Geometric Construction and Static Analysis on Timber-Arched Structural System of Shouning Timber-Arched Lounge Bridge

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Abstract. Due to the disrepair, many timber-arched lounge bridges have structural safety hazards and require protection. This paper analyzed the structural composition as well as the composition principle of Shouning timber-arched lounge bridge. It is found that the timber-arched bridge structure belongs to highly indeterminate. The ANSYS finite element simulation analysis of timber-arched lounge bridge shows that three-node and five-node seedlings are the components which are mainly subjected to axial force. Their shear stress is only 12% of the axial stress. Three-node and five-node seedlings make full use of the tensile and compressive properties of wood. At the same time, the portal framed bent, horse leg also play an important part in the structure. The double bridging is the important component to guarantee the wind resistance, earthquake resistance and transverse stability of bridges. The results of this paper have academic guidance meaning for the maintenance and reinforcement of timber-arched lounge bridge.

1. Introduction
The historical site resources in Shouning timber-arched lounge bridge are abundant and 19 ancient timber-arched lounge bridges exist in the territory. With ingenious structure and superb construction technology, those timber-arched lounge bridges have the highest bridge technology in ancient China\cite{1}. However, as time passes, Shouning timber-arched lounge bridge has many problems, such as decadent main component, serious local deformation and disconnecting base node. All of those problems need to be solved by maintenance and reinforcement. This paper analyzed the stress characteristics of Shouning timber-arched lounge bridge and provided the theoretical support and countermeasures for the reinforcement of timber-arched lounge bridge.

2. Analysis of structural composition of Shouning timber-arched lounge bridge
Shouning timber-arched lounge bridge is made by wooden components (as shown in Figure 1) and it stretches across the stone pier at both ends of the valley. Its timber arch is the structure system which has the highest technology in the ancient wooden bridge \cite{2}. The upper gallery has the post and lintel frame with four columns and nine beams \cite{3}, which is covered with grey tiles. The arch span structure of Shouning timber-arched lounge bridge is mainly formed by two groups of seedling systems interspersed with each other. The first system is called three-node seedling system, which consists of three seedlings and two beams (called cow head). The second system is called five-node seedling system, which consists of five
seedlings and four beams [4]. The first system and the second system weave each other to form the load-bearing unit, which is formed by the repeated arrangement along the horizontal direction (as shown in Figure 2). The formed timber-arched structure consists of nine three-node seedling systems and eight five-node seedling systems.

![Figure 1. Scene of Shouning timber-arched lounge bridge](image1)

![Figure 2. The combination of three-seedling system and five-seedling system](image2)

The combination of three-seedling system and five-seedling system and the bridge deck seedling system is called timber-arched structure system, as shown in Figure 3. The main components of the whole bottom timber-arched structure include seedlings, cow head, double bridging, small framed bent, horse leg general column and deck seedling (as shown in Figure 3).
Figure 3. Composition of timber-arched structure system

The seedling in the figure refers to the longitudinal round timber; the cow head is the joint between the seedling and the seedling; double bridging is cross-shaped, whose ends are connected with cow head and samson post; small framed bent is the portal structure for supporting side span seedling; horse leg is the diagonal component for supporting the small framed bent under the bridge deck; samson post is the main king tower in the bridge platform.

3. Geometry variability analysis of timber-arched structure system

The timber-arched structure is the reticulated structure, which consists of seedling and cow head. The cow head and seedling are connected by the swallow tail. The Cunninghamia lanceolata used in the bridge belongs to softwood, so the swallow tail head could rotate, which is similar to the plastic hinge. Therefore, the node of cow head is simplified to the joint point. Based on the analysis above, the timber-arched structure system is simplified to the hinge structure of bar and the geometry variability analysis of the system is shown as Table 1.

According to the geometry variability analysis principle in the structural mechanics, the variance in the structure $w$ is calculated by formula:

$$w = 2j - b$$

where $j$ represents the number of pin-connected joint and $b$ represents the constraint number of chain pole.

The result shows that the three-node seedling system and five-node seedling system are the geometrically unstable systems, but they become statically indeterminate structure after superposition. The unit formed by three-five-node seedling and bridge deck seedling system has ten redundant constraints. Therefore, the whole bridge has eighty redundant constraints, which has eight complete units.

Table 1. Calculation of geometric variability of timber-arched structure system.

| System            | Structural Illustration | $W$          |
|-------------------|-------------------------|--------------|
| Three-seedling    |                         | $2j - b = 2 \times 4 - 3 - 7 = 1$ |
| Five-seedling     |                         | $2j - b = 2 \times 6 - 5 - 4 = 3$ |
4. Finite element analysis of timber-arched structure under the under static load

4.1. General situation of finite element modeling

Based on the actual size of Shouning timber-arched lounge bridge, this section used the finite element software ANSYS to establish the model. The model adopted the beam element with circular section to replace the seedling. According to the actual mapping results, the diameter of seedling is 250 mm. The mortise-tenon joint among seedlings use solid joint and put down freedom degree, which imitates the pin-connected joint [5-6]. The manual partition is used in the division of the units and the cell density is increased in the connecting place to improve the calculation accuracy.

In the aspect of loads applying, the action of the vertical and horizontal loads is considered. The vertical load is exerted in the cell node of the bridge deck. Every node has 1N and there are totally 4000 nodes and 4000N vertical uniform loads. The lateral load is exerted in the side of bridge deck and there are 4000N lateral loads.

4.2. Force analysis under uniform vertical load

Under the action of vertical load, the characteristic of the three-node seedling and five-node seedling of the timber-arched structure is its axial compressive stress. As shown in Figure 4, the largest compressive stress is 4.83Kpa. When the shear stress is relatively small, the largest shear stress is 0.59Kpa, which is 12% of the largest compressive stress. Therefore, the characteristics of the three-node seedling system and five-node seedling system are compression structure, small bending moment and shear force. The systems make full use of the compressive strength of the wood. However, there is stress concentration and even large tensile stress in the cow head of seedling, which will lead to the release of the contact between the cow head and the seedling mortise.

Portal small framed bent of both sides plays an important role in supporting the load from the bridge deck seedling. The setting of the portal frame column is insufficient, which will make the sinking deformation of the bridge deck seedlings more serious, as shown in the figure 4. The uprightly post of portal framed bent is subjected to relative large axial compressive stress. As the component to support the small framed bent, horse leg is still under the large pressure. Although these two components are small and quantity is few, their bearing effect is large, which needs to be taken seriously.

Figure 4. axial compressive and shear stress nephogram

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4.3. Force analysis under the action of horizontal loads

As shown in Figure 5, under the action of horizontal loads, tensile stress occurs on the left and right sides of the three-node seedling and five-node seedling and the closer they are to the pier, the greater the tensile stress appears. In the actual practice, the seedlings are directly supported by the pier and they have no tying. Therefore, the seedlings are the important hidden dangerous part. The axial tension stress and compressed stress that the double bridging are subjected to reach the largest value. It is found that the double bridging plays an important role in the horizontal load, wind load and earthquake loading, which effectively guarantees the lateral stability of the bridge.

Figure 5. axial compressive and shear stress nephogram under the action of horizontal loads

5. Conclusions

This paper carried out the geometric structure and force analysis of timber-arched lounge bridge and made the following conclusions, which provided theoretical guidance for strengthening and repairing timber-arched lounge bridge.

(1) In the system of timber-arched structure, the three-node seedling and five-node seedling are geometrically unchangeable system, but they become the statically indeterminate structure after the first superposition and become bridge deck seedling system after the second superposition, which significantly increases the number of statics. Therefore, during the process of bridge repair, part of the seedling is allowed to be replaced without making the bridge become the variable system under the condition of guaranteeing the bearing capacity.

(2) The three-node seedling and five-node seedling form the main load-bearing system, whose force is reasonable. Under the action of vertical load, the seedling is mainly subjected to the axial compressive force and its shear stress is small. Therefore, it can be inferred that the bending moment is also small. In the actual practice, it is necessary to guarantee the safety of the seedling and replace the corrosive and serious cracked seedling in time. It is suggested to increase the number of portal framed bent and horse leg to reduce disturbance of bridge deck seedling since they are subjected to the large axial stress under the vertical load.

(3) As the developing node of seedling, the cow head has obvious stress concentration. Therefore, it is more reasonable to use hardwood as the cow head.

(4) With the largest force under the lateral load, the double bridging is the important component to guarantee the wind resistance, earthquake resistance and transverse stability of bridges. The strength of scissors gallows timber should be sufficient and the nodes need to be firmly connected.

References

[1] Chunping Cao(2009). Fujian-Zhejiang Timber- Arched Bridge. Fujian Architecture,(9):10.
[2] Huancheng Tang(2010). Chinese Timber- Arched Bridge. China Architecture & Building Press. Beijing.
[3] Ying Zhang(2011). Technical Analysis of the Construction of Fujian-Zhejiang Timber- Arched Bridge. Journal of Fuzhou University (Natural Science Edition). 39:918-919

[4] Wenqiang Lu, Bo Zhang(2011). Development and Protection Measures for the Value of Fujian-Zhejiang Wood Arch Corridor Bridge. Sichuan Academy of Architectural Sciences, 37:105-108

[5] Jiajia Ou(2014). Finite Element Analysis of Stress Mechanism of Timber- Arched Gallery Bridge. Zhejiang University, Hangzhou.

[6] Weirong Lv. Zhi Chen.,(2014). Numerical simulation and internal force analysis of long-span wooden arch bridge. Journal of Central South Forestry University.34;87-88