Research on the Stress Analysis and Performance Optimization of Lounge Bridge— A Case Study of Xuezhai Bridge

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Abstract. Lounge bridge is a historic form of bridge, widely distributed in Fujian and Zhejiang provinces in China. Through the lap and support of wooden poles, the structure is simple but very strong, and it is considered to be a unique structure in the history of bridges in the world. In this paper, taking Xuezhai Bridge as an example, the lounge bridge is divided into three main stress systems: bridge deck, three-link and five-link mechanism. The method of elastic mechanics and finite element is analyzed, and the performance of the main materials used in the lounge bridge and the connection mode of mortise and tenon are combined to find the structural defects and the design that can be optimized. By studying the content obtained by analyzing the Xuezhai Bridge in the previous researches, and using modern knowledge, a scheme is proposed to improve the mutual lap design, structural stability and joint strength of the lounge bridge, so that the lounge bridge is more in line with the modern use needs.

Keywords: Lounge Bridge; stress analysis; tenon; Timber Bridge; structural optimization.

1. Introduction

Lounge bridge, also known as "wooden arch bridge that can be penetrated by wind and rain". Because there is a bridge corridor built on the bridge as the main use area, it is also called "house bridge". The wooden arch bridge originated from the Northern Song Dynasty in China and is mainly distributed in the rugged terrain of Fujian and Zhejiang. Currently, there are more than 100 ancient lounge bridges preserved in China, which are facing the problem of gradual disappearance. In 2009, the skill of building Chinese lounge bridges was included in the UNESCO's "List of Intangible Cultural Heritage in Need of Urgent Safeguarding" [1]. The construction techniques of lounge bridges include two major parts: design and construction. Before building a bridge, it is necessary to design lounge bridges with different spans based on natural and hydrological environmental factors. Lounge bridges have a multi-layer complex stress structure, with beams interlaced and pressed to form an arch bridge. The bridge piers are supported on rocks on both banks, and the base is formed by dozens of large round timbers spliced vertically and horizontally to form a "chair-type structure". No nails or rivets are used, and it relies entirely on its own strength, friction, diameter, angle, and horizontal distance for clever jointing. Although the structure is simple, it is extremely solid. Its unique wooden weaving form not only increases the span of the bridge, but also uses a large amount of mortise and tenon joinery for connection. It is composed of all wooden materials to form a large-span arch shape, and is therefore considered a unique structure in the history of bridge engineering worldwide [2].

The structural system of the lounge bridge includes four force-bearing systems: multiple sets of three-link mechanism, multiple sets of five-link mechanism, bridge decking, and the superstructure. Each structural system is internally connected using mortise and tenon joints, and more wooden poles are used for overlap and support between structures. The three-link mechanism and five-link mechanism are connected to the stone pads, and the overall structural load is transferred to the ground through the vertical force-bearing bars at the edges [3]. This paper focuses on the single-arch lounge bridge, which is the most widespread and commonly used type. Taking Xuezhai Bridge (built in 1856) in Taishun County, Zhejiang Province, China, as an example, the superstructure is considered as a rigid body without internal force analysis. The focus is on analyzing the internal forces within the bridge decking, three-link mechanism, and five-link mechanism, as well as the interaction between

the force-bearing systems. At the same time, the mechanical properties of the mortise and tenon joints in the lounge bridge are explored. Through these analyses, combined with modern practical needs, the structural defects and areas for improvement can be identified.

2. Structural Analysis of Lounge Bridge

The lounge bridge has a simple but ingenious supporting structure, as shown in Fig. 1. The primary material used in the construction of lounge bridges is Chinese fir. Whole logs are particularly employed for the three-link mechanism and five-link mechanism, serving as the main load-bearing supports of the bridge [4]. In terms of mechanical properties, the tensile and compressive strength of Chinese fir along the grain direction is significantly higher than that in other directions. According to research, the bending strength of Chinese fir in the grain direction is 15 N/mm^2, shear strength is 1.5 N/mm^2, and compressive strength is 12 N/mm^2. However, over time, the bending capacity of Chinese fir gradually decreases. Therefore, the force-bearing form of the three-link mechanism and five-link mechanism in lounge bridges should be more inclined towards tension and compression, in order to fully utilize the material's performance [5].



(a) Three-link Mechanism (b) Five-link Mechanism (c)Main Load Transfer Structure

Fig. 1 3D Diagram of the Main Stressed Structure

2.1. Bridge Deck

According to actual monitoring measurements, it is observable that on the Xuezhai Bridge, under constant load, there are three distinct downward deformation records in the areas unsupported by the three-link and five-link mechanism [6]. Notably, the middle section of the bridge deck experiences the most significant downward concavity, as exemplified by the case of the Guangfu Bridge. Beneath the middle section of the bridge deck lies the top bar of the five-link mechanism. Therefore, during the design phase, it is crucial to leave sufficient clearance between the bridge deck and the top bar of the five-link mechanism, rather than having them in close contact. If the middle section of the bridge deck experiences excessive concavity, it can transfer bending loads to the top bar, significantly increasing the bending load on the top bar of the five-link mechanism, making the structure more susceptible to damage.

2.2. Three-Link and Five-Link Mechanism

The three-link mechanism, located beneath the bridge deck and the superstructure, directly supports these two components while connecting downward to the abutments. Interlaced with the five-link mechanism, it serves as the most crucial load-bearing structure of the entire bridge, primarily responsible for transmitting loads. The forces it experiences are primarily axial compressive forces, with the maximum axial force occurring at the bottom brace of the three-link mechanism. Shear forces are relatively minor, with the maximum occurring at the center of the top bar. According to the study by An and Wu [6], the maximum axial force in the three-link mechanism of the Xuezhai Bridge is located at the connection of the side bar's lower section, reaching up to 164.1 kN, with a maximum positive stress of 6.45Mpa. In contrast, the maximum shear force, occurring at the connection of the top bar, is only 24.1 kN, resulting in a shear stress of 0.97 Mpa.

The five-link mechanism passes through the three-link mechanism, increases the path of the superstructure and the bridge to the lower part of the load transfer, plays the role of sharing the load

in the stressed structure, and can be used as the insurance of the three-link to ensure the safety of the bridge body in an emergency. However, according to the calculation of SAP2000, the bearing capacity of the five-link mechanism is 7.6% to 14.4% lower than that of the three-link mechanism, which can only be used as an auxiliary support, and must be repaired in time when the three-link mechanism is damaged, so in most cases it should be used as an auxiliary structure with three-links mechanism [7]. At the same time, because there is no direct connection between the three-link and the five-link mechanism, and the structure is relatively simple the structure of the lounge bridge has a poor ability to resist the lateral load through the finite element method [1]. And, there is a possibility of failure in the case of large and uneven left and right loads [8].

2.3. Mortise and Tenon Joints

The internal connections of each load-bearing system in the lounge bridge are facilitated by mortise and tenon joints. These joints rely on axial bearing capacity, bending bearing capacity, and structural friction to connect different components. A crucial aspect is enhancing the bearing capacity of the mortise and tenon joints [1]. The primary types used are the straight mortise and tenon joint and the swallowtail mortise and tenon joint. The mechanical properties of these joints are influenced by the connection angle, pin length, and cross-sectional area of the pin. Specifically, the cross-sectional area of the pin positively correlates with the ultimate bearing capacity and stiffness of the mortise and tenon structure. However, once the diameter exceeds 320mm, the growth rate rapidly diminishes. Longer pins enhance the rigidity of the joint, and the ultimate bearing capacity reaches its maximum at a pin length of 180mm. Increasing the pin length beyond this point leads to a decrease in ultimate bearing capacity. Additionally, a larger connection angle between the bars enhances the ultimate bearing capacity of the mortise and tenon joint but does not significantly affect its rigidity. In traditional lounge bridge designs, the connection angle of the mortise and tenon joints is typically around 45°, balancing load-bearing performance and increasing the bridge's span. However, due to varying load requirements, different bridges may adjust this angle according to practical considerations [9].

3. Structural Defect Optimization

In the afore mentioned structural analysis and research on lounge bridges, taking Xuezhai Bridge as an example, it can be found that these bridges excel in their ability to bear and transfer loads. However, numerous defects in this type of bridge have also been identified. Based on the structural analysis, many structural functions that can be optimized have been discovered, including the additional bending load imposed on the five-link mechanism by the bridge deck, the vulnerability to damage under asymmetric loads, and the limitations in force bearing capacity of the mortise and tenon structure. This paper further analyzes and dismantles these three issues, attempting to propose solutions to make the bridge structure more reasonable and reliable.

3.1. Treatment of Extra Bending Load

The support provided by the five-link mechanism to the bridge deck mainly relies on the connection between the top bar and the side bar or the direct force bearing capacity of the top bar. This results in direct contact or a small gap between the bridge deck and the top bar of the five-link mechanism [7]. Once the middle section of the bridge deck is stressed and bends, it will transmit additional bending loads to the top bar. Over time, the deformation of the bridge deck and the additional bending of the top bar will continue to increase. Bending and tension-compression are the main load-bearing modes of the top bar of the five-link mechanism. The addition of extra bending loads increases the probability of its damage.

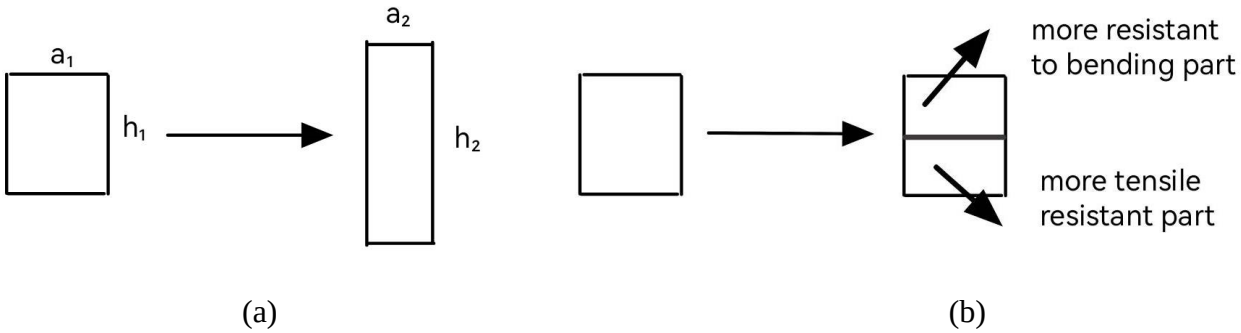

Fig. 2 Top Bar of the Five-Link Mechanism

To address this issue, there are two potential approaches. Firstly, the bending height between the bridge deck and the top bar can be increased to maintain tensile performance while enhancing bending capacity without adding additional structure. This can be achieved by increasing the height and reducing the width of the top bar's wooden material, thus improving the bending height without affecting tensile performance, as shown in Fig. 2(a).

Alternatively, the top bar of the five-link mechanism can be divided into two separate bars, with the upper bar made of a material with greater stiffness and bending resistance. This upper bar will be closely attached to the bridge deck, bearing the bending moment transmitted from the bridge deck and part of the tensile force from the side bars. The lower bar will be made of a material with higher tensile strength, primarily bearing the axial force from the side bars. The cross-sectional area of the two bars combined will be the same as the original five-link top bar. A gap can be left between the upper and lower bars to further reduce the impact of the bridge deck's bending moment on the lower section, as shown in Fig. 2(b).

3.2. Vulnerability to Damage Due to Asymmetric Loads

Both the three-link and five-link mechanism of lounge bridge are unable to effectively transfer excessive loads from one side to the supporting structure on the other side when faced with large, concentrated loads on one side [8]. When the same force is applied at different locations, it can generate loads on both sides that exceed normal conditions, leading to greater structural challenges. This is primarily due to the deformation of the three-link and five-link mechanism caused by horizontal component forces. As one side of the structure deforms and collapses downward, the change in the angle of force application further increases the load, rendering the other side's supporting members ineffective. This deformation may even cause the three-link and five-link mechanism to collide and compress each other, significantly increasing the risk of structural failure [7].

To address this issue, structural enhancements can be made to the five-link mechanism. Compared to the three-link mechanism, the five-link mechanism is more inclined towards horizontal load transfer and provides greater support span for the bridge deck. As the three-link mechanism serves as the primary load-bearing structure, its structural stability is crucial for the overall structure. Modifying its structure and altering its load-bearing mode can significantly reduce the structure's load-bearing capacity. Therefore, it is more feasible to enhance the functionality of the five-link mechanism. The only two horizontal external forces supporting the five-link mechanism are provided by the two fixed anchoring piers at the bottom. The upper side of the five-link mechanism is prone to deformation when subjected to horizontal forces. To address this, a bar to expand the stress can be connected between the secondary and bottom bars of the five-link mechanism, extending towards both banks (Fig. 3). This expands the stress bar primarily provides horizontal tensile force, allowing the structure to receive horizontal restraint in addition to that provided by the piers when subjected to horizontal component forces. This reduces the structural deformation when faced with large, asymmetric loads, enabling a stable and uniform downward load transfer. Furthermore, this expand the stress bar is

directly connected to the riverbank, which applies a significant upward tensile force, reducing the additional downward load on the five-link mechanism caused by the additional structure.

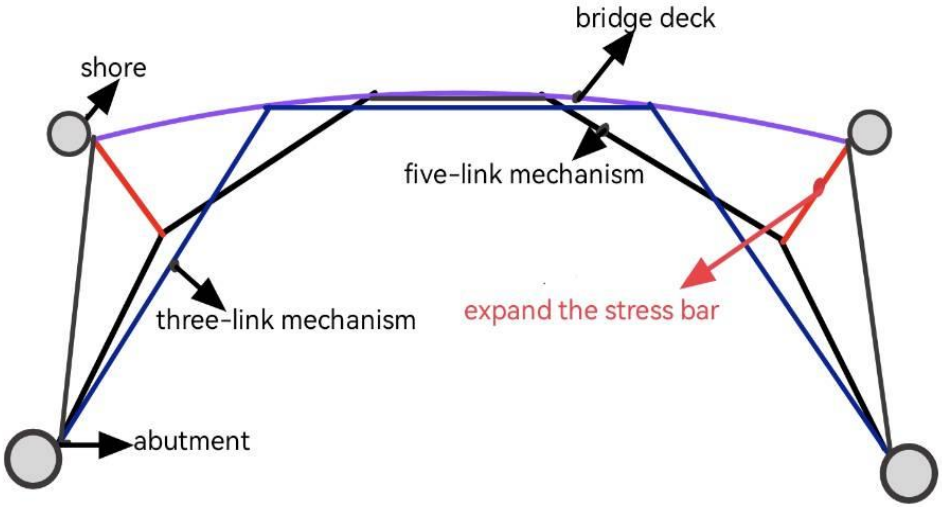

Fig. 3 Diagram of Stress Bar Expansion

3.3. Optimization of the Mortise and Tenon Structure Performance

The mortise and tenon structure are an intelligent and excellent form of connection, maintaining nearly the same strength as the original material at the connection points. However, as the most important and vulnerable part of the entire structure, the connection points can fully utilize modern materials to further enhance the bearing capacity of this excellent connection method. For example, inserting a thin steel bar vertically at the mortise and tenon connection can improve the shear bearing capacity of the connection to prevent fractures. There are many similar methods, and the impact on the overall weight of the structure is minimal.

4. Conclusion

(1) Structurally speaking, the lounge bridge is ingenious and excellent. It creates a bridge with a large span and good bearing performance solely through the overlapping and support of wooden structures. The division of the structure is also very reasonable and effective. The three-link and five-link mechanisms provide two forms of support to the bridge deck. The two load-bearing systems share the load and provide mutual insurance. Through a very simple structure, the functional structure composed of the superstructure and the bridge deck obtains effective support and load transfer. The mortise and tenon structure are utilized at the connection points, and this excellent connection method enables the connection to have nearly the same strength as the original material without using other strengthening materials.

(2) This ancient form of bridge also faces many structural issues. For example, the bridge deck may cause additional bending loads on the five-link mechanism, and this problem may increase the chance of bending failure of the three-link top bar over time compared to other members. This issue can be effectively addressed by improving the bending capacity and performance of the top bar. When facing large asymmetric loads, the deformation of the support structure is also an important issue. Expanding the five-link mechanism to obtain additional horizontal constraints is one of the good methods to solve this problem. At the same time, the mortise and tenon structure can also play a better role with the help of new materials.

(3) Lounge bridges are the treasures of Chinese culture and have been listed in the Urgent Safeguarding List of the Intangible Cultural Heritage of Humanity by UNESCO. At present, China has rebuilt many lounge bridges to review history and strengthen the local cultural hypothesis. It is crucial and urgent to carry out modern adaptive transformation and promote the development of their

structures. It is hoped that this paper can inspire and encourage people who are building and improving the structures of lounge bridges, so that the time-honored lounge bridge can rejuvenate.

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