A Brief Analysis of Traditional Chinese Woven Timber Arch System

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Abstract. The Chinese woven arch system has captivated the interest of numerous engineers and architects due to its elegant appearance and stable structure as an ancient invention. The ancient wood structure has an unknown load transfer pattern. This article aims to analyze the load transfer condition of the woven timber arch bridge and propose solutions to rebuild the same structure under different conditions. The FEM analysis has been introduced to figure out the load transfer condition. The result has preliminarily revealed that the woven timber arch systems are scientifically stable. This ancient structure can provide modern engineers and architects with more possibilities and inspiration for their future designs.

Keywords: Woven timber arch bridge, Reciprocal structure, Ancient structure, Intangible cultural heritage

1 Introduction

The Chinese Woven Timber Arch Bridge, also known as a "Rainbow Bridge" or "Fairy Bridge," is a traditional form of architecture and engineering that has been used for over 1, 000 years in China. It is typically made of wooden planks or bamboo, which are woven together to form a curved arch that spans a river or other obstacles. This type of bridge is commonly used in the Min-zhe area, which is in the southeast part of China. Hongqiao, which is also called the rainbow-shaped bridge, is one of the most famous woven timber arch bridges. It can be found in the famous painting Riverside scene during Qingming Festival shown in Fig. 1. This painting was created during the Song dynasty (960-1127), which proves that the woven timber arch structure has existed for at least 1000 years [1].

As shown in Fig. 1, Hongqiao is standing in the center of the picture, crossing the river, and loaded up with all kinds of people. The bridge was braided with plenty of timber beams and columns, beams and columns loading and supporting each other at the same time, forming a texture of the braided fabric. The span of the bridge is about 20 meters. Its main structure is thin, without any nodes or any metal elements. The only materials that the bridge contains are timbers in different directions. This type of reciprocal structure has two main advantages simple system and economic friendly. This

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type of bridge has not been discovered in the bridge history of other countries around the world. It seems like the ancient Chinese are thinking differently about solving bridge-building problems [2].

Fig. 1. Hongqiao in the riverside scene during the Qingming Festival

After 1000 years since the woven timber arch structure was created, the mechanical principle of this structure has not been discovered yet. Recently, more and more attention has been paid to this ancient bridge style. The Chinese government has provided a large amount of funding to protect around a hundred ancient traditional woven arch bridges in China. After thousands of years of the baptism of time, most timber bridges are not functional, and repair and rebuilding have become a big problem [3-6]. This study aims to analyze the woven timber arch structure to understand its load-carrying mechanism with the help of modern technology. It aims to discuss the potential of creating new woven timber arch structural systems to be applied to modern structures.

2 Structural System

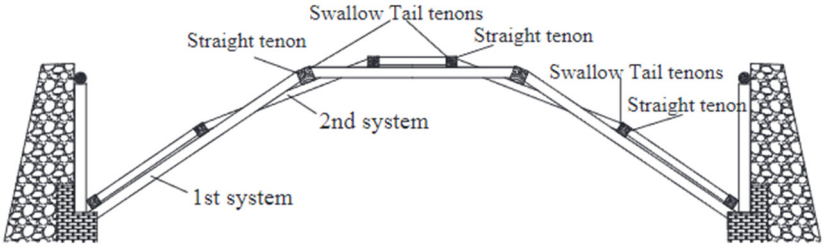


Fig. 2. The structural system of the Chinese woven timber arch bridge

Woven timber arch bridges date back over 1000 years in China but were only rediscovered in the 1980s. Combining 'beam-weaving' techniques with mortise-and-tenon joints, as illustrated in Fig. 2, they provide visually elegant structures with superior mechanical performance [7].

The woven timber arch bridge is composed of 2 sub-systems, which are the first and second systems. The first system in Fig. 2, also called the main system, consists of 3 timber beams and 2 tenons. The second system has 5 beams and 4 tenons. The beams of the main system and the second system do not intersect with each other but are connected by tenons, which form a perfect reciprocal structure. This type of structure also has X-shaped braces to resist the possible horizontal forces due to wind or earthquake loading. The sample structural diagram made by Chinese architect Liu [8] is shown as Fig. 3 below.

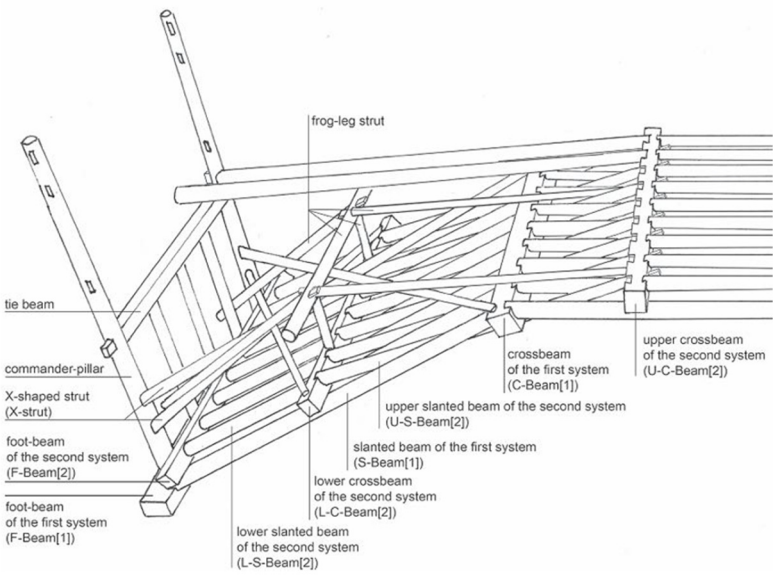


Fig. 3. Structural diagram of the Chinese woven timber arch bridge

3 Mechanical Behavior

The structure is similar to a reciprocal frame. The name 'reciprocal frame' comes from Graham Brown, who developed this type of structure in the UK. Graham used 'reciprocal' because of how the beams mutually support each other [9]. Coincidentally, reciprocal structures have appeared in several regions around the world in history, but no one has figured out their mechanical behavior.

A finite element analysis of the woven timber arch structure was done by Yang et al. [10]. They have built 2 models with the same structural details as the woven timber arch shown in Fig. 4, hinged on the position of the tenon and the other rigid. The ex-

periment was done in the elastic stage, and the result shows that the model's displacement changes linearly with the increasing load applied. At the same time, both models show symmetric deflection under symmetric loading and asymmetric deflection under asymmetric loading. They also conclude that the deflection of the hinged model is larger than the rigid one under the same loading condition. The difference becomes larger when the loading condition is asymmetrical. Another conclusion they have made is that the 2 systems of the woven arch can work together through the load transferring of the tenons or separately under some other loading conditions.

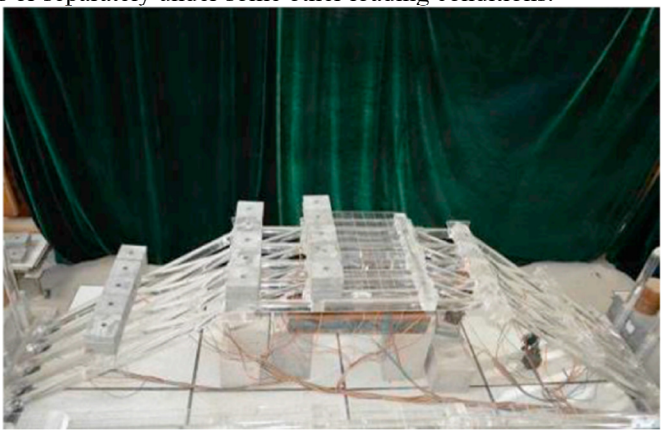
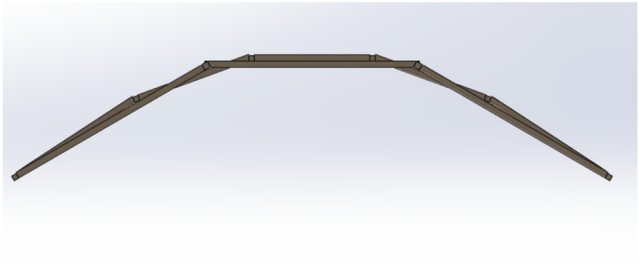


Fig. 4. Model made by Yang et al. [10]

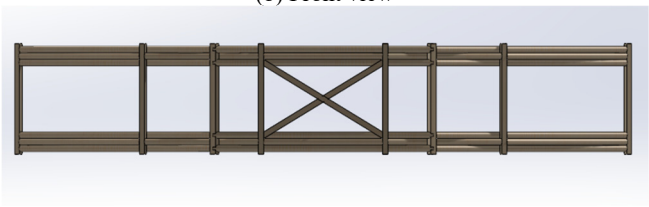
4 Application

When the woven timber arch structure is applied for decoration purposes, no extra vertical live load needs to be considered besides its self-weight. As a result, no extra supporting members are required in the vertical direction. For the horizontal direction, X-shaped braces are added to resist wind or other potential horizontal forces, as illustrated by Fig. 5. The proposed system can behave well under large horizontal loads.

(a) 3D view



(b) Front view

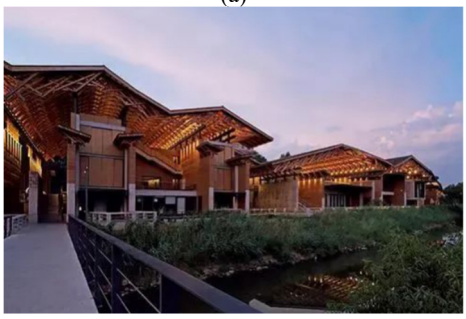


(c) Top view

Fig. 5. Proposed improved woven timber arch system with bracings

The Pulitzer Prize winner Shu Wang has applied a more complicated woven timber arch structural system to his project WaShan shown in Fig. 6. The woven timber arch structural system provides more possibilities to architects when they are designing timber or other structures.

(a)

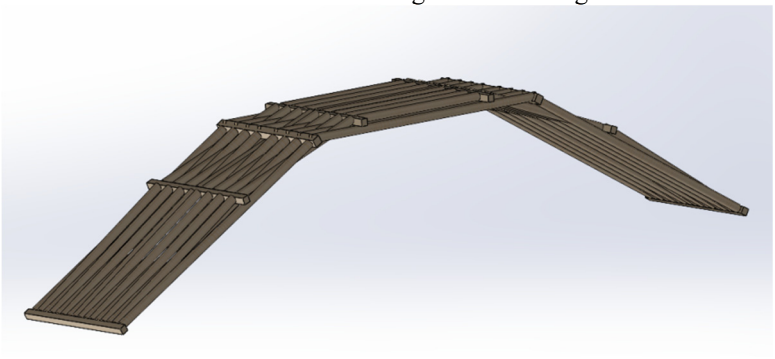


(b)

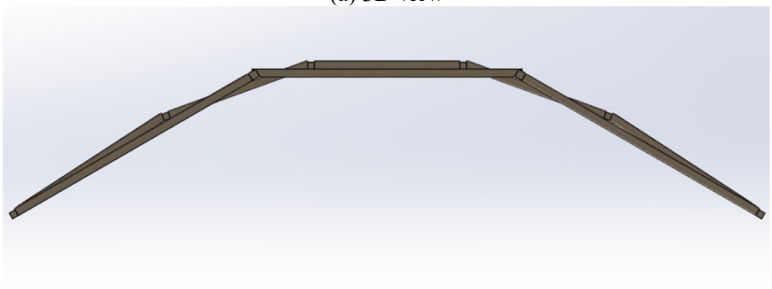
Fig. 6. Woven arch project by Shu Wang

Regarding reciprocal structures, projects by Wang are just in the preliminary stage. Cheng suggests that to detect more possibilities of the system, one architect and structural engineer are not enough. It may take many generations of architects and structural engineers to accumulate experience [11].

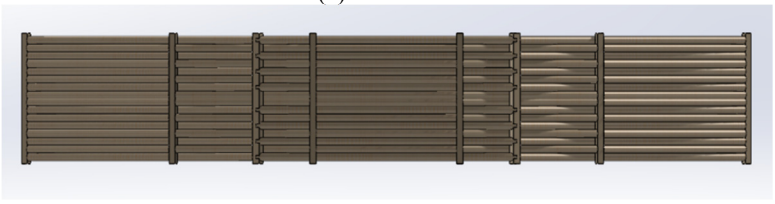
When the woven timber arch structure is applied to bridges, more vertical load-carrying capacity is required. To achieve a large load capacity, a close arrangement of several arrays of members is employed, as illustrated in Fig. 7. Furthermore, the close arrangement of timber members also provides higher horizontal resistance. As a result, horizontal force resisting members sometimes may not be necessary. Fig. 8 shows some pictures of traditional woven timber arch bridges and buildings.



(a) 3D view



(b) Front view



(c) Top view

Fig. 7. Woven timber arch system with multiple arrays of members

(a)

(b)

(c)

Fig. 8. Existing & in building woven arch bridges

5 Conclusion

In conclusion, the Chinese traditional woven timber arch structural system applies to modern society for multiple uses. Numerical analyses generally explain how to load

transfers in the structure. This provides structural engineers direction to improve the structure and make connections between ancient intelligence and modern technologies. Moreover, for the architects, there are significant meanings to rebuilding or improving the intangible cultural heritage so that the culture of woven timber arch bridges can be extended for another 1000 years.

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