni Islands, Croatia, July 10-14, 163-170

Baochun Chen and Guihan Peng, 2010, Strengthening of suspended deck system in Shitanxi CFST arch bridge, *Proceedings of 12th International Conference on Ispection, Appraisal, Repairs and Maintenance of Structures*, Yantai, China:15-20

Baochun Chen, 2013, Chapter 8: Arch Bridges, in the *Handbook of International Bridge Engineering* (Second Edition) edited by Hai-Fah Chen and Lian Duan, CRC Press

Baochun Chen; Jiazhan Su; Shangshun Lin; etc.， 2017, Development and application of concrete arch bridges in China， *Journal of Asian Concrete Federation*, Vol. 3, No. 1, pp. 12-19

CJJ 99-2017, Technical Code for Maintenance of City Bridge

Hanwan Jiang, Jinquan Zhang, Yufang Fu and Ye Ma, 2011, Condition Evaluation of Arch Bridge Based on 3d Benchmark Graphics, *Proceedings of 3rd Chinese-Croatian Joint Colloquium on Long Span Arch Bridges*, Zagreb, Croatia: 369-376

Hong-wei Ren, Wan-heng Li, Jin-quan Zhang, etc., 2008, Inspection and Design Suggestion on Rigid-frame Arch Bridge, *Proceedings of Chinese-Croatian Joint Colloquium on Long Span Arch Bridges*, Brijuni Islands, Croatia: 309-316

Jing Gao, Bin Zhao and Chunmiao Chen, 2013, Problems in Suspenders of Arch Bridges in China, *Proceedings of 7th International conference on arch bridges*, Trogir-Split, Croatia:101-108

JTG H11—2004, Code for Maintenance of High Bridges and Culverts

Ke Chen, Fei Yu, Huicheng Li, etc., 2011, Cause Analysis of Structural Deterioration of Reinforced Concrete Rib Arch Bridges, *Proceedings of 3rd Chinese-Croatian Joint Colloquium on Long Span Arch Bridges*, Zagreb, Croatia, 347-352

Ping Shanggun, Wei-dong Zhou, 2007, Repair and Strengthening of Two-way Curved Arch Bridge, *Proceedings of the Fifth International Conference on Arch Bridge*, 12-14, Sept., Madeira, Portugal: 729-734

Yong Xu; Chen, L.; Xie, H.Q.; and Hu, J.T., 2011, Design of the Beipanjiang Bridge on the high-speed railway between Shanghai and Kunming, *Proceedings of 3rd Chinese-Croatian Joint Colloquium on Long Span Arch Bridges*, Zagreb, Croatia, 71-82.

Zhouhong Zong and Zhanghua Xis, 2008, Field Testing and Performance Evaluation of A Reinforced Concrete Box Arch Bridge, *Proceedings of Chinese-Croatian Joint Colloquium on Long Span Arch Bridges*, Brijuni Islands, Croatia, 301-308