Overview of Concrete Filled Steel Tube Arch Bridges in China

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Abstract: This paper briefly introduces the present situation of concrete filled steel tube (CFST) arch bridges in China. More than 200 CFST arch bridges were investigated and analyzed based on the factors of type, span, erection method, geometric parameters, and material. Some key issues in design calculation were presented, such as check of strength, calculation of section stiffness, and joint fatigue strength. It will provide a comprehensive reference of CFST arch bridges for the bridge designers and builders.

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Introduction

Concrete filled steel tube (CFST) arches surpass steel tubular arches and reinforced concrete arches. The filled-in concrete delays local buckling of the steel tube. The steel tube reinforces the concrete to resist tension stresses and improve its compression strength and ductility. Moreover, in construction, the tube also acts as a formwork for the concrete. With the rapid development of the economy in China, CFST arch bridges become a good alternative to reinforced concrete (RC) arch bridges or steel arch bridges (Chen 2005). Besides, they present a more artistic appearance. The first CFST arch bridge in China, Wanchang Bridge, with a main span of 115 m, was completed in 1990 (Chen et al. 2004). From then on, numerous CFST bridges have been built. Up to March 2005, 229 CFST arch bridges, with a span over 50 m, have been built or are under construction (Chen 2007a,b). 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 CFST arch bridges are analyzed based on the most important factors, including type, span erection method, geometric parameters, and materials. The aim of this paper is to provide a comprehensive reference of CFST bridges for the bridge engineers and builders. In the following analyses, the span of all adopted bridges is equal to or longer than 100 m.

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) (Fig. 1). It should be noted that for the deck and half-through arch with thrust, the span is clear span; where as for the no-thrust arch, the span is from the center line of pier to pier.

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. Until now, the Fengjie Meixihe Bridge has the longest span of 288 m (Fig. 2), but the Zhijinghe Bridge, under construction with a main span of 430 m, will break this span record (Chen, 2004a, 2007b). However, only 8% of investigated CFST arch bridges are deck bridges, most of them are half-through and through bridges.

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%) 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 of 460 m is kept by Wushan Yangtze River Bridge (Fig. 3), which is also the record for the longest CFST arch bridge in the world (Mu et al. 2007).

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 bridge will increase with the span of the bridge because the horizontal reactions are not avail-

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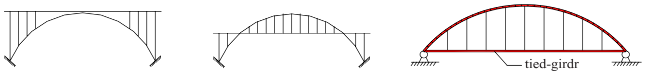
Table 1. CFST Arch Bridges (Span > 200 m)

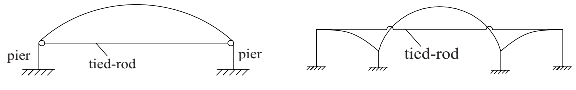
Bridge name	Completion year	Main span (m)	Type	Construction method
Enshi Nannidu Bridge in Hubei	2002	220	Deck (true) arch	Cantilever
Beipanjiang Railway Bridge in Guizhou	2001	236	Deck (true) arch	Swing
No. 1 Qiandaohu Bridge in Zhejiang	2005	252	Deck (true) arch	Cantilever
Meixi Bridge in Fengjie,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

able until the tied girder is completed. Generally, such bridge type is a good option for a midspan bridge, say from 50 to 150 m.

The longest span of this type of bridge is found in Moon Island Bridge in Liaoning Province with a span of 202 m, where as the Second Yellow River Highway Bridge in Zhengzhou, completed in 2004, has the largest scale of this bridge type. There are two separate bridges in the road section, and each bridge carries four lanes in each direction and has a net width of 19.484 m. The main bridge is composed of eight spans of CFST tied arch bridges with each span of 100 m, as shown in Fig. 4 (Zhang et al. 2004).



(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

Fig. 1. Types of CFST arch bridges

Double-deck bridge also appears in the CFST arch bridge, e.g., the Qiangjiang No. 4 Bridge, with a span arrangement of 2 × 85 m + 190 m + 5 × 85 m + 190 m + 2 × 85 m, as shown in Fig. 5.

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 method. For small span bridge, the piers can stand small thrust forces caused by light self-weight of steel tubular arch rib and for a large span bridge, temporary tied

Fig. 2. Fengjie Meixihe Bridge (Reprinted with permission from Mr. Tingmin Mou)

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Fig. 3. Wushan Yangtze River Bridge

bars can be used. The construction of this type of bridge is easier than that of the 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 prestressed 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 cracks which appear in reinforced concrete piers during construction due to in-span horizontal forces caused by prestressing of tied bars and out-span thrusts from the arches, construction monitoring based on careful calculations according to the construction stages is necessary (Yang and Chen 2007).

In through arch bridge, no side span is required as in a 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. The span of this type of bridge is generally 80–150 m. The longest span of such bridge type is 280 m in No. 3 Hanjiang Bridge (Fig. 6) in Wuhan City. Most of the CFST through rigid-frame tied arch has single span; some of them, however, have two or even more spans with separate tied bars for each span.

Fig. 4. Second Yellow River Highway Bridge

Fig. 5. Hang-zhou Qian-jiang No. 4 Bridge

Fig. 6. No. 3 Hanjiang Bridge (Reprinted with permission from Ms. Ye Sheng)

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 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. This bridge type has a large spanning capacity. There are nine of such bridges with a span above 200 m. The longest two bridges of this type are the Maochaojie Bridge, with a main span of 368 m and completed in 2006, and the Yajisha Bridge, with a main span of 360 m and completed in 2000 (Fig. 7). The latter was erected by combining vertical and horizontal swing method.

In CFST fly-bird-type arch bridge, it is 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 the central span and RC deck structure is used in side spans. Further, 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 the main span. The key issue in design of such bridges is that

Fig. 7. Yajisha Bridge in Guang-zhou

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Table 2. Quantity of Each Type of CFST Arch

Type	Quantity	Percentage (%)
Deck (true) arch	11	8
Half-through (true) arch	62	47
Fly-bird-type arch	24	18
Through deck-stiffened arch	18	14
Through rigid frame tied arch	16	13
Total	131	100

under dead load the central span should act as a fixed arch, whereas the side spans act as half-arches rather than cantilever girder (Chen et al. 2006).

All bridges in Table 1 are typical CFST arch bridges in China which have spans greater than 200 m. The quantity of each type of CFST arch bridge with a span no less than 100 m is shown in Table 2. From Table 2, it can be seen that the half-through arch and through arch are the main types of CFST bridges in China. By contraries, the majority of long-span concrete arch bridges (88%) are deck bridges, and only 12% are through and half-through bridges (Chen et al. 2007).

Spans of CFST Arch Bridge

The spans of CFST arch bridges shown in Fig. 8 have been altered since 1990. It can be seen that before 1995 there were few CFST arch bridges with spans greater than 100 m. From then on, with the advanced analysis and new construction technology, the spans and the quantity of CFST arch bridges have both increased. The following are some typical bridges at different time periods: Wangcang Donghe Bridge, with a span of 115 m, was the first one completed in 1990. Nanhai Sanshanxi Bridge, with a span of 200 m, was completed in 1995. Yajisha Bridge of 360 m span was built in 2000. Up to now, the Wushan Yangtze River Bridge, completed in 2005 and shown in Fig. 3, has been the bridge with the longest span (460 m). Presently, corresponding to the five aforementioned types of CFST arch bridges, the span records are, respectively, 288 m for the deck arch (Fengjie Meixihe Bridge), 460 m for the half-through arch with thrust (Wushan Yangtze River Bridge), 368 m for the fly-bird-type arch (Maochaojie Bridge), 202 m for through arch of arch-girder combined system (Moon Island Bridge), and 280 m for through rigid frame tied arch (No. 3 Hanjiang Bridge).

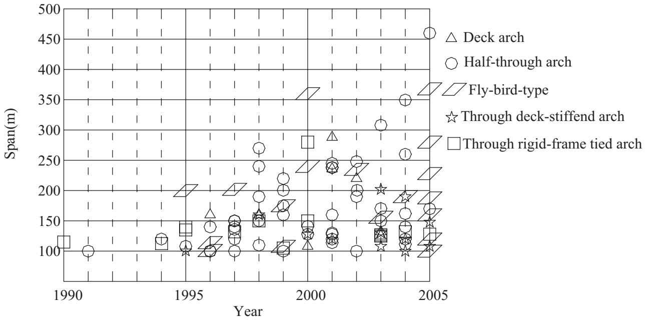

Fig. 8. Variance of CFST arch span with time

Table 3. Quantity of CFST Arch Bridges Based on Different Construction Methods

Bridge type	Construction method: Cantilever	Swing	Scaffolding	Others	Total
Deck (true) arch	5	3	1	1	10
Half-through (true) arch	39	4	3		46
Fly-bird-type arch	12	4	3		19
Through deck-stiffened arch	4	2	6	1	13
Through rigid frame tied arch	9	2	3	1	15
Total	69	15	16	3	103

Erection Method of CFST Arch

It is well known that the fundamental problem in large arch bridges is the construction, because the arch does not function as an integrated arch during the construction until it is completely closed. 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 the 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. The cantilever method, swing method, and scaffolding method are three major erection methods for the construction of CFST arch bridges (Chen 2005). For those bridges for which the construction methods are known, the quantity of CFST arch bridges built by different erection methods is shown in Table 3. The relationship between construction methods and spans of arches is shown in Fig. 9.

From Table 3 and Fig. 9, it can be found that for concrete arch bridges, the cantilever method and swing method are more popular than the scaffolding method in the construction of CFST arch bridges. However, these two construction methods have been improved with the development of CFST arch bridges.

In the 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 the arch ring can be controlled by adjustment of the internal force of the fasten cables more easily than before. This method was adopted by 67% of the bridges. In these eight bridges with a span no less than 300 m,

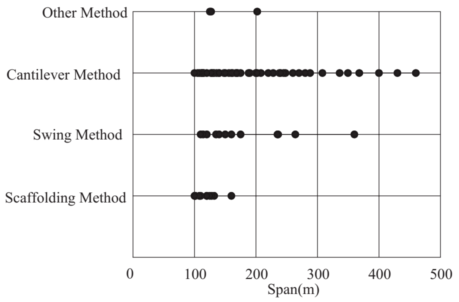

Fig. 9. Relationship between construction methods and spans

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Fig. 10. Erection procedure by cantilever method (Wushan Yangtze River Bridge)

seven used this method, including the world's largest bridge, the Wushan Yangtze River Bridge with a 460 m span (Fig. 10) (Mu et al. 2007). It is evident that the cantilever method has the most potential in construction of CFST arch bridges due to its wide range of application, especially for long span bridges.

Another main erection method used in CFST arch bridges is the swing method, which has been rapidly developed in recent years in China. This method includes the 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. The swing method is not used as prevalently as the cantilever method. Statistics show that about 15% adopted this construction procedure.

In the vertical swing method, the semiarch ribs are fabricated in low position and hoisted up into design level. This method is different from the one used in other countries where half-arches are built on the springs vertical and then rotated down on their lower end to close at the crown (Troyano 2004). This up-lift vertical swing method is mainly used in CFST arch bridge, for the tubular structure is much lighter than concrete arch ribs. Among those investigated bridges, Liantuo Bridge, Jing-hang Canal Bridge, and Wuzhou Guijiang Bridge are constructed by the vertical swing method.

The first two CFST arch bridges constructed by the horizontal swing method are the Huangbaihe Bridge and Xialaoxi Bridge near the Three Gorge Dam (Duan and Yan 2001). The first CFST arch bridge in railway—the Beipanjiang Railway Bridge opened in 2001—was also constructed by this method (Ma et al. 2001). Based on jakes pushing system as the drawing power, the rotated capacity in the swing method is much greater than that by using windlass pulling system as mentioned before in concrete arch bridges. The arch span can be much longer because the self-weight of the steel tubular arch rib is much lighter than that of the concrete arch.

A new method by combining the vertical and horizontal swing method has been developed in CFST arch bridges, such as Wenfenglu Bridge and Yajisha Bridge. For the Yajisha Bridge, as shown in Fig. 11, the half-arch of the main span and cantilever half-arch near it composed a rotation unit (Zheng et al. 2000). First, the cantilever half-arch was erected and the main half-arch was fabricated along the riverbank. Then, the main half-arch was rotated vertically into the 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 1 m long rib segment. The total weight of each horizontal rotating body is 136,850 kN (Zhang and Chen 2004).

It can be seen from Fig. 9 that the scaffolding method is mainly used for the bridges with a shorter span, most of which are through deck-stiffened arch bridge, due to their short span and difficulty in applying other no-scaffolding methods. One advantage of the CFST arch bridge is the convenience construction procedure: the hollow steel arch rib could be erected first, and then the CFST arch ribs can be formed by pouring concrete into the tubes. As a result, it is easy to use the no-scaffolding construction method for the erection of hollow steel tube arch rib with less self-weight. So for other types of CFST arch bridges, the scaffolding method was seldom adopted and, if adopted, it is only for the bridges with short span.

For different construction conditions, various combined methods can be adopted. For example, the two side segments of Moon Island Bridge were erected by using the vertical swing method first. Then, the middle segment was vertically lifted up by a hoist. For middle or shorter span, the construction procedure has more varieties. Jing-hang Canal Bridge in Xiyi Expressway with a span of 90 m was built by dividing the rib into two segments. The rib of the bridge was located by floating pontoon and then lifted. The rib of the Kuokou Bridge in Fujian was erected by floating into position integrally (Chen 2007a).

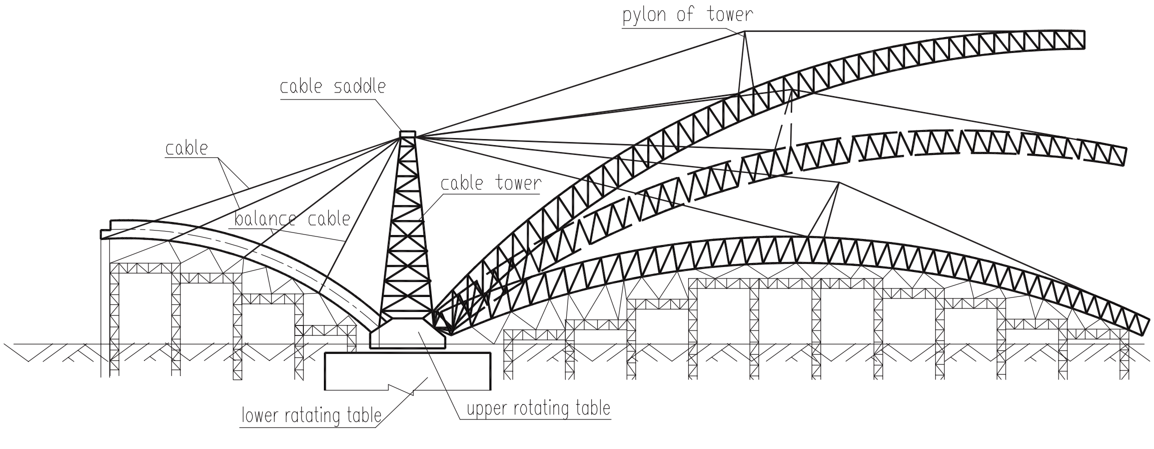

Fig. 11. Vertical swing procedure (Yajisha Bridge)

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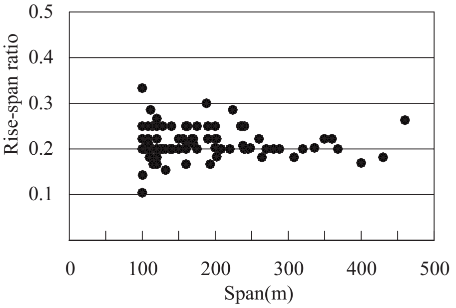

Fig. 12. Relationship between span and rise–span ratio

Geometric Parametric Analyses

Rise–Span Ratio

Rise–span ratio is an important parameter for an arch. The lower rise–span ratio means the greater thrust and axial force of the arch. The arch is suitable for bearing axial force, but it will lead to more redundant force for statically indeterminate structure. On the other hand, the greater thrust will result in the increasing of substructure cost. The rise–span ratio adopted depends on several factors such as axial line shape, landform, etc. It can be seen from Fig. 12 that there is little relationship between span and rise–span ratio of arches. For bridges with shorter span, the rise–span ratio can be adopted in a wider range. But for longer span bridges, the rise–span ratio is adopted near 1/5. Fig. 13 shows that most bridges have a rise–span ratio between 1/4–1/5 in which 1/5 is the most common value. In all investigated cases, most of the bridges with rise–span ratio greater than 1/4 or less than 1/5.5 are scenery bridges.

Longitudinal Shape of Rib

In order to exploit the particular advantage of concrete filled steel tube structure, the longitudinal neutral axis of an arch should be close to the compression line. The statistical data of longitudinal shapes adopted in CFST arch bridges are shown in Table 4 and Fig. 14. It can be seen that the catenary function is adopted for the longitudinal shape of all deck arches and catenary or parabola is adopted for most through and half-through arches. The CFST arch bridges with catenary longitudinal shape are around 68%. Spine or arc is rarely used for longitudinal shape of rib. In the application of the catenary longitudinal shape, the variation of catenary coefficient, which represents the character of catenary, will affect the moment generated in the arch rib. The relationship between catenary coefficient and span is shown in Fig. 15. From Fig. 15, there is no correlation between them. The values of catenary coefficients are mostly between 1.0 and 1.7.

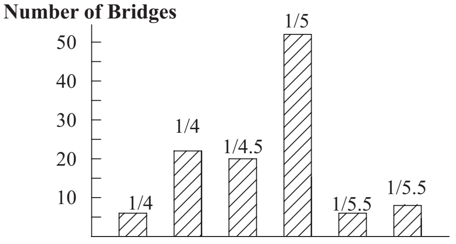

Fig. 13. Relationship between quantity and rise–span ratio

Table 4. Longitudinal Shapes of CFST Arch Bridges

Longitudinal shape	Catenary	Parabola	Others	Total
Deck (true) arch	10			10
Half-through (true) arch	33	15	2	50
Fly-bird-type arch	13	5	2	20
Through deck-stiffened arch	4	10		14
Through rigid-framed tied arch	14	1		15
Total	74	31	4	119

Cross Section of Rib

Based on the different cross sections of arch ribs, there are singular tube arches, dumbbell type arches, and multitube type arches (also called truss type), as shown in Fig. 16, as well as other shapes.

The quantity of cross sections of arch ribs is shown in Fig. 17. In the 119 CFST arch bridges investigated, truss cross section represents 55% and dumbbell cross section 35%. The remaining 10% is for single-tube and others. In the 65 bridges with truss cross sections, 26 bridges, more than one-third, adopt transverse dumbbell sections, in which the tubes in the upper or bottom level of the arch rib are connected by two slabs and the space between the two slabs are filled with concrete. However, this cross section should be applied cautiously because of the complicated mechani-

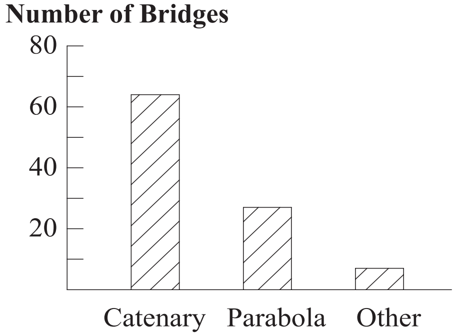

Fig. 14. Bridge quantity in different longitudinal shapes

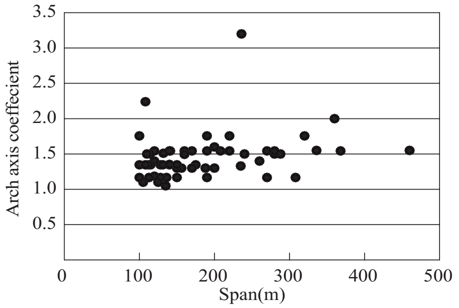

Fig. 15. Relationship between catenary coefficient and span

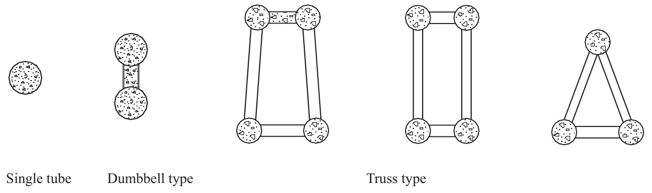

Fig. 16. Cross-sectional types

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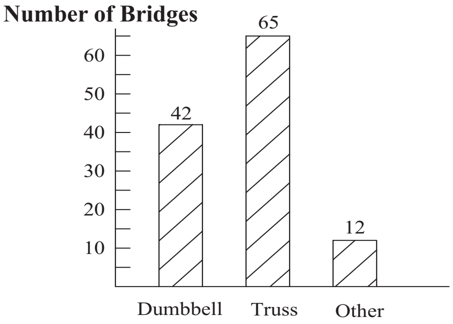


Fig. 17. Cross sections of arch rib

cal behavior of its web and some other complicacies. The relationship between the shapes of cross sections and spans is shown in Fig. 18. It indicates that truss section is adopted most widely and is suitable for long span bridges. In bridges with dumbbell sections, the longest span is only 160 m.

As a bearing structure, the height of the cross section of CFST arch rib is a primary parameter in design. It is related to span, design traffic load class, etc.

For designing highway bridges in China, loads are stipulated in the "General Code for Design of Highway Bridges and Culverts" (MOC 2004c). The up-to-date code JTG D60-2004 (MOC 2004c) was published to supersede the primary code JTJ 021-89 (MOC 1989). In JTJ 021-89, four classes of truck train loads, i.e., Vehicle-over 20, Vehicle-20, Vehicle-15, and Vehicle-10, were used as the standard traffic live loads. The number in the class name indicates the gross weight of a truck, e.g., the truck weighs approximately 20 t (200 kN) in Vehicle-20. Fig. 19 shows the truck train load of Vehicle-over 20 and Vehicle-20 in JTJ 021-89 (MOC 1989). In JTG D60-2004 (MOC 2004c), the system of truck train loadings is superseded by equivalent lane loading, which consists of a uniform load accompanied by a concentrated load. Equivalent lane loadings, Highway-I and Highway-II (as shown in Fig. 20), are adopted to replace Vehicle-over 20, Vehicle-20, and Vehicle-15. Vehicle-10 is abolished. However, most of the CFST arch bridges analyzed in this paper were designed according to truck train loads Vehicle-over 20 and Vehicle-20 by the primary code—JTJ 021-89 (MOC 1989). Therefore, Fig. 21 gives the relationship between the ratio of span to height of cross section (span–height ratio) and span of arch bridges under design load of Vehicle-20 and Vehicle-over 20.

The height of cross section of these bridges is identical from spring to crown of arch rib. It can be concluded that the span–height ratio of the CFST arch bridges is between 40 and 60. This relationship for CFST arch bridges between span and span–height ratio of various heights is shown in Fig. 22. In these bridges, the span–height ratio is from 40 to 100 with the design load of Vehicle-20 and from 20 to 80 with Vehicle-over 20.

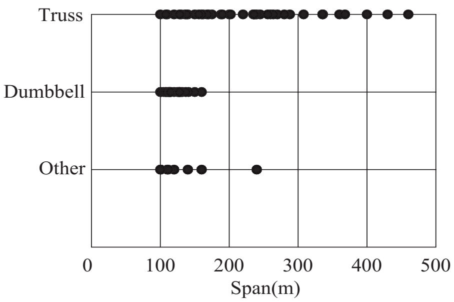
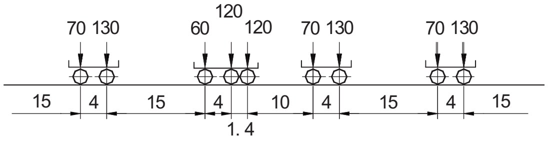
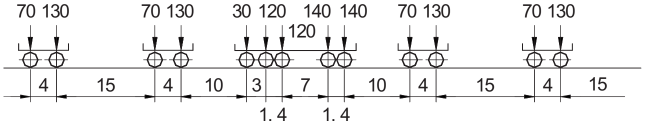


Fig. 18. Relationship between cross sections and spans



(a) Vehicle-20



(b) Vehicle-over 20

Fig. 19. Train load of Vehicle-20 and Vehicle-over 20 in China JTJ 021-89 (MOC 1989)

Materials of Arch Rib

The main mechanical properties of the commonly used structural steel Q_{235} and Q_{345} in Chinese standards GB 50017-2003 (Ministry of Construction 2003) are given in Table 5. By comparing with the steel properties of the American Society for Testing and Materials (ASTM) it is recognized that the Q_{235} steel is essentially identical to the ASTM A36 steel, whereas the Q_{345} steel is similar to the ASTM A572 Grade 50 steel.

The properties of steel and concrete are important for the mechanical behavior of the CFST structures. The Q_{345} steel is adopted in 80% of the investigated bridges and the Q_{235} steel in 20%. To achieve a better and more economical performance of CFST structures, the grade of concrete inside should be neither too low nor too high. Superimposed stresses method is used in the design of CFST arch bridges and the design result is always controlled by the stress of steel tube with the low stress of core concrete. If the grade of concrete is too high, it will not only lead to construction difficulty but also decrease the economic value of CFST structures. On the other hand, if the grade of concrete is too low, the advantage of ultimate carrying capacity of CFST structure will be undermined.

The statistic data of concrete grade applied in CFST arch bridges are shown in Fig. 23. It indicates that with the development of construction techniques, the concrete grade is adopted from C40 to C50, which is used most widely for bridges built after 1995. C30 concrete was only used by four bridges built in the early 1990s. C60 was only adopted in the Wushan Yangtze River Bridge and Fengjie Meixi Bridge. Therefore, the match of steel and concrete strengths is important for the mechanical be-

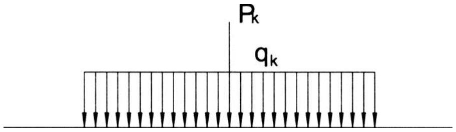


Fig. 20. Lane load in China JTG D60-2004 (MOC 2004c)

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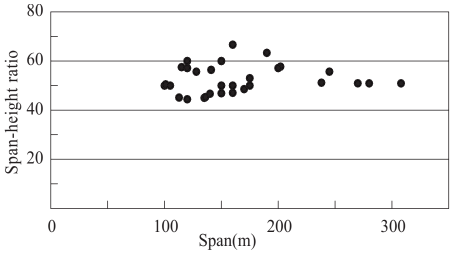
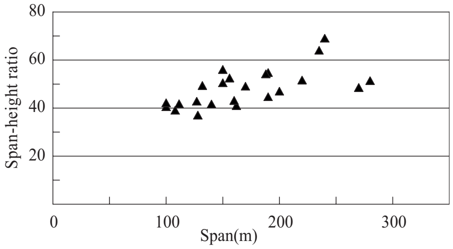


(a) Load of Vehicle-20



(b) Load of Vehicle-over 20

Fig. 21. Relationship between span–height ratio and span

havior of CFST arch bridges. In general, for CFST arch ribs, concrete C30 and C40 can be used to match the Q_{235} steel and C40 and C50 are appropriate for the Q_{345} steel.

Key Issues on Design Calculation

Check for Strength

Almost all of the CFST arch bridges are highway bridges, except one or two of them that are railway bridges, such as the Beipanjiang Bridge in Guizhou Province (Ma et al. 2001). Though many CFST arch bridges have been built, there is no special design specification for highway CFST arch bridges in China. Further, there is no design specification for highway steel–concrete composite bridges because only a few such bridges have been built.

For highway bridges in China, there are serial design codes issued by the Ministry of Communications of the People's Republic of China. Besides the "General Code of Highway Bridges and Culverts" (JTG D60-2004) mentioned before, others are the "Code for Design Highway Masonry Bridges and Culverts" (JTG D61-2004) (MOC 2004a), "Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts" (JTG D62-2004) (MOC 2004b), "Code for Design of Ground Base and Foundation of Highway Bridges and Culverts" (JTG D63-2007) (MOC 2007), and "Code for Design of Highway Steel and Timber Bridges and Culverts" (JTJ 024-86) (MOC 1985). Design methods for masonry, reinforced concrete, and prestressed concrete bridges are based on inelastic behavior, similar to the load and resistance factor design (LRFD) method in the United States; and the allowable stress design (ASD) method is used for steel and timber bridges.

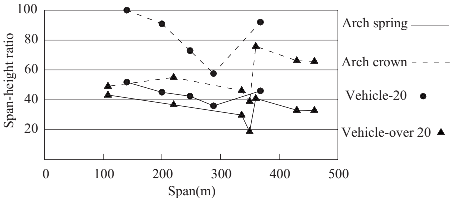


Fig. 22. Relationship between span and span–height ratio of various heights

Table 5. Mechanical Properties of Steel Q_{235} and Q_{345} in Chinese Standards

Designation	Thickness or diameter (mm)	Min. f_y (MPa)	Design value of strength f (MPa)	Design value of shear strength f_v (MPa)
Q_{235}	≤16	235	215	125
	>16–40	225	205	120
	>40–60	215	200	115
Q_{345}	≤16	345	310	180
	>16–35	325	295	170
	>35–50	295	265	155

Note: f=design value of strength of compression, tension, and flexure.

Therefore, in designing CFST arch bridges, some engineers consider them as reinforced concrete arch bridges and use the LRFD method, where as others treat them as steel bridges and use the ASD method.

A "Design Specification for Highway CFST Arch Bridges" has been edited and submitted to the Ministry of Communications of the People's Republic of China for approval. In this specification, the LRFD method is adopted, consistent with the design method for reinforced concrete and prestressed concrete bridges. In this method, the ultimate load-carrying capacity of the CFST member can be calculated by design specification of CFST structures, such as the "Specification for Design and Construction of Concrete Filled Steel Tubular Structures" (CECS 28:90) (CSC 1990). Experimental studies on the CFST model arches and nonlinear FEM analyses have been carried out and a simplified method to estimate the ultimate load-carrying capacity of CFST arch has been proposed (Chen 2003; Chen et al. 2004; Chen 2007a; Wei 2007). However, the influences of initial stress, shrinkage, and creep of concrete to the ultimate load-carrying capacity of CFST arch should be further investigated in the future (Chen 2004b, 2007a).

However, the "Design Specification for Highway CFST Arch Bridges" has not yet been published. In order to make the CFST arch bridges more reliable, most of the bridge designers prefer to adopt the ASD method for safety reasons, even though it maybe too conservative. Generally speaking, the steel tube of the arch rib in the CFST arch bridge will be very thick by this design method.

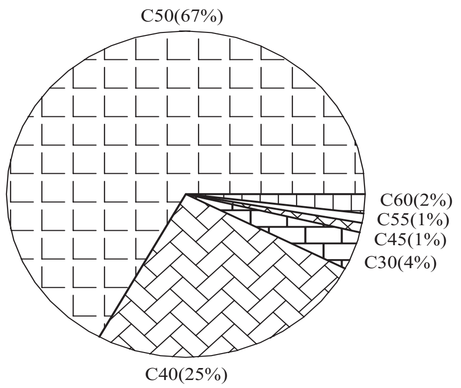


Fig. 23. Concrete strength used in arch rib

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Table 6. Suggestion on Stiffness Calculation of CFST Arch Ribs

	Inner forces and stresses		Elastic buckling and deformation	
Cross section	Compression α_1	Flexural α_2	Compression α_1	Flexural α_2
Single tube	1.0	1.0	0.4	0.4
Dumbbell shape	1.0	1.0	0.4	0.4
Truss	0.4	1.0	0.4	0.4

Stiffness of Arch Rib

CFST is a composite member made of steel and concrete. The calculation methods of its cross-sectional stiffness differ from code to code. Generally speaking, the compressive and flexural stiffness can be expressed by

$$EA = E_S A_S + \alpha_1 E_C A_C$$

$$EI = E_S I_S + \alpha_2 E_C I_C \tag{1}$$

where EA and EI=compressive and flexural stiffness of CFST cross section, respectively; E_s and E_c=elastic moduli of steel and concrete, respectively; A_s and A_c=areas of steel tube and filled concrete, respectively; I_s and I_c=moments of inertia of steel tube and filled concrete, respectively; and α_1 and α_2=coefficients to reflect the weakened infection of concrete cracking to compressive and flexural stiffness, respectively.

α_1 and α_2 vary from 0.2 to 1.0 in various codes (Mitani et al. 1997; Chen 2007a). It is suggested that different coefficients α_1 and α_2 be used to calculate the stiffness for different cross sections and for different calculation purposes, as listed in Table 6 (Wang 2007).

In order to indicate the improvement in the stiffness of the arch ribs using concrete-filled members as opposed to simple tubular sections, three typical CFST arch bridges with rib sections of single tube, dumbbell shape, and truss are selected as case studies. Section stiffnesses calculated by the method suggested in this paper [Eq. (1) and Table 6] are listed in Table 7. Table 7 clearly indicates that concrete filled steel tubes significantly improve the stiffness of the arch ribs.

The three cases are as follows:

Case 1. Qunyi Bridge with single tube rib. It is a half-through CFST arch bridge with a clear span of 46.00 m. The bridge has two parallel arch ribs, each of which is a single Q_{235} steel tube of 800 mm diameter and 14 mm thickness, filled with C30 concrete (Wei et al. 2004).

Case 2. Xintongshan Bridge with dumbbell shape rib. It is a rigid-framed tied arch with three spans of 51 m+75 m+51 m. The arch ribs are CFST dumbbell-shaped sections. In central span, the arch rib with a height of 2.0 m comprises two Q_{345} steel tubes with a diameter of 800 mm and thickness of 12 mm as well as two web slabs of 12 mm thickness, filled with C40 concrete in the two tubes (Wang 2007).

Case 3. Shi-tan-xi Bridge with truss rib. It is a half-through CFST truss arch bridge with a clear span of 136 m. The arch rib consists of four chords. Each is a Q_{345} steel tube of 550 mm diameter with 8 mm thickness wall, filled with C40 concrete. The four-chorded CFST members are connected with web steel tubes of 219 mm diameter and transverse steel tubes of 400 mm diameter. The width of the rib is 1.6 m and the height is 3.0 m (Chen and Chen 2003).

Joint Strength and Fatigue

As mentioned before, truss ribs are usually adopted for long span CFST arch bridges. The truss ribs consist of CFST chords and hollow steel tube web members, welding together. It is well known that the strengths of both one-time loading and repeated loading (fatigue) are dominated in steel tubular truss bridge structure. Experimental studies on CFST truss models and CFST tubular joints indicated that their failure models under one-time loading or repeated loading (fatigue) were similar to those of the hollow steel tubular truss models or joints. But the filled concrete would improve their strength and fatigue strength significantly because the stress and stress concentration factor in steel tube joint are cut down defectively (Chen and Huang 2007; Gao 2003; Ai 2005). Taking the world's longest CFST arch bridge, the Wushan Yangtze River Bridge, as a case study, experimental research and finite element analysis results indicated that the fatigue intensity was not dominant in the design (Gao 2003). Estimation method for fatigue strength of CFST joints was presented by modifying the method for hollow steel tubular joints (Gao 2003; Ai 2005; Fan and Zhang 2007).

Conclusions

The CFST structure has been applied prevalently and rapidly to arch bridges since 1990. Based on the rising demand of transportation in developing China, CFST arch bridges have a strong potential in bridge engineering. The main advantages of CFST arch bridges are as follows:

1. Arch bridge is a structure which resists compression predominantly. For CFST, an interactive force under axial compression confines the concrete core, which enhances its load-carrying capacity and improves its ductility. Moreover,

Table 7. Stiffness Calculation of Three Examples of CFST Arch Ribs

			Compressive stiffness (kN)		Flexural stiffness (kN m^2)	
Example	Cross section	Purpose	CFST	Steel tube	CFST	Steel tube
Qunyi Bridge	Single tube	1	2.126E+07	7.221E+06	1.081E+06	5.579E+05
		2	1.284E+07	7.221E+06	7.670E+06	5.579E+05
Xintongshan Bridge	Dumbbell shape	1	5.348E+07	1.535E+07	1.782E+07	5.474E+06
		2	3.060E+07	1.535E+07	1.041E+07	5.474E+06
Shi-tan-xi Bridge	Truss	1	2.302E+07	1.138E+07	9.202E+07	2.603E+07
		2	2.302E+07	1.138E+07	5.243E+07	2.603E+07

Note: Purpose 1 means the stiffness is used for calculating inner forces and stresses and Purpose 2 means the stiffness is used for calculating elastic buckling and deformation.

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the steel tube reinforces the concrete to resist tension stresses. The strength of CFST is stronger than that of masonry or reinforced concrete, thus allowing the span of the CFST arch bridge to be longer.

2. Concrete filled in steel tube will delay or completely prevent the steel tube from local buckling; therefore, steel tube in CFST arch rib can be thinner than that in hollow steel tubular arch rib. CFST can provide larger stiffness than steel arch. It will decrease the deformation and increase the whole buckling critical load.
3. The filled concrete in chords will enhance the joint strength and fatigue strength in CFST truss arch ribs.
4. In the construction of CFST arch, it is easier to erect a steel tubular arch than to erect a concrete or a steel arch with same span because its self-weight is light. After its closure, the steel tube serves as a form for casting the concrete. Therefore, construction cost and time of CFST arch bridge will be reduced and the arch span can be longer than that of concrete arch bridges.
5. Various types of CFST arch bridges can suit different site conditions, environments, and demands. Generally speaking, they present a more artistic appearance and are appreciated by engineers and citizens.

In China, the analysis of design theory, construction techniques, and structure detail design specifications have become significant areas and have been funded by government agencies and other funding.

There are only a few CFST arch bridges in the United States, such as the New Damen Avenue Bridge in Chicago with a main of 90 m (Cassity et al. 1999). It is a half-through true arch bridge with two single tube ribs and no bracing member. The ribs are only filled with concrete in spring areas and it is considered as a steel bridge in design.

Among the five main CFST arch bridge types, through rigid-frame tied arch and fly-bird-type arch (half-through tied rigid-frame arch) are not commonly applied in steel or concrete arch bridges. The other three common types of the CFST arch bridges, deck true arch bridges, half-through true arch bridges, and through deck-stiffened arch bridges, are recommended at the advent of the application of CFST arch bridges. In this paper, as a preliminary study, fundamental information of CFST arch bridges proposed will serve as a valuable reference for practicing engineers, construction managers, and contractors in bridge engineering.

References

Ai, Z. N. (2005). "Research on fatigue life of tubular joints used in concrete-filled steel tube arch bridges." Master's thesis, Southwest Jiaotong Univ., Chengdu, China (in Chinese).

Cassity, P., Furrer, M., and Price, K. (1999). "Synthesizing form and function." *Modern steel construction*, Vol. 12, AISC, Chicago, 30–37.

Chen, B. C. (2003). "Nonlinear characteristics and ultimate load-carrying capacity of concrete filled tubular arch." Ph.D. thesis, Kyushu Univ., Fukuoka, Japan.

Chen, B. C. (2004a). *Examples of concrete filled steel tubular arch bridges (No. 1)*, China Communications Press, Beijing (in Chinese).

Chen, B. C. (2004b). "Recent advances on design theory of CFST arch bridges." *Int. Assoc. for Bridge and Structural Engineering Symp. on Metropolitan Habitats and Infrastructure*, IABSE, Shanghai, China, Vol. 88, 244–245.

Chen, B. C. (2005). "State-of-the-art of the development of arch bridges in China." *Proc., 4th Int. Conf. on New Dimensions of Bridge*, Fuzhou, China (Keynote paper), 13–24.

Chen, B. C. (2007a). *Concrete filled steel tube arch bridges*, 2nd Ed., China Communications Press, Beijing (in Chinese).

Chen, B. C. (2007b). "An overview of concrete and CFST arch bridges in China." *Proc., 5th Int. Conf. on Arch Bridge*, Madeira, Portugal, (invited lecture), Multicomp, Lda., 29–44.

Chen, B. C., and Chen, Y. J. (2003). "Nonlinear finite element analysis of concrete-filled steel tubular truss arch." *Proc., Int. Conf. Advances in Concrete and Structure (ICACS)*, China Science Press House, Xuzhou, China, 1367–1372.

Chen, B. C., Chen, Y. J., Qin, Z. B., and Hikosaka, H. (2004). "Application of concrete filled steel tubular arch bridges and study on ultimate load-carrying capacity." *Proc., 4th Int. Conf. on Arch Bridge*, CIMNE, Barcelona, Spain, 38–52.

Chen, B. C., Gao, J., and Ye, L. (2007). "Long-span concrete arch bridges in China." *Proc., fib Symp. on Concrete Structures—Stimulators of Development*, SECON HDGK, Dubronvnik, Croatia, 69–76.

Chen, B. C., Gao, J., and Zheng, H. Y. (2006). "Studies on behaviors of CFST 'fly-bird-type' arch bridge." *Proc., Int. Conf. on Bridges*, SECON HDGK, Dubrovnik, Croatia, 205–212.

Chen, B. C., and Huang, W. J. (2007). "Experimental research on ultimate load-carrying capacity of circular section truss girders." *J. Build. Struct.*, 28(3), 31–36 (in Chinese).

Construction Standard Committee (CSC) of China. (1990). *Specification for design and construction of concrete filled steel tubular structures. CECS 28:90*, China Planning Press, Beijing (in Chinese).

Duan, M. G., and Yan, G. R. (2001). "Rotation construction of two concrete-filled steel tube arch bridges (CFST)." *Proc., 3rd Int. Conf. on Arch Bridges*, Press de I'ecole nationale des Pnots et chausses, Paris, France, 839–844.

Fan, W. L., and Zhang, J. Y. (2007). "Experimental research on fatigue of tubular-plate joints for concrete-filled steel tube arch bridges." *Proc., 5th Int. Conf. on Arch Bridge*, 359–364.

Gao, P. (2003). "Test and research on bearing stress of tubular joints used in concrete-filled steel tube arch bridges." Master thesis, Southwest Jiaotong Univ., Chengdu, China (in Chinese).

Ma, T. L., Xu, Y., He, T., and Chen, K. (2001). "China's first concrete-filled steel tube (CFST) arch railway bridge: The Beipanjiang long span bridge on the Shuicheng-Baiguo line." *Proc., 3rd Int. Conf. on Arch Bridges*, Press de I'ecole nationale des Pnots et chausses, Paris, France, 877–882.

Ministry of Communication (MOC) of China. (1985). "Code for design of highway steel and timber bridges and culverts." *JTJ 024-86*, Beijing (in Chinese).

Ministry of Communication (MOC) of China. (1989). "General code for design of highway bridges and culverts." *JTJ 021-89*, Beijing (in Chinese).

Ministry of Communication (MOC) of China. (2004a). "Code for design of highway bridges and culverts." *JTG D61-2004*, Beijing (in Chinese).

Ministry of Communication (MOC) of China. (2004b). "Code for design of highway reinforced concrete and prestressed concrete bridges and culverts." *JTG D62-2004*, Beijing (in Chinese).

Ministry of Communication (MOC) of China. (2004c). "General code for design of highway bridges and culverts." *JTG D60-2004*, Beijing (in Chinese).

Ministry of Communication (MOC) of China. (2007). "Code for design of ground base and foundation of highway bridges and culverts." *JTG D63-2007*, Beijing, China (in Chinese).

Ministry of Construction of China. (2003). "Code for design of steel structures." *GB 50017*, 1st Ed., Beijing (in Chinese).

Mitani, I., Matsui, C., Kawano, A., and Tsuda, K. (1997). "Comparison of several codes for concrete filled tubular beam-columns." *Proc., Int. Association for Cooperation and Research of Steel-Concrete Composite Structures (ASCCS) Seminar*, Innsbruck, 125–134.

Mu, T. M., Fan, B. K., Zheng, X. F., Zheng, Y. H., and Xie, B. Z. (2007).

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"Wuxia Yangtze river bridge in Wushan, China." *Proc., 5th Int. Conf. on Arch Bridge*, Multicomp, Lda., Madeira, Portugal, 911–918.

Troyano, L. F. (2004). "Procedures for the construction of large concrete arch." *Proc., 4th Int. Conf. on Arch Bridge*, CIMNE, Barcelona, Spain, 53–63.

Wang, J. P. (2007). "Studies on designed stiffness value of CFST arch ribs." Master thesis, Fuzhou Univ., Fuzhou, China (in Chinese).

Wei, J. G. (2007). "Research of in-plane nonlinear critical loads for tubular arches." Ph.D. thesis, Fuzhou Univ., Fuzhou, China (in Chinese).

Wei, J. G., Zhao, L. Q., Chen, B. C., and Peng, G. H. (2004). "The influence of rigidity value of concrete filled steel tubular (single tube) arch rib to static calculation results." *Proc., 4th Int. Conf. on Arch Bridge*, 726–732.

Yang, Y. L., and Chen, B. C. (2007). "Rigid-frame tied through arch bridge with concrete filled steel tubular ribs." *Proc., 5th Int. Conf. on Arch Bridge*, 863–868.

Zhang, L. Y., and Chen, J. (2004). "Application and development of the rotation construction method of arch bridges in China." *Proc., 4th Int. Conf. on Arch Bridge*, CIMNE, Barcelona, Spain, 883–888.

Zhang, W. Z., Chen, B. C., and Huang, W. J. (2004). "Design of the second highway bridge over Yellow River in Zhengzhou, China." *Proc., 4th Int. Conf. on Arch Bridge*, CIMNE, Barcelona, Spain, 531–537.

Zheng, Z. F., Chen, B. C., and Wu, Q. X. (2000). "Recent development of CFST arch bridge in China." *Proc., 6th ASCCS Int. Conf. on Composite and Hybrid Structures*, 205–212.

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