Analysis of an Ancient Single-Arch Covered Bridge to Peach Blossom Spring, China

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Ancient Chinese covered bridges are attracting increased attention due to their architectural appearance and manufacturing technique. In this study, an ancient single-arch covered bridge, Yinjia bridge, in Peach Blossom Spring in China has been investigated, mainly in the field of its cultural background, art aesthetics, and mechanical behavior. The methods of field measurement and finite element analysis were combined. First, the structural dimensions and construction of Yinjia bridge are introduced. Then, the historical origin and cultural connotation, the bridge corridor and decoration are considered, and the Chinese culture reflected behind the bridge design are investigated. A finite element model was built to study the mechanical behavior of the bridge. The numerical results indicate that the maximum vertical deflection of 4.32 mm is under but close to the limit of L/600, while no horizontal deflection exists at the foot of the arch crown. The maximum and minimum normal stress of 0.04 MPa and -0.12 MPa in components of bridge corridor are much less than the ultimate values of wood. The maximum compressive stress of 0.05 MPa of the bridge arch is within the limit value of the ultimate compressive strength of stone. This means that the structural safety performance of this ancient bridge is acceptable, and indicates that no significant structural damage has been found yet in the Yuxian bridge.

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INTRODUCTION

Ancient bridges are notable for their unique structural design and historical significance (Mao 1985; Wacker and Duwadi 2010; Knapp 2021). In ancient China, the covered bridge type was common and well received by civilians (Dai *et al.* 2017; Xie *et al.* 2023). The main bearing system of these bridges is a cantilever beam or arch bridge design. In Hunan province, China, most of the bearing system of ancient covered bridges are wood cantilever beams, and a few of them are stone arches. The corridors are generally made of wood. However, the number of well-preserved ancient, covered bridges is quite limited due to erosion caused by wind and rain (Xie *et al.* 2024). In recent years, more people have attached importance to the protection of historical buildings (Liang 2006; Xiang *et al.* 2009; Guo 2015) and timber bridges (Rostampour Haftkhani *et al*. 2022). These historical structures serve as important carriers of social development memory, embodying the cultural, social, and political dynamics of their times (Harfield 2007). They reflect the identity and history of specific neighborhoods or cities, contributing to a region's cultural heritage and national dignity. Protecting historical bridges is a comprehensive endeavor that involves preserving their historical and cultural significance, ensuring structural integrity, and promoting sustainability. These efforts collectively contribute to the continuity and appreciation of historical heritage for future generations.

Yuxian Bridge, an ancient single-arch covered bridge located on Taohua Creek in Tao Yuan County, Hunan Province of China, has been listed as a historical and cultural heritage protected at the national level due to its historical, cultural, and architectural value. This bridge was first built as an arch bridge in the late Ming dynasty during the period of 1621 and 1627, and a bridge corridor was constructed above the bridge arch to form a single-arch covered bridge under the governance of the Kangxi Emperor of Qing dynasty during the period of 1703 and 1709. It is well-preserved due to its excellent stone material and sophisticated building techniques.

Taking the Yuxian bridge as an example, this paper presents the unique structural system of an ancient single-arch covered bridge, including the stone bridge arch, wood bridge corridor, and roof. The historical origin, cultural connotation, and artistic features of the bridge are discussed. In addition, a finite element analysis bridge is investigated with ANSYS software to study the mechanical properties of the bridge. This study can be used as a reference for the preservation of historical and cultural heritage and is meaningful for the development of ancient bridges.

STRUCTURAL DIMENSIONS

As shown in Fig. 1, Yuxian bridge is a stone single-arch bridge, 4.66 m wide, and the computed span of the bridge is 3.30 m at the initial time. The computed rise of the bridge arch is 1.83 m, and the rise-span ratio is 0.55. As the main load-bearing part of the bridge, the main arch ring thickness is 200 mm, the distance between the vault and the bottom of bridge deck is 400 mm, the depth of bridge deck is 300 mm (200 mm +100 mm), as shown in Fig. 2.

Fig. 1. General view (a) and stone materials of Yuxian bridge arch and abutment (b)

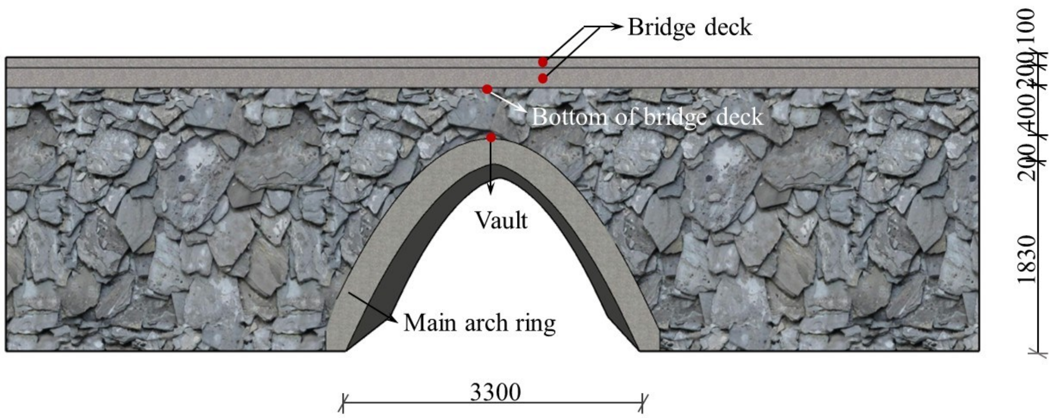

Fig. 2. Dimension of bridge at the initial time (unit: mm)

Above the bridge arch, a bridge corridor was constructed for pedestrians to rest during the period of 1703 and 1709, as shown in Fig. 3. Along the bridge, there are 8 columns in each side, and the longitudinal distances of the columns are 1600 mm, 1000 mm, 4400 mm, 1000 mm, and 1600 mm, respectively. In the transverse direction, there are 8 columns in each side, and the distances of the columns are 1110 mm, 2000 mm, and 1110 mm, respectively. All the columns use the same diameter of 240 mm.

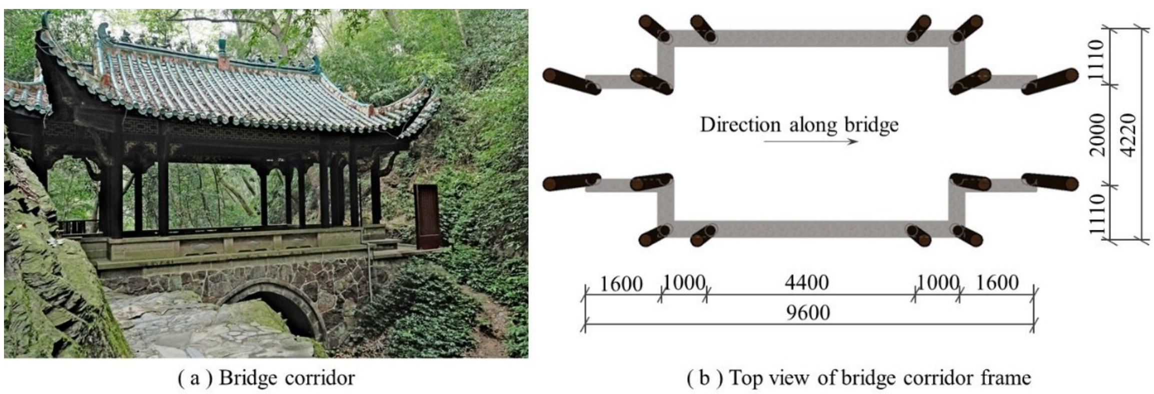

Fig. 3. Dimension of bridge corridor constructed later (unit: mm)

HISTORICAL ORIGIN AND CULTURAL CONNOTATION

The history of Yuxian bridge can be traced back to the natural rock bridge stage. The original bridge was initially formed by naturally collapsed boulders lying horizontally. As time went on, an arch bridge was first built in the late Ming dynasty and a bridge corridor was constructed above the bridge arch in the Qing dynasty. Its geographical location closely aligns with the path to the peaceful, happy, free, and equal village in Peach Blossom Spring described in the “Record of the Peach Blossom Spring”, written by the famous pastoral poet Yuanming Tao who lived from the Eastern Jin Dynasty to the Southern and Northern Dynasties, creating a mysterious cultural atmosphere for this bridge. Influenced by Yuanming Tao’s article, the location of the Yuxian bridge was regarded as a clue to connect reality with the ideal realm.

The name of Yuxian Bridge relates to many legends. It is said that a fisherman in Wuling encountered an immortal here by chance and gained guidance to enter a paradise on earth. There is also a folk story related to the bridge about choosing a son-in-law through poetry. A talented woman used the poem "On the Bridge of Encountering Immortals" as a condition for choosing a son-in-law, which was engraved on a stone tablet beside the bridge (Fig. 4). In this poem, the end of the previous sentence was used as the beginning of the next sentence, connecting adjacent sentences to form a rhetorical device that loops back and forth. These legends have enriched the cultural connotation of Yuxian bridge, making it the core carrier of the Peach Blossom Spring legend, carrying the symbolic significance of ancient Taoist culture, reclusive culture, and folk ideal society.

Fig. 4. Landscape around Yuxian bridge

DESIGN AND DECORATION OF BRIDGE CORRIDOR AND ROOF

A bridge corridor is usually used in the covered bridge for two functions. It works as a barrier to protect pedestrians from wind and rain (Liu 2017), and it also reflects the ancient Chinese political, cultural, and feudal hierarchical system at the ancient times (Wang 2019). Unlike the residents near the Yanzi bridge (Xie *et al.* 2024), tourists who travel back and forth to Peach Blossom Spring often rest here. As shown in Fig. 5(a), the bridge corridor consists of columns, beams, Fangs, and a roof. The lower end of a column stands on the bridge deck, and the upper end supports a beam up in the bridge corridor. Between each column upper end and the other, there is a horizontal beam called Fang that connects the two columns. The columns, beams, and Fangs are interconnected to form a framework to bear loads. The function of the beams is to bear the weight of the roof above, then transmit it downwards to the columns, then downwards to the arch bridge, and finally to the foundation. On top of the corridor, a bridge roof consisted of two gable and hip roofs (Fig. 3 (a)) is not only beautiful but also provides shelter from wind and rain for pedestrians.

As a typical wooden covered bridge relic, the Yuxian Bridge faces dual challenges of wood biodegradation and environmental erosion. As shown in Fig. 5(b), the decorative components set under the Fang, which are often made of hollow wooden grids or carved boards with paintings, present a dual value dimension: at the technical level, a physical protective layer is formed through covering coloring, effectively slowing down the erosion rate of wooden components by environmental factors such as sun exposure, rain, insect infestation, and mold growth; at the level of cultural representation, by utilizing the mechanism of visual symbol translation, regional life philosophy and collective memory are encoded into a perceptible aesthetic schema system.

Under the bridge roof, golden carvings on red background with the theme of immortality are hung. They are exquisite due to excellent craftsmanship. The construction of this visual order not only conforms to the traditional spatial cognitive paradigm of building a "round sky and square earth" (He *et al.* 2023), but also forms a visually harmonious, stable, and rhythmic aesthetic through the principle of Yin-Yang coupling composition, giving people a profound aesthetic experience. Through its expression, it symbolizes the continuity of life and the longevity of a beautiful life, as well as metaphorically represents the philosophy of "harmony of the universe" and "endless vitality". On the spine of the roof, simple auspicious patterns are used as decorative elements (Fig. 3 (a)), the sculptural fish and dragon appear to be kissing the roof, adorned with immortals and a group of beasts.

The Yuxian Bridge reveals the cultural efficacy of traditional architectural decoration beyond the aesthetic realm (He *et al.* 2024). The painted layer is not only a physical barrier to delay the decay of wood, but also a symbolic carrier for the transmission of regional knowledge.

This dual dimensional survival wisdom provides important inspiration for contemporary heritage protection, and it is necessary to reconstruct the cultural interpretation path in technological innovation.

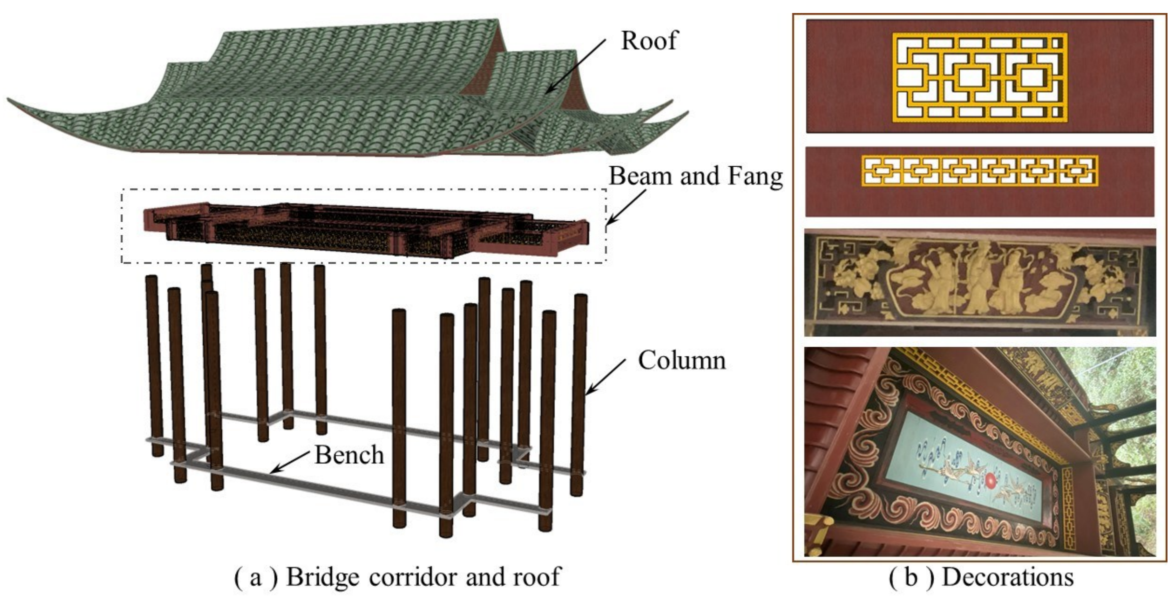

Fig. 5. Bridge corridor and decoration

FINITE ELEMENT ANALYSIS

To study the mechanical performance of the Yuxian bridge, a finite element (FE) model was built with the numerical software ANSYS (Fig. 6). The wood beams and columns of Yuxian bridge corridor were both simulated with a Beam 189 element, and the main body of the stone arch bridge was modeled with a solid 185 element. The densities of the stone and wood were considered to be 2550 kg/m^3 and 790 kg/m^3, respectively. According to the Technical Specification of China, Urban Pedestrian Overcrossing and Underpass (CJJ69-95 1995), a crowd load of 3.6 kN/ m^2 was taken into account as the bridge load.

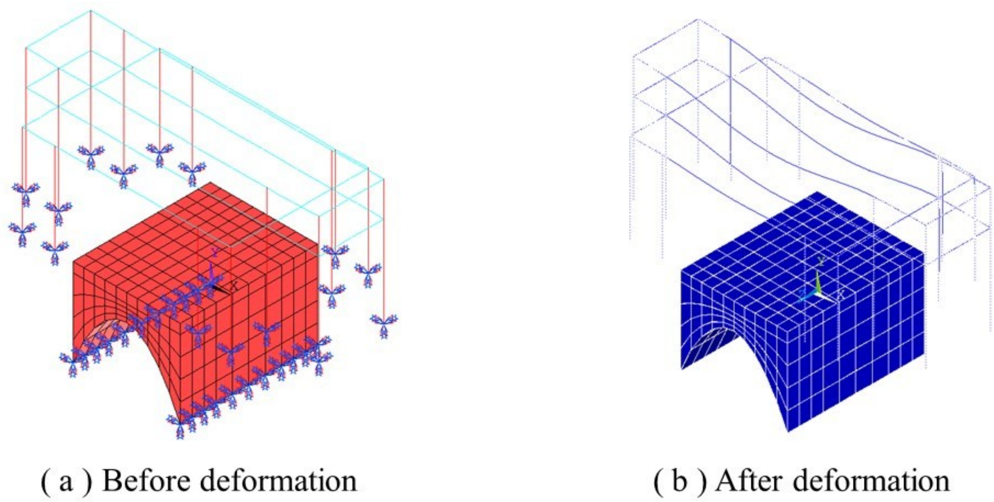

Fig. 6. Finite element model for Yuxian bridge

As shown in Fig. 6, the deformation is specified for all the components, such as the stone arch and wood corridor and roof. The bridge deforms symmetrically but negligibly, with the maximum vertical downward deflection reaching 4.32 mm at the top of the spandrel structure when considering both gravity and crowd load under serviceability limit state, and the maximum horizontal deflection is -0.05 mm occurs on the wooden columns of the bridge gallery, while no horizontal deflection exists at the foot of the arch crown. The deflections are both under the limit of L/600 as detailed in the pedestrian bridge specification (CJJ69-95 1995). In addition, the mechanical properties of the Yuxian bridge under ultimate limit state was studied. The normal stress, bending moment, and shear forces of components in bridge corridor (including wood columns, beams, Fangs) and solid elements in bridge arch are listed in Table 1. For the bridge corridor, the maximum normal stress of 0.04 MPa and the minimum normal stress of -0.12 MPa are within the limit value of the ultimate tensile strength and ultimate compressive strength of wood, respectively. The maximum shear force is 0.20 kN, and the maximum bending moment of the bridge is 0.10 kN·m. For the bridge arch, the maximum compressive stress of 0.05 MPa exists at the foot of the arch crown and is within the limit value of the ultimate compressive strength of stone. The normal stress of the arch crown is mainly discussed here because it is important for arch bridge, while shear force and bending moment are ignorable. The internal force state of the components presented above indicates that the performance of the bridge is good. The numerical results are consistent with the good state of the actual project, because no significant structural damage has been found yet.

Table 1. Typical Results of Yuxian Bridge

Components	Numerical Results	Normal Stress (MPa)	Bending Moment (kN·m)	Shear Force (kN)
Corridor	Max	0.03	0.10	0.20
	Min	-0.12	-0.10	-0.20
Arch	Max	0	-	-
	Min	-0.05	-	-

CONCLUSIONS

1. This paper investigated the Yuxian bridge, a historical and cultural heritage protected at the national level in China, mainly in terms of its cultural background, art aesthetics and mechanical properties.
2. The dimension of the bridge was introduced, including the characteristic of the bridge corridor and bridge decoration. The bridge was simulated with a finite element (FE) model, and the mechanical properties were investigated. According to the numerical results, the maximum vertical deflection of 4.32 mm is under but close to the limit of L/600, while no horizontal deflection exists at the foot of the arch crown. The maximum and minimum normal stress of 0.04 and -0.12 MPa in components of bridge corridor are much less than the ultimate values of wood. The maximum compressive stress of 0.05 MPa of the bridge arch is within the limit value of the ultimate compressive strength of stone.
3. The Finite Element model results indicate that the Yuxian bridge is in good condition. To date, no significant structural damage has been found yet due to proper maintenance. However, the bridge monitor should be executed to prevent bridge damage.
4. This study is beneficial for conserving China's historical and cultural heritage.

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