Shed Light on the Geometrical Configuration and Structural Principle of an Ancient Wooden Bridge in Qingming Shanghe Tu

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Abstract: In the centre of the famous Chinese painting, Qingming Shanghe Tu, an arch-shaped timber bridge, Hongqiao, stands like a rainbow over the river Bianhe. Unfortunately, Hongqiao was damaged during floods from the Yellow River, and we can only see her beautiful form in Qingming Shanghe Tu. While, the geometrical dimensions, structural principle, as well as the construction methods of the bridge are still an interesting mystery. In the present paper, the author uncovers the structural principle and the geometric dimensions of the bridge as well as its history background. Furthermore, the author introduces two new structural systems, Lap-Beam and 1.5-Layer space frame, which are inspired by the structural principle of the Hongqiao.

Key words: Lap-beam, 1.5-layer space frame, arch bridge, Hongqiao, Qingming Shanghe Tu, wooden bridge.

1. Introduction

Qingming Shanghe Tu is a scroll painting about 5.28 m in length and 24.8 cm in width, and known as one of the most famous Chinese cultural heritage works. Zhang Zeduan, a famous artist in Northern Song Dynasty period (960-1127 A.D.), drew the painting with a bird's eye view, and represented the beautiful scenery of the capital city of Northern Song Dynasty, Kaifeng China. In the painting, there are more than 500 personages, more than 50 livestock, more than 20 ships and sedan chairs etc. An arch-shaped wooden bridge, which is currently called Hongqiao (a Rainbow Bridge in Chinese), stands at the center of the painting attracting the eyes. Fig. 1 shows a part of the painting with Hongqiao standing over the river Bianhe which was the main shipping pass connecting the capital city with other canals in ancient China. Crowding people, coaches, livestock, sedan chairs and stalls are represented vividly on the bridge, so that its structural frame must be built strong

Fig. 1 The Hongqiao Bridge in Qingming Shanghe Tu.

enough to support all these loads and made a big span for ships passing the river.

Unfortunately, the Hongqiao Bridge was damaged around 1290 A.D. during a flood from the Yellow River, and we can only see her beautiful form in the painting Qingming Shanghe Tu. Now, the government of Kaifeng city has built a theme park with the Hongqiao Bridge as a cultural and heritage destination. But the new Hongqiao is built in reinforced concrete, and does not represent the geometrical and structural features of the ancient one.

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For investigating on the spot and collecting references, the author has visited Kaifeng and found some issues on the painting. But few ancient records were found focusing on the structure and construction technology of the bridge. The geometrical dimensions, structural principle as well as the construction method of the bridge are still an interesting mystery. However, ancient structures are rich in great intelligence of human being. Therefore, methodology for modern structural design inspired by ancient structures to enhance with aesthetic originality should be promoted. In such a context, to shed light on the historical mystery as well as the geometrical configuration and the structural principle of the Hongqiao are, for all practical purpose, very important. In fact, researches on Hongqiao has been a subject by the author, and brief reports have been issued [1, 2]. In the present paper, the author will report some new discoveries on its structural details and geometrical dimensions, as well as application examples of its structural principle for the design of modern spatial structures.

2. History and Structural Principle

2.1 The History of the Hongqiao

In ancient China, shipping was one of the important transportation methods. In order to meet the requirements for both the water and land transportation, various styles of bridges were built in Song Dynasty. However, most bridges were built with girders supported by piers. Some Song Dynasty articles record that ships ran into collision with the piers and both the ships and bridges were damaged. Based on the research of Mr. Tang Huan-Cheng [3], an officer who lived around 1015 A.D. named Wei Huaji, started to build “Wujiaoqiao” (a bridge without foot). It is said that Wei Huaji tried to connect timbers with nails, and, unfortunately, his research did not achieve a realization, and the author is unable to find any report on Huaji’s technology in detail.

Several years after Huaji’s challenge, an intelligent soldier promoted an idea for a bridge construction in

southern China. The bridge, which is known as Nanyang Bridge or Flying-Bridge in Hunan province, was built without pier standing in the river, and its abutments were rooted into the stone banks, such that ships could pass safely without pier-obstacle. Unfortunately, the author has not found any record in detail about the technology of the ancient Nanyang Bridge. However, this story shows that the first big span arch shaped timber bridge in China was probably built about 1,000 years ago in Hunan province.

Around 1040 A.D., it was recorded that a ship ran into collision with bridge piers in the capital city Kaifeng. Then, Chen Xi-Liang, an officer there, was ordered to rebuild the bridge, and he introduced the technology of the Nanyang Bridge for the construction. Therefore, the Bridge Hongqiao was built by Chen Xi-Liang in about 960 years ago [2, 3].

Today, many old bridges with similar configuration of Hongqiao can be found in provinces of Gansu, Fujian, Henan, Zhejiang and some mountain areas around China [3, 4]. Fig. 2a shows the structure of the Meichong Bridge standing in Zhejiang Province [3, 4], and Fig. 2b shows the picture of the bridge. The characteristic of this configuration is a lap beam system constituted with horizontal members clipped mutually by the timbers in arch direction.

2.2 The Main Frame of Hongqiao

The elevation section and structural principle of Hongqiao is shown in Fig. 3. The main frame work of the bridge is constituted with two styles of timber arches. One style of the arch is built by three timbers with one settled horizontally at the top, while the other style is built by four members with two timbers jointed at the central top. The two styles of timber arches stand in different vertical planes, and five horizontal timbers are set across the arch planes and clipped by the arch members mutually. The author, studied several scaled models to demonstrate the structural principle of the bridge (Fig. 4 shows one of the scaled models).

Fig. 2 Meichong bridge: (a) The configuration of Meichong Bridge [3]; (b) Meichong Bridge standing in Zhejiang Province [4].

Fig. 3 The elevation section of the Hongqiao.

Fig. 4 The study model of the Hongqiao.

In Qingming Shanghe Tu, rope-like lines can be found around the joints of the bridge (Figs. 1 and 6), but the author infers that there was neither nail nor rope fastened to the main frame. However, the deck plates may be fastened to the main frame by nails. The author believes that suitable cross cut lap joints with mortises were used to resistant sliding and rotating, while mortise cutting can be found in almost all ancient wood structures in China. In addition, there was neither nail nor rope was used in similar traditional structures in China, as that shown in Fig. 2 [3, 4]. Fig. 5 shows the inferred cross cut lap joints of Hongqiao.

In Fig. 5, end lap joint of a horizontal timber appears rectangular section. While, rectangular sections of end lap joints can also be found in the painting. Both the end lap joints of the model and that in the painting are almost the same, as shown in Fig. 6, and this proves that the joints of the Hongqiao might be cross cut lap (mortise).

2.3 The Geometrical Dimensions

In this section, the author reports some calculation results on the ranges of the dimensions of the Hongqiao. The width of the bridge is almost 10 times as the width of a sedan chair on the bridge, such that the range of the width of the bridge is inferred as $W = 8-9$ m (Fig. 7). While, there are 21 arch frames, so that

Fig. 5 Cross cut lap joints used in Hongqiao.

Fig. 6 Rectangular ends caused by cross cut lap joints.

Fig. 7 Some dimensions are found by ratio.

the thickness of the timbers D can be obtained as $D = W/21 \Rightarrow 37 \text{ cm} - 41 \text{ cm}$. In the painting, an interesting scene is presented in great detail that a wrecked ship floating near the bridge, and people crowded on one side of the bridge trying to give help. Two or three men were crowing between two nearby banister-posts, and the distance between the two nearby banister-posts is about 0.85 m. There are 24 banister-posts on one side of the bridge, and the arc length of the bridge is inferred as $L = 20\text{--}22 \text{ m}$.

Assuming the timbers were in same lengths and same thickness, it is easy to find that the shape of the structural section is in a circular segment with radius R . Hence, with a simple calculation model shown in Fig. 8, the geometrical relationship takes the form as $L = 6\alpha R$, $d = R(1 - \cos\alpha)$, $\frac{L}{d} = \frac{6\alpha}{1 - \cos\alpha}$. Then, the span and the member length can be calculated by $l = 2R\sin(3\alpha)$ and $l_t = 2R\sin\alpha$ respectively. The calculation results of the range of these dimensions are shown in Table 1. In order to infer the dimensions of the bridge, the author studied the architectural materials of Song Dynasty, and found that big timbers of about 40 cm in thickness and longer than 7 m in length were used in buildings [5].

In the painting, tables and benches of market stalls can be found conspicuously, and it is easy to image that the slop of the bridge must not be steep for the furniture stand stately. Hence, a group of dimensions making a loosen slop can be selected from Table 1 as the possible dimensions the bridge:

Span: 18.42, Rise: 4.61 m, Member length: 7.02 m, Member thickness: 37 cm.

2.4 The Structural Feature

The Hongqiao is in form of arch. However, an ideal arch structure is known to be in form of catenarian or parabola and transfers thrusts mainly, and causes very small bending moment inside. In order to investigate the general structural properties of the bridge, static structural analyses were carried out with a simple model shown in Fig. 9.

Fig. 8 The geometrical model.

Table 1 Possible range of dimensions (m).

No.	L	D	d	l	h	l_t	l/h
A-1	20.47	0.37	0.55	17.37	4.61	6.70	3.77
A-2	20.47	0.38	0.57	17.11	4.78	6.69	3.58
A-3	20.47	0.40	0.60	16.84	4.94	6.68	3.41
A-4	20.47	0.41	0.63	16.47	5.15	6.67	3.20
B-1	20.93	0.37	0.55	17.90	4.63	6.86	3.87
B-2	20.93	0.38	0.57	17.63	4.80	6.85	3.68
B-3	20.93	0.40	0.60	17.37	4.96	6.84	3.50
B-4	20.93	0.41	0.63	17.01	5.17	6.82	3.29
C-1	21.39	0.37	0.55	18.42	4.64	7.02	3.97
C-2	21.39	0.38	0.57	18.16	4.81	7.01	3.77
C-3	21.39	0.40	0.60	17.91	4.98	7.00	3.60
C-4	21.39	0.41	0.63	17.55	5.19	6.98	3.38
D-1	21.85	0.37	0.55	18.94	4.65	7.17	4.07
D-2	21.85	0.38	0.57	18.69	4.83	7.16	3.87
D-3	21.85	0.40	0.60	18.43	4.99	7.15	3.69
D-4	21.85	0.41	0.63	18.08	5.21	7.14	3.47
E-1	22.31	0.37	0.55	19.45	4.66	7.33	4.17

E-2	22.31	0.38	0.57	19.21	4.84	7.32	3.97
E-3	22.31	0.40	0.60	18.96	5.01	7.31	3.79
E-4	22.31	0.41	0.63	18.62	5.23	7.29	3.56

Fig. 9 The model for structural analysis.

For a simple analysis process, referring to features of common wood, the material of the timbers is assumed as isotropic with an elastic modulus of 10^4 N/mm², and its density is assumed as 6×10^{-6} N/mm³. However, it is difficult to determine the exact loads applied on the bridge about 900 years ago. For the purpose to investigate the general properties of the structure, the distributed load applying on the bridge is assumed as 1.5 kN/m². While, hinged supports are taken as the boundary condition applied at the bridge feet, and the beams in same plane are connected one by one with pins.

As the analysis results, the deformation of the structure is shown in Figs. 10–12, show the distribution of the axial forces and the bending moments respectively. Then, the structural characteristics of the bridge are found below:

(1) Bending moments in an arch beam appear in both minus and plus direction, such that the extreme moments are smaller compared to that of a simple beam;

(2) Smaller axial forces appear at the top and bigger forces at the foot, which is similar to a typical arch structure.

However, it is very difficult to define the loading and boundary condition of a bridge built in more than 900 years ago. Different results may be obtained if

Fig. 10 The image of the deformation.

Fig. 11 Distribution of axial forces.

Fig. 12 Distribution of moments.

different analysis conditions were used. However, we may conclude that the bridge caused moments in its members, and thrusts occurred in the members as an arch structure does. Hongqiao was built with a very special structure system, which is different from trusses, arches and beams. Therefore, it is a new system for the modern structure, and the author names it “Lap-beam system”.

3. Application to Modern Structural Design

3.1 Lap-beam System

To create a new structural system by studying ancient structures and arts has been the research subjects of the author. By extending the horizontal members of the Hongqiao into an enough length, a cylindrical frame shown in Fig. 13a can be obtained. If the horizontal members of the cylindrical frame are designed in form of arch, a dome of Lap-beams can be obtained (Fig. 13b). It is interesting that the configuration of the Lap-beam system is similar to that of a basket meshing shown in Fig. 13c. In an ancient record the construction of a similar bridge was represented with a Chinese word “編(Bian)” which means “knitting”, and this word is basically used to represent making of baskets and closes, etc.. Therefore,

it is easy to image that the configuration of the bridge might be imitated from a mesh style of baskets. Of

course, several baskets are found in the painting Qingming Shanghe Tu.

Fig. 13 Lap-beam frame imitated from a basket mesh.

Fig. 14 A conic structure of Lap-beam.

Fig. 15 Lap-beam system with radial members.

Other study models of Lap-beam are shown in Figs. 14 and 15. Then, the geometrical characteristics of a Lap-beam system can be represented as:

(1) Two ends of a member are respectively set at the upper and lower joint-layers of other members;

(2) Two members clips another member mutually which works like cross-lap joints, or one end of a member laps onto another member.

3.2 1.5-Layer Space Frame

In the last section, the author pointed that the configuration of the Lap-beam system, as well as Hongqiao Bridge, might be imitated from a mesh style of baskets. While, there are several different meshing styles of baskets in ancient times and today, and Fig. 16a shows one of them. Study model shown in Fig. 16b represents the central lines of the bamboo mesh of the basket of Fig. 16a. By adding upper chords on to the frame of Fig. 16b, a frame shown in Fig. 16c can be obtained. Then, the author found that such a frame may emerge a new structural system which can be categorized as a type of space frame. It is easy to find that the frame has two layers of joints and one layer of members linked by diagonal members, so that the author named it a “1.5-Layer space frame”. Though the methods to assemble 1.5-Layer space frames are under research, the author tries to define such a structural system as: A 1.5-Layer space frame is a bar-linked structure with two layers of joints and there are not two or more joints in the same layer are linked by a member for one certain layer of joints.

The simplest unit used to assemble a 1.5-Layer space frame is found in form of a king post truss or a similar framework shown in Fig. 17. A 1.5-Layer space frame can be constructed by connecting one end of such a basic unit (point A in Fig. 17) onto the central point (point C) of another basic unit. By such a method, various types of 1.5-Layer space frames can be created. Fig. 18 shows two models of 1.5-Layer space frames in grids of rectangles and triangle-hexagons respectively.

It is easy to find that each lower joint of the structures in Figs. 16 and 18 has one degree of freedom in horizontal direction. This degree of freedom in horizontal direction can be constrained by suitable joint treatment or adding diagonal members as shown in Fig. 17. However, the basic units work as a bending system if we regard the whole unit as a continuum of a deep beam (a panel). Hence, the concept of the 1.5-Layer space frame shows the characteristics of the Lap-Beam of Hongqiao.

Because the 1.5-Layer space frame may be constituted by very few members, its structural

stability should be demonstrated. If a structure is not a stable one, a linear static analysis could not be run correctly for the rank of the stiffness matrix must be smaller than the number of equilibrium conditions, and that is the common knowledge. On the other hand, it is easy to predict that a flat frame with one layer of members and some diagonal members may cause big vertical displacement. In order to demonstrate the stability and deformation feature of a 1.5-Layer space frame, a linear static analysis is carried out with an analytical model of flat frame shown in Fig. 19.

The analytical model spans 30 m with vertical members of 1.5 m in length, and all the member section areas are assumed as 50 cm². Referring to common steel space frames, the elastic modulus of member material is assumed as 2.1×10^5 N/mm², and concentrated load of 18 kN is acting vertically at every joint. However, these analysis parameters are defined for simple mechanical demonstration only, and calculation for structural design is not carried out.

Fig. 16 Imitation of 1.5-Layer space frame.

Fig. 17 The basic unit.

Fig. 18 The possible assembling patterns of 1.5-Layer space frames.

Fig. 19 Analytical model of 1.5-Layer space frame.

Fig. 20 The displacement imagine.

The analysis results show that the extreme value of the vertical displacement is 7.45 cm which is found around the centre of the structure. Then, the extreme values of member forces are 332 kN and -473 kN. These results demonstrate that such a 1.5-Layer Space

Frame is stable, and suitable for big span space structures.

4. Conclusions

The present paper uncovered the structural principle of the Hongqiao, and calculated its dimensions as 18.42 m in span, 4.61 m in rise, with members of length 7.02 m and thickness of 37 cm. The author proved that the joints of the Hongqiao should be cross cut lap (mortise).

The present paper promoted two structural systems for modern structural design, Lap-Beam and 1.5-Layer space frame, which are inspired by the configuration of the Hongqiao. Both of the systems are very stable and suitable systems for big span space structures. However, structural features of Lap-Beam and the 1.5-Layer space frames are remained for further researches.

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References

- [1] P. S. Chen, Configuration and structural principle of an ancient Chinese wood bridge Hongqiao, in: IASS 2007 Symposium, Sep. 3–6, 2007.
- [2] P. S. Chen, A study report on an ancient wood bridge Hongqiao, SEI (Structural Engineering International) 18 (1) (2008) 84–87.
- [3] H. C. Tang, Chinese Ancient Bridges, Wenwu Publishing House, 1987. (in Chinese)
- [4] Cultural Bureau of Fujian Province, Researches on Wooden Corridor Bridges of Hongqiao Style in Ningde City, Science press, Beijing, 2006. (in Chinese)
- [5] S. C. Liang, Collected Works of Architecture, SDX Joint Publishing Company, 2006. (in Chinese)