An overview of concrete and CFST arch bridges in China

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ABSTRACT: The general information on stone, steel, concrete and concrete filled steel tubular (CFST) arch bridges in China has been introduced. An investigation on concrete and CFST arch bridges in China is carried out. The survey has shown that there are more than 151 concrete arch bridges and more than 130 CFST arch bridges with a span equal or longer than 100m built or under construction in China. General information of span, structural types, construction method and some key parameters in structure are analyzed based on statistical data from the investigation. At last, the development of arch bridges in China is prospected.

1 INTRODUCTION

Arch bridge is a main bridge type in China. Stone arch bridge has long history and achieved high prestige, such as the Chaw-Zhou Bridge, completed in 605 A.D. with a span of 37.4m, which is still in service today.

Stone arch bridges are adopted widely in highways in 1950-1970s. Even at present, they are also used in hilly or mountainous areas. New Danhe Bridge, opened to traffic in 2000, is a stone arch bridge with a span of 146m and deck width of 24.8m. It ranks as the world's longest span stone arch bridge (Chen 2005).

It is well known that reinforced concrete (RC) can be used economically in arch bridges ranging from 35 to 200m. Many RC arch bridges have been built in China. The statistics shows that around 70% of highway bridges are arch bridges until 1990s (Xiang 1993). Among these arch bridges, most of them are stone and reinforced concrete arches. Because labor, material of stone and concrete are cheaper, stone or reinforced concrete arch bridges were economic to be built for a long time until 1980s.

From the 1960's to the 1970's, many concrete arch bridges with light self-weight were presented and applied, in order to save materials, lighten the substructure and foundation, made erection easy. These bridges include curvature arch bridge, rigid-framed arch bridge, trussed arch bridge and prestressed trussed arch bridge.

From 1980, thank to the development of economic, many arch bridges with reinforced concrete box rings and ribs have been constructed. Most of them are deck fixed arch with RC spandrel columns and simple deck girders. Accompanied with the developing of erection technologies such as the horizontal swing method, the embedded scaffolding methods, the span record was refreshed continually. Till 1990, the typical concrete arch bridges built in China are as follows: the Mamingxi Bridge erected by cantilever method with a span of 150m and completed in 1979; the Baoding Bridge with a main span of 170m built by steel scaffolding in 1982; the Fuling Bridge with a main span of 200m erected by horizontal swing method which was completed in 1989; and the Yibin Xiaonanmen Bridge with a main span of 240m built by embedded shaped steel scaffolding at the next year.

In 1990，the first Concrete filled steel tubular (CFST) arch bridge was built in China. It is the Wangcang Donghe Bridge, a through tied rigid-frame arch bridge with a span of 115m, dumbbell arch ribs erected by cantilever method.

CFST structure is one of steel-concrete composite structures. It has better strength than those of masonry or reinforced concrete and can provide larger stiffness than steel tubes. The tubular arch itself can be erected with lighter self-weight and outstanding stiffness. Then concrete can be filled into the tubes to form CFST structures. Therefore, CFST arch bridges can meet the requirements of economy, material saving, easy erection and high load carrying capacity. With the trend of increasing the use of steel material and decreasing the labor in bridge construction due to the rapid development of economy, CFST arch bridge became a good alternative to achieve a kind of balance between reinforced concrete arch bridges and steel arch bridges. In addition, it has a more pleasing appearance.

Since 1990, many CFST arch bridges have been building in China. In 1995, Nanhai Sanshanxi Bridge in Guangdong with a main span of 200m was completed, which is the first fly-bird-type CFST arch bridge and the first one with a span to 200m. In 2000, Yajisha Bridge in Guangdong with a main span of 360m was open to traffic (Fig. 19), which was erected by combining vertical and horizontal swing method and held the span record at that time (Chen et al. 2004). In 2005, the Wushan Yangtze River Bridge with a span of 460m was completed (Fig. 13), which is the largest one at present. Currently, there are still some large CFST arch bridges are under construction, such as Taipinghu Bridge and Zhijinghe Bridge. The Taipinghu Bridge, located in Anhui Province, is a lifting-basket half-through CFST arch bridge with a main span of 336m. The Zhijinghe Bridge in Hubei Province is a deck CFST arch bridge with a main span of 430m.

CFST are not only used as arch ribs in China, but also are taken as embedded scaffolding to construct concrete arch bridges. It makes the embedded scaffolding method very economic and the span of concrete arch bridge can reach longer.

In 1996, Yong-jiang Bridge (Fig. 1) with a main span of 312m was completed, using CFST arch as embedded scaffolding. In construction, the steel tubular truss arch was erected by cantilever method and concrete was filled into steel tubular chords after its closure to from a CFST arch. Then concreting was carried out to form the two box ribs by means of a cable crane (Wang et al. 2004).

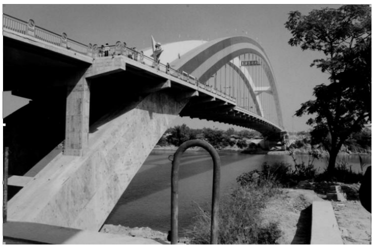


Figure 1: Yong-jiang Bridge

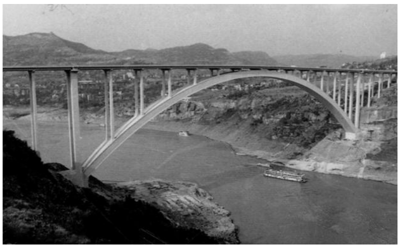


Figure 2 : Wanxian Yangtze River Bridge

The present world record for the span of concrete arch bridge--the Wanxian Yangtze River Bridge was also constructed by this method, which is a deck box ring arch bridge with a clear span of 420m and deck width of 24m (Fig. 2). The main arch rib is a three-cell rectangular box, 7m height and 16m wide. It was completed in 1997 (Yan and Yang, 1997).

Steel is a material with superior strength and ductility, so it is possible to make the span of arch bridge longer. In China, for a long period, steel products per person were very small; so few steel arch bridges have been built before 2000. On June 28, 2003, the Lu Pu Bridge was open to traffic. This bridge in Shanghai with a main span of 550m, crossing the Huangpu River, is the longest span of arch bridge in the world. In recent years, some steel arch bridges with large spans are under construction or planning in China, such as the Xinguang Bridge in Guangzhou, Caiyuanba Bridge and Wangjiatuo Bridge in Chongqing (Chen 2005). However, stiffness required for steel arch bridges consumes more steel and causes difficulty in fabrication or erection, compared with girder-typed bridges or cable-stayed bridges. Therefore, steel arch bridges are generally expensive than other bridges and it is not reasonable to built too many long span steel arch bridges.

From the brief review of arch bridges in China, it is obvious that the concrete and CFST arch bridges are the two main types of arch bridges in China. They will be built in the future for its great advantages. In this paper, these two type arch bridges with a span equal or longer than 100m have been investigated. General information of span, structural types, construction method and some key parameters in structure are analyzed based on statistical data from the investigation. At last, the development of arch bridges in China is prospected.

2 CONCRETE ARCH BRIDGES

2.1Structural forms

The concrete arch bridges in China can be classified as main three forms as well as other types. The main three types are deck (true) arch, light deck arch, half-through arch. The investigated bridge forms are listed in Tables 1.

Table 1: Bridge Forms

Structure form		Amount		Percentage	
Deck arch	Box ring	50	62	38	47
	Ribbed	12		9	
Light arch	Double-curved	13	50	10	39
	Rigid-frame	5		4	
	Truss	0		0	
	Prestressed truss	32		25	
Half-through		16		12	
Others		3		2	
Total		131		100	

The most suitable site for deck arch bridge is a valley, with the arch foundations located on dry rock slopes to decrease the cost and with an aesthetic appeal to be harmonic with surrounding. It is indicated from table 1 that the majority of long-span concrete arch bridges are deck (true) arch bridges with box ring or ribs, which accounted for 47% of the total 131 bridges. Most of the deck arch bridges adopted box rings, only some of them adopted box ribs. Because of its excellent rigidity and capacity to resist bending, box cross section is usually an economical style for long span concrete arch bridges. Thanks to the economic development and sufficient supply of steel and cement, many concrete box deck arch bridges have been constructed from 1980 in China. Almost all of the arches are fixed. Spandrel structures usually are reinforced concrete ones, i.e., reinforced concrete spandrel columns, simple deck reinforced or prestressed concrete girders or spandrel arches. Many of the deck arch bridges have a long span. In the 13 bridges listed in Table 2, seven of them are deck arch bridges, in which the longest one is Waxian Yangtze River Bridge with a span of 420m (Fig. 2).

Among the investigated concrete arch bridges, only 16 bridges, accounted for 12% of the total, are half-through arch bridges, but some of them have longer spans, such as Weiping Bridge (198m span), Yibin Xiaonanmen Bridge (240m span) and Yong-jiang Bridge (312m span, Fig.1). All of these three bridges were built by embedded scaffolding method. It is worth to note that all the through concrete arch bridge is below 100m.

Light concrete arch bridges were the main bridge form constructed in 1960s-1980s There are 50 of them, accounted for 39% of the total.

Double curvature arch bridge composed of ribs and bracings, cross curved plates and covering arched plates (Fig.3). They generally are open spandrel arches with reinforced spandrel column. Roadways are placed directly on the filled material retained by short wall and the spandrel arches as well as the crown area of the main arch (Peng and Hong, 2004).

In construction, small prefabricated reinforced concrete arch ribs and the bracings are first erected to form an arch scaffoldings, and then prefabricated reinforced concrete curved files are placed between two neighbor ribs to form formwork of the arch ring. Finally, concrete is cast in-situ over the erected ribs and files to assemble them together to form an arch rib. Because the curved files display a curve shape in both the cross-section and the arch axis directions, the arch ring is called double-curved ring and so for the arch name.

The longest one is the Qianhe Bridge (Fig.4) in Henan Province built in 1968 with a clear span of 150m. The rise-to-span ratio is 1/10. There were 12 spandrel arches which span was 9 meters. Because of 29 transverse beams, the whole performance of arch ribs was good.

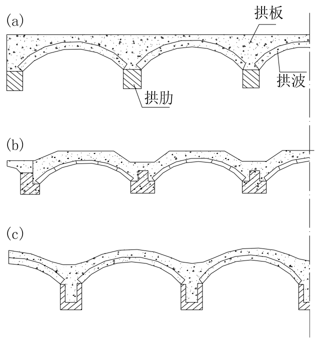


Figure 3 : Cross-section of double-curved bridge

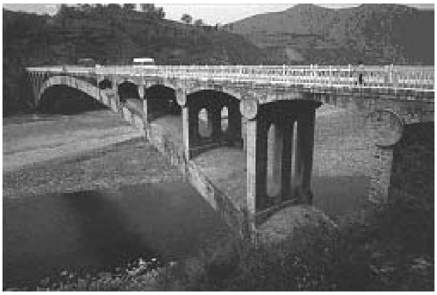


Figure 4 : Qianhe bridge

Both reinforced concrete and prestressed concrete truss arch bridges have been built in China. The concrete truss arch bridge is erected by hoisting the prefabricated slice of braced spandrel arch one by one and connected by lateral bracings. Limited by the hoisting capacity, the span just reaches to 60m.

The prestressed concrete truss arch bridge is built by cantilever launching method. The deck is continuous from the main arch to the approach and broken in 0.5-0.6L of the main arch to release the tension force in the deck girder, as shown in Fig.5. This bridge form has a long span. Jiangjiehe Bridge (Fig. 6) with a span of 330m holds the first record of this bride form. Its total length is 416m, the deck is 13.4m wide and the rise-span-ratio is 1/6. The main arch rib, with a a three-cell box section, is 2.7m high and 10.56m wide.

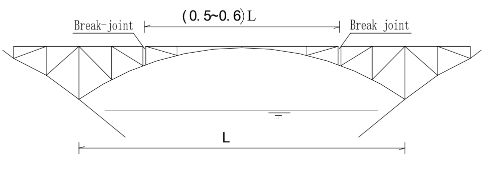


Figure 5 : Prestressed Truss Arch Bridge

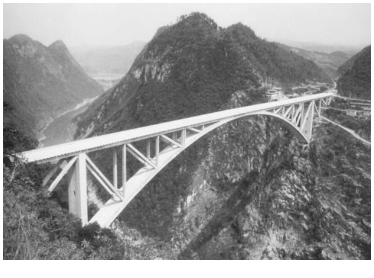


Figure 6 : Jiangjiehe Bridge

In rigid-frame arch bridge, the horizontal members rigidly attached to two main inclined legs with a curve intrados. In a longer span case, two or more subordinate inclined straight legs are connected to arch seat and the horizontal members (Fig. 7). This bridge type is applicable for bridges with medium span length. The longest span reinforced concrete rigid-frame arch bridge is the Taibai Bridge (Fig. 8) with a span of 130m. The rise-span ratio is 1/9 and the clear rise is 16.5m. The arch composed of twin RC box ribs. It was constructed by the horizontal swing method with CFST as its stiffened skeleton. The weight of the swing system is 18100KN.

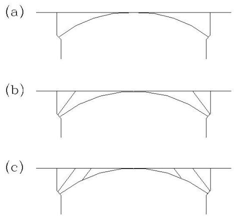


Figure 7: Rigid-frame Arch Bridge

Figure 8 : Taibai Bridge

These light concrete arch bridges are economic and made it possible to build many bridges at that time for shortage of cement and steel and plenty labors. However, with low design load standard, deficient load capacity, small bridge width, these bridges can not satisfy the increasing traffic demand at present. Moreover, these bridges have inherited insufficiency of integrity, load carrying capacity and cracks are apt to appear in the web joints in double-curved arch rings and rigid joints of the truss arch bridges. Many of them have been removed and rebuilt. Fewer such new bridges were built after 1980. But there are still a great deal of them in service in substandard in one way or another with different extend, therefore, overall inspection, rehabilitation and strengthening for these light concrete arch bridges are serious in China.

Besides the three main forms, there are also other forms. In the investigation, there are two prestressed concrete rigid-frame arch bridges without spandrel columns, which are the Bitan Bridge located in Taiwan Province with a main span of 160m and the Yuxizhou Ming River Bridge with a main span of 120m. And the third one in other form is the New Qijiang Arch Bridge with the extrados partially stepped for pedestrians. The bridge is 7.5m wide and 130m long, two arch ribs are inclined inward and combined into a box ring, so it is also called an X-shaped arch bridge by its plan shape.

2.2 Construction methods

Construction methods used in concrete arch bridges in China can be classified into four types, i.e., scaffolding, embedded scaffolding, cantilever method and swing method.

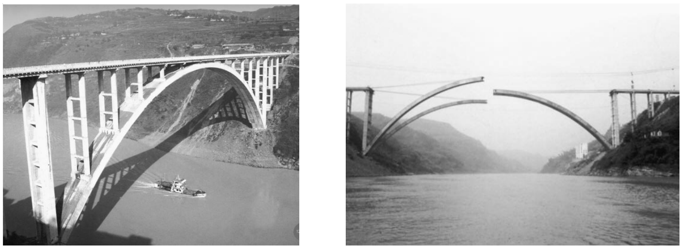
There were 13 bridges used classical scaffolding method, most of them built in 1960s and 1970s. It is most suitable for the small span bridges, especially when it crosses non-navigable river. In China, most of the scaffoldings are made of timbers; only few of them used steels, such as Baoding Bridge with a main span of 170m and Xuguo Bridge with a span of 220m

Currently, the most widely adopted construction method in concrete arch bridge is cantilever method. Among 87 bridges, 52 of them adopted this method, accounted for 60% of the total; in particular, the entire light arch bridges built during 1960s to 1980s adopted this method. For those bridges built by embedded scaffolding method, the scaffoldings were also erected by cantilever method. Therefore, this method is the only one for large-span concrete arch bridge.

Cantilever method can be further divided into cable-stayed and cantilever truss method. In China, cantilever truss method was only used in the prestressed truss concrete arch bridges, such as the Jiangjiehe Bridge (Fig. 6). In terms of cable-stayed method used in China, the arch ribs are prefabricated in segments and hoisted by cable crane, so it is also called cable crane method or cantilever launching (assembling) method, only adopted in one bridge under construction with a span of 150m, the arch ribs are concreted in-situ.

Embedded scaffolding method is another main construction method. In 1980s, in order to reduce the steel assumption, scaffoldings without enough stiffness were employed and many control methods were presented, such as the method using the weight of water tanks hanging in the scaffolding as a balance when concreting, adjustment of internal forces of fastening cable tied to the scaffolding. However, the geometric form of the arches was not easy to control. Thanks to CFST member applied in the embedded scaffoldings, many long span concrete arch bridges have been built in China in recent years.

Swing method consists of building two half bridges, which are then rotated vertically or horizontally on temporary pivots to closure. The horizontal swing method has been used in various bridges, such as cable-stayed and T-rigid frame bridges. However, only in China it is used in arch bridges. From 1975, research on horizontal swing technique in construction of concrete arch bridge was carried out and it was successfully applied in Shining Bridge in 1977, which is 70m span box ribbed reinforced concrete arch bridge. The fabricated semi-arch and the counterweight abutment on the rotation disk were rotated horizontally around a pivot and a preinstalled Teflon ring-like slide to closure position. However, this method is limited by the self-weight of concrete arch ribs when the span is larger. Therefore, a swing system without balance weight was developed. After successfully applied in Longmen Bridge, it was employed in the Fuling Bridge with a main span of 200m in 1989 (Fig. 9). The three-cell box ring was divided into three parts in construction. The two side cells were erected by horizontal swing method without balance weight (Fig.3). In this method, only the arch ribs on the pivot were rotated to closure. Then two box ribs were connected by casting in-situ to form the middle cell (Zhang and Chen, 2004).



(a) Completed (b) Construction

Figure 9: Fuling Wujiang Bridge

2.3 Amount and span

According to our investigation, 151 concrete arch bridges in China, with a span equal to or longer than 100m, have been built or under construction up to March, 2006. It is noteworthy that 53 of them have a span equal to or longer than 150m and 13 with a span equal to or longer than 180m, listed in Table 2.

Table.2 Concrete arch bridge (span≥180m)

No.	Bridge Name	Time	Span(m)	Structure	Construction Method
1	Wanxian Yangtze River Bridge	1997	420	deck arch	Embedded scaffolding
2	Jiangjiehe bridge	1995	330	Prestress truss	Cantilever
3	Yongjiang Bridge	1996	312	half-through	Embedded scaffolding
4	Xiaonanmen Bridge	1990	240	half-through	Embedded scaffolding
5	Xuguo Bridge	2001	220	deck	Scaffolding
6	Xingduicha Bridge	under construction	205	deck	Swing
7	FuLing Bridge	1989	200	deck	Swing
8	Weiping Bridge	2001	198	half-through	Embedded scaffolding
9	Liuguihe Bridge	2005	195	deck	Cantilever
10	Modong Bridge	1999	180	deck	Cantilever n
11	Huapichong Bridge	1999	180	deck	Embedded scaffolding
12	Yanxi Bridge	2003	180	Prestress truss	Cantilever
13	Shatuo Bridge	2002	180	Prestress truss	Cantilever

Fig.10 shows the relationship between completion year and span of concrete arch bridge in China

This demonstrates that the span increases with time till 2000, but since then the trend is opposite. This downtrend is probably actual and also possibly caused by lacking of data of the new bridges.

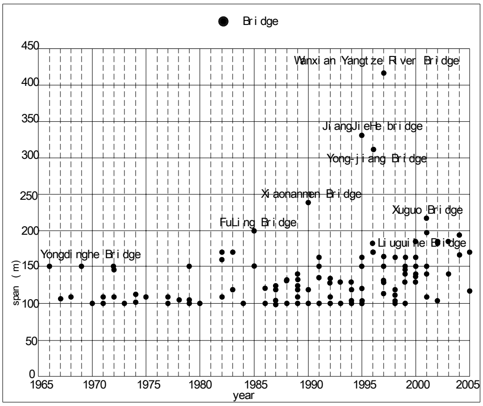


Figure 10 : Variance of the span with time

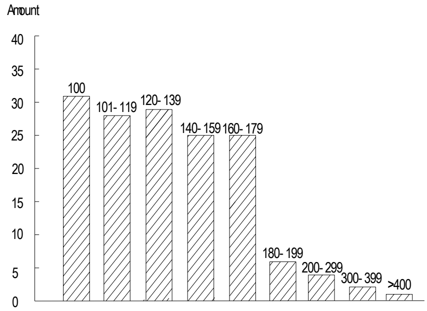


Figure 11: Statistics of span

Fig.11 shows the statistics of span in concrete arch brides in China. From the figure it is possible to understand that for span from 100m to 179m, there are 137 bridges, accounted for about 91% of the investigated bridges. Concrete arch bridge with a span under 180m is not difficult to construct and can meet the requirement of economy, especially in mountainous area. In addition, approximately 9% are bridges with span of 180m -199m and 5% equal to or longer than 200m.

2.4 Arch structure

Box cross-section is much more frequently and popularly used in concrete arch bridges for its excellent rigidity and capacity of resisting bending, especially for long span bridges. It is indicated that 44 of the 55 deck bridges adopted box ring arch, the abovementioned Wanxian Yangtze River Bridge and Jiangjiehe Bridge are good examples. According to our investigation, there are 58 bridges of them adopted box cross sections, accounted for 80% of the 71 bridges known cross-section. Generally speaking, the height of the box is of 1/29~1/75 of the span at spring and 1/44~1/75 of the span at crown. The double-curved cross-section was used in the light concrete arch bridges with a span from 100m to 120m in the past decades, 12 bridges of the 71 was adopted this section. In deck bridges, only one use I-shaped arch rib, i.e., Yalongjiang Bridge with a span of 170m built in 1996.

With regard to half-through arch bridge, 21 bridges of the investigated used box rib. Box ribs can also be used in long span arch bridges, such as Yong-jiang Bridge and Xiaonanmen Bridge. The box is 1/34~1/67 of the span high at spring and 1/34~1/80 of the span high at crown.

Statistic demonstrates that most bridges has a rise-span ratio between 1/4~1/8 and 1/6 is the most popularized one. In particular, aiming at reducing the height of the spandrel column, a smaller rise-span ratio is the most possible choice in deck arch bridge.

Regarding to arch axis, in the 85 investigated bridges, 72 of them adopted catenary curves as their axis, accounted for 84.7%; 11 of them (12.7%) use parabolic curves. That is to say the most appropriate arch axis form in concrete arch bridges is of catenary curves. It is worth to note that catenary axis is also widely adopted in all deck bridges and some through and half-through bridges, while parabolic axis is used in most through and half-through bridges.

3. CONCRETE FILLED STEEL TUBULAR ARCH BRIDGES

3.1 Structural forms

CFST arch bridges can be classified into five main types, i.e. deck (true) arch, half-through true arch, fly-bird-type arch (half-through tied rigid-frame arch), through deck-stiffened arch and through rigid-frame tied arch. 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.

3.1.1 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 PC structures, 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 150m. The longest span until now is Fengjie Meixihe Bridge with a span of 288m (Fig. 12), and the Zhijinghe Bridge under construction with a main span of 430m will break this span record. However, being different with concrete arch bridges, only 8% of investigated CFST arch bridges are deck bridges, most of them are half-through and through bridge.

Figure 12: Fengjie Meixihe Bridge

3.1.2 Half-through True Arch Bridge

Sometime, it is possible that arch span is large, so the rise of it will be much higher than the road elevation, half-though bridge is a good choice. Half-through (true) arch bridges are accounted for 62 (47%) of the investigated 131 CFST arch bridges. Moreover, it can reduce the height of the spandrel columns. Many long-span CFST half-through true arch bridges have been built. The span record is kept by Wushan Yangtze River Bridge with a span of 460m (Fig. 13), which is also the record of CFST arch bridge in the world.

Figure 13 : Wushan Yangtze River Bridge

3.1.3 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 form will increase with the span of the bridge because the horizontal reactions are not available until the tied girder is completed. Generally, such bridge form is a good option for mid-span bridge, say from 50m to 150m.

The longest span of this bridge form is Moon Island Bridge in Liaoning Province with a span of 202m, while Second Yellow River Highway Bridge in Zhengzhou, completed in 2004, is the largest scale of this bridge form. There are two separate bridges in the road section; each bridge carries 4 lanes in a direction and has a net width of 19.484 m. The main bridge is composed by 8 spans of CFST tied arch bridges with each span of 100m as shown in Fig. 14.

Double-deck-bridge also appeared in CFST arch bridge, *e.g.*, the 4th Qiangjiang River Bridge, with a span arrangement of 2×85m+190m+5×85m+190m+2×85m, as shown in Fig. 15.

Figure 14: Second Yellow River Highway Bridge

Figure 15 : Hang-zhou Qian-jiang No.4 Bridge

3.1.4 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. High strength strands are employed as tied bars, which is pre-stressed to produce horizontal compression forces to balance the thrust of the arch ribs produced by dead loads. It can be erected similar to true arch using cantilever launching method.

In through arch bridge, no side span is needed like cable-stayed bridge or continuous girder bridge when only a main long span is needed to cross a railway or highway (Fig. 16). 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 jointed together and tied bars are anchored there. The span of such bridge form is generally 80m - 150m. The longest span of such bridge form is 280m in No.3 Hanjiang Bridge (Fig. 17) in Wuhan City. 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.

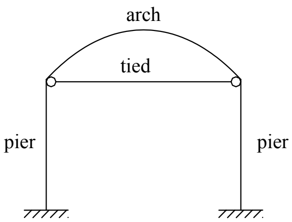


Figure 16 : Rigid-frame tied through CFST arch bridge

Figure 17 : No.3 Hanjiang Bridge

3.1.5 Fly-bird-type Arch Bridge

The most interesting structure form in CFST arch bridges are the so called fly-bird-type arch. This bridge form generally consists of three spans (Fig. 18). 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 form has a large spanning capacity, there are 9 of such bridges with a span above 200m.The longest two bridges of this form is the Maochaojie Bridge with a main span 368m completed in 2006 and the Yajisha Bridge with a main span of

360m completed in 2000 (Fig. 19). The latter was erected by combining vertical and horizontal swing method (Fig. 20 and 21).

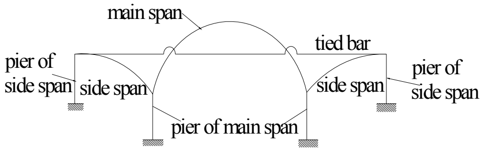


Figure 18: Fly-bird-type arch

Figure 19 : Ya-ji-sha Bridge in Guang-zhou

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 larger span, so great 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 small span, small 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 applied in central span and RC deck structure are used in side spans. Furthermore, there are two end beams at the ends of side spans, which is not only necessary for connecting the arch bridge and the approach, anchoring the tied bar, but also helpful to balance the horizontal thrust of main span. The key issue in design of such bridge form 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).

3.2 Construction methods

In construction of 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. Though the thin-walled steel tubular arch has a lighter self-weight than concrete or shaped steel arch rib, it is still a key issue in construction when the span is longer. The popular erection methods used in CFST arch bridges are cantilever launching method and swing method as used in concrete arch bridges. However, these two construction methods 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 at past. Therefore, the alignment of arch ring can be controlled by the adjustment of internal force of the fasten cables more easily than before. This method was adopted by 67% of the bridges, i.e. 69 bridges. In the 8 bridges with a span no less than 300m, there are 7 used this method, including the world's largest one, the Wushan Yangtze River Bridge with a span 460m (Fig. 13). It is evident that Cantilever is the most potential in the construction of CFST bridges for its wide range of application, especially for long span CFST arch bridges.

Another main erection method used in CFST arch bridges is swing method, including vertical swing, horizontal swing. Statistics shows that there are 15 bridges (about 15%) adopted this construction procedure. In vertical swing method, the semi-arch ribs are fabricated in low position and hoisted up into design level. This is difference as in other countries to build half-arches on the springs vertical and then rotate down on their lower end to close at the crown. This up-lift vertical swing method is mainly used in CFST arch bridge for the tubular structure is much lighter than concrete arch ribs.

The horizontal swing method with balance weight was first used in the Huangbaihe Bridge and Xialaoxi Bridge near the Three Gorge Dam (Duang et al. 2001). Adopting jakes pushing system as the drawing power, the rotated capacity in swing method is much greater than that by using windlass pulling system as before. And the arch span can be much longer because steel tubular arch rib is much lighter than that of concrete arch.

A new method by combining vertical and horizontal swing method has been developed in

CFST arch bridges, such as Wenfenglu Bridge and Yajisha Bridge. The half arch of the main span and cantilever half arch near it composed a rotation unit. First, the cantilever half arch was erected and main half arch was fabricated along the riverbank. Then, the main half arch was rotated vertically into right position. After that, the two half-arches were rotated horizontally, one 90° and the other about 117°. Finally, the arch rib was closed by a 1m long rib-segment. The total weight of each horizontal rotating body is 136,850kN (Zhang and Chen, 2004).

Figure 20 : Vertical Swing of Ya-ji-sha Bridge Figure 21 : Horizontal Swing of Ya-ji-sha Bridge

Some CFST arch bridges were built on scaffoldings, especially the through tied arch bridges with short or medium span.

Other construction methods are applied in the erection procedure of CFST arch rib based on different conditions. For example, in the Moon Island Bridge, vertical swing method was partially used for the first two segments at the springs. The remainder of the arch was lifted up by the hoisting. Tianzishan Bridge was erected by cantilever truss method.

3.3 Amount and span

The latest survey shows that 230 CFST arch bridges, with the span above 50m, were built or under construction until March 2006, 132 bridges of them have a main span equal to or longer than 100m, which is analytical basis of this paper, and 33 bridges with a span equal to or longer than 200m, listed in Table 3.

Table 3 : CFST arch bridges (span ≥ 200m)

No.	Bridge name	Completion Year	Main span(m)	Form	Construction method
1	Enshi Nannidu Bridge	2002	220	Deck arch	Cantilever
2	Beipanjiang Bridge	2001	236	Deck arch	Swing
3	No.1 Qiadao Lake Bridge	2005	252	Deck arch	
4	Meixi Bridge in Chongqing	2001	288	Deck arch	Cantilever
5	Zhijinghe Bridge	Under construction	430	Deck arch	Cantilever
6	Wuhan No.3 Hanjiang Bridge	2000	280	Through tied rigid-frame Through tied arch	Cantilever
7	Moon Island Bridge in Dandon	2003	202	Through tied arch	Other Method
8	Yangtze River Railway Bridge in Yichang	Under construction	264	Half-through arch	Swing
9	Longtan River Bridge in Zigui	1999	200	Half-through arch	Cantilever
10	Jialing River Bridge in Hechuan, Chongqing	2002	200	Half-through arch	Cantilever

11	Wangcun Yushui River Bridge in Zhangjiajie	2003	200	Half-through arch	Cantilever
12	Liujing Yujiang Bridge in Guanxi	1999	220	Half-through arch	Cantilever
13	Tongwamen Bridge in Zhejiang	2001	238	Half-through arch	Cantilever
14	Luojiao River Bridge in Guizhou	1998	240	Half-through arch	
15	Sanmen Jiantiao Bridge in Zhejiang	2001	245	Half-through arch	Cantilever
16	Zigui Qingganhe Bridge in Hubei	2002	248	Half-through arch	Cantilever
17	Jinshajiang Rongzhou Bridge in Yibin	2004	260	Half-through arch	Cantilever
18	Sanan Yongjiang Bridge in Guangxi	1998	270	Half-through arch	Cantilever
19	Sanmenkou North-gate Bridge in Xiangshan	Under construction	270	Half-through arch	Cantilever
20	Sanmenkou Middle-gate Bridge in Xiangshan	Under construction	270	Half-through arch	Cantilever
21	Chunan Nanpu Bridge in Zhejiang	2003	308	Half-through arch	Cantilever
22	Nanning Yonghe Bridge in Guangxi	2004	335.4	Half-through arch	Cantilever
23	Huangshan Taiping Lake Bridge in Anhui	Under construction	336	Half-through arch	Cantilever
24	Wushan Yangtze River Bridge in Sichuan	2005	460	'Fly-bird-type' arch	Cantilever
25	Nanhai Sanshanxi Bridge in Guangdong	1995	200	'Fly-bird-type' arch	Cantilever
26	Mianyang Pujiang Bridge in Sichuan	1997	202	'Fly-bird-type' arch	
27	Shenmi Bridge in Nanchang	Under construction	228	'Fly-bird-type' arch	Cantilever
28	Jinghang Canal Bridge in Xuzhou	2002	235	'Fly-bird-type' arch	Swing
29	No.5 Hanjiang Bridge in Wuhan	2000	240	'Fly-bird-type' arch	Cantilever
30	Dongguan Shuidao Bridge in Guangdong	2005	280	'Fly-bird-type' arch	Cantilever
31	Yajisha Bridge in Guangzhou	2000	360	'Fly-bird-type' arch	Swing
32	Maocaojie Bridge in Nanxian	Under construction	368	'Fly-bird-type' arch	Cantilever
33	No.4 Xiangjiang Bridge in Xiangtan	Under construction	400		Cantilever

Fig. 22 shows the variance of span and amount of CFST arch bridges with time. It can be known that there are few CFST arch bridges above 100m constructed in China before 1995. From then on, along with the development of theory and advancement in construction method, the span and amount increased with time

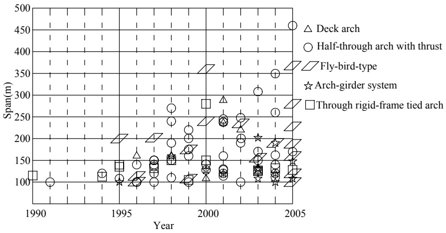


Figure 22 : Variance of CFST arch span with time

3.4 Arch Structure

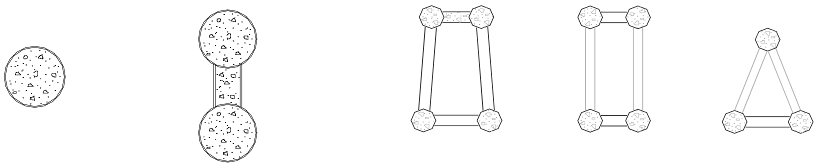
3.4.1 Rise-span ratio and arch axis

Rise-span ratio is an important parameter for arch. It can be found from the built CFST arch bridges that there is no distinct relation between span and rise-span ratio. For small span bridges, the rise-span ratio has a wider range, most of them are 1/4~1/5. Additionally, 1/5 is the widely used especially for longer bridges. In terms of the bridges with a rise span ratio larger than 1/4 or smaller than 1/5.5, most of them are scenery bridges.

Most of the CFST arch axis are catenary and parabola curves, in which catenary curve is accounted for 68%. With regard to the bridge forms, catenary axis is used in all deck bridges as well as some through and half-through bridges, while parabola axis is used in most through and half-through bridges.

3.4.2 Arch rib cross section

In CFST arch bridges, cross-section of the arch rib can be varied, from single tube to multiple tubes, as shown in Fig 23. With regard to the dumbbell shaped cross-section, the two CFST tubes are connected by two steel web slabs. Both the single and dumbbell shaped section are solid rib. Generally speaking, single tube section is suitable for shorter bridges, the maximum span of such bridges is 80m, while dumbbell shaped section is widely used in the bridges with a span about 100m, 160m is the largest span in this kind of built bridge until now.



(a)Single tube (b)Dumbbell (c)Truss (multi-tube type)

Figure 23 : Cross-section type

When more than two CFST tubes are used in a rib, they are connected by steel tubular web members to form a truss section, as shown in Fig. 23(c). CFST tube number in truss section can be three, four and six, but the three-tube section and six-tube section is only in some special cases. The cross-section of Yilan Mudangjiang Bridge, with two main spans of 100m, is composed of three CFST tubes. It is worth to note that this bridge is half-through arch bridge without bracings. Yajisha Bridge is the only one used the six-tube section (Fig. 23), in which the arch rib consists of six tubes of 750mm diameter filled with C60 concrete. In a word, the four-tube section is the most widely used truss section in CFST arch bridges.

As for the 119 bridges which cross-section is known, the arch rib of single tube, dumbbell, truss cross section are accounted for 12 (10%), 42 (35%) and 65 (55%) respectively. Truss section is the most widely used, and it should be preferential in long span bridges. It is found from further investigation that the height-span ratio (the height of cross-section) of CFST arch bridges is between 1/40~1/60 for constant cross-section and between 1/20~1/100 for varying cross-section.

3.4.3 Arch rib material

In terms of steel tube, 80% of the investigated CFST arch bridges adopted Q345 steel, others adopted Q235 steel. The grade of concrete filled in the steel tubes varies from C30 to C60. It is demonstrated that along with the development of construction techniques, the concrete grade increases. However, from the point view of economic it is not necessary to use too high grade concrete filled in the tube, C40 to C50 is enough. Generally speaking, for CFST arch ribs, C30 and C40 concrete match for Q235, C40 and C50 match for Q345.

3.5 Other structures

Spandrel columns in deck bridges are CFST columns or reinforced concrete columns, except in Zhijinghe Bridge with a main span of 430m, steel columns are applied to reduce its self-weight. The hangers in through or half-through bridges are made of high-strength steel cables similar to those in cable-stayed bridges. Tied bars in tied rigid-frame arch bridges are also made of high-strength steel cables.

The deck systems in CFST arch bridges are generally reinforced or prestressted concrete structures for their economy. Sometimes steel-composite structures are used to reduce the self-weight, especially for those wide bridges carrying four to six lanes as wide as 20 to 30m or even wider than it. Concrete deck slabs placed on the transverse girders carry the traffic road. Transverse girders are hanged or supported on the arch ribs.

Abutments and the foundations in CFST deck or half-through true arch bridges are similar to concrete arch bridges. Piers and abutments as well as their foundations in through deck-stiffened arch bridges are similar to that in girder bridges. In tied rigid-frame CFST arch bridge (both through and half-thorough), the piers are generally made of reinforced concrete structures and the foundations are piles.

4 DEVELOPMENTS OF ARCH BRIDGES IN CHINA

Since 1980, along with the opening and reform in China, economic development needs transportation to grow ahead, which results in large scale construction of highway and rail, many long-span bridges and large scale bridge engineering have been built. By the end of last century, China has more than 240.6 thousand highway bridges with a total length of 8,655km. In the first 20 years of this century, more than 1600 thousand km highway (including about 70 thousand km express way) will been built. About 2000 thousand bridges with a total length about 10 thousand km are prospected to be built, in which more than 100 bridges with a span longer than 400m. Many new arch bridges will still be built in the future, especially in mountain area.

Great effort to improve structure and construction techniques of concrete arch bridges has been made and great achievements of this type bridge have obtained by Chinese bridges engineers. In mountain area, when bridges cross over V-shaped or U-shaped valleys, concrete arch bridges are still suitable and economic to be used at the range of 30m to 200m. Because the construction difficulty and material consuming increase with the arch span becomes longer, research should be carried out on the new structure type, high strength and light materials and the erection methods in super-large span concrete arch bridge research projects. The research of a new type arch bridge--corrugated steel web concrete arch bridge is carried out and will soon be used in Sichun Province (Chen et al. 2006).

CFST arch bridges have been developing quickly since 1990. The code for design and construction techniques of CFST arch bridge will be published soon after. The researches on design theory, construction techniques, structure detail design are hot topics these days and are supported by many funds and engineering projects. These research works will make the design theory and construction techniques of CFST arch bridge progress and more CFST arch bridges be built more reasonably and economically.

Many concrete and CFST arch bridges have been built in China in the past and will still take an important role in the future in China. At the same time, some steel arch bridges with long span have been built or still under construction in China at recent years. Although the higher strength-to-weight ratio of steel can significantly reduce arch thrusts and can reach longer span than other material arch, it is prone to buckle under compression and requires extensive stiffening and bracing. Therefore, steel arch bridges are still very expensive to be built. Moreover, its fabrication techniques and design experience are still at a relatively low level today because few steel bridges have been built in China before. Therefore, it is unseasonable to build too many large steel arch bridges in China at present.

For stone arch bridge, it is completely unstable until the arch rib enclosed. Therefore it should be built by elaborating scaffolding, or "centering," below the spans to support them during arch rib construction. In many cases, it is not an economy bridge type to be considered. After 1990s, only four stone arch bridges larger than 100m has been built. It is prospected that only few small stone arch bridges will be built in mountain area with plenty stone material and cheap labor.

On the other hand, there are many arch bridges in service in China. The maintenance, rehabilitation and strengthening of these bridges have become key issues. Many research works have been carried out and engineering experiences have been accumulated. However, at present most money and bridge engineers are attracted in the new bridge construction. Therefore, not enough attention has been taken by bridge management authorities and bridge engineers. In the future, with more arch bridges been built and the service time extending, the service arch bridges will become a more serious problem.

Stone and steel arch bridges, limited by the economical efficiency, will face some practical difficulty to surpass span record, so they won't become the main research topics of super-long span arch bridges. The research work will focus on concrete arches and CFST arches. As for concrete and CFST arch bridges, it is possible to built super-long span arch bridge economically than other type bridges based on the research and application of high performance material, development of construction technology and innovation structural design.

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