DEVELOPMENT AND TECHNICAL INNOVATION OF CONCRETE-FILLED STEEL TUBULAR ARCH BRIDGES

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After several decades of development, concrete-filled steel tubular (CFST) arch bridges have become one of the main forms of arch bridges. The development history of CFST arch bridges is outlined in this paper. Through the analysis of case data of nearly 450 CFST arch bridges, the design theory, structural system and construction method of CFST arch bridges are summarized. Aiming at the typical diseases of CFST arch bridges such as concrete separation inside the tube, corrosion and local deformation of steel tube, fatigue damage of tubular joint, corrosion and breakage of hanger, the causes of the disease are analyzed from the aspects of arch bridge structure, materials, construction and maintenance. Combined with the introduction of typical engineering cases of CFST arch bridges, the main technical innovations of CFST arch bridges are summarized.

Keywords: CFST, Arch Bridge, Typical diseases, Technical innovation.

1 Introduction

The concrete-filled steel tube (CFST) structure is a steel-concrete composite structure formed by filling concrete into a thin-walled steel tube. Under the axial force, the inner core concrete of CFST members is restrained by the outer steel tube, which is in a three-way compression state, so that the core concrete has higher compressive strength and stronger plastic deformation (Han 2014). CFST members have superior mechanical properties such as high strength, light weight, good ductility, fatigue resistance and impact resistance. The CFST structure is applied to the arch bridge with compression, which shows great superiority in mechanical properties, construction, economy and aesthetics. When constructing a CFST arch bridge, hollow steel tube and concrete are usually constructed step by step, hollow steel tube arch rib are formed at first, and then the concrete are poured into the steel tube to form main arch. On the one hand, the lifting weight of the arch segment is greatly reduced, on the other hand, the steel tube also acts as formwork during construction, which greatly improves the construction efficiency. Compared with steel arch, CFST arch can save 50% of steel with the same bearing capacity; compared with reinforced concrete arch, the cross-sectional area of arch ribs can be reduced by half, so the self-weight of ribs can be reduced by 50%. Focusing on the steel-concrete composite effect (Lou 2013), structural stability (Liu 2018), structural seismic performance (Xin 2019) and fatigue behavior of CFST joints (Musa 2018), a lot of researches have been carried out to provide scientific support for the design, construction and maintenance of CFST arch bridges. After several decades of development, CFST arch bridges have become one of the main forms of arch bridges.

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2 The history and current status of CFST arch bridges

The application of CFST structures in civil engineering can be traced back to 1879. CFST piers were first used in a railway bridge in the UK. However, the purpose of pouring concrete in the hollow steel tubes was to prevent rust and improve the stability of the hollow steel tube. From the end of the 19th century to the beginning of the 20th century, some truss bridges with CFST piers were built in the United States, such as the Red Bridge (built in 1892) in Iowa and the Wagon Wheel Bridge (built in 1911).

The world's first CFST arch bridge was built in 1939, which located in the Ural region of Russia across the Iset River. The main span of the bridge adopts a crescent-shaped two-hinge arch with a span of 140m. After that, within half a century, few CFST arch bridges were built in the world. Until 1990, Wangcang Donghe Bridge was built and became the first CFST arch bridge in China, which is a tied arch bridge with a span of 115m. In 1994, the Antrenas Bridge was built in France, which is a steel tube space truss arch with a span of 56m. The main arch ribs are hollow steel tube and concrete is only filled in the section near the arch abutments. In 2001, Escudo Viaduct was built in Spain, each of arch ribs consists of two CFST members.


Kamensk bridge (Russia)


Wangcang Donghe Bridge(China)


Antrenas Bridge (France)

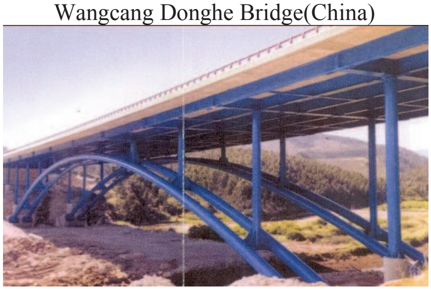

Escudo Viaduct (Spain)

Figure 1. Early concrete-filled steel tube arch

With the in-depth study of CFST structures, the span record of CFST arch bridges has been continuously broken, and the structural forms are constantly innovating, and the technology is constantly improving. According to incomplete statistics, by the end of 2018, the number of CFST arch bridges has exceeded 450, and there are more than 200 arch bridges with a span of more than 100m, and there are nearly 50 arch bridges with a span of more than 200m, and there are more than 10 arch bridges with a span of more than 300m. At present, the First Hejiang Yangtze River Bridge, which opened in 2013, is the longest CFST arch bridge in the world, and ranks third in terms of the longest main span of all arch bridges. Nanping third Bridge is under construction in China with a span of 560m. Table 1 shows the top 10 CFST arch bridges with the largest span in the world (Zheng 2018).

Table 1. The top 10 CFST arch bridges with the largest span in the world.

Name	years	Span	*f/l*	Bridge type	Cross-section
Hejiang 1st Yangtze River Bridge	2013	530	1/4.5	Half through	Four-tube truss
Wushan Yangtze River Bridge	2005	460	1/3.8	Half through	Four-tube truss
Zhijing River Bridge	2008	430	1/5.5	Deck arch	Four-tube truss
Xiangtan Liancheng Bridge	2007	400			Six-tube truss
Zhunshuo Railway Yellow River Bridge	2016	380	1/6	Deck arch	Four-tube truss
Yiyang Maocao Street Bridge	2006	368	1/5	Flying swallow	Four-tube truss
Guangzhou Yajisha Bridge	2000	360	1/4.5	Flying swallow	Four-tube truss
Zongxi River Bridge	2015	360	1/5.127	Deck arch	Four-tube truss
Xiao River Bridge	2009	338	1/5	Deck arch	Six-tube truss
Taiping Lake Bridge	2007	336	1/4.94	Half through	dumbbell truss
Nanning Yonghe Bridge	2004	335.4	1/4.5	Half through	dumbbell truss

Based on the investigation and analysis of CFST arch bridges with main spans over 50m, the variation of spans of CFST arch bridges are given in Figure 2.

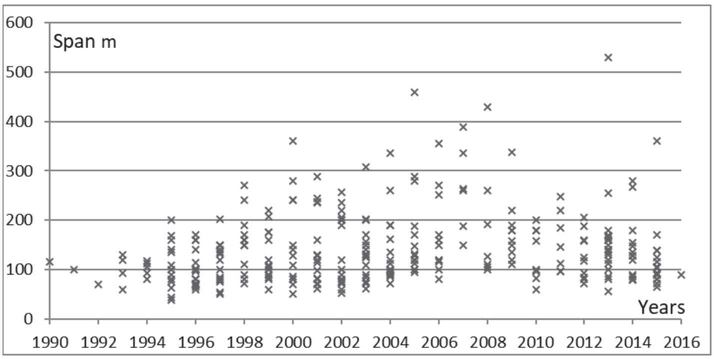
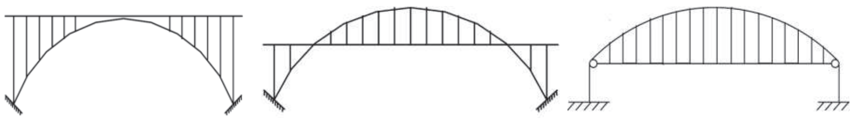


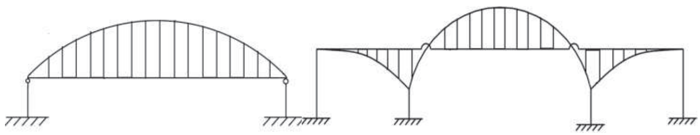
Figure 2. The variation of spans of CFST arch bridges

With the rapid development of theoretical research, design level and construction technology of CFST arch bridge, the structure of CFST arch bridge tends to be lightweight, and the span of various structural forms of CFST arch bridge increases continuously. According to a leap in five years, it has reached the span level of steel arch bridge. Generally, CFST arch bridges can be classified into five main types, including deck arch bridge, half-through arch bridge, simple support through arch bridge, rigid frame through arch bridge and Flying swallow type arch bridge (Chen 2009), as shown in Figure 3. The most interesting structure type in CFST arch bridges is the so-called flying swallow type arch. This type of bridge generally consists of three spans. The central span is a half-through CFST arch and the two side spans are cantilevered half-arches. Both the main arch ribs and the side arch ribs are fixed to the piers and prestressed steel bars are anchored at the ends of the side spans to balance the arch thrusts.

In terms of structural form, the proportion of the half-through arch bridge and the through arch bridge are 31% and 49%, respectively, followed by the flying swallow arch bridges with 11% and the deck arch bridge with 9%, as shown in Figure 4.



a) Deck arch bridge b) Half-through arch bridge c) Simple support through bridge



d) rigid frame through arch bridge e) Flying swallow type arch bridge

Figure 3. Structural form of CFST arch bridge

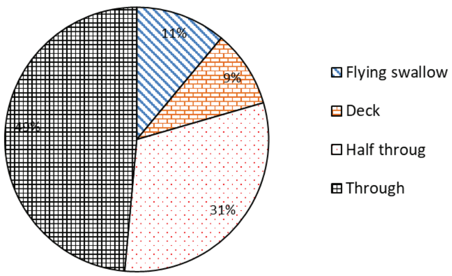


Figure 4. Proportion of various types of Arch Bridges

Figure 5 shows the span increasing of three kinds of CFST arch bridges with years. It can be seen that the span of through arch bridges (including flying swallow type) has been growing faster than the other two type of CFST arch bridge since the mid-1990s. After the span of through bridge approached 300m at the beginning of this century, there has been no breakthrough in more than 10 years. Every breakthrough in the span of through arch bridge will lead to the catching-up of the span of through CFST arch bridge.

Since the discovery of confined concrete has greatly improved the concrete bearing capacity of the general structure, a series of research on its mechanical behavior have been carried out and valuble results have been achieved. Despite this, there are still many different viewpoints on CFST, and theoretical research is still not perfect, such as the constitutive relationship of CFST, especially the core concrete constitutive relationship under triaxial compression. Even the most basic CFST short-column, the longitudinal strain of the steel tube and the longitudinal strain of the core concrete are not consistent. There are many methods to determin the mechanical properties of CFST structures. The main difference lies in how to estimate the "effect" caused by the mutual restraint between steel tube and core concrete, so as to reflect the actual bearing capacity of CFST structures.

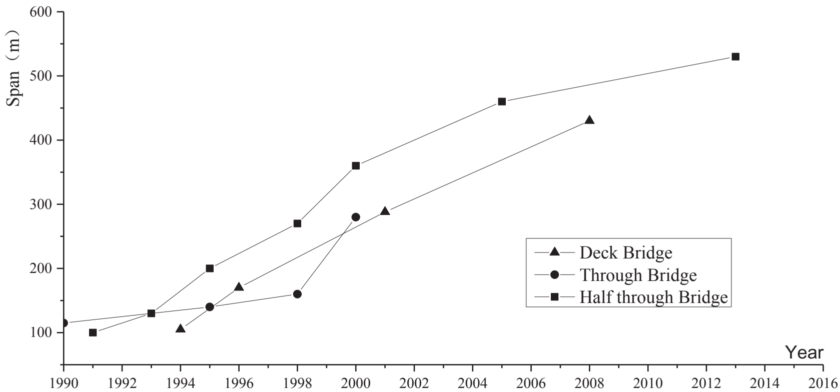


Figure 5. Span increasing of three types of CFST arch bridges

3 Main disease of CFST arch bridge

The design theory and construction technology of CFST arch bridges have been greatly developed, but there have been many problems in some CFST arch bridges. Through the investigation of existing CFST arch bridge, it can be found that the disease mainly manifests as the separation of concrete and steel tube, steel tube corrosion, hanger fracture, CFST joint cracking and tie bar broken wire. Some typical diseases are shown in Figure 6.

3.1 *Separation of concrete and steel tube*

The separation of concrete and steel tube is the most common disease of CFST arch bridges. It has a great influence on the bearing capacity of CFST arch bridges. In CFST arch bridges, the crown section is more susceptible to separation. There are many reasons for the separation of concrete and steel tube, including the insufficient expansion performance of the expansion concrete in the steel tube, the improper mix ratio of the concrete, the insufficient concrete grouting, the shrinkage and creep of the concrete, and the different linear expansion coefficients of the steel and concrete materials.

3.2 *Steel tube corrosion*

Corrosion is one of the main factors affecting the durability of steel structures. Corrosion of steel tube in CFST arch bridges is mainly caused by atmospheric corrosion. The rate of atmospheric corrosion and the degree of corrosion depend on atmospheric humidity and atmospheric environment. CFST arch bridges with spray protection are used, and most of the corrosion of steel tube occurs during the construction process due to local corrosion caused by the destruction of the anti-corrosion system. The protective layer of the CFST arch bridge protected by polymer materials is easily damaged, and the steel tube is seriously corroded.

Hanger fracture Hanger corrosion

Steel tube corrosion CFST joint fatigue cracking

Figure 6. Typical disease of CFST arch bridge

3.3 *Hanger fracture*

Hanger fracture of CFST arch bridges usually goes through the process of protective sleeve damage, steel wire corrosion and steel wire breakage. Protective sleeve damage is very common, which is the beginning of the durability failure of the hanger system. For steel protective sleeve, the steel tube is rarely damaged and the mortar poured into the steel tube is severely cracked by the repeated action of the mortar shrinkage and the hanger force. In addition, the airtightness of both ends of the hanger is poor, and the air and rainwater easily penetrate the protective sleeve to cause the hanger to rust. The damage of the polyethylene sheath mainly includes longitudinal cracking, annular cracking and reticular cracking. The main causes of the polyethylene sheath damage are: raw material problems, aging materials, low tensile strength, improper construction, and mismatch of the thermal expansion coefficient between the protective sleeve material and the hanger steel.

The fatigue damage of hanger caused by repeated loads is an important reason of the broken wire of the hanger. The damage of the hanger in the atmosphere is caused by the joint action of fatigue and corrosion. The alternating fatigue load reduces the effectiveness of the anti-corrosion measures, and the corrosion directly weakens the tensile strength of the hanger.

3.4 *CFST joint fatigue cracking*

In CFST truss, the prepared ends of brace members are connected to the surface of chord members by intersecting line welds and CFST joints are formed. Induced by complicated joint structures, high stress concentration and inherent weld defects, fatigue cracks generally tend to initiate from the surface of tubular joints under cycle loading. The safety and durability of CFST truss are affected by material performance degradation and local damage accumulation combined with environmental influence in long-term service. Recently, fatigue cracks have been detected in the tubular joints of some CFST truss arch bridges.

CFST joints can by divided into multiplanar joints and uniplanar joints, and T-joints, Y-joints, K-joints, N-joints, X-joints and TK-joints are the typical type of uniplanar joints. After investigating the fatigue damage of all kinds of tubular joints in different loading condition, it is concluded that fatigue cracks are always occurs at weld toe of intersection lines weld between brace and chord tube and propagate along weld toe line.

4 New technology of CFST arch bridge

After nearly 30 years of engineering practice, the calculation theory of CFST arch bridges has been continuously improved, and the design, manufacturing and construction techniques have made great progress.

4.1 *New material*

The concrete in the main tube is generally pumped and poured, and can only rely on the self-weight of the concrete to be dense. In order to effectively reduce the separation between the inner concrete and the steel tube, the self-compacting shrinkage compensation concrete was developed for the CFST arch bridge. According the design code, the free expansion rate of the concrete in a closed environment should be controlled at 2×10^{-4}-6×10^{-4}. At the same time, high-efficiency water reducing agent and expansion agent should be added to the concrete.

In order to solve the problem of steel tube corrosion, weathering steel has been applied in CFST arch bridges in recent years. The Zangmu Yalu Tsangpo River Bridge has an altitude of more than 3,300 meters. It is very difficult to maintain during the service period. Therefore, the main material of the bridge is weathering steel Q345qENH and Q420qENH. In the natural environment the steel will automatically form oxidation protection on the outer surface, which can play a long-term anti-corrosion effect.

4.2 *New structural type*

In order to meet the requirements of high-speed railway train operation, high-speed railway bridges should have high rigidity, good dynamic performance and good durability. CFST arch and prestressed concrete continuous beam combination system and CFST arch and prestressed concrete continuous rigid frame combination system were developed, as shown in Figure 7. The CFST arch can effectively reduce the deformation at the mid-span of the main beam and improve the mechanical behavior of the main beam.

Figure 7. CFST arch and PC beam combination system.

4.2 *New construction technology*

In the construction of a CFST arch bridge, three methods including cable-stayed fastening-hanging cantilever assembly, rotation construction, and large-segment lifting construction, have been widely used in the erection of the steel tube arch truss. The statistical results show that most of the CFST arch bridges are constructed by the cable-stayed fastening-hanging cantilever assembly method. Rotation construction interferes the least with the space under the bridge, does not change the mechanical behavior of the structure in the process of rotation, and has a good safety performance. To assure the compactness of the concrete that is cast in the tube, vacuum-assisted pumping-up pouring method for in-tube concrete has been invented for the development of CFST arch bridges (Zheng 2018).

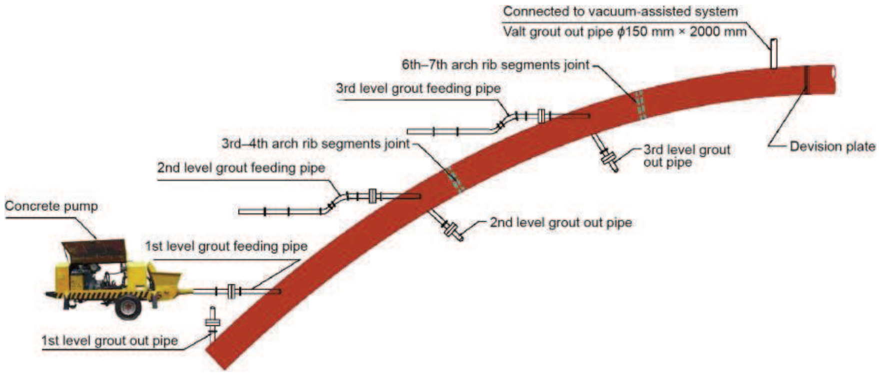


Figure 8. Three-level continuous vacuum-assisted pumping-up pouring method for in-tube concrete.

5 Conclusions

Concrete-filled steel tubular arch bridges have the advantages of excellent mechanical performance and good economy. They are a very competitive form of bridges in the span of 200m-500m. The advancement of analytical theory, design methods and construction techniques, coupled with the application of new materials, will drive the continued development of CFST arch bridges.

References

Chen, B.C. and Wang, T.L., Overview of Concrete Filled Steel Tube Arch Bridges in China. *Practice Periodical on Structural Design and Construction*, 14(2):70-80,2009.

Han, Y., Tests on the Vacuum-Aided Casting Technique for Concrete in Tubes of Concrete-Filled Steel Tube Arch Bridges and Its Engineering Applications. *Structural Engineering International*, 28(1):28-34,2018.

Liu, C., Hu, Q., Wang, Y., & Zhang, S., In-plane stability of concrete-filled steel tubular parabolic truss arches. *International Journal of Steel Structures*, 1-12,2018.

Luo, K., Pi, Y.L., Gao, W., and Bradford, M.A., Creep of concrete core and time-dependent non-linear behaviour and buckling of shallow concrete-filled steel tubular arches. *Computer Modeling in Engineering & Sciences*, 95(1), 32-58,2013.

Musa, I.A., Mashiri, F.R., Zhu, X. and Tong, L., Experimental stress concentration factor in concrete-filled steel tubular t-joints, *Journal of Constructional Steel Research*, 150: 442–451,2018.

Wei, X., Wen, Z., Xiao, L., and Wu, C., Review of fatigue assessment approaches for tubular joints in CFST trusses. International Journal of Fatigue, 113, 43-53,2018.

Xin, L., Li, X., Zhang, Z. and Zhao L., Seismic behavior of long-span concrete-filled steel tubular arch bridge subjected to near-fault fling-step motions. *Engineering Structures*, 180:148–159,2019

Zheng, J. and Wang, J., Concrete-Filled Steel Tube Arch Bridges in China. *Engineering*, 4:143–155,2018

Zong, Z.H., Jaishi, B., Ge, J.P., and Ren, W.X., Dynamic analysis of a half-through concrete-filled steel tubular arch bridge. *Engineering Structures*, 27(1), 3-15,2005.

Han, L.H., Li, W., and Bjorhovde, R.., Developments and advanced applications of concrete-filled steel tubular (CFST) structures: members. *Journal of Constructional Steel Research*, 100, 211-228,2014.