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Study on the Architectural Structure of Yunnan Wooden Arcade Bridge

-- Based on the Comparison with Fujian Wooden Arch Corridor Bridge

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Abstract. As the most representative ancient bridge in Yunnan, the wooden arch gallery bridge in Yunnan has its own unique architectural structure. It not only reflects the superb architectural structure of ancient bridges but also reflects the unique aesthetic taste, folk customs, and cultural concepts of local ethnic minorities. This paper makes a comparative study of the architectural structure of the Yunnan wood arch corridor bridge and Fujian wood arch corridor bridge and shows the unique single outrigger beam system and saddle frame system of the Yunnan wood arch corridor bridge. At the same time, the reasons for the adoption of through and half-through wooden arch bridges in Yunnan and the adoption of upper-bearing wooden arch bridges in Fujian were analyzed and studied.

Keywords: Yunnan Province; Wooden Arcade Bridge; Building Structure.

1. Distribution of Wooden Arcade Bridge

Yunnan is a mountainous plateau terrain. The topography of the whole province is high in the northwest and low in the southeast, and it descends step by step from north to south. The northwest is high and the southeast is low, and the rivers are interspersed with deep mountains, forming a canyon landform with high mountains, deep valleys, and rapids. There are many rivers and lakes in the province. The unique natural and geographical conditions in Yunnan have brought many difficulties to the construction of wooden arcade bridges, so the development of covered bridges tends to be concentrated in a small part. Wooden arcade bridge is more common in Tengchong City, Yunlong County, and other places, forming a concentrated ancient bridge community on the Bijiang River.

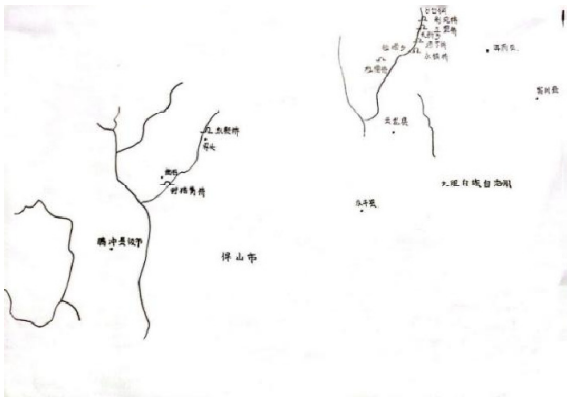


Fig 1. The distribution map of ancient bridges in Yunlong County

2. Classification of the Wooden Arcade Bridge

2.1. Simple Braced Wooden Arcade Bridge Arch

The simple braced arch wooden arcade bridge is an ancient wooden bridge construction form, and it is a stage of beam-to-arch evolution. Its characteristic is that the lower part of the bridge is attached with a brace, which is fixed on the ground through simple support, forming a stable bridge structure [1]. The whole truss system of the simple braced arch wooden arcade bridge is composed of two diagonal members or three diagonal members, that is, the most common herringbone and splay supports, which rely on the stress and bearing capacity of wood to support the bridge, so this support form is also called the basic system. In the later period, the wooden arcade bridge gradually evolved on the basis of the basic system, from simplicity to complexity, and gradually formed a complete wooden arcade bridge system [2]. In addition, most wooden arcade bridges usually build wooden eaves, corridors, and other buildings on the bridge deck. Among them, the wooden arcade bridge with a simple support frame in Yunnan is represented by Fengqing Dahua Bridge, Weishan Yongji Bridge, Yunlong Wuli Bridge, and Jiancao Bridge.

2.2. Cantilever Wooden Arcade Bridge

The cantilever wooden arcade bridge is a simple-supported beam with one or both ends hanging out freely with its upper structure as its main load-bearing structure. In Yunnan, the horizontal outrigger and splayed braced wooden arcade bridge are commonly used. The horizontal outrigger is a structural system with one end extending from the fulcrum to support a hanging beam. The structural characteristics do not affect the requirements of the bridge itself for geological conditions and temperature conditions, but the outrigger is adopted to make it adapt to occasions with large river spans [3]. It is similar to the combined bridge structure, and its corresponding construction technology is more complicated than that of the simple braced wooden arcade bridge, so the combined bridge structure is seldom used in other areas, while the horizontal outrigger and splayed braced wooden arcade bridge are widely used in the complex river system of Bijiang, Yunnan. Among them, there are Tongjing Bridge, Caifeng Bridge, and Yongzhen Bridge in Yunlong County, Dali, which are representative of the wooden arcade bridge.

3. Comparison of Architectural Structures between the Wooden Arcade Bridge in Yunnan Province and the Wooden Arcade Bridge in Fujian Province

The wooden arcade bridge community in Yunnan Province is relatively concentrated, among which the wooden arcade bridge in Yunlong County is the most representative. The wooden arcade bridge in Yunlong County cannot erect piers in the middle because of the wide river surface and fast current. It is necessary to erect wooden purlins from the piers on both sides of the river, which extend to the center of the river in turn, just like an outstretched arm to support the whole bridge. The bridge is also covered with tiles to shelter pedestrians from the wind and rain, which is also called the “Fengyu Bridge”. At the same time, it looks like a promenade on the water from a distance, which is also called a “Covered Bridge”.

The wooden arcade bridge in Fujian is also known as “Fengyu Bridge”. Covered bridges have a history of about 2,000 years in China, and there are only more than 110 wooden arcade bridges in China. As a concentrated area of wooden arcade bridge cultural heritage buildings in Fujian and Zhejiang, there are more than 80 wooden arcade bridge buildings in Fujian, which are mainly distributed in Ningde, Nanping, and Fuzhou in the northeast part of Fujian. At the same time, Fujian province has a subtropical monsoon climate, with abundant rainfall, rich water resources, and complex and changeable topography and landforms, which have created a developed water system in this area. There are many tributaries of the river, which are distributed in a dendritic or reticular manner, and the river has a large span, so the single-span covered bridges are not enough to meet the requirements of strength and stability. Therefore, most of the covered bridges in Fujian are multi-span covered bridges [4]. The Fujian wooden arcade bridge is constructed by vertical integration of

subsystems from bottom to top. The three-part structural system of the abutment (pier), bridge body, and corridor house is relatively independent and integrated, which not only forms a unique structural mode of the covered bridge but also forms a style of bridging the river, building corridors on the bridge, protecting the bridge with corridors and integrating the bridge with corridors [5]. In terms of the structure, Fujian wooden corridor arch bridge adopts wood-weaving technology and tenon-mortise technology, and it can be stable and firm without using nails and iron sheets in the construction process.

Due to the influence of geographical environment, ethnic customs, and regional factors, the wooden arcade bridge in the two places is quite different. The following will compare and analyze the architectural structures of the wooden arcade bridge in Yunlong County and the wooden arcade bridge in Fujian Province.

3.1. The Comparison of Piers

Pier is the main support of the bridge, and the superstructure of the bridge is set above the pier. The abutment, located at both ends of the bridge, supports the superstructure of the bridge and is connected with the embankment. The abutment can not only bear the pressure generated by the superstructure of the bridge and transmit it to the bridge foundation but also resist the pressure brought by the mountain behind the abutment, stabilize the bridgehead, and make the bridgehead line and the bridge line achieve the effect of a reliable and stable connection. As the supports and joints of bridges, piers, and abutments also have certain regional differences, that is, different pier and abutment structures are produced in different regions to adapt to different environments.

In Yunlong County, Yunnan Province, the site selection of bridge construction is mostly the river section with a small river span, which flows through the Nujiang River, Lancang River, and Bijiang River in Yunlong County, and the water is fast, so it is not suitable to erect piers in the middle. Therefore, the single-span wooden arcade bridge is adopted, and piers and abutments are only erected at both ends of the bridge. However, the water systems of Minjiang River, Oujiang River, Feiyun River, and Jiaoxi River, which flow through Fujian Province, are complex. For the river sections with large river spans, a multi-span wooden arcade bridge should be built, and piers should be erected in the center.

In Yunlong area, there are mostly wooden arcade bridges with stone piers. Piers are only set at both ends, such as Tongjing Bridge, which adopts a stone-solid structure. The piers are provided with pier caps and connected to the foundation, which makes full use of the compressive properties of materials. Moreover, the piers of Yunlong Stone Pier wooden arcade bridge are mostly very thick rectangular solid piers, which bear external forces in vertical and horizontal directions by virtue of their large cross-sectional size and weight, and can better resist the impact of water flow, adapt to the deep water level and the environment with large water level changes, and are erected to the center of the river in turn. However, the multi-span wooden arcade bridge in Fujian Province is mainly built with boat-shaped solid stone piers. Because of the large span of the river, it is necessary to build piers in the middle of the river to provide support to ensure the strength and stability of the bridge. For example, Wan' an Bridge is a wooden arcade house bridge with five piers and six holes, with a length of 98.2 meters. The long span causes Wan' an Bridge to erect five ship-shaped solid stone piers in the middle, with unequal spans. The shortest arch span is 10.6 meters and the longest arch span is 15.2 meters. The stone pier is thick and has a certain height, which can resist large water impact and adapt to the river basin with large water level change and will not cause the wood of the bridge body to be eroded due to the rising water level, thus affecting the overall safety of the bridge. In order to further improve the overall safety of the bridge, a stone pier is built in the middle of the long-span bridge, which can reduce the impact of water flow and solve the problems of the long-span bridge. The continuous decline in the middle of the span and the cracking of the beam. The long-span bridge also has the characteristics of a high tower, large span, light weight, flexibility, and weak damping, so it is very sensitive to wind. Erecting a pier in the middle can effectively avoid structural damage caused by bridge resonance caused by wind. Ship-shaped stone piers, which can reduce the impact of water flow,

can be divided into single-pointed ships and double-pointed ships. Single-pointed stone pier, generally with the pier tip set upstream, has little effect on blocking water flow and can reduce the impact of water flow on the pier. Double-pointed stone piers are equipped with water diversion tips upstream and downstream, and the downstream water diversion tips can weaken tidal waves.

Fig 2. Bridge piers are set at both ends of Tongjing Bridge

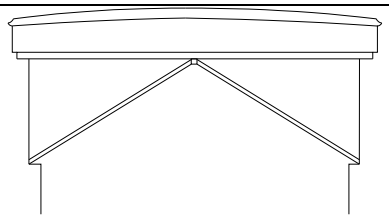
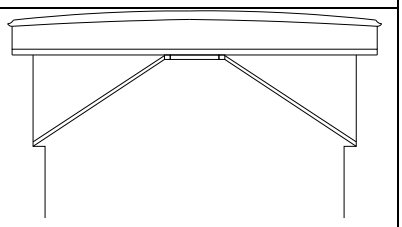
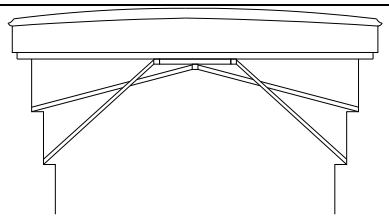
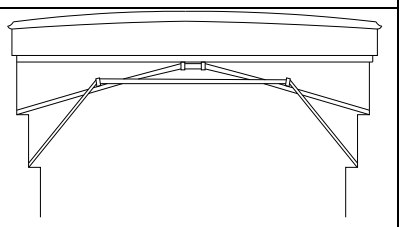
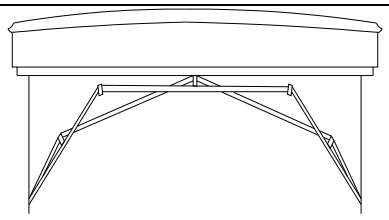
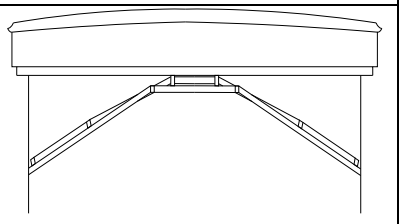
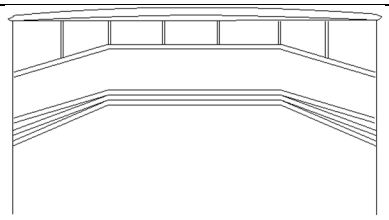
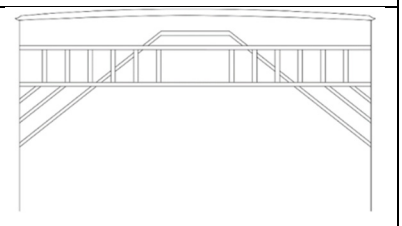
Fig 3. Five ship-shaped stone piers are erected in the middle span of Wan' an Bridge

3.2. The Comparison of Bridge Arch Structures

As the main load-bearing structure of the bridge, the arch structure of the bridge body is located at the upper part of the bridge. The most typical systems of bridges in Yunnan Province are the cantilever beam system and saddle frame system in Yunlong County, Dali City. The abutment of the single outrigger system is made of stone, and the upper main deck is made of wood to bear the load. On the abutments at both ends of the bridge, wooden purlins are used to pick it out layer by layer. After each pick-out, a crossbar is used to connect and reinforce it, and then the second floor is picked out based on the first pick-out, so that the original straight line of wood is gradually picked out layer by layer, and an arc curve is formed on the whole bridge body through this process. Therefore, it can be said that the load-bearing part of the outrigger wooden arcade bridge transits from a straight line to an arc, which endows the bridge with a soft curve [6]. Yunlong County adopts a single cantilever beam system that is lifted from the abutment, and usually, it will be lifted three times. However, for long-span systems, in order to shorten the net span of the bridge deck beam and increase the stability of the bridge, the number of times of picking can also be increased, such as Tongjing Bridge, which has been picked up for 7 times in total. As a unique oblique support system in Yunlong County, Dali City, Yunnan Province, the saddle frame system, based on the single cantilever beam system, extends an oblique wooden support column from the abutment to the middle of the bridge, and receives a girder upward to form a saddle frame composite member. As the upper part receives the girder, the saddle frame presents a suspension structure and hangs on the bridge deck, which helps the bridge deck girder to share the load and reduce the stress, thus significantly reducing the number and section of the bridge deck girder, and meanwhile increasing the binding force, making the connection more stable.

Although wooden arcade bridges in Fujian and wooden arcade bridges in Yunnan are the same in appearance, wooden arcade bridges in Fujian are different from the above two typical wooden arcade bridges in arch structure, and the supporting wooden arcade bridges in Yunnan Province are mainly middle-bearing and under-bearing structures and wooden arcade bridges in Fujian Province are mostly upper-bearing structure, which causes the differences in bridge technology between Yunnan Province and Fujian Province. This paper will analyze and discuss the reasons in the fourth section. The most distinctive feature of the wooden arcade bridge in Fujian lies in the arch system of the wooden arcade bridge and the seedlings that form the arch. There are six types of arch structures in the wooden arcade bridge in Fujian, from simple to complex, and the type abbreviation is named in the form of "the number of arches in the first system-the second system". Type II, the most basic herringbone arch system, is called the two-section seedling arch system, which belongs to the most basic arch system. It is developed from a wooden flat beam bridge. The two supports meet at one point to form a herringbone, and the supporting points crossing in the middle can reduce the weight of the bridge, while the received weight is transferred from the two supporting points to the pier. Type III, called the eight-shaped arch system or the three-section seedling arch system, is changed on the basis of the herringbone arch system, and a through-long beam is added at the intersection of herringbone supports. This utility model reduces the bearing capacity of the bridge, improves stability, and also provides two crossed herringbone braces as upper supports. Type III-II, which is an arch rib combined with a herringbone arch system and a splayed arch system. The intersection of herringbone diagonal braces is under the horizontal beam of the splayed arch system, which supports the horizontal beam and complements each other to jointly reduce the bearing capacity of the bridge and increase stability. Type III-III is a combined arch system with two splayed arch systems, but the difference is that the height and elevation of the bottom of diagonal braces in these two splayed arch systems are different. The lower the bottom height of diagonal braces is, the greater the elevation angle is; the higher the bottom height of diagonal braces is, the smaller the elevation angle is, and the length of horizontal beams is unequal. The longer the horizontal beams indirectly bear the bridge weight, the shorter the diagonal bars, and the longer the diagonal bars directly bear the bridge weight. The node beams in the long horizontal support bar system are pressed in the diagonal bars in the system that directly bears the weight of the bridge, providing support for each other and sharing the load of the bridge together. Type III-IV, a set of three-section arches and a set of four-section arch combined arch are special in that these two arch systems are not stable structures when they are used for bearing alone, but are combined with each other to form a relatively stable arch. Type III-V, a group of three-section arch and a group of five-section arch combined arch, like type III-IV, are all combined to form a relatively stable arch, and it is also the most commonly used wooden arcade bridge arch system in Fujian. The wooden arcade bridge of Wan' an Bridge adopts a tenon-mortise structure as the main structural mode of its building. During construction, beams and timber are overlapped, and the timber with limited length is woven up and down to form a long-span columnless arch bridge. The structure is simple, but it is very strong [7]. At the same time, in order to prolong the service life of the bridge itself under the condition of heavy rainfall and high humidity in the south for a long time, the idea of covering the bridge deck with a verandah came into being, and the gravity of the verandah itself and the stress of the upward rebound of the bridge formed a pair of balancing forces to further stabilize the bridge body. However, the span of the verandah bridge itself is large, and the bridge deck is mostly gentle slope or flat, and more boards, bricks, and stone surfaces are laid, so the main system row bars are provided with scissors to prevent the bridge body from being subjected to lateral forces. The wooden arcade bridge built with a "braided beam" structure has become a major feature in Zhejiang and Fujian, and the system composed of six arch structures is even more noticeable.

Table 1. Comparison of six kinds of arch structures in Fujian Province and two kinds of arch structures in Yunnan Province

Province	Arch name	Diagrammatic presentation	Arch name	Diagrammatic presentation
Fujian Province	Type II		Type III	
	III-II type		III-III type	
	III-IV type		III-V type	
Yunnan province	Single cantilever beam system		Saddle frame system	

Wan' an Bridge uses the III-V type. Compared with the common wooden arch bridge, the combined arch with three-section arch and five-section arch has the advantage that the three-section seedling system and the five-section seedling system are more closely meshed and interpenetrated with each other, forming an overall shared load, so that the overall stress of the bridge body is enhanced, and the wooden arcade bridge can solve the span problem of the bridge body to the greatest extent [8]. Wan' an Bridge is a five-pier, six-hole wooden arcade house bridge, with five piers and six holes. Each hole has an independent three-seedling system arch system and a five-seedling system arch system, but the most unique feature of Wan' an Bridge arch system is that no nails and iron sheets are used for the handover between the arch systems. In addition, the middle of the three-seedling flat seedlings and the inclined seedlings are connected by a cross bar called a bull's head, and the bridge head's part is overlapped by tenon and mortise technology. Five-section seedlings, upper oblique seedlings, and lower oblique seedlings are also overlapped by five-section seedlings with tenon and mortise technology to solve that overlapping problem of the arch frame system in the length direction of the bridge body. When the bridge body is overlapped in the width direction, the three-section seedling and the five-section seedling are placed adjacently, that is, one arch frame is made into three-section seedlings, and then the adjacent arch frames are made into five-section seedlings, which are placed in sequence and bite each other. The load borne by the three-section seedlings can be transferred to the five-section seedlings, and the five-section seedlings play a supporting role for the three-section seedlings, and vice versa. At the same time, scissors seedlings are used to support them to share the load and improve the stability, thus improving the bearing capacity of the bridge.

Fig 4. Tongjing Bridge single outrigger beam system pick out 7 times

Fig 5. Internal structure of saddle frame system

Tongjing Bridge in Yunlong County is a one-way outrigger beam system with a saddle frame system, and wooden purlins are stacked layer by layer to connect the bridge deck to form a one-way outrigger. The bridge body is usually composed of three thick logs, which bear the girder and extend out of the bridge deck diagonal brace, forming a saddle frame system as the main load-bearing structure. Inside the corridor of Tongjing Bridge, a saddle frame is formed by upper bearing girders and diagonal braces, and three logs with relatively thick bottoms of five rectangular piers are obliquely braced upward and combined with the upper bearing girders through the bridge deck. There are columns on the railings at both sides of the corridor, and the upper bearing girders are clamped in the columns, which are assisted by the upper bearing girders and connected by tenon and mortise. The abutment on both sides of the single outrigger beam combined with a saddle frame system is composed of three parallel logs and one cross beam to assist the stress of laminated outrigger beams. On five parallel small rectangular piers, there are two relatively thick square timbers at the bottom to form a single outrigger so as to stack wooden beams. The five small rectangular piers correspond to a wooden inclined beam, and the lower pier and two thick square timber beams are weighted. Then, the wooden inclined beam is picked out as the starting point, and then a slender crossbar is connected with the parallel wooden inclined beam to reinforce it. The second pick-up is carried out, totaling seven times. On the bridge deck, five thicker wooden beams are used to form a beam, and four thinner square beams are used to form a longitudinal beam. The longitudinal beams with thicker square beams on both sides are tenoned with stacked wooden trusses to support the outriggers and the big wooden beams on the beam. After forming a triangular empty room, the longitudinal beams and the transverse beams are also connected together through the tenoning technology of wooden trusses, and in the saddle frame system, the bearing columns are assisted to bear the beams and are connected through the bridge deck and the longitudinal beams to form a bridge deck bearing system. The bridge deck is paved with wooden boards and railings are erected on both sides. Yunlong Wooden Cantilever Bridge is made up of wooden purlins crisscrossing, which are stacked layer by layer. The bridgeheads on both sides of the river are pushed into the center of the river layer by layer, connected by beams after a certain distance, and connected by “tenon and mortise technology”. The whole bridge does not use

any nails and adopts a wooden truss tenon structure, which ensures the firmness of the bridge body on the premise of ensuring a large single arch span.

The independent saddle frame system in Yunlong County is a composite component consisting of an upward-inclined wooden column and a girder extending from both ends of the abutment. The suspended structure reduces the load and stress on the bridge deck girder and also reduces the number and sections of the bridge deck girder. For example, Yonglai Bridge and Yongji Bridge, both of which are located in Liandeng Village, Jiancao Township. Yongji Bridge has a hundred years of development history. Its bridge is north-south and consists of three parts: the north-south bridge pavilion and the bridge corridor. The south-north bridge pavilion hangs from the top of the mountain with five purlins passing through the bucket. The bridge corridor is also a cantilever beam with five purlins, and the span is very small. It is an innovation based on the general simply supported wooden beam bridge with diagonal braces. The diagonal braces are all located on the bridge deck and are connected by four relatively thick beams and two cross beams with tenons and mortises, which are located on both sides of the bridge deck. The space inside the gallery house forms a splayed arch structure through beams and diagonal braces, and the beams connect the pillars of the gallery house to form a half-supported and half-suspended bridge deck. This semi-supported and semi-suspended bridge arch technology is similar to the “horse-rack” technology of the ancient tea-horse road, which can be called a major innovation in the application of horse-rack technology in bridge construction, making this kind of beam bridge in Yunlong has obvious advantages such as simple assembly, material saving, high strength and stable framework. Like many methods to protect the bridge deck, in order to protect the wooden beam from the sun and rain, people also choose to build a gallery house on the bridge deck, a memorial archway building, or a bridge pavilion at both ends of the bridge, etc. There are fixed railings on the left and right sides of the bridge deck inside the gallery house for pedestrians and residents to rest.

Fig 6. Yonglai Bridge internal saddle frame system

3.3. The Comparison of Bridge Galleries

The verandah structures in wooden arcade bridges, in Yunnan Province and Fujian Province are also quite characteristic. The arch structure of the bridge body is protruding and has an upward force. The verandah is covered on the bridge body to increase the weight of the bridge deck. The gravity on the verandah itself and the upward force on the arch structure are in different directions, which balance each other, thus making the whole covered bridge more stable. Taking Tongjing Bridge in Yunlong County as an example, the cantilever wooden arcade bridge deck is covered with a veranda, and archways or bridge pavilions are built at both ends of the bridge body. The left and right sides of the bridge deck inside the veranda have fixed railing chairs for pedestrians and residents to have a rest and shelter from the wind and rain, and play a role as a place for folk cultural activities. The porch on the bridge is ingenious. The corridor surface is made of four relatively thick timber, and two pillars in the center support the upper tripod, which is also provided with ridge purlin and top tile. A one-

step beam or three-frame beam is supported on the column, and members such as purlins and purlins are picked out from the beam ends, and the purlins are directly drained. Yunlong's covered bridge has a variety of columns, including square columns, columns, and mixed columns. The column of Yunlong Corridor Bridge is connected with the main body by the joint of the ground purlin, and the eaves column is also connected with the ground purlin. The column, the ground purlin, and three beams are connected into a whole frame, which makes the overall structure of the house stable and integrated. Most of the covered bridges adopt semi-open structures, and the floodgates are installed on the riverside side of the benches for pedestrians to rest, but the upper surface of the floodgates is not made of material, which not only protects the wooden bridge from rain erosion but also ensures the pedestrians' visibility. Compared with the covered bridges in Yu Yunlong, the wooden arcade bridge in Fujian is more folk-like. Local residents in Fujian offer sacrifices and deities on the wooden arcade bridge and provide seats on the bridge for pedestrians to have a rest, and even evolve into customs such as walking off the bridge and gathering. The bridge has evolved from a single traffic function into a public activity place that is closely related to residents' lives and is more humanistic [9].

Fig 7. Yunlong County Caifeng Bridge gallery at both ends of the building archway or bridge pavilion

Fig 8. Longjin Bridge, Pingnan County, Fujian Province

4. Analysis of the Causes of Architectural Structure in Wooden arcade bridge in Yunnan

According to the location of the carriageway, the span structure of the arch bridge can be divided into three types: upper-bearing type, under-bearing type, and middle-bearing type. When the bridge deck is above the arch crown, it is an upper-bearing arch bridge; when it is at or below the arch foot, it is an under-bearing arch bridge, and when it is between the arch crown and the arch foot, it is a middle-bearing arch bridge. As the main form of the early braced bridge, the upper-bearing bridge gradually evolved into the middle-bearing bridge and the under-bearing bridge. However, the middle-bearing bridge and the under-bearing bridge are mainly used in the wooden arcade bridge in Yunnan Province, while the upper-bearing bridge is mainly used in the wooden arcade bridge in Fujian Province. There are such great differences in bridge structure in the region. This paper analyzes and probes into three reasons, which are the span and height of the bridge, the influence of earthquake action, and the mechanical structure.

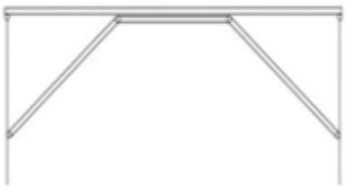


Fig 9. Upper bearing type

Fig 10. Middle bearing type

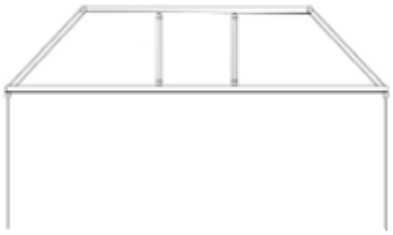


Fig 11. Under bearing type

4.1. Bridge Span and Height

By comparing the bridge length, clear span, span, and height of wooden arcade bridge in Yunnan Province and Fujian Province, it can be found that wooden arcade bridge in Yunnan Province is mostly single-span bridge with a relatively long span, and the under-bearing type and middle-bearing type structures can better meet the bearing requirements of long-span bridges. Taking Tongjing Bridge as an example, Tongjing Bridge is located on the tributary of the Bijiang River, which is the longest span in the bridge group of the ancient bridge of the Bijiang River and adopts a single-hole structure. The adoption of a middle-bearing type can prevent the diagonal braces from bending because they cannot bear excessive bridge deck load, and the diagonal braces pass through the bridge deck and form a whole with the upper part of the bridge deck, which can improve the bearing capacity and overall stability. There are many long-span porous bridges in wooden arcade bridges in Fujian. To increase the stability and bearing capacity of the bridge, the load of the bridge can be better dispersed and the deformation and displacement of the bridge can be reduced by adopting the upper-bearing structure. Taking Wan' an Bridge as an example, Wan' an Bridge is a wooden arcade bridge with five piers and six holes, which is twice as long as Tongjing Bridge. However, by setting piers, the long span is continuously reduced, and the span is reduced from 10.6 meters to 15.2 meters. By setting piers, the length of the upper-bearing brace is reduced, and the bending resistance is stronger. At the same time, the bottoms of both braces are supported by piers, and the bridge deck load can be dispersed to each span through diagonal braces.

Table 2. The length and altimeter of representative bridges in Yunnan Province

Province	Bridge name	Bridge length (m)	Clear span (m)	Height (m)
Yunnan province	Tongjing Bridge	40	29	12.5
	Caifeng Bridge	34.3	21.2	7.5
	Yongji Bridge	27.1	14.66	7

Table 3. The length and height table of representative bridges in Fujian Province

Province	Bridge name	Bridge length (m)	Hole span (m)	Height (m)
Fujian Province	Wan' an Bridge	98.2	10.6-15.2	8.5
	Qiancheng Bridge	62.7	27	9.7
	Baixiang Bridge	38	35	27

Meanwhile, when the building height of the bridge is strictly limited, it is often difficult to use the upper-bearing arch bridge, so it can be used to meet the building height under the bridge. In the multi-hole continuous arch bridge with unequal spans, in order to balance the horizontal thrust of the left and right piers, the ratio of span loss of a hole with a larger span is increased to make a middle-bearing arch bridge, which can reduce the horizontal thrust of the long span, and the height of the deck can be reduced by adopting the middle-bearing arch bridge and the middle-bearing arch bridge [10]. Caifeng Bridge and Baixiang Bridge are both single-hole wooden arcade bridges, and the span of the bridge body is not much different. However, Caifeng Bridge adopts a middle-bearing type, which

obviously reduces the deck height. Baixiang Bridge adopts an upper-bearing type and does not have plain conditions, so it is difficult to reduce the deck height.

4.2. Reasons for Earthquake Action

According to the earthquake distribution maps of Yunnan Province and Fujian Province, it is found that Yunnan Province is located in the Mediterranean-Himalayan seismic belt, and the seismic belts in Yunnan Province are mainly distributed in the Daguan-seismic belt, Xiaojiang deep seismic belt, Tonghai-Shiping seismic belt, Simao and Pu' er-Laizhou seismic belt and Tengchong-Gengma seismic belt. Fujian Province is adjacent to the Taiwan Province earthquake zone. Generally, Fujian Province is only affected by aftershocks from the surrounding earthquake zones, because Fujian Province is not in the Pacific Rim earthquake zone, and there are few or no spontaneous earthquakes. According to the survey, we compared the seismic data of Yunnan Province and Fujian Province in the past five years from January 1st, 2019, to July 20th, 2023.

Table 4. Comparison of seismic data between Yunnan Province and Fujian Province in the past five years from January 1st, 2019 to July 20th, 2023

Comparison of seismic data between Yunnan Province and Fujian Province in the past five years from January 1st, 2019 to July 20th, 2023			
Province	Number of earthquakes (unit: times)	Major cities with wooden arcade bridge	Number of earthquakes (unit: times)
Yunnan Province	263	Dali and Tengchong	91
Fujian Province	9	Ningde, Nanping, Fuzhou [11]	0

According to the comparative earthquake analysis, it is found that the number of earthquakes in Yunnan Province is much higher than that in Fujian Province, and the main area of the wooden arcade bridge in Yunnan Province is also an earthquake-prone area. Therefore, based on this, the influence of earthquake action on the wooden arcade bridge is analyzed.

Bridge seismic damage falls into two categories, namely, damage caused by foundation failure and damage caused by strong structural vibration. The reasons for their failure are different, that is, the former belongs to static action, which is a structural failure caused by relative displacement caused by foundation failure. The latter belongs to dynamic action, which is caused by the inertia force caused by vibration. The upper-bearing bridge is similar to other forms of bridges, and earthquake resistance is also an unavoidable problem. Compared with the middle-bearing arch bridge and the under-bearing arch bridge, the center of gravity of the upper-bearing arch bridge is slightly higher than that of the middle and under-bearing arch bridge because of its higher arch height. During the earthquake, when the local seismic wave propagates to the foundation, the bridge foundation will be subjected to horizontal and vertical vibration, which will lead to horizontal and vertical vibration of the bridge itself, thus generating horizontal and vertical seismic loads. In addition, the entire arch ring will be deformed due to stress, reducing the bearing capacity of the bridge. The displacement of rock and soil causes the displacement of the arch foot, which directly affects the arch bridge structure, and the energy released by the earthquake will be transformed into the bridge structure [12]. In terms of the wooden arcade bridge in Fujian, the skew seedlings of the upper-bearing bridge are directly in contact with the foundation, so the requirements for the foundation are higher. When the earthquake occurs, on the one hand, the foundation vibrates, and the skew seedlings supporting the whole arch system will be displaced, which will influence the bridge. On the other hand, the essence of an earthquake is a process of energy release, which can be divided into two stages. The first stage is from the source to the underground bedrock, and the second stage is from the underground bedrock to the buildings on the ground surface. For the upper-bearing wooden arcade bridge in Fujian Province, it is transmitted to the arch bridge through oblique seedlings, which causes the displacement of the arch foot of the arch bridge and the change of the energy of the whole bridge, and the internal force of the arch ring changes greatly. If the energy exceeds a certain earthquake input, the bridge

will be damaged [12]. Middle-bearing and under-bearing arch bridges are generally composed of arch ribs, suspenders, deck systems, and piers. The arch ribs are the main stress components and bear large axial pressure. Cross braces are usually arranged between the two arch ribs to improve the lateral stability of the structure. The deck system is a secondary stress component, and the vertical load acting on the deck system is transferred to the arch rib through the suspender and then transferred to the pier by the arch rib [13]. In Yunnan Province, the middle-bearing and under-bearing wooden arcade bridges are adopted, and the middle-bearing structure can absorb and transmit the seismic force through the abutment and pier, so as to avoid excessive stress on the cantilever section of the bridge. The under-bearing structure can transfer the seismic force of the bridge to the pier through the arch bone, and at the same time, both the middle-bearing and under-bearing structures form a certain connection with the bridge deck, which enhances the overall stability of the bridge.

To sum up, fewer earthquakes happen in Fujian Province and more upper-bearing wooden arcade bridges can meet the requirements, while more earthquakes happen in Yunnan Province, so adopting middle-bearing and under-bearing bridges with better seismic performance can resist the earthquake.

4.3. Mechanical Structure Reasons

The reason why wooden arcade bridges in Fujian Province chose the upper-bearing structure is also based on the consideration of mechanical structure characteristics. Wooden arcade bridge in Fujian Province is usually composed of huge logs with uniform size, whether it is simple type II and III or complex type III-II, III-III, III-IV, III-V. The flat seedlings and inclined seedlings of its arch structure system are crisscrossing, overlapping, supporting each other, and extending section by section, thus forming a complete wooden frame-type main arch skeleton. This structure makes the weight of the bridge mainly borne by the vault and arch foot, and the weight of the bridge deck is relatively small. The upper-bearing structure can directly transfer the load of the bridge deck to the pier through the flat and inclined seedlings, and then the load is transferred to the foundation by the pier, thus reducing the load of the pier on the foundation and improving the stability and safety of the bridge.

Wooden arcade bridges in Yunnan Province adopt middle-bearing and under-bearing structures, which are integrated with the bridge deck structure and can better bear the load of the bridge, so that the bridge can bear more load and also disperse the load to the bridge body, thus increasing the stability and safety of the overall structure. The middle-bearing system combining the saddle frame and cantilever beam can transfer the load to both sides through the vault because the saddle frame passes through the bridge deck and forms an integral bearing system with the bridge deck, which enhances the overall stability. Meanwhile, the middle-bearing and under-bearing structures can make the weight of the bridge better distributed. In the middle-bearing and under-bearing structures, the weight of the bridge is mainly transferred to both sides through the vault, which is helpful to reduce the stress and stress concentration of the pier and improve the overall stability of the bridge. Finally, the adoption of middle-bearing and under-bearing structures in wooden arcade bridges can make the bridge more beautiful. Because middle-bearing and under-bearing bridges do not need additional supporting structures, they can maintain the overall shape and aesthetics of the bridge and show the unique architectural style and charm of the wooden bridge.

5. Conclusion

Wooden arcade bridges in Yunnan Province have added and innovated components to the traditional foundation beam bridge structure and formed a complete system with its own style. On the basis of a simple framed wooden beam bridge, the wooden arcade bridge system combined with horizontal outriggers and splayed braces is more suitable for the complex geographical environment of the deep-water network in Yunnan, so it is more widely used. Comparing the wooden arcade bridge in Yunlong County with the wooden arcade bridge in Fujian Province, in terms of building structure, in order to adapt to the complex water system and the wide and dense distribution of rivers, wooden arcade bridges in Yunlong County are mostly erected piers in the ends, and mostly used single-span

structures to erect them on small rivers. Simultaneously, in order to resist the impact of the current, the piers in the Yunlong area are mostly built as stone piers wooden arcade bridges, and only piers are set at both ends, which is different from the boat-shaped solid stone piers built in Fujian Province. This structure provides solid support for the wooden brace which extends to the center of the river in turn, and the construction process is simpler and raw materials are saved. As far as the bridge body is concerned, the most distinctive buildings in Yunlong Bridge Group are the wooden arcade bridge's arch system, namely, the cantilever beam system and the saddle frame system. The single-arm system is the transition from a straight line to an arc line, which is both practical and aesthetic. The saddle frame system is suspended above the bridge deck, and the auxiliary bridge deck shares a lot of load. In terms of the veranda, the wooden arcade bridge in Fujian Province is more folk-like, and local residents sacrifice and worship deities on the wooden arcade bridge, which is more humanistic. However, the traditional cantilever wooden arcade bridge in Yunnan is covered with a veranda, with archways or bridge pavilions at both ends of the bridge, and fixed bar chairs on the left and right sides of the bridge deck in the veranda, which provides a place for pedestrians and residents to rest, which is more life-like. Finally, the phenomenon that wooden arcade bridges in Yunnan Province are mainly middle-bearing and under-bearing, while wooden arcade bridges in Fujian Province are mainly upper-bearing is analyzed for three reasons, which are the span and height of the bridge, the influence of earthquake action and the mechanical structure. It is concluded that the adoption of middle-bearing and under-bearing wooden arcade bridges in Yunnan can better adapt to topographic conditions in Yunnan Province and have strong seismic capacity and bearing capacity.

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References

[1] Mao Yisheng. China Ancient Bridge Technology History [M]. Beijing: Beijing Publishing House, 1986.

[2] Tang Huancheng. History of Science and Technology in China: Bridges Volume [M]. Beijing: Science Press, 2000.

[3] Li Yali, Teng Mingyu. Architectural Research on Bridge Images in Han Dynasty [J]. Southern Cultural Relics, 2014 (02):181-185.

[4] Wei Jincheng. Research on Plastic Arts in wooden arcade bridge, Fujian [D]. Chongqing University, 2015.

[5] Cheng Fei, Xiao Dong. The wooden arcade bridge's construction skills and repair techniques [J]. Natural and Cultural Heritage Research, 2019, 4(S2): 50-55.

[6] Wei Hongbing. Investigation of the current situation of Fengyu Bridge in Dali, Yunnan Province and study of its construction characteristics [D]. Changsha University of Science and Technology, 2018.

[7] Tai Xiaoan, Zhao Xuetong, Wu Jianfeng, etc. How to protect the wooden arcade bridge from the Riverside Scene at Qingming Festival [N]. Xinhua Daily Telegraph, 2022-08-12(012).

[8] Jiang Ye. China covered bridge architecture and culture research [D]. Central South University, 2010.

[9] Wu Shidan. Dialectical inheritance of traditional construction techniques of wooden arch bridge in "non-legacy" project-taking wooden arcade bridge, Fujian as an example [J]. Journal of Nanjing University of Science and Technology (Social Science Edition), 2020, 33(01): 27-32.

[10] Yu Lianhai. Structure and characteristics of the long-span middle-bearing arch bridge [J]. Henan Science and Technology, 2009, 423(07): 74-75.

[11] Chen Xiaoyue, Yao Liyan, Ma Ying. Spatial distribution characteristics and influencing factors of Fujian, Zhejiang and wooden arcade bridge [J]. Journal of Shandong Agricultural University (Natural Science Edition), 2020, 51(06): 1163-1169.

[12] Wei Luyao. Failure mechanism and dynamic analysis of upper-bearing arch bridge under earthquake [D]. Chongqing Jiaotong University, 2012.

[13] Zhang Guangpo. Seismic performance analysis of middle-bearing and under-bearing arch bridges [D]. Zhengzhou University, 2007.