STRUCTURAL FORM OF TIMBER ARCH BRIDGES AND RESERCH VALUE OF A CHINESE WOWEN TIMBER ARCH

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SUMMARY

Timber arch has various structure forms. In this paper, three main structural forms and several other forms had been detailed described. Among of three main forms, woven arch is a special structural form, it only been used in timber arch bridge and built in China, also called as Chinese woven timber arch. Conception of Chinese woven timber arch is ingenious. It has an arch structure made by weaving longitudinal and transverse straight logs in a special way. The main arch ring is two longitudinal polygonal arch systems consisting of straight logs. The two longitudinal systems are mainly subjected to compressive forces with different polygonal sides, and the transverse members contribute to an improvement of the load bearing capacity by integrating the whole structural system. There is no corresponding analysis method for it since its structure is neither the general two-dimensional plane structure and nor three dimensional space structure. Research on the Chinese woven timber arch has very important for development the theory of structural mechanics. It can accelerate application and development of timber structural bridge, and improve practical potential of the woven timber arch bridge in long span bridge.

Keywords: *Timber arch bridge, structural form, difference, Chinese woven timber arch bridge, research value.*

1. INTRODUCTION

Ancient arch bridge was built more often using stone rather than timber due to the susceptibility of timber to rotting and attacks from the insects. But many countries had ever built timber arch bridges [1, 2]. Unfortunately, there are few ancient timber arch bridges survived now. Based on the historical records and remains, timber arch bridges can be divided into four structural forms, among of them, timber rib arch, timber truss arch and woven timber arch are the primary forms [3]. There are many timber rib arch bridges and timber truss arch bridges in Europe due to strongly influenced by stone arch structures once used predominantly in church architecture. The woven timber arch bridges only had been built and survived in China. The conception of woven timber arch is ingenious, and it has an arch structure made by weaving longitudinal and transverse straight logs in a special way achieved a long span length, the longitudinal system is compose of two different polygonal arch systems in two planes [4]. From the view of structural mechanics, there is no corresponding analysis method for it since its structure is neither the general two-dimensional plane structure, nor three dimensional space

structure [5]. Until now, the core value of woven timber arch had not been revealed. In this regard, a comparison study on the timber arch bridge forms would be of interest. In this paper, three main structural forms and several other forms had been detailed described and compared. Especially, the two branches of Chinese woven timber arch bridge had been detailed described and compared. From the view of bridge engineering, Chinese woven timber arch bridges have high research value. Research on the Chinese woven timber arch has very important significance for development the theory of structural mechanics, it can accelerate application and development of timber structure bridge, and improve practical potential of the woven timber arch bridge in long span bridge.

2. STRUCTURAL FORM OF TIMBER ARCH BRIDGE

2.1. Timber rib arch bridge

Timber rib arch bridge is the most original timber arch bridge. Its main arch ring is made directly by bending the logs into the desirable shape. Construction of timber rib arch bridge is not convenient because the logs are bent into a curve shape needs more processing. In ancient times, they are all made by the logs, because they entirely depending on the logs length, the span length are rather small. Figure1 (a) shows a timber rib arch bridge in Italy. With the development of laminated wood, an increased span length of the timber arch bridges can be made possible. Some long span rib arch bridges had been built in Europe. Figure1 (b) shows a long span timber rib arch bridge in Croatia made by laminated wood.

a) Timber rib arch bridge in Italy *b) Timber rib arch bridge in Croatia*

***Fig. 1**. Timber rib arch bridge.*

2.2. Timber truss arch bridge

As early as in the Renaissance era, Andrea Palladio, a great Italian architect, described the structure of timber truss arch in his treatise *I quattro libri dell'architettura* (The Four Books of Architecture) [6]. Timber truss arch is made up of primarily short logs that are joined together to form a truss structure. Few materials are needed in this case so that the bridge tends to be lightweight, at the same time, timber truss arch is at an advantage over the simply supported beam and timber arch rib in terms of span length, as it exploits the stable triangular structure and the balance of compressive and tensile load applied to the members. So the span is larger than timber beam bridge and timber rib arch bridge. For

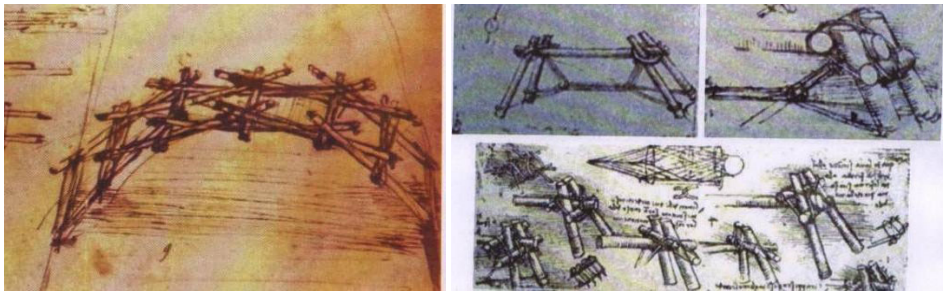
instance, Ponte dell'Accademia, a magnificent timber truss arch bridge across the Grand Canal near the Accademia di Belle Arti di Venezia (Venice) in Italy, as shown in Figure 2 (a), has a single span of about 50 m, significantly greater than any previous architecture in Italy. Thanks to careful protection and maintenance, it has been still in use now. Figure 2 (b) shows the longest span timber truss arch bridge, which is built in Suzhou in 2013. It has a single span of 75.7m with length of 120m and width of 6m.

(a) Ponte dell' Accademia in Italy *(b) Xujiang Bridge in China*

Fig. 2. *Timber truss arch bridge.*

2.3. Woven timber arch bridge

In Europe, the imaginary woven timber arch bridge had been described in the Atlantic Code in word and picture by Leonardo in the last decade of the fifteenth century, as shown in Figure 3 (a) [7]. It is consisted of two longitudinal arch center systems. The logs were interlaced and tied using ropes, as shown in Figure 3 (b). The force was transmitted to the logs through the ropes used to fix them. The logs belonging to the same arch center system were not at the same plane, thus resulting in a great load at the hinge [7]. Unfortunately, the imaginary woven timber bridge had not been built in Europe.



a) Imaginary woven timber arch bridge *b) The binding joint*

Fig. 3. *The imaginary woven timber arch bridge by Leonardo.*

The really woven timber arch bridge had only been built in China. According to their present situation, location, and structural details, woven timber arch bridges can be further divided into two types: one is exemplified by the non-extant ancient Bianhe

rainbow bridge and the other by the extant Min-zhe timber arch bridge, as shown in Figure 4. They achieves large span by weaving longitudinal and transverse logs in a special way, the longitudinal system has two different polygonal arch systems in two planes. It is take full advantage of the parallel to grain compressive strength of the wood and successfully utilizes the short construction element to achieve a large span. The detail of structure will be described in Section 3.

a) Bianhe rainbow bridge *b) Min-zhe timber arch bridge*

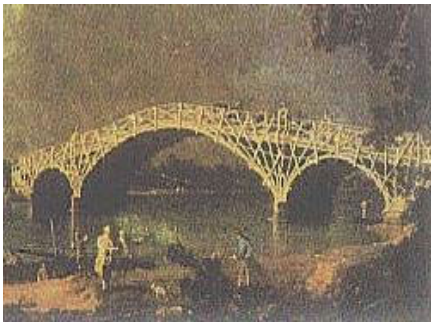
Fig. 4. *Chinese woven timber arch bridge.*

2.4. Other form of timber arch bridges

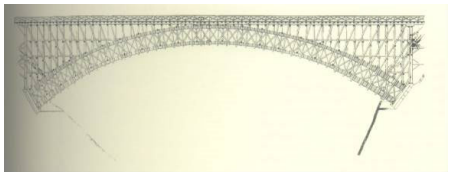
There are many other timber arch bridges that can be hardly classified into any of the classes mentioned above. Fig. 5a shows a continuous multiple-arch bridge, Apollodorus Bridge was depicted in the relief of Trajan's Column. It was designed and engineered by Apollodorus of Damascus in 105 AD under the command of the Emperor Trajan. Several wooden arches, each spanning 35 to 38 m, were set on twenty high-rising masonry pillars. The original bridge was estimated to be about 1100 m in total length, the longest arch bridge for more than 1,000 years in both total and span length. Fig. 5b shows Walton Bridge with 40m of central span across the River Thames at Walton-on-Thames in Surrey, England. The United Kingdom and United States were ahead of the other countries in bridge construction techniques at the first half of the nineteenth Century. A detailed account was provided by a German structural engineer, Karl Culmann, in 1950 in his study tour to these countries. For instance, the Cascade bridge with a span length of 90 m built in 1848, as shown in Fig. 5c, was considered to be the best timber structure in the United States, or most probably in the world at the time. Fig. 5d and Fig. 5e show Tournus bridge, a five-span arch bridge with a span length of 27.3 m for each arch built in 1801 across the Sanoe river and Choisy bridge, a five-span highway deck bridge with a span length from 21 to 24 m built in 1811 over the River Seine in France, respectively.

Fig. 6 show the Kintaikyo Bridge in Japan, The bridge is composed of five sequential wooden arches on four stone piers and two wooden piers. The total length of this bridge is about 193 m, including a central span of 35 m and side span of 34 m, and the width is 5m [8]. Its wooden members were connected piece by piece using hoop irons, U-shaped irons or iron wires, as shown in Fig. 10c).

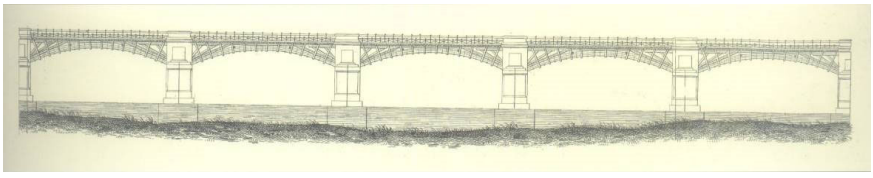
a) Apollodorus Bridge.



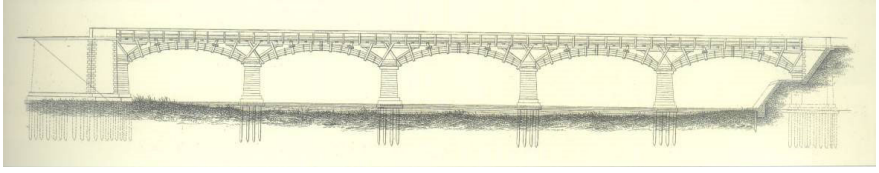
b) Walton bridge.



c) Cascade Bridge [1].



d) Tournus Bridge [1].



e) Choisy Bridge [1].

Fig. 5. *Other form of timber arch bridges.*

a) Panorama.

b) Upward view of the main arch ring; *c) Detailed structure.*

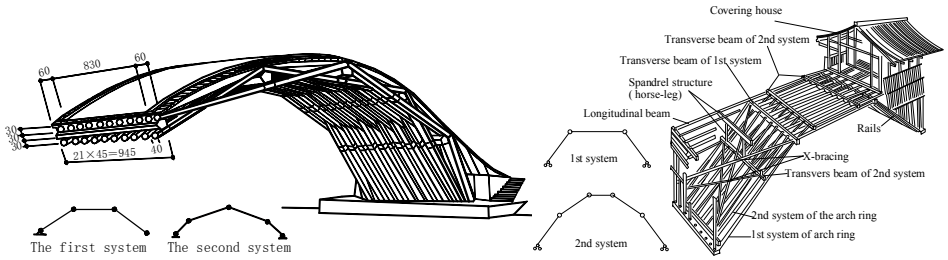
Fig. 6. *Kintaikyo Bridge in Japan:*

3. DETAILED DESCRIPTION OF CHINESE WOVEN TIMBER ARCH BRIDGE

No one ancient Bianhe Rainbow Bridge is survived, the structures can only be seen from the famous painting of "Chhing-Ming Shang Ho Thu" (Festival of Pure Brightness on the River), shown in Fig. 4 a), from the painting, a sketch of the bridge structure was drawn as shown in Fig. 7 (a) [9]. Investigation indicated that there are 128 timber arch bridges in service in Fujian and Zhejiang Province of China [10]. A typical structure of a Min-zhe timber arch bridge is illustrated in Figure7 (b). Both of them have a structure made by weaving longitudinal and transverse straight logs in a special way, and the longitudinal systems composed of two systems [11].

Compare with the two branches, there are some differences between them not only in appearance but also in structural details. The ancient rainbow bridge shaped in arc with the extrados steps for pedestrians. While the Min-zhe timber arch bridge has spandrel structure and the side-covering boards for the arch make it look like a polygon structure, which is no step and improves its traffic function for both people and animal-carts. The other side, covered or uncovered is the most distinct difference between them, the Min-zhe timber arch bridge has covering house. In terms of function, the covering house protects its arch structure from heavy rainwater in the southeast mountain area, giving a

more reasonable design than the Bianhe rainbow bridge, and makes it possible for many Min-zhe timber arch bridges to survive until today [12].For the structure detail, the first system in both of them is a three-line polygonal arch rib with three longitudinal straight logs of the same length and two transverse beams, the second system has some



a) Bianhe rainbow bridge *b) Min-zhe timber arch bridge*

Fig. 7. *Three views of the Chinese timber arch bridges.*

difference between them. In the Bianhe Rainbow Bridge, it is consist of four longitudinal straight logs and three transverse beams, whereas in the Min-zhe timber arch bridge, it is consist of five longitudinal straight logs and four transverse beams. This structure is successes to achieve a large span by short elements. According to the recording and painting, the arch frameworks and the transverse beam of the Bianhe Rainbow Bridge were bound together by ropes as shown in Fig. 8a, but for Min-zhe timber arch bridge, the logs of the two systems connected by theirs the transverse beams are all with the mortise and tenon nodes, as shown in Fig. 8b. All the members are straight and need not to be curved. This makes the member processing more easily than the rib timber arch bridge with curved members. And the joint numbers in them are less than that of the truss timber arch bridges, which is also benefit for construction. Besides, there are X-bracings in the Min-zhe timber arch bridge (Fig. 9) and many wood blocks (Fig. 10) are inserted between springing members, which are good for integrity and stability of the bridge structures, while these two structure approaches have not found in the Bianhe Rainbow Bridge [12].

a) Binding of Bianhe Rainbow bridge. *b) The mortise and tenon nodes.*

Fig. 8. *The joint of Chinese timber arch bridges.*

Fig. 9. *The X-bracings.*

Fig. 10. *Wood blocks.*

4. RESEARCH VALUE OF CHINESE WOVEN TIMBER ARCH BRIDGE

Due to the difference of architectural culture between Chinese and western, we can find there are some differences in the main structural form of timber arch bridge between them The timber rib arch and the timber truss arch are the mainly structural forms in western, but the woven timber arch is the unique structural form in China. From the view of bridge structure, the rib arch and truss arch are not the special for the timber arch; we can find they had been widely used in other material arch bridge, like as concrete arch bridge, steel arch bridge. But woven arch had not been used in other material arch

bridges; on the other side, from the view of structural mechanics, there is no corresponding analysis method for it since its structure is neither the general two-dimensional plane structure and nor three dimensional space structure [5]. So it has very important significance in the world bridge history.

From the scope of international, wood as a kind of environmental protection material, it will been got in the good graces of more and more architects, due to the ecotype and the sustainable development become more and more important today. At the same time, with the development of industrial technology, the disadvantage of the wood as building component can been overcome with the industrials technology, and then, its superiority become more and more obvious. Some new timber bridges and timber composite bridges had been built in recently year.

Not only timber structure but also its construction technology, they are relative success for many developed country. The design of timber structure is convenient, and timber structure can show full of variety architectural style, it is one of most elegant appearance and delectable structure. Timber structure had achieved high great effect and achievement in ancient China, it has a large practical potential in long span structure, at the same time, China is stand in large-scale bridge construction period, research on the Chinese woven timber arch bridge from the view of bridge and structure engineering, it can provide references for further studying, designing and constructing of timber arch bridges as well as inspiring to use the structure in bridge engineering and structural engineering in the future.

5. CONCLUSIONS

Woven arch is a special structure. Compared with the other structural forms, woven arch only been used in timber arch bridge and built in China. The woven timber arch structure is neither the general two-dimensional plane structure, nor three dimensional space structure. It has important technological value in bridge history in the world. Research on the technical characteristic has a great significance for development of the theory on structural mechanics. At the same time, it can accelerate application and development of timber structure bridge, and improve practical potential of the woven timber arch bridge in long span bridge.

In addition, the reason why this kind of woven timber arch bridge only existed in these two countries, and why Chinese woven timber arch bridge is similar to the imagining woven timber arch bridge by Romans.

Whether there is existing origin and exchange relationship between them, whether they are completely independent. And then, for a long time, the engineers, historians and archaeologists are all considered that most culture and technology in Japan transfer from China, but the Kintai Bridge only been built in Japan, and the woven timber arch bridge had not been built in Japan. But no research work on theses questions had been carried out till now, and these questions are worth researching by researcher in China.

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