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# Construction and structure analysis of Yongshun Bridge in Lichuan

Fawen Zhu,<sup>1</sup> Jianfeng Zhou,<sup>2</sup> Tianyi Zhu<sup>1</sup>, Baofeng Li<sup>1</sup>

<sup>1</sup>School of Architecture and Urban Planning, Huazhong University of Science and Technology, Wuhan, China

<sup>2</sup>School of Civil Engineering, Huazhong University of Science and Technology, Wuhan, China

libaofeng\_1956@hust.edu.cn

**Abstract.** Lichuan YongShun Bridge is the only wooden arch lounge bridge, which composites stretching timber beam and inverted v-shaped brace, in Wuling Mountain. This paper introduces the basic situation of YongShun Bridge, analyzes the relationship between its special construction and structure. Through establishing the finite element model and simulating the stress and displacement of the bridge under the action of dead load and live load, the paper summarizes the main mechanical behavior of the bridge and the influence of special construction on the bridge structure. The research results have certain guiding value for the protection and maintenance of the bridge and the construction of modern wooden structure bridge.

## 1. Introduction

Yongshun Bridge, located at the junction of Huaban Village and Shibao Village, Maoba Town, Lichuan City, Enshi Prefecture, Hubei Province, was built in 1859 (nine years of Qing Xianfeng), and has been maintained for more than 150 years (1880, 1952, 1967, 1991). As one of the few remaining Tujia wooden Lounge Bridges in Wuling Mountain, Lichuan Yongshun Bridge is also the only wooden arch lounge bridge, which composites timber cantilever beam and inverted v-shaped brace.

Wooden Lounge Bridge, commonly known as wind and rain bridge, in Tujia area, known as cool bridge or pavilion bridge, refers to a wooden structure with a house on the bridge. The architectural form of the bridge has a long history, which can be traced back to the early days of the ancient dry hurdles, and then, the structure and form of the bridge continue to evolve with time and region. According to the evolution order of the bridge span structure, the Wooden Lounge Bridges in China can be classified into timber simple beam structure, timber cantilever structure, timber brace structure, timber arch structure and so on. [1,2] Before each stage structure system matures, everyone has its transition stage. The multiple timber arch structure of Yongshun Bridge is a variation from the timber cantilever structure to the timber arch structure. Yongshun bridge combines many characteristics of the timber cantilever beam, the timber brace and the timber arch, and has its unique feature.

## 2. Structural analysis of Yongshun Bridge

Yongshun Bridge is 26.9m long and 3.5m tall. The bridge deck is 25.2 m in length, 3 m in width, with 7 rooms in depth, 3.6m long per room. The valley is about 17m wide and 15m deep (figure. 2). The bridge can be divided into three parts: bridge foundation, bridge span and bridge roof. The bridge span



is a timber multiple arch structure which is composed of inclined stretching timber beam and inverted v-shaped brace. Yongshun Bridge has three special structures: cantilever beam structure, multiple arch structure, bridge roof structure (figure. 3).

- Cantilever beam structure: the cantilever beam is arranged on the bridge foundation at an angle of about 12° to the horizontal plane, extends out of the abutment about 4.5m, extends into the bank of the foundation about 2m. It consists of two longitudinal timbers and four transverse timbers, which are used to carry on the upper bracing timber system.
- Multiple arch structure: the multiple arch is placed on the cantilever beam. It is made of 2-layer inverted v-shaped braces with cross ties stack in the middle. The inverted v-shaped brace consists of five groups of oblique wood on both sides and four groups of horizontal wood in the middle. The oblique and horizontal wood cross each other with four cross ties.
- Bridge roof structure: eight groups of columns of bridge house fall evenly on the span of bridge, and its main structure is 8 *four columns and three-room Chuandou systems*. There are 32 columns in the whole bridge. The structure of each beam frame is the same, but the length of column is different. These columns connect the bridge house, deck and span and make them be together. The load of the roof and deck is transferred to the bridge span through these columns, which make the overall force of the bridge uniform.

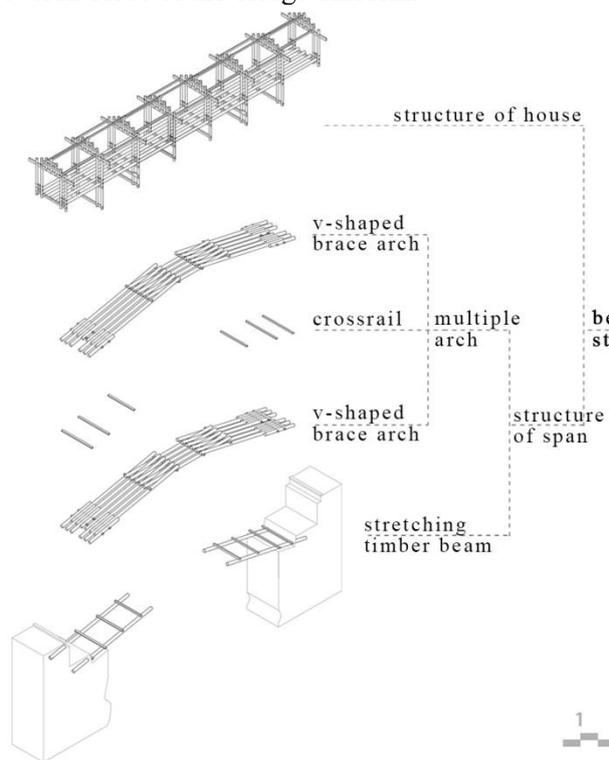


Figure 3. Structural decomposition diagram



Figure 1. Status photo of Yongshun Bridge

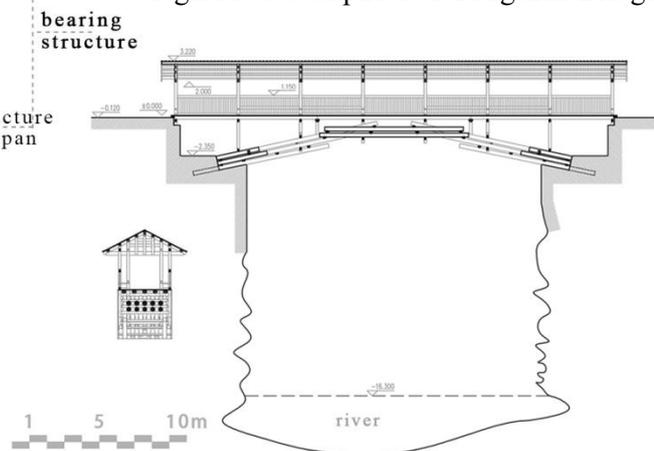


Figure 2. Elevation and section drawings

### 3. Analysis of mechanical properties

#### 3.1 Comparison between single arch and multiple arch

##### 3.1.1 Finite element model and loading condition

Yongshun Bridge adopts the form of two-story wooden arch with cantilever beam. In order to discuss the difference of bearing capacity between single-layer wood arch and double-deck wood arch, the finite element models of single-layer wood arch and double-layer wood arch are established by Midas

Civil. In these models, the timber components of Yongshun Bridge are simulated by beam element.(figure. 4)

The boundary conditions are as follows: the end of the cantilever beam of the single-layer wooden arch and the double-deck wooden arch is fixed end constraint, the end part of the first layer wood arch is hinged constraint, and the end part of the second layer wood arch of the double-layer wood arch is only constrained by the displacement along the bridge. The connection between wood members is simulated by elastic connection, so the linear displacement in y and z direction is constrained by a large linear stiffness, and the linear stiffness SDy, SDz is taken as 1011kN / m, while the linear displacement in x direction is constrained by a smaller linear stiffness. The linear stiffness SDx is 2000kN / m; The rotational stiffness of x and z directions is restricted, and the rotational stiffness is taken as 1011kN.m/ [ rad], the rotation stiffness of y direction is 0 kN.m/ [rad].[3,4]

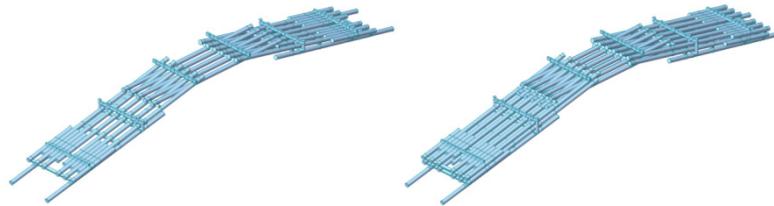


Figure 4. Finite element models of single arch and complex arch

The loading conditions of single-layer wooden arch and double-deck wood arch can be divided into three types: ①deadweight; ②deadweight + concentrated force of 5kN node of full-bridge; ③deadweight + concentrated force of 5kN node of semi-bridge. The node position is the joint between the column and the wooden arch of Yongshun Bridge.

3.1.2 Finite element analysis

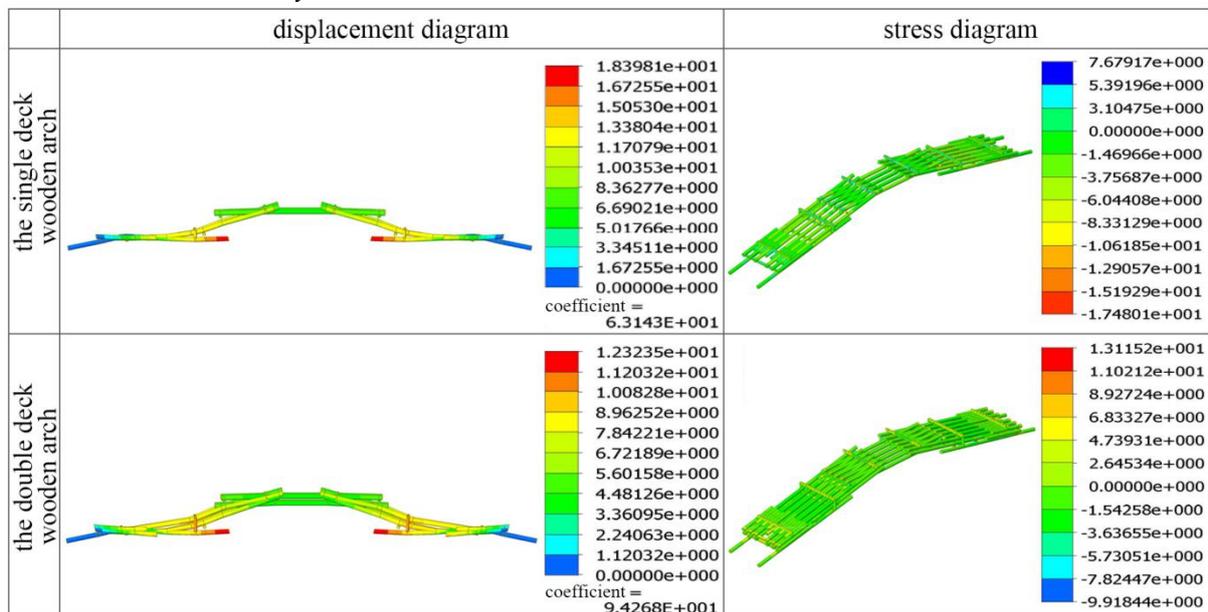


Figure 5. Working condition 2 displacement diagram and stress diagram of the double-deck wooden arch for issuing orders

Table 1. Maximum displacement and stress values of single and double deck wooden arch

	wood arch	condition 1	condition 2	condition 3
maximum displacement /mm	single	3.13	18.40	32.78
	double-decked	3.30	12.32	19.63

maximum stress /MPa	single	2.73	17.48	15.34
	double-decked	3.40	13.11	11.87

Limited to space, this paper only lists the displacement diagram and stress diagram of single and double deck wooden arch under working condition② (figure. 5), and finite element results under various working conditions (table 1).

As can be seen from figures and tables:

- The maximum displacement of single and double deck wooden arch under various working conditions is located at the free end of cantilever wooden beam. The force distribution is uniform, indicating that the two structural forms are reasonable.
- The maximum displacement and stress of double-deck wooden arch are larger than that of single-layer arch under the action of working condition ① because of the high deadweight of double-decked wood arch. Wooden arch under conditions②and ③, the maximum displacement and maximum stress of the double-deck wood arch are smaller than that of the double-deck wood arch, and the stress distribution of the double-deck wood arch is more uniform. The result means that the double deck wooden arch improves the bearing capacity of the structure, though the wood consumption is increased by a certain amount.

### 3.2 Mechanical Analysis of Yongshun Bridge

#### 3.2.1 Finite element model

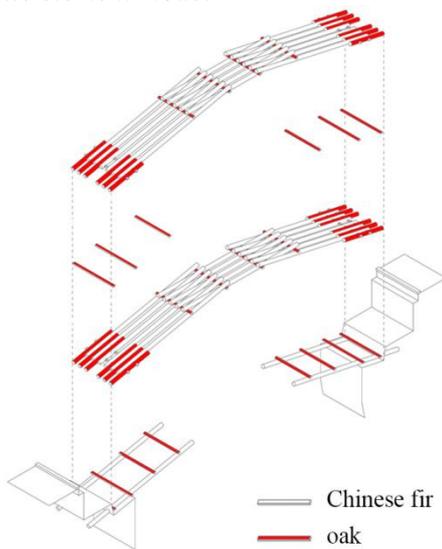


Figure 6. Chinese fir, oak location

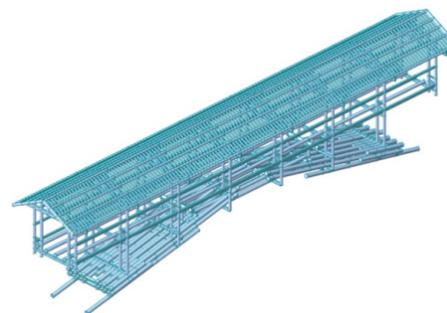


Figure 7. Finite element model of Yongshun Bridge

Table 2. strength design values and modulus of elasticity of wood such as square wood, log, etc. (N/mm<sup>2</sup>)

strength grade	group	anti-bending <i>f<sub>m</sub></i>	parallel to grain			compressive strength perpendicular to grain <i>f<sub>c,90</sub></i>			Modulus of elasticity <i>E</i>
			anti-compression <i>f<sub>c</sub></i>	anti-tensile <i>f<sub>t</sub></i>	anti-shear <i>f<sub>v</sub></i>	full surface	local surface and tooth surface	tension bolt pad	

TC11	A	11	10	7.5	1.4	1.8	2.7	3.6	9000
	B		10	7.0	1.2				
TB17	--	17	16	11	2.4	3.8	2.7	7.6	11000

Yongshun Bridge used two kinds of wood, Chinese fir and oak. The bridge used Chinese fir as a whole and oak as the crossbeam between wooden arches ( figure. 6). According to the *Code for Design of Wood structure(GB50005-2017)*, Chinese fir belongs to TC11A strength class, oak belongs to TB17 strength class. The material parameters of Chinese fir and oak are shown (table 2). The bulk density of Chinese fir and oak is 0.376 and 0.75 respectively. According to the measured size of Yongshun Bridge, the finite element model is established by Midas Civil (figure. 7).

### 3.2.2 Loading conditions

Three load conditions are applied to Yongshun Bridge:

- Condition 1: deadweight. Besides the bearing structure, the deadweight includes the subsidiary structure, such as, bridge deck, railing, tile and other ancillary members. The subsidiary structure is simulated by means of line load. The line load of 98N/m applied on the roof purlin simulates the uniform load of tile on the roof. There are five longitudinal beams under the deck of the bridge. In order to simulate the load on the deck, the line load of the left and right longitudinal beams is set to 23.4N/m, and the middle one is set to 46.8N/m.
- Condition 2: deadweight + load on the whole bridge. According to the *general code for highway bridge and culvert design (JTG D60-2015)*, for bridges whose span is less than 50m, the standard value of crowd load is 3.0kN/m<sup>2</sup>. The crowd load is converted into the line load applied to the five longitudinal beams under the bridge deck. The line load of the left and right longitudinal beams is set to 0.9525kN/m, and the middle one is set to 1.9050kN/m.
- Condition 3: deadweight + load on the half bridge. The load of working condition 2 is arranged along the left half span of the bridge.[5]

### 3.2.3 Finite element analysis

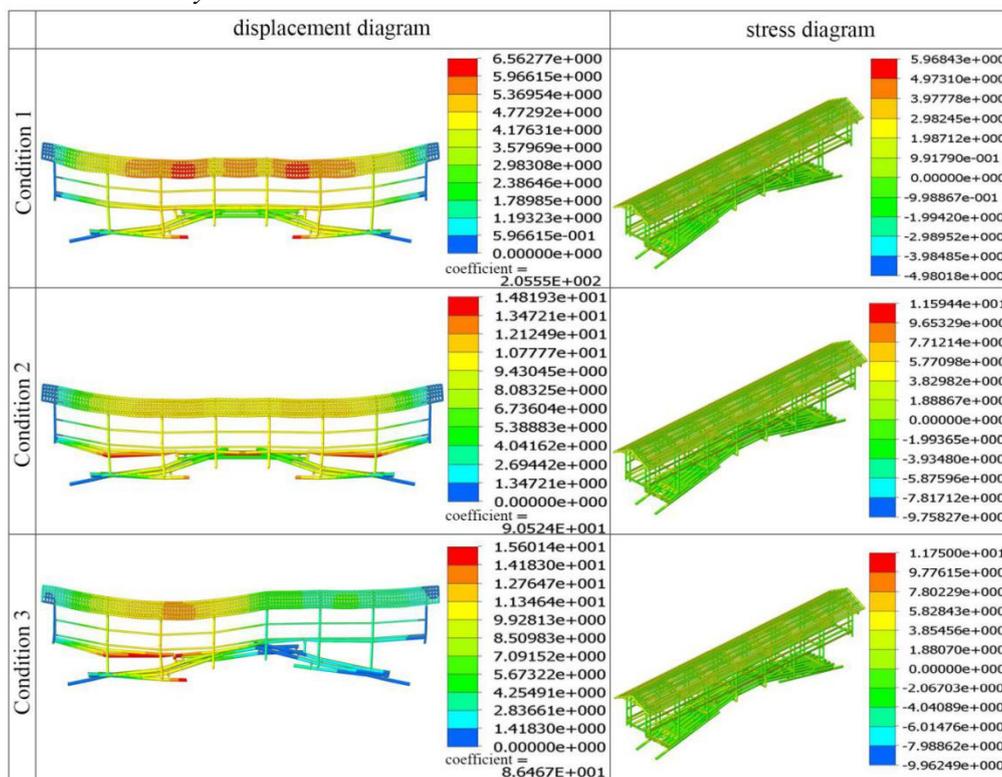


Figure 8. Full bridge displacement and stress diagram

Table 3. Maximum displacement and stress values of full bridge

	condition 1	condition 2	condition 3
maximum displacement /mm	6.56	14.82	15.60
maximum tension and compression stress/MPa	5.97/-4.98	11.59/-9.76	11.59/-9.76

Through the finite element software calculation and analysis, the displacement diagrams and stress diagrams of the whole bridge under three kinds of working conditions are obtained.(figure. 8 , table 3)

1) Displacement analysis

- Under three working conditions, the maximum displacement of the bridge is 6.56 mm, 14.82 mm, 15.60 mm, respectively; Under condition 1 and 3, the maximum deformation position of the whole bridge is the free end of the cantilever wooden beam. The maximum deformation position of the whole bridge under working condition 2 is the middle span of the longitudinal beam on the deck, the maximum deformation position of the wooden arch part is the free end of the cantilever wooden beam, and the deformation is relatively small.

- According to the current highway and bridge code, the allowable ratio of deflection to span is L/600, and the maximum ratio of deflection to span under three working conditions is as follows.  $15.60/25200 = 1/1615$ , less than the allowable value. The stiffness of Yongshun Bridge meets the operational requirements.

2) Stress analysis

It can be seen from the table 2 that the compression and pressure limit of Chinese fir is 10 MPa, the tensile limit is 7.5 MPa, the compression and compression limit of oak is 16 MPa, and the tensile limit is 11 MPa.

- Under the action of the deadweight, the maximum tensile stress and the maximum compressive stress meet the requirements of the code.

- Under condition 2 and 3, the maximum tensile stress of the bridge is a little more than the required value of the code, and the stress concentration is located at the cross beam of the span part of the bridge. The maximum compressive stress of the bridge is far less than the required value of the code. (figure.9)

- Under the action of three working conditions, the stress distribution of Yongshun Bridge is uniform, and the stress of most of the components is in the allowable standard. Only part of the beam has too much stress, which indicates that the overall mechanical performance of Yongshun Bridge is good, and some of the beam members need to be strengthened. (figure. 10)

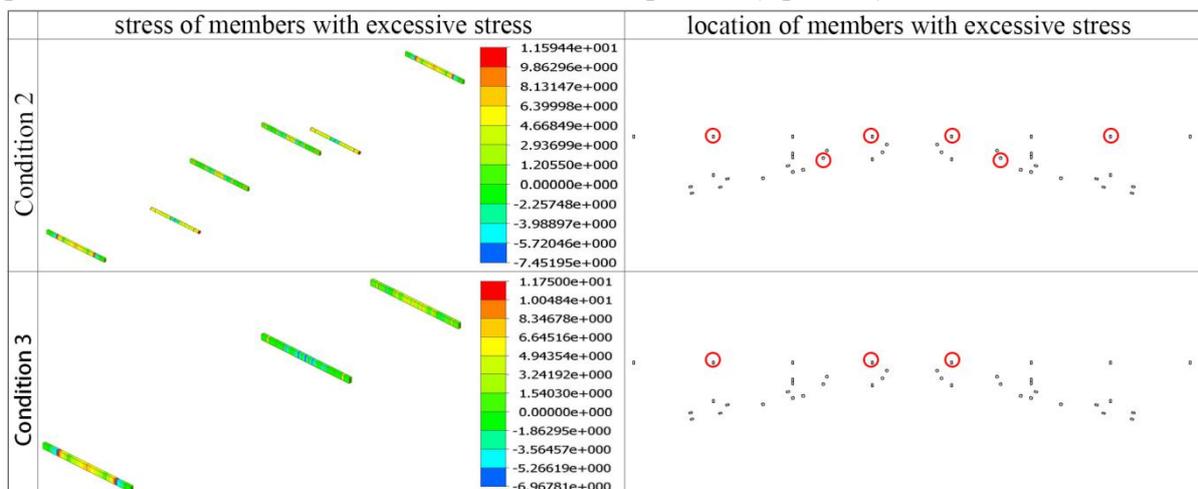


Figure 9. Stress and location of members with excessive stress

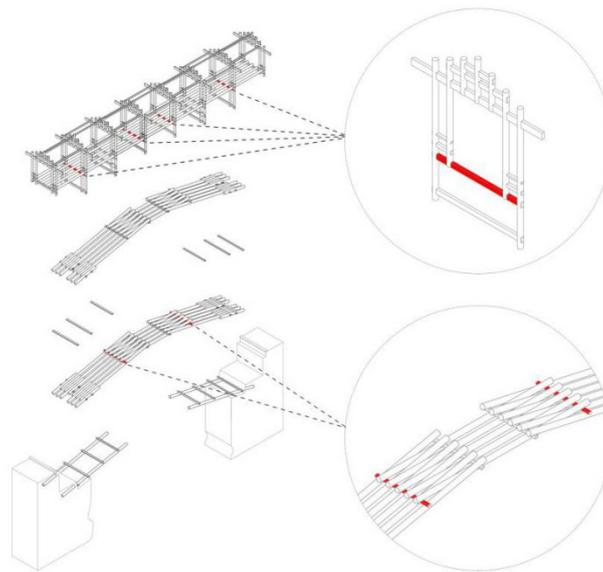


Figure 10. location of members with excessive stress

#### 4. Conclusion

YongShun Bridge is the only timber arch lounge bridge, which composites timber cantilever beam and inverted v-shaped brace, with a special structure and construction. Three special structures such as cantilever beam structure, double arch structure and bridge roof structure are of great significance to the reasonable force of the structure.

Based on the finite element analysis method, the single arch and multiple arch structures of Yongshun Bridge are analyzed. Through the comparative study, it is found that the multiple arch structure has obvious advantages over the single arch structure.

Based on the finite element analysis method, the stress and deformation laws of the bridge under dead and live loads are calculated, and the maximum stress and maximum deformation of the structure are obtained. Compared with the timber allowable stress and the ratio of deflection to span of the current highway bridge code, it is found that the whole structure of Yongshun bridge has good mechanical performance, and only a few crossbeams have excessive stress problems. The paper provides a certain theoretical guidance to the protection and maintenance of Yongshun Bridge and the construction of modern wooden structure bridge.

#### Acknowledgments

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