

Ancient Wooden Covered Bridge in Taoyuan, China – A Mechanical Analysis

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Wooden covered bridges attract attention due to their architectural appearance and manufacturing technique. In this study, an ancient wooden covered bridge in Taoyuan, China, has been investigated, mainly with respect to its construction form and mechanical behavior. First, the same type of raw material used for the bridge, namely, beech, was tested to obtain its mechanical properties. Then, the material experimental values were used in a finite element model to study the mechanical behavior of the bridge, and the stress state and internal forces of the bridge were obtained. The numerical results indicate that the maximum deflection of the bridge of 10.73 mm under gravity load meets the requirements of not exceeding $L/600$ in the specification while it reaches 15.62 mm under both the gravity load and crowd load, exceeding the limit by 1.3%. The maximum and minimum normal stress of 1.13 MPa and -2.03 are much less than the ultimate tensile and compression strength of the wood, respectively. This means that the structural safety performance of the ancient wooden covered bridge is acceptable if the pedestrian number be controlled effectively. Finally, some tiny damage of the bridge was apparent. Some suggestions were provided according to the numerical results and the complex actions of long-term loads and a severe environment on the bridge to preserve this old historical bridge.

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INTRODUCTION

Wooden covered bridges are notable for their unique structural design and historical significance (Mao 1985; Wacker and Duwadi 2010; Knapp 2021), particularly in China (Xie *et al.* 2023; Dai *et al.* 2017). However, the number of well-preserved ancient wooden bridges is quite limited due to erosion caused by wind, rain (Xie *et al.* 2024), and major floods. In recent years, the protection of historical buildings and wooden structures has become more important (Liang 2006; Xiang *et al.* 2009; Guo 2015; He *et al.* 2016; Xie *et al.* 2017). These historical buildings are significant carriers of social memory and cultural heritage, acting as witnesses and participants in urban development. Their preservation and regeneration are crucial for maintaining cultural continuity and promoting national cultural confidence. These structures not only embody the architectural styles of their times but also reflect the social, political, and economic contexts in which they were built (Harfield 2007).

Yinjia bridge, an ancient wooden covered bridge in Taoyuan, China, has attracted more attention in recent years. This bridge was first built in the late Ming dynasty. Its bridge corridor was reconstructed under the governance of the Daoguang Emperor of Qing dynasty in 1831. The bridge is well-preserved due to its excellent wooden material and sophisticated building techniques. In December 1934, the Chinese Workers' and Peasants' Red Army captured the Wuxi river and Taoyuan. They rested near this bridge and prepared to fight. Qishan Xu, the captain of the 74th Army of the National Revolutionary Army, passed through Yinjia bridge during the Changde Battle in 1943 and wrote a patriotic poem in the corridor of the bridge (Jiang and Jing 2023). Due to the historical, cultural, and architectural value, Yinjia bridge has been listed as a historical and cultural heritage protected at the city level.

Taking the Yinjia bridge as an example, this paper presents the unique structural system of an ancient wooden covered bridge, including the structural dimensions, corridors and roofs. The finite element analysis bridge is investigated with ANSYS software. In addition, the damages of the bridge are discussed. This study can be used as a reference for the preservation of historical and cultural heritage and is meaningful for the development of wooden bridges.

EXPERIMENTAL

Structural Dimensions and Material

As shown in Fig. 1, Yinjia bridge is a single span bridge that is 3.85 m wide and the total length and clear span of the bridge are 11.90 m and 9.25 m, respectively. Seven longitudinal simply supported main beams with approximate cross-sectional size of 300 mm × 300 mm were set over the stone abutments, and the size of each main beam is different, since the wood is made from natural trees. Upon the main beams, a bridge corridor is set. The bridge superstructure is made entirely of wood and built without any nail or metal connection, while the abutments are constructed with stones. The superstructure of the bridge was constructed of beech, a local, rich forest resource at that time, according to the local residents guarding the bridge.

To investigate the behavior of Yinjia bridge in ancient times, the same type of raw material was found from a local wood mill. The compressive strength of 16 wood cubes with dimension of 20 mm × 20 mm × 20 mm was tested according to GB/T 50708 (2012), and the tensile strength of 16 wood specimens was tested according to GB/T 1938-2009 (2009), as shown in Fig. 2. The average compressive strength and tensile strength of the wood were determined to be 65.5 and 233.0 MPa, respectively. The experimental mean modulus of elasticity (MOE) of the wood was 9.84 GPa at a moisture content of 11.5%. Its compressive strength was found to be larger than that of American beech mentioned in the Wood Handbook (2010), 50.3 MPa.



Fig. 1. General view and material tests of Yinjia bridge

Bridge Corridor and Roof

In addition to serving as a functional component to protect pedestrians from rain and storm (Liu 2017), the bridge corridor is also a symbol of the politics and culture, as well as a good reflection of the old feudal hierarchy (Wang 2019). In the leisure time, the villagers nearby also enjoy the cool breeze or engage in entertainment activities on the bridge corridor (Xie *et al.* 2024).

For the Yinjia bridge, a bridge corridor was constructed upon seven wooden main beams. The bridge corridor has 5 segments in total in the longitudinal direction, and the two ends are connected to the roads by stairs, respectively. On each side of the passageway, 6 peristyle columns and 6 hypostyle columns are set, as shown in Fig. 2. The diameters of the two types of columns are both 160 mm, and their longitudinal spacing is 2020 mm. A frame system mainly consists of the transverse purlin beams and longitudinal Fangs, which are assembled with columns through joints. The cross-sectional dimensions of the transverse purlin beam and Fang are 180 mm × 130 mm and 170 mm × 70 mm, respectively.

On top of the corridor, a gable and hip roof (Fig. 2 (b)) is used to shelter pedestrians. The Yinjia bridge also adopted the eaves on two sides of the bridge corridor (Fig. 2 (b)) to protect the lower wooden components from rain.

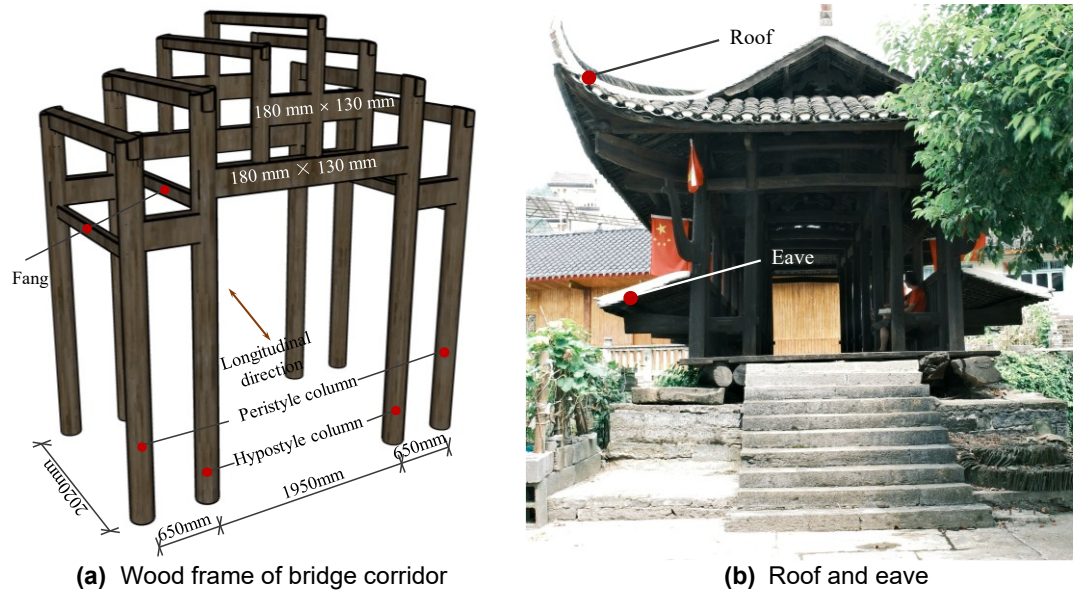


Fig. 2. Bridge corridor and roof

RESULTS AND DISCUSSION

Finite Element Analysis

To study the mechanical performance of the Yinjia bridge, a finite element (FE) model was built with the numerical software ANSYS (Fig. 3). The wood beams and columns of Yinjia bridge were both simulated with Beam 189 element, and the bridge deck, roof, and eaves of the bridge were modeled with Shell93 element. The overall properties of the bridge were the main areas of concern, while the local mechanical properties of the mortise and tenon joints were ignored in the study. Accordingly, the relationship of purlin beams, columns and Fangs was regarded as rigid connections. The density of the beech was tested to be 0.79 kg/cm^3 . According to the Technical Specification of China Urban Pedestrian Overcrossing and Underpass (CJJ69-95), a crowd load of 3.6 kN/m^2 was taken into account as bridge load.

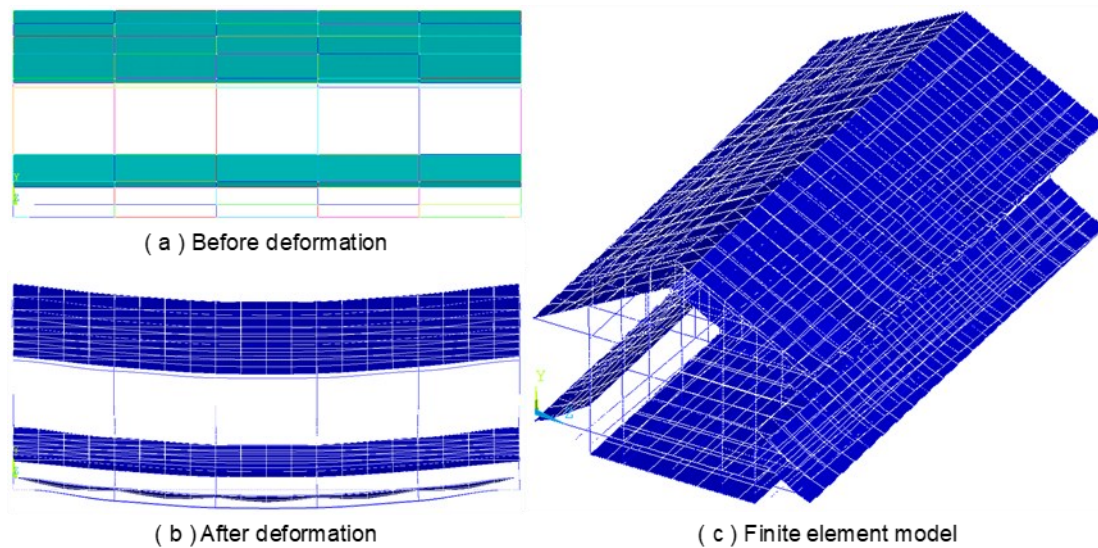


Fig. 3. Finite element model for Yinjia bridge

As shown in Fig. 3, the bridge deforms symmetrically with the maximum vertical deflection of 10.73 mm in the midspan only considering gravity load under serviceability limit state. It reaches 15.62 mm under both the gravity load and crowd load. It is under the limit of $L/600$ as detailed in the pedestrian bridge specification (CJJ69-95, 1995) when the gravity load is considered only, while that exceed the limit by about 1.3% consider both loads. In addition, the mechanical properties of the Yinjia bridge under the combined action of gravity and crowd load was studied under ultimate limit state (EN 1995-2; BS EN 1990: 2002). The normal stress, bending moment, and shear forces are listed in Table 1. The maximum normal stress of 1.13 MPa and the minimum normal stress of -2.03 MPa are within the limit value of the ultimate tensile strength and ultimate compressive strength of wood, respectively. The maximum shear force is 2.08 kN, and the maximum bending moment of the bridge is 0.75 kN · m.

Table 1. Typical Results of Yinjia Bridge

Numerical results	Normal stress (MPa)	Bending moment (kN · m)	Shear force (kN)
Max	1.13	0.75	2.08
Min	-2.03	-0.75	-2.08

The mechanical properties of the main beams were investigated, and the numerical results of one of the seven main beams are shown in Fig. 4. Since four sections of the main beams are supported in longitudinal direction, the Yinjia bridge behaves as a continuous beam bridge. The maximum and minimum bending moments are 0.09 kN · m and -0.09 kN · m, respectively. The maximum normal stress of the main beams is 0.46 MPa and the minimum normal stress is -0.53 MPa. The peak shear force of the main beams is 0.37 kN.

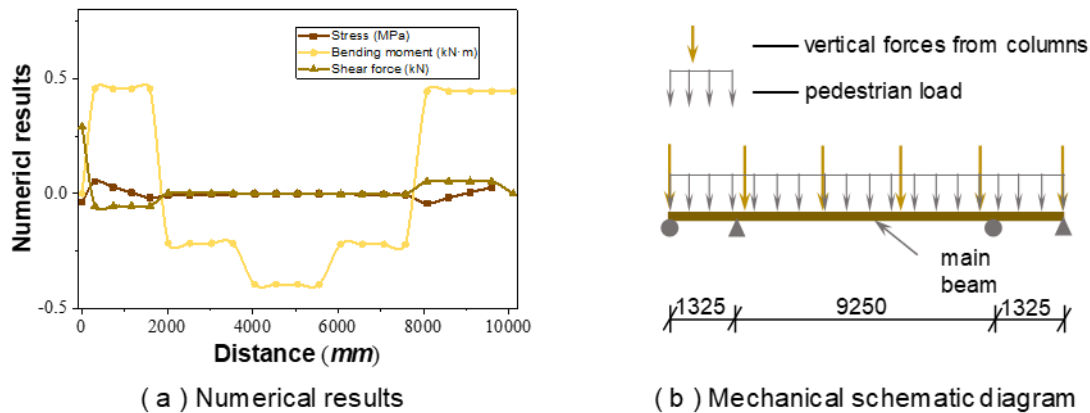


Fig. 4. Numerical results and mechanical schematic diagram of main beams

Bridge Damage

Having been exposed to the environment, some damage inevitably had occurred somewhere in the bridge, although the bridge corridor of Yinjia bridge was refurbished in 1831. The main beams were judged to be in good condition. There were only a small amount of tiny cracks in the end part, relatively speaking, while some cracks in the columns and beams of the bridge corridor parallel to the fiber direction occurred under the external loads and gravity of the upper components and roof (Fig. 5). Fortunately, the cracks had not penetrated through the entire section of these components, such that the damage can be ignored at present. The components of the mortise and tenon joint connect well enough, and this makes the structural stability of the entire bridge corridor.

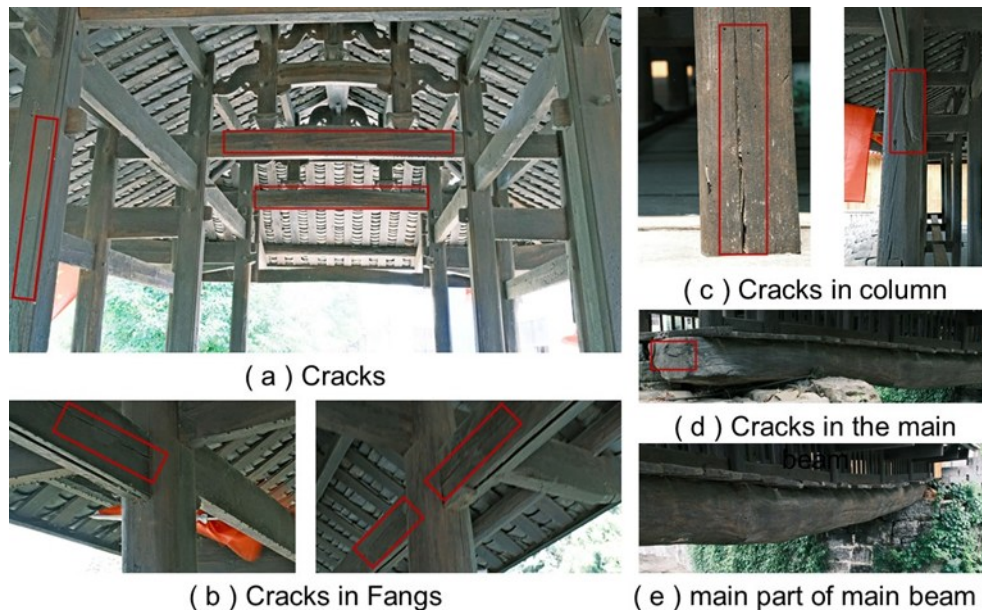


Fig. 5. Cracks of Yinjia bridge

From the numerical results presented above and perspective of the overall structural stability of the bridge, the local damage mentioned above are under normal usage status, and is not severe enough to cause brittle collapse, since there are fewer pedestrians passing by and the crowd load is less than the value in the standard. Although no reinforcement is required, some mechanical monitoring, such as deflection, stress, and strain monitoring, should be performed regularly considering the complex actions of long-term loads and a severe environment. Nonetheless, the vertical deflection of the bridge should be controlled, as the numerical maximum deflection of 10.73 mm is close to the limit value of 15.42 mm, and the deflection considering both the gravity and crowd load exceed the limit by about 1.3%. The load near or larger than the pedestrian load should be avoided on the Yinjia bridge.

CONCLUSIONS

1. This paper comprehensively investigated the Yinjia bridge, a historical and cultural heritage protected at the city level in China, mainly in terms of its construction form and mechanical properties. The same type of raw material used to construct the Yinjia bridge, beech, was tested to obtain its average compressive strength and tensile strength of 65.5 and 233.0 MPa, respectively.
2. The mechanical properties of the material obtained from tests were used in a FE model to simulate the mechanical behavior of the bridge, assuming that the bridge does not contain hidden internal rot or hollow parts. According to the numerical results, the maximum deflection of 10.73 mm in the midspan, when only considering gravity load under serviceability limit state is under but close to the limit of $L/600$. It reaches 15.62 mm under both the gravity load and crowd load and exceeds the limit by 1.3%. The maximum and minimum normal stress of 1.13 and -2.03 MPa are much less than the ultimate values of wood. These results indicate that the Yinjia bridge is in good condition if the pedestrian number are limited to less than the crowd load.
3. All the damage in the bridge is parallel to the fiber direction but not severe enough to cause brittle collapse; thus, no reinforcement is required. However, according to the numerical results and the complex actions of long-term loads and a severe environment, the load near or larger than the crowd load should be avoid, and regular monitoring, care, and maintenance are necessary to preserve the old historical bridge.
4. This study is beneficial for conserving China's historical and cultural heritage.

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