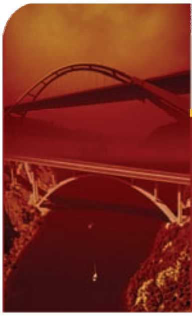

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NEW DEVELOPMENT OF LONG SPAN CFST ARCH BRIDGES IN CHINA

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Key words: Concrete filled steel tube, arch, design, construction, 2000, China

Abstract: *The Concrete Filled Steel Tubular (CFST) structure has been applied prevalently and rapidly to arch bridges since 1990 and this tend is continued with more and more long span CFST arch bridges been build since 2000. This paper briefly introduces the present situation of CFST arch bridges, their five main structure types and the construction methods. Many selected CFST arch bridges built since 2000 and some still under construction are presented.*

1. INTRODUCTION

For Concrete Filled Steel Tubes (CFST) arch, the in-filled concrete delays local buckling of the steel tube, while the steel tube reinforces the concrete to resist tension stresses and improve its compression strength and ductility. In construction, the tube also acts as a formwork for the concrete. Besides, they present a more artistic appearance. With the rapid development of economy in China, CFST arch bridges become a good alternative to Reinforced Concrete (RC) arch bridges or steel arch bridges and have been applied widely in China (Chen 2005). Up to March 2005, 229 CFST arch bridges, with the span over 50 m, have been built or are under construction (Chen 2007A; Chen 2007B). Among them, 131 bridges have a main span longer than 100 m and 33 significant bridges with a span greater than 200 m (Table 1).

In this paper the new application of CFST arch bridges in China since 2000 are introduced with typical examples, including its structures and erection methods.

2. MAIN TYPES OF CFST ARCH BRIDGES

CFST arch bridges can be classified into five main types, i.e. deck (true) arch, half-through true arch, through deck-stiffened arch, through rigid-frame tied arch and fly-bird-type arch (half-through tied rigid-frame arch) (Figure 1). It should be noted that for the deck and half-through arch with thrust, the span is clear span; while for no-thrust arch, the span is from the center line of pier to pier.

3. ERECTION METHOD

For a CFST arch bridge, the steel tubular arch is erected at first and then concrete is pumped into steel tubes to form CFST arch ribs. Because the thin-walled steel tubular arch has a lighter self-weight than concrete or shaped steel arch rib, it is easier to erect a steel arch than to erect a concrete or a steel arch with same dimensions. In other words, with the same construction equipment and method, a longer span of CFST arch bridge can be built.

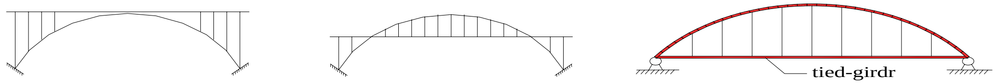
However, the erection of long span steel tubular arch rib remains a key issue in construction of CFST arch bridge, especially for those with long spans. Cantilever method, swing method, and scaffolding method are three major erection methods for the construction of CFST arch bridges (Chen 2005), in which cantilever launching method and swing method are more popular than scaffolding method and both of them have been improved with the development of CFST arch bridges.

In cantilever method, both main and auxiliary cables are used to maintain stability and balance during construction. These cables are stayed and controlled by jacks instead of windlass in the past. Therefore, the alignment of arch ring can be controlled by the adjustment of internal force of the fasten cables more easily than before.

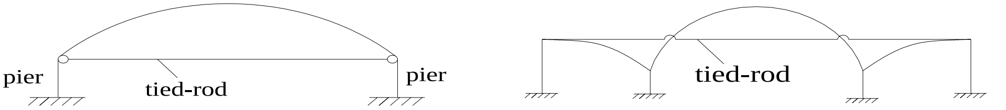
Another main erection method used in CFST arch bridges is swing method, which has been rapidly developed in recent years in China. This method includes vertical swing method and horizontal swing method. It is more suitable in some special conditions, such as gorge, or high requirements for clearance. Therefore, an appropriate landform and structural configuration are necessary for this method. Swing method is not used as prevalently as cantilever method.

<table>
<tr><th>Bridge name</th><th>Main span (m)</th><th>Completion Year</th><th>Type</th><th>Construction Method</th></tr>
<tr><td>Enshi Nannidu Bridge in Hubei</td><td>220</td><td>2002</td><td rowspan="5">Deck (true) arch</td><td>Cantilever</td></tr>
<tr><td>Beipanjiang Railway Bridge in Guizhou</td><td>236</td><td>2001</td><td>Swing</td></tr>
<tr><td>No.1 Qiandaohu Bridge in Zhejiang</td><td>252</td><td>2005</td><td rowspan="3">Cantilever</td></tr>
<tr><td>Meixi Bridge in Fengjie, Chongqing</td><td>288</td><td>2001</td></tr>
<tr><td>Zhijinghe Bridge in Hubei</td><td>430</td><td>Under construction</td></tr>
<tr><td>No.3 Hanjiang Bridge in Wuhan, Hubei</td><td>280</td><td>2000</td><td>Through rigid-frame tied arch</td><td>Cantilever</td></tr>
<tr><td>Mood Island Bridge in Dandong, Liaoning</td><td>202</td><td>2003</td><td rowspan="2">Through deck-stiffened arch</td><td>Other</td></tr>
<tr><td>Yangtze River Railway Bridge in Yichang, Hubei</td><td>264</td><td>Under construction</td><td>Swing</td></tr>
<tr><td>Longtanhe Bridge in Zigui, Hubei</td><td>200</td><td>1999</td><td rowspan="16">Half-through (true) arch</td><td rowspan="19">Cantilever Method</td></tr>
<tr><td>Jialingjiang Bridge in Hechuan</td><td>200</td><td>2002</td></tr>
<tr><td>Wangcun Yushuihe Bridge in Hunan</td><td>200</td><td>2003</td></tr>
<tr><td>Liujing Yujiang Bridge in Guangxi</td><td>220</td><td>1999</td></tr>
<tr><td>Tongwamen Bridge in Zhejiang</td><td>238</td><td>2001</td></tr>
<tr><td>Luojiaohe Bridge in Guizhou</td><td>240</td><td>1998</td></tr>
<tr><td>Sanmen Jiantiao Bridge in Zhejiang</td><td>245</td><td>2001</td></tr>
<tr><td>Zigui Qingganhe Bridge in Hubei</td><td>248</td><td>2002</td></tr>
<tr><td>Jinshajiang Rongzhou Bridge</td><td>260</td><td>2004</td></tr>
<tr><td>Sanan Yongjiang Bridge in Guangxi</td><td>270</td><td>1998</td></tr>
<tr><td>Sanmenkou North-gate Bridge</td><td>270</td><td>2007</td></tr>
<tr><td>Sanmenkou Middle-gate Bridge</td><td>270</td><td>2007</td></tr>
<tr><td>Chunan Nanpu Bridge in Zhejiang</td><td>308</td><td>2003</td></tr>
<tr><td>Nanning Yonghe Bridge in Guangxi</td><td>335.4</td><td>2004</td></tr>
<tr><td>Huangshan Taipinghu Bridge in Anhui</td><td>336</td><td>2007</td></tr>
<tr><td>Wushan Yangtze River Bridge</td><td>460</td><td>2005</td></tr>
<tr><td>Nanhai Sanshanxi Bridge</td><td>200</td><td>1995</td><td rowspan="9">‘Fly-bird-type’ arch</td></tr>
<tr><td>Mianyang Pujiang Bridge in Sichuan</td><td>202</td><td>1997</td></tr>
<tr><td>Shenmi Bridge in Nanchang</td><td>228</td><td>2006</td></tr>
<tr><td>Jinghang Canal Bridge in Jiangsu</td><td>235</td><td>2002</td><td>Swing</td></tr>
<tr><td>No.5 Hanjiang Bridge in Wuhan</td><td>240</td><td>2000</td><td rowspan="2">Cantilever</td></tr>
<tr><td>Dongguan Shuidao Bridge</td><td>280</td><td>2005</td></tr>
<tr><td>Yajisha Bridge in Guangzhou</td><td>360</td><td>2000</td><td>Swing</td></tr>
<tr><td>Maocaojie Bridge in Hunan</td><td>368</td><td>2006</td><td rowspan="2">Cantilever</td></tr>
<tr><td>Liancheng Bridge in Hunan</td><td>400</td><td>2007</td></tr>
</table>

Table 1: CFST Arch Bridges (Span>200m)



(a) Deck (true) arch (b) Half-through true arch (c) Through deck-stiffened arch



(d) Through rigid-framed tied arch (e) 'Fly-bird-type' arch

Figure 1: Types of CFST Arch Bridges

4. EXAMPLES

4.1 Deck Arch Bridge

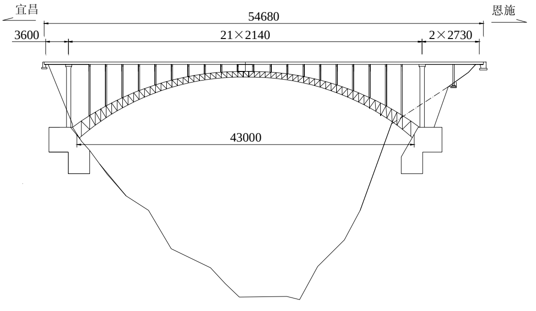
In deck bridge, the arch ribs can be several vertical dumbbell (two tubes) shaped CFST ribs in medium span bridges or two vertical truss (four tubes) CFST ribs connected by lateral bracings of steel tubes. Generally, the decks are RC or Prestressed Concrete (PC) structures, and the spandrel columns are CFST or steel structures. The true arch bridge has a great crossing capacity. The deck arch has been built for spans over 150 m.

All of the CFST arch bridges are highway bridges till Baipanjiang railway CFST arch bridge completed in Nov., 2001. The bridge is located in the Liupanshui District, Guizhou Province of the southwest of China. The gorge it crosses is very deep and the bridge is as high as 280m from the deck to the water level of the river. CFST arch bridge was selected as the main bridge after comparison of more than 10 bridge schemes. The main bridge is a deck CFST arch bridge with a main span of 236m (Figure 1). The arch ring is composed of two tilted ribs, connecting by lateral bracings. The steel tubular arch was erected by horizontal swing method, each rotation unit (including the arch rib, the rotation basement, etc.) is 104000kN in weigh, Figure 2 (Ma, T. L., Xu, Y., He, T., and Chen, K., 2001).

Figure 2: Baipanjiang Railway Bridge

Figure 3:Horizontal Swing

An investigation on CFST arch bridges in China shows that only about 8% of CFST arch bridges are deck bridges, while it account for 86% in concrete arch bridges (47% for box rings or ribs and 39% for light arch bridges, such as double-curved arch bridge, truss arch bridge and rigid-frame arch bridge)(Chen, 2007B; Chen, B. C., Gao, J., and Ye, L., 2007). However, most of them have spans longer than 150m. Until now, the Fengjie Meixihe Bridge has the longest span of 288 m, but the Zhijinghe Bridge, under construction with a main span of 430 m (Figure 4a), will break this span record (Chen, 2004B; Chen 2007B). Figure 4(b) is a photo taken on May 17th, 2008 by the author, which shows the erection of the steel tubular arch ribs of the Zhijinghe Bridge by cantilever cable-stayed method with cable crane.



(a) Layout(Unit: cm)

(b)Under construction

Figure 4: Zhijinghe Bridge

4.2 Half-through True Arch Bridge

Half-through bridge is a good choice when the rise of the arch bridges is much higher than the road elevation for the long span. Half-through (true) arch bridges are counted for 62 (47%) in the investigated 131 CFST arch bridges with a span no smaller than 100m (Chen, 2007). Moreover, it can reduce the height of the spandrel columns. Many long-span CFST half-through true arch bridges have been built. This type bridge can also have large spaning capacity. There are four of such bridges with spans longer than 300m have been built, they are Chunan Napu Bridge in Zhe-jian with a main span of 308m, Nanning Yonghe Bridge in Guangxi with a main span of 335.4m, Huangshan Taipinghu Bridge in Anhui with a main span of 336m and Wushan Yangtze River Bridge in Chongqing with a main span of 460m (Figures. 5 to 8) (Chen, 2008).

Figure 5: Chunan Napu Bridge

Figure 6: Nanning Yonghe Bridge

Figure 7: Huangshan Taipinghu Bridge

Figure 8: Wushan Yangtze River Bridge

The span of 460 m in Wushan Yangtze River Bridge is not only the span record in deck CFST arch bridge, but also the record of the longest CFST arch bridge in the world. The bridge completed in 2005 is a half-through concrete filled steel tubular arch bridge with a rise-span ratio of 1/3.8. The bridge width is 19m, in which 15.0m for traffic lane and 2×1.5m for walk side road as well as 2×0.5m for rails. There are two CFST truss arch ribs with a center to center distance of 19.7m. Each width of the rib is 4.14m and the height varies from 7.0m in crown to 14.0m in the spring. The steel tubular arch was erected by cantilever method with cable crane as the hoisting equipment, which is very suitable to the steep banks, as shown in Figure 9 (Mu et al, 2007).

Figure 9: Erection of Steel Tubular Arch of Wushan Yangtze River Bridge

4.3 Through Deck-stiffened Arch Bridge

CFST through deck-stiffened arch bridge is composed by CFST arch ribs and PC or steel tied girders. The hangers are high strength strands and the deck structure can be concrete or steel-composite structures, including cross beams and deck slabs. The construction difficulty of this type of bridges will increase with the span of the bridge because the horizontal reactions are not available until the tied girder is completed. Generally, such bridge type is a good option for mid-span bridge, saying from 50 m to 150 m.

The Second Yellow River Highway Bridge in Zhengzhou, completed in 2004, is a through deck-stiffened CFST arch bridge in large scale. There are two separate bridges in the road section, each one carries 4 lanes in one direction and has a net width of 19.484 m. The main bridge is composed of 8 spans of CFST tied arch bridges with each span of 100 m, as shown in Figure 10a. In construction, two temporary bridges were constructed along the two sides of the bridge to be built. All the substructures and foundations were built of cast in situ reinforced concrete. A special gantry crane with lifting capacity of 600kN was designed and erected for the handling of the steel tubular rib segments and other precast PC or RC members, as shown in Figure 10b (Zhang et al. 2004).

(a) Night view (b) Construction site

Figure 11: Second Yellow River Highway Bridge

Double-deck-bridge also appears in CFST arch bridge, e.g., the Qiangjiang No. 4 Bridge, with a span arrangement of 2×85m+190m+5×85m+190m+2×85m, as shown in Figure 11. In the construction of this bridge, the steel arch ribs were erected before the stiffened girders and a large cable crane was employed as the main transportation method. The main structure of the cable crane is a three-tower and four-span cable structure, as shown in Figure 12. The span arrangement is (250+692.25+650.75+250)m. The central tower is 104m high and 48m wide and the each of the two side towers is 120m high and 42m wide (Chen, 2008).

Figure 11: Hang-zhou Qian-jiang No.4 Bridge

Figure 12: Cable Crane in Construction of Hang-zhou Qian-jiang No.4 Bridge

4.4 Through Rigid-frame tied Arch Bridge

In CFST rigid-frame tied arch bridges, arch ribs are fixed to the piers to form a rigid frame, so the arch rib can be erected similar to true arch using cantilever cable-stayed method. For small span bridge, the piers can stand small thrust forces caused by light self-weight of steel tubular arch rib and for large span bridge, temporary tied bars can be used. The construction of this type of bridges is easier than that of tied arch with deck girder stiffened bridges. The difficulty with the latter arises from the fact that the horizontal reactions are not available until the deck is completed.

High strength strands are employed as tied bars, which are pre-stressed to produce horizontal compression forces to balance the thrust of the arch ribs produced by dead loads. The tied bar should be tensioned step by step along with the increase of the dead load in the construction to balance the thrust, therefore, the tension sequence and tension forces of the tied bar must be determined in the design. In order to prevent crack which appears in reinforced concrete piers during the construction by in-span horizontal forces caused by prestressing of tied bars and out-span thrusts from the arches, a construction monitoring based on carefully calculation on construction stages is necessary (Yang and Chen 2007).

In through arch bridge, no side span is required like cable-stayed bridge or continuous girder bridge when a single main long span is needed to cross a railway or highway. The structure of the joint between the arch spring and arch seat on the top of the piers is very complicated, because arch rib, pier and end cross beams are joined together and tied bars are anchored there. Span of this type of bridge is generally 80 m ~ 150 m. The longest span of such bridge type is 280 m in No.3 Hanjiang Bridge (Figure 13) in Wuhan (Chen 2008).

Most of the CFST through rigid-frame tied arch has single span, while some of them have two or even more spans with separate tied bars for each span, such as Yanyan Yellow River Bridge in Lanzhou with three spans of 87 m +127 m +87m (Figure 14) (Chen 2008).

Figure 13: No.3 Hanjiang Bridge

Figure 14: Yanyan Yellow River Bridge

4.5 Fly-bird-type Arch Bridge

The most interesting structure type in CFST arch bridges is the so called fly-bird-type arch. This type of bridges 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 pre-stressed steel bars are anchored at the ends of the side spans to balance the arch thrusts. This bridge type has a large spanning capacity. There are 9 of such bridges with a span above 200 m. The longest two bridges of this type are the Maochaojie Bridge (Figure 15) (Chen 2008), with a main span of 368 m and completed in 2006, and the Yajisha Bridge(Chen 2004), with a main span of 360 m and completed in 2000 (Figure 16). The former was erected by cantilever method, while the latter by combining vertical and horizontal swing method as shown in Figure 17 and 18.

Figure 15: Maochaojie Bridge in Hunan

Figure 16:Yajisha Bridge in Guang-zhou

(a) A rotation unit after vertical swing (b) Horizontal swing

Figure 17: Construction of Yajisha Bridge

In CFST fly-bird-type arch bridge, it's necessary to have a good balance between the central span and side spans and minimize the bending moments in arch spring sections (especially in the side RC half arch). The dead load should be taken into major consideration in design because it generally occupies a large part of the total load. Compared with the side spans, the central half-through arch has a longer span, so high rise-to-span ratio and light material (CFST) of arch rib should be used to decrease the thrust forces. In contrast, for the side half-arch with shorter span, low rise-to-span ratio and heavy material (generally RC) of arch rib should be used to increase the thrust. Sometimes, steel-concrete composite deck structure is applied in central span and RC deck structure is used in side spans. Furthermore, there are two end beams at each end of side spans, which are not only necessary for connecting the arch bridge and the approach, as well as anchoring the tied bar, but also helpful for balancing the horizontal thrust of main span. The key issue in design of such bridges is that under dead load the central span should act as a fixed arch, while the side spans act as half arches rather than cantilever girder (Chen et al. 2006).

Most of the fly-bird-type arch bridges are composed of three spans, however, there are some of them are composed of four spans or five spans. Ji-an Bailu Bridge (Figure 18) is one of the few five span fly-bird-type arch bridge. The arch ribs in the central three spans are triangular cross-section consisting of three CFST chords and were erected by cable stayed cantilever cable-stayed method, shown in Figure 19(Chen 2008).

Figure 18: Ji-an Bailu Bridge in Jiangxi

Figure 19: Erection of the arch ribs of Ji-an Bailu Bridge in Jiangxi

4.6 Other Types

Besides the above-mentioned five main types, there are other types CFST arch bridges, some of them have long spans.

The main span of Wanbian Bridge in Fuzhou, crossing Wulong River, is an arch-frame composition bridge with a span arrangement of 45m+90m+106m+90m+45m. In the central three spans, the two separated prestressed concrete continuous rigid-frames are combined in transverse direction by cross beams which is hanged to arch ribs fixed at the V-shape pier (Figure 20). The section of the arch rib is made of concrete filled steel tubes (CFST). Prestressed continuous box girders for the approach bridges and prestressed concrete continuous rigid-frame with V-shape pier for the main structure for the main bridge were selected based on the economic reason. For the three arches in the main bridge, it is not so much for strengthening for the continuous rigid frames as aesthetic advantages. This bridge is still under construction and will be completed at the end of 2008 (Chen 2007A).

Figure 20: Image view of Wanbian Bridge in Fuzhou

The main span of Lianxiang Bridge in Hunan is a cable-stayed CFST arch bridge (Figure 21a) (Chen 2008). Its span arrangement is 120m+400m+120m. The domain structure is a three-span fly-bird-type arch, in which the central span is a CFST truss arch and the two sides are cantilever concrete half arches. Two towers stand on the main piers to carry cables to stay the central CFST arch ribs and the side span decks. The side spans were constructed by cast in-situ. The steel tubular arch ribs in central span were erected by cantilever cable-stayed method with cable crane. Two temporary steel structures stand on the top of the cable stayed tower to serve as the tower of the cable crane, as shown in Figure 21b.

(a) Completed photo (b) Construction

Figure 21: Lianxiang Bridge in Hunan

5. LAST MARKS

The CFST structure has been applied prevalently and rapidly to arch bridges since 1990 and this tend is continued with more and more long span CFST arch bridges been build since 2000. Since continues rising demand of transportation in developing China, there are still many new highways and railways in plan, we can foresee that more CFST arch bridges will be built in the future for their inherent advantages such as high strength, large stiffness, easy to construction and special economics especially in mountain area.

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