State-of-the-art of steel arch bridges in China

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ABSTRACT: The history of steel arch bridge construction is reviewed briefly in this paper; then most of steel arch bridges in China are investigated and analyzed with respect to their numbers, spans, structure styles, rib types, construction methods, and development tendency. After the nation-wide survey, it is found that most of these bridges are half-through or through box arch bridges spanning from 100m to 150m, the common arch axis of which have the line shape of parabola with the ratios of rise to span varying from 1/4 to 1/5. Furthermore, for those bridges with relatively larger spans, the cantilever erection method is mainly used while the others with medium or small span always take the bracing method.

1 INTRODUCTION

China has a long history of building arch bridges. According to the materials used in the main structure, arch bridges can be classified into masonry arch bridge, metal arch bridge, concrete arch bridge and composite arch bridge. Up to now, each of the four types has its own remarkable span record, for example, the New Danhe Bridge in Shanxi Province being a stone arch bridge with a span of 146m, the Chaotianmen Bridge of a steel arch bridge with a span of 552m, the Wanxian Yangze River Bridge of a reinforced concrete (RC) arch bridge with a span of 420m and the Wuxia Yangze River Bridge of a CFST arch bridge with span of 460m (Chen Baochun 2004, 2005; Chen Baochun and Ye Lin 2006).

Compared with other three types of arch bridges, only few steel arch bridges have been built before 2000 in China. With the rapid development of economy and transportation, more and more steel arch bridges have being constructed since 2000, However, the number of steel arch bridges is still less than other three types . Actually, there are still many problems existing in the design of steel arch bridges, such as the design method of ultimate bearing capacity, local and integral buckling. Therefore, the construction of steel arch bridges in China should refer to the specifications from other countries, need perfect construction specifications and well-trained technicians (Gao Jing and Chen Baochu 2005).

In this paper, based on collected mass information of steel arch bridges in China, the construction history of steel arch bridges has been reviewed at first. Then statistical analysis on these bridges is obtained focusing on their numbers, spans, structural styles, construction methods and so on, in order to provide reference to the further study and application of steel arch bridges.

2 OVERVIEW OF STEEL ARCH BRIDGE DEVELOPMENT

In China, steel bridges have not been paid attention to for a long time, especially for highway bridges. And most steel bridges are railway bridges. Most of the existing steel bridges are plate girder and truss girder bridges. But RC arch bridges are generally more economical since there is no sufficient steel material supply in China. There are some earliest typical steel arch bridges in China:

(1) the No.2 Panzhihua Brdige (the Dukou Bridge) finished in 1966 with the main span of 180m, the arch rib of which uses steel-box-shaped section;

(2) the No.3 Panzhihua Brdige (the Midi Bridge) using steel trussed arch rib, finished in 1969;

(3) the Jiujiang Yantze River Bridge finished in 1992 with a span of 216m, which is a continuous structure composed of rigid steel trussed beam and flexible steel arch.

In recent three decades in China, more steel has been used in bridge engineering, such as the construction of some long span cable-stayed bridges and suspension bridges. In 2003, the steel arch bridge with the largest span in the world at that time, the Lupu Bridge in Shanghai was finished, whose main span is a half through steel tied arch bridge while each side span is a deck arch bridge having composite girders. The spans of the Lupu Bridge are 100+550+100m, and the arch rise is 100m with the rise to span ratio of 1/5.5.

The construction of the Lupu Bridge turns people's attraction into steel arch bridges again that several steel arch bridges have been constructed later in China. The Jianghai Bridge finished in 2006, lying in the Xingguang Expressway of Guangzhou City, is a steel trussed arch bridge with the main span of 428m. The Caiyuanba Yantze River Bridge finished in 2007 in Chongqing City is a steel box arch bridge with the main span of 420m,. The Chaotianmen Bridge located in Chongqing City has the largest span among the steel trussed arch bridges in the world, with a span length of 552m.

3 QUANTITY AND SPAN LENGTH

Up to July of 2010, 65 steel arch bridges in China have been investigated, and 52 of which have their spans longer than 100m and are selected as analysis bridges later. Table 1 lists 27 steel arch bridges having spans longer than 150m.

Fig.1 shows steel arch bridges in China during different construction periods. It is found that the quantity or span lengths of them has been increasing rapidly since 2000.

Fig.2 shows that among those steel arch bridges spanning longer than 100m, 50.0% of which (about 26 bridges) have spans varying from 100m to 149m; 19.2% (10 bridges) spanning from 150m to 199m; 11.5% (6 bridges) spanning from 200m to 249m; no bridges have the spans between 250m and 299m; 5.8% of which (3 bridges) spanning from 300m to 349m; only 1 bridge is spanning between 350m to 399m; 6 bridges have spans longer than 400m.

The steel arch bridges spanning shorter than 100m are almost foot bridges or piping bridges constructed a long time ago, which are not modern bridges because, for bridges with small spans, plate or girder bridges can serve well at low cost and simple construction, while arch bridges need more materials to strengthen the structure to prevent buckling. And besides, the construction procedure is complex and cost expensive. At present, for large span bridges, arch bridges are not so attractive due to the development of cable-stayed bridges. For example, steel cable-stayed bridges use less steel material and can be built in a more convenient construction procedure with lower requestment of equiptments and devices than steel arch bridges when the spans range from 250m to 500m. Therefore seldom steel arch bridges with such a span length are constructed.

For steel arch bridges spanning shorter than 250m, construction technology has been achieved to some degree with reasonable costs. When the span is between 250m and 400m, the construction might have difficulty which can be overcome. Thus such a span length for steel arch bridges is still competitive. When the span is longer than 500m, the construction obvious becomes very difficulty. Now in the world, there are only 5 steel arch bridges with spans longer than 500m, two of which are existing in China. Therefore the construction technology for steel arch bridge needs to be advanced if a span of longer than 500m is requested.

Table1: Steel arch bridges in China(span≥150m)

No.	Bridge Name	Span (m)	Type	Completed Year	Construction Method
1	Zhujiang Baishahe Bridge in Guangzhou	150	Half through arch	2008	—
2	Kanjing Bridge in Taiwan	150	Though arch	2002	—
3	Jingde Bridge inTaiwan	155	Though arch	2001	—
4	Guandu Bridge in Taiwan	165	Half through arch	1983	Scaffolding Method
5	Jilonghe Bridge	166	Double deck	—	—
6	No.1 Mengshuai Bridge in Taiwan	170	Double deck	2001	—
7	Yaojiang Bridge in Ningbo (Wantou Bridge)	180	Through arch	2009	Scaffolding Method
8	No.2 Panzhihua Bridge(Dukou Bridge)	180	Deck	1966	—
9	No.3 Panzhihua Bridge (Midi Bridge)	181	Deck	1969	—
10	Baling Bridge in Taiwan	185	Half through arch	2005	—
11	Min River Bridge located in Fuxia railway	198	Half through arch	2009	Scaffolding Method
12	Zhongzhaiwan Bridge in Xiamen	208	Half through arch	2004	Scaffolding Method
13	Jiubao Bridge in Hangzhou	210	Through arch	Under construction	Launching Method
14	No.2 Mengshuai Bridge in Taiwan	210	Through arch	1996	—
15	Jiujiang Yantze River Bridge	216	Double deck	1992	Cantilever Method
16	Rongjiang Railway Bridge in Shantou	220	Half through arch	Under construction	—
17	Dongpingshuidao Railway Bridge in Guangdong	242	Half through arch	2009	Cantilever Method
18	Nanning Bridge in Guangxi	300	Half through arch	2009	Cantilever Method
19	Dongping Bridge in Foshan	300	Half through arch	2006	Swing Method
20	Da-sheng-guan Yangtze River Bridge in Nanjing	336	Half through arch	2009	Cantilever Method
21	Wangzhou Yangtze River Railway Bridge in Chongqing	360	Half through arch	2005	Cantilever Method
22	Da-ning-he Bridge in Chongqing	400	Deck	2010	Cantilever Method
23	Caiyuanba Yangtze River Bridge in Chongqing	420	Half through arch	2007	Cantilever Method
24	Xin-guang Bridge in Guangzhou	428	Half through arch	2006	Cable Hoisting Method
25	Mingzhou Bridge in Ningbo	450	Half through arch	Under construction	Cantilever Method
26	Lupu Bridge in Shanghai	550	Half through arch	2003	Cantilever Method
27	Chao-tian-men Bridge in Chongqing	552	Half through arch	2007	Cantilever Method

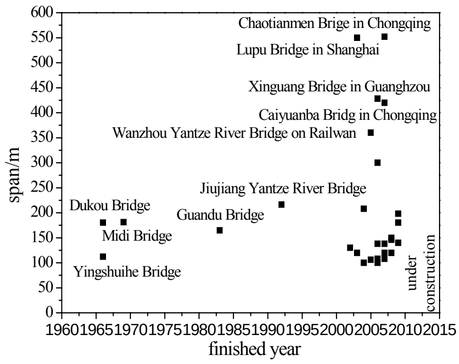

Figure 1 : span and finished year of steel arch bridge

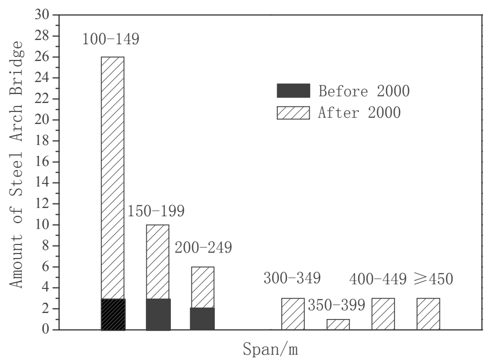

Figure 2 : span arrangement

4 STRUCTURE STYLE

Similar to other arch bridges, steel arch bridges can be classified into 4 types: fixed (hingeless) arches, arches with single hinges, two-hinge arches and three-hinge arches according to the bearing types of arches. The information shows that most steel arch bridges use fixed arches while few of them use single-hinge, two-hinge or three-hinge arches in China.

According to their structure systems, steel arch bridges can be classified into simple systems, composite structure of arch and girder. It can be also classified into arches having thrust or no thrust. When considering the deck location, steel arch bridges have 4 types, i.e.,deck arch bridge: half through arch bridge, through arch bridge and double decked arch bridge. Besides, it can be classified into parallel arches and basket-shaped arches according to the lateral arrangement of arch ribs.

A deck arch bridge consists of an arch ring (rib) and a spandrel structure. In steel arch bridges, spandrel structures often use steel material, while deck systems sometimes adopt composite structures of steel and concrete. The arch is named as simple system arch when the deck is only under local loads. For large-span steel arch bridges, continuous girders are always used in the deck system as the main part, which behaves with the integral structure such that the bridge becomes a composite system of arches and girders.

As shown in Table 2, among the collected bridges, 3 bridges are deck arch bridges with the percentage of 6.5%, 28 bridges take half through arches and 12 bridges are through arches, both of which with the percentage of 87.0%, while there are 3 double decked arch bridges with the percentage of 6.5%. In other words, half through and through arch bridges constitute most of Chinese steel arch bridges, similar to CFST arch bridges. But most RC arch bridges are deck arch bridges.

Table 2 : Structure styles of steel arch bridges

structure	Amount of bridges	Percentage	structure	Amount of bridges	percentage
deck	3	6.5	through	12	26.1
Half through	28	60.9	Double deck	3	6.5

5 ARCH ANALYSIS

5.1 Ratio of rise to span

Ratio of rise to span is an important factor for steel arch bridges, which has influence on the inner forces and steel cost of an arch. A unreasonable ratio will require more steel in construction and affect the harmony between a bridge and its surroundings. A smaller value brings larger additional stress and shearing forces due to the deflection. On the other hand, large value will influence the lateral stability of arches and induces additional stress due to arch lateral displacements. Generally, deck steel arch bridges usually locate in mountain areas and take relatively large ratios of rise to span for a beautiful scene. While the through steel arch bridges are often found in plane areas using relatively small ratios of rise to span considering the harmony between the bridge and the environment. Besides, the selection of suitable construction methods is related to this ratio in steel arch bridge (Chen Baochun 2007).

From the collected steel arch bridges, it is found that the usual ratios of rise to span for Chinese steel arch bridges are between 1/2-1/8, 1/4-1/5 of which is often taken, as given in Fig. 3. The value between 1/5-1/6.5 has little effect on saving the construction materials. Sometimes, small values such as 1/2.5 are taken considering the engineering specialty. Fig. 4 shows that there is no direct relationship between ratios of rise to span and span lengths.

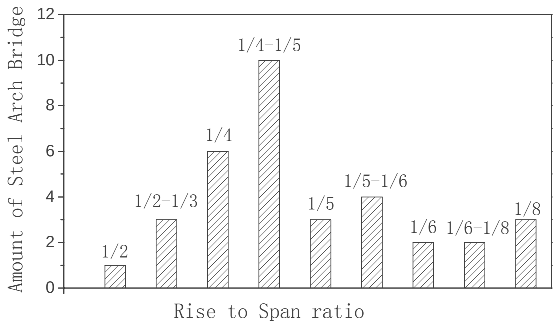

Figure 3 : Ratio of rise to span arrangement

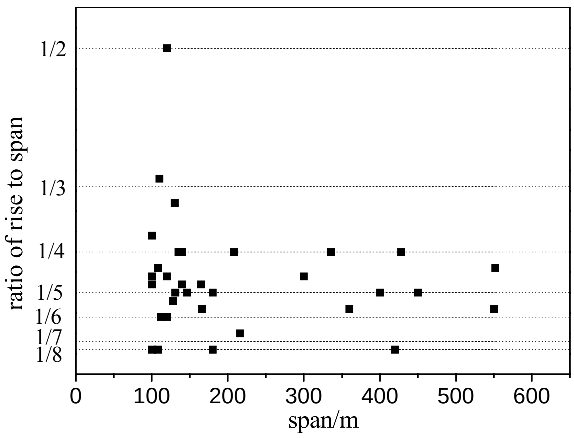

Figure 4 : relationship between ratio of rise to span and span

In China, the usual ratios of rise to span for RC arch bridge are between 1/5-1/8, and 1/6 is most often used. For CFST arch bridges, this value always varies from 1/4 to 1/5, and 1/5 is popular. Therefore, the ratios of rise to span for RC arch bridges are generally less than those of CFST arch bridges in China, and both of them are included in the value range of steel arch bridges.

5.2 Arch axis

Arch axis is generally expected to be close to the pressure lines of dead loads in order to extract more compressive resistance of arches. For RC or CFST arch bridges, catenary or parabola is mainly used in the design of arch axis, and very few bridges use circular shaped axis or other curves. It is similar case in steel arch bridge, parabola is the most common axis line due to dead loads are nearly uniformly distributed, as can be seen in Table 3. Only 24 steel arch bridges are known of their arch axis in this investigation, from 45 bridges with their spans longer than 100m. It is shown that, 6 bridges use catenary arch axes with the percentage of 25.0%, and 14 bridges use parabola as the axes with the percentage of 58.3, and only 4 bridges take other types of arch axes with the percentage of 16.7%.

Table 3 : Arch axis of steel arch bridge

Arch axis shape	parabola	catenary	other
Amount of bridges	14	6	4
percentage	58.3	25.0	16.7

5.3 Section of arches

The section with box or truss shape is mainly applied in the steel arch bridges of China, instead of “H”, “I” or circular shaped sections which are usually filled with concrete to be CFST structures. CFST arch bridges in China have been constructed so successfully that steel tubular is used in CFST arch bridges, instead of steel arch bridges.

Arch ribs with box-shaped sections have many advantages, such as large torsion resistance, integral behaviours of structure, economical construction, and convenient erection. Most box steel arch bridges use rectangular sections, only few adopt irregular one. As an example, the No.2 Chanba River Bridge in Xi’an takes octangular section, and the Changjiang Bridge in Zhongshan as well as the Liuwu Bridge in Lasha uses oval section. The arch ribs with two connected boxes appear, in which one is upon the other in order to make the arch bridge behave well when the span is large, such as the Lupu Bridge and the Yongjiang Bridge.

Rigid arch bridges with steel trussed ribs belong to a traditional type of bridge, which presents the beauty of bridge structures for a composite system of stiff truss arches and slender suspenders. In the ribs of steel arch bridges, the upper and lower chords have the sections of steel boxes, shaped steel or steel tube, which can also be used in the web members. Recently, box chords are popularly applied to this type of bridges with relatively large spans in China. The web members are bolted to the chords, and the chords can be bolted or sealed to each other in the factory or bolted in the erection site. Compared to solid ribs, trussed ribs can be produced, moved and fixed conveniently for the smaller members. Furthermore, the deflection of a bridge with trussed ribs under live loads is less than that of a bridge with solid ribs. And trussed ribs are often adopted in highway steel arch bridges under heavy loads or railway bridges under heavy live loads when spans are relatively small.

In this paper, 39 steel arch bridges spanning longer than 100m are classified into two types, according to the sections of arch ribs (Table4). It is found that there are 25 box arch bridges and 14 trussed arch bridges. Box shaped sections are mainly used in the steel arch bridges in China because these bridges usually have midium or small spans. For example, steel arch bridges with spans ranging from 100m to 150m occupy 50.0% of all bridges. RC arch bridges always adopt double-parabolic arches, separated ribs or ribs with the box sections (Chen Baochun and Ye Lin 2006). Most CFST arch bridges take trussed sections for arch ribs, followed by dumbbell shapes (Chen Baochun and Yang Yalin 2005).

Table 4 : Arch rib sections of steel arch bridges

section	Box shape	Truss shape
Amount of bridges	25	14
percentage	64.1	35.9

6 CONSTRUCTION METHOD

Construction methods of arch bridges can be classified into four ways. In the first way, there are also two types: self-erection and non self-erection, considering if the finished part of a bridge works as the support of the left structure. Self-erection methods can be further classified into cantilever and stiffened scaffolding methods. And non self-erection methods can be classified into scaffolding method, swing method, cableway method and cable-hoisting method. In the second way, construction method of arch bridge includes scaffolding method and unscaffolding method. In the third way considering hoisting device, construction method can be classified into cable-hoisting method, floating method and crane method. In the last way, methods of cast-in-site and prefabrication can be obtained (Chen Baochun 2007).

For RC arch bridge, construction method commonly used are cantilever erection method, stiffened scaffolding method, scaffolding method and main method of swing erection (Chen Baochun and Ye Lin 2006, Leonardo Fernández Troyano). For CFST arch bridge, swing method and scaffolding method are often taken, but cantilever erection method is the most common one (Xu Wei 2006, Chen Baochun 1997). The construction of steel arch bridge in China always uses cantilever method, scafolding method, launching method, cable-hoisting method and swing method. The construction of steel arch bridge is superior to other types of arch bridges, especially when spans are large.

Cantilever method is the most popular for steel arch bridge construction. According to the bearing structure composed by temporary members and arch ribs or rings, cantilever method can be further divided into cable-stayed cantilever method, free cantilever method, and cantilever truss method. Free cantilever method is often employed in the construction because steel members are prefabricated and not heavy. In China, cable-stayed cantilever method is the most popular when the bridge span is relatively large. In this kind of method, pylon and cable are used to hold the cantilever arch advanced from spring to crown. Temperate pylon can be built on piers or at abutments. Stayed cables hold the cantilever arch with rear stays anchored to the ground or approach bridges. Before the bridge arches are closed, the arches are not efficient bearing structures, and auxiliary members or structures are necessary during the construction.

Scaffolding method is usually used in railway steel arch bridges with stiffened girders and flexible arches. During the construction, arch ribs are erected through scaffolds on decks which are finished using the method as that of common girder bridges. For some steel arch bridges with small spans, when the river is shallow with allowable navigation requirement, temporary studded scaffolding method is sometimes used (Lai Wuzhao et al. 1999).

Swing method, global launching method and cable-hoisting method are used in a few steel arch bridges. The Dongping Bridge in Foshan adopted the swing method, the Jiubao Bridge in Hangzhou did the global launching method, and the Xinguang Bridge in Guanghzou used the cable-hoisting method in which the trussed ribs above the deck were divided into three segments lifted by two scaffolds in the water.

According to the construction methods mentioned above, the collected steel arch bridges can be classified as listed in Table 5. It shows that the main construction methods: cantilever method and scaffolding method have the percentage of 87.1%, and other methods occupy only 12.9%. Fig. 5 shows the relationship between construction method and span, from which it is found that cantilever method can be used in steel arch bridge with different span lengths, while scaffolding method is mainly applied in composite structures of arches and girders with small spans.

Table 5 : Construction methods of steel arch bridges

Construction method	cantilever method	Scaffolding method	swing method	launching method	cable hoisting method
Amount of bridges	14	13	2	1	1
percentage	45.2	41.9	6.5	3.2	3.2

It is known that construction method has large influence on the bridge technology for arch bridges. Steel arch bridge's construction method, towards less-scaffolding or non-scaffolding, is related to bridge location, construction cost and project duration.

7 FIGURE PURSUING AND STRUCTURE DISSIMILATING

Arch, favoured by many bridge designers, especially architects, is a structure with aesthetics, which can be integrated with the nature well while it services as a structure, just like that T.Y.Lin said, "Many arch bridges are selected due to their values in aesthetics". At the same time, aesthetics pursuing causes the change and development of bridge figures and dissimilation of structures (Chen Baochun 2007).

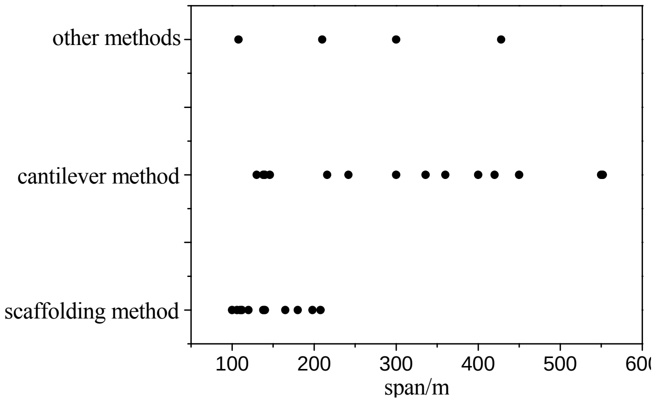

Figure 5 : relationship between construction method and span

The transverse stability of arches should be alarmed during the bridge design. Generally, the style of two or more arch ribs connected through transverse systems of braces, or of basket shapes is selected to increase the transverse stability of arch bridges. However, a very different butterfly-shaped arch style, with two ribs outwards each other and no transverse bracing between them, is adopted in the Nanning Bridge in Guangxi Province and the Changjiang Bridge in Zhongshan City. Obviously, such kind of structure is unreasonable in its bearing system, which requires a high cost of construction.

Besides, in some steel arch bridges, the ribs have different span lengths in the same bridge, such as the Fenghua Bridges and the Dagu Bridge in Tianjin, or the arch axis are dissimilated, such as the Bengbu Bridge in Tianjin and the Jiubao Bridge in Hangzhou, or the ribs have different rises. There are so many dissimilation styles, some of which are realized and some are just assumptions.

8 CONCLUSIONS

Few steel arch bridges have been built before 2000. However, the quantity as well as span lengths of this type of bridge increases at a high speed in the last decade. As mentioned above, steel arch bridges have many advantages, which are needed in the massive traffic infrastructure construction in China. Thus, it is important and necessary to conduct further study on the design theory, structure style topology, construction method and so on. Based on the information collected for steel arch bridges in China, their present situation is presented in this paper, and the author wish the analysis results on some parameters could provide references for the design and construction as well research of this type of bridge in the future.

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