The Evolution and Research Progress of the Arch Structure

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Abstract. With its unique structural system and rich history and culture, wooden structure bucket arch has become a typical component of Chinese wooden structure architecture. Based on the analysis of the shortcomings of wooden structure, with the emergence of modern antique buildings, wooden structure bucket arch is gradually replaced by prefabricated concrete structure bucket arch. This paper introduces the development and evolution of the bucket arch structure, analyses the research progress of the bucket arch structure, puts forward the advantages and disadvantages of the wooden structure and the concrete structure, and defines the research direction of the prefabricated concrete bucket arch structure.

Introduction

The bucket arch is a unique structure in ancient Chinese wooden frame buildings, and is often used in some landmark buildings, such as temples, palaces, and ancient gardens. On the one hand, it plays a decorative role, on the other hand, as a transition part between the column and the roof, it can transmit part of the force on the roof to the column to play the role of bearing and energy dissipation. With the development of society, population growth, timber resources are becoming more and more tense. In order to save wood and environmental protection, and also consider the fireproofness, durability and post-maintenance of buildings, the bucket arches are gradually changed from wood structure to the concrete structure.

Development and Evolution of Wooden Structure Bucket Arch

The wooden structure bucket arch is located between the top of the column and the eaves. The load-bearing structure that is arched out from the upper fang to support the eaves is called the "arch", and the square block that acts as a support between the arch and the arch is called "bucket". Together they are called the bucket arches.

During the Western Zhou Dynasty to the Warring States Period, it was the original embryonic period of the arch, which was a bucket arch subsystem and a bucket arch system. In the Han Dynasty, the form of the bucket arches were mostly a bucket two liters, a bucket three liters, and a herringbone arch. At this time, the scale of the bucket arch is strong and large, and it is directly placed on the pillar head, which belongs to the pillar paving. Structural effects of supporting, cantilevering and reducing bending moment and shear force are obvious, and has the basic form of the mature bucket arch in later generations[1]. From the Northern and Southern Dynasties to the Sui and Tang Dynasties, Bucket arch evolved from a form of a bucket three liters to a form of bracket sets between columns. The eaves of the Tang Dynasty were generally far-reaching, so that the arches were magnificent, which also reflected the structural beauty of the arch itself. During the Song Dynasty, the bucket arch was from large to small, from simple to complex, and the function of structure was weakened while the decorative function was gradually strengthened. From the Ming Dynasty to the Qing Dynasty, it was the stage of complete decoration of the arch. The development and definition of the arches symbolizes the perfection of the wooden structure system of ancient Chinese architecture. Its design and combination are very strict and exquisite [2].

According to the position of the bucket arch on the building, it is divided into three categories:
① On the top of the column, called the bracket set on columns. It refers to the bucket arch sitting on the eaves pillar, which mainly acts as the supporting beam frame and has a certain bearing function in the structure function.

② On the forehead between the columns, it is called the bracket set between columns. Its function is far less important than that of the stigma. It is mainly placed on the forehead of the column to play a decorative role.

③ On the top of the corner column, it is called the bracket set on corner. Compared with the above two types of bucket arches, the horn is relatively complicated in structure and is in two different directions, so that, there are two exteriors at the same time.

The functions of the bucket arch are as follows:

① The function of transmitting load: The bucket arch stands between the column and the beam, which is the transition between the top of the column and the roof truss. It bears the load transmitted from the roof and the upper frame and transmits the load to the beam or the pillars, which are then passed from the pillars to the foundation.

② The function of protruding the eaves: The bucket arch will eaves the outermost layer of a certain distance, making it a cantilever structure, so that the building is more far-reaching, more beautiful and spectacular shape. The overhang of eaves can also protect the bottom of columns and walls from erosion and erosion by rainwater.

③ The function of reducing the span of beams: The bucket arch stands on the top of the column, and it spreads both sides indoor and outdoor at the same time. The span between beams and pallets decreases obviously due to its protrusion toward depth.

④ The function energy dissipation and shock absorption: Each component of bucket arch is connected by tenon and mortise, the specific structure is shown in Figure 1. The combination of tenon and mortise guarantees the coordination of the stiffness of the building. When an earthquake occurs, the combination of tenon and mortise will be "loose" but not "scattered". It consumes the energy transmitted by the earthquake and greatly reduces the seismic load of the whole building.

⑤ Decorative function: The structure of the bucket arch is exquisite and its shape is unique. With different decorations or paints, the decorative performance of the bucket arch is prominent, for example, in Figure 2. The bucket arch is outwardly picked up to make it look more beautiful.

Research Status of Wooden Structure Bucket Arch

Xuan LV[2] analyzed the force transmission mechanism and failure mode of each member of the bucket arch, and studied the vertical stiffness of the bucket arch and the variation law of the rotational stiffness; Guo-an WEI[3] carried out the axial compression test and the low cycle repeated load test of the bucket arch. The load of the bucket arch under the vertical load is obtained and the displacement curve and hysteresis curve are drawn; Xiao-wei LI[4] established a Qing Dynasty nine purlin palace model with bucket and side foot by finite element method, and analyzed the elastic-plastic displacement response and acceleration response of the model system to study its structural response under earthquake action; Jun-hai ZHAO[5] conducted a dynamic experimental study on the node of bucket arch and obtained the frequency response curve, natural frequency and damping ratio of the bracket node model. And the influence of boundary conditions and vertical loads on the natural frequency and damping ratio is discussed; Duo ZHANG[6] took Sakyamuni pagoda in the northern Shanxi Province as the research object. The element group simulation of
bucket arch joints is carried out, and the stiffness of it joints is determined by the measured modal analysis results of the wooden tower structure; Jian-yang XUE\textsuperscript{[7]} used the seismic shaking table to study the dynamic performance and seismic response of the palace timber structure. The results show that the seismic response of the upper structure can be greatly reduced by sliding between the column bottom and the foundation stone, and friction and damping between mortise and bucket arch; Da-feng GAO\textsuperscript{[8]} discussed the isolation, shock absorption mechanism and corresponding vertical limit bearing capacity of the bucket arch under the vertical earthquake by the experimental study of three shrinking bucket arches under vertical loads; In the United States, W. Mbulleit et al.\textsuperscript{[9]} proposed a calculation model of nodes and such wood structures based on detailed research on various tenon joints nodes with concealed sales; Dyna FD of the University of Bath, UK 'Ayala et al.\textsuperscript{[10]} studied the seismic destructiveness of traditional Taiwanese stacked wood structures.

Although the structure of wooden bucket arch is more far-reaching and graceful by the way of overhanging, and has its own characteristics in seismic performance, especially, mortise-and-tenon connection is adopted between them, so that the building structure can consume extra energy when it encounters earthquakes. However, with the deepening of our research on wooden structure in ancient buildings, the shortcomings of wooden structure gradually emerged. There are serious defects in anti-corrosion, fire prevention and insect prevention, which also restrict the development of wooden structures in today's society.

**Evolution of Wooden Structure Bucket Arch to Concrete Structure Bucket Arch**

With the development and progress of society, the domestic tourism industry has also developed vigorously, and a large number of cultural tourism, leisure and entertainment places have been built in various regions. As a result, a large number of archaic buildings have been built, as shown in Figure 3. Ancient architecture refers to the buildings which are used to imitate and replace ancient buildings, traditional religious buildings, traditional landscaping, historical buildings, cultural relics buildings, ancient villages, and restore historical features. Because of a series of defects in wood itself, especially in terms of durability, archaic buildings are basically concrete structures, and wooden structure bucket arch is gradually replaced by concrete structure bucket arch.

![Figure 3. An antique building in Hengdian Show City.](image)

**Research Status of Concrete Bucket Arch**

Because of the advantages of simple construction, convenient connection and strong durability and safety, concrete structure bucket arch is more and more widely used in the current archaic building construction.

Hai-peng WANG\textsuperscript{[11]} through the research of the connection technology between concrete column and wood beam, found that the joint between concrete and wood structure is very weak. It is necessary to strengthen the research of the connection technology to make up for the defects of the traditional connection technology; Lei JIANG\textsuperscript{[12]} compares the characteristics of traditional wood structure and concrete structure through engineering practice and case study, and summarizes the principles of concrete archaic architecture design; Li-juan KANG\textsuperscript{[13]} Through an example of seismic design of a temple concrete archaic building structure, the solutions and measures adopted in structural layout, seismic structure and bucket-arch joint design are briefly described; Guang-hui SU\textsuperscript{[14]} through the study of archaized bucket arch joints made of concrete, metal and other materials, found that due to the different materials, the mechanical properties of bucket arch joints are
different, and ultimately will affect the internal force distribution and mechanical properties of the whole structure.

There are two main connection modes of concrete bucket arch, one is cast-in-situ, the other is prefabricated in prefabrication yard.

Integral cast-in-place is the most direct connection method, which means that the steel bars of the concrete bucket arch are tied directly when supporting the formwork, but the concrete column is usually supported by a single row of steel pipes at the bottom of the concrete bucket arch formwork. Finally, concrete pouring is carried out, and later maintenance is strengthened, so that the connection between the bucket arch members and concrete columns can be realized.

When prefabricated prefabricated concrete bucket arch is used, the bucket arch of each layer is made according to the size of the die, and the reserved steel bar is set inside the longitudinal bar of the concrete bucket arch. When installed, one end of the reserved steel bar is welded with the steel bar on the column and the other end of the reserved steel bar is through coagulation. Longitudinal members of soil bucket arch are connected with a small amount of fine sand concrete between each layer of arch to make it a whole. The installation schematic diagram of reserved steel bar and part of bucket arch warping is shown in Figure. 4 below. This method has the following advantages:① It can be prefabricated in advance in the prefabricated yard without being affected by the time of the main structure of the building, and the construction period is short.② The quality is guaranteed, and the shortcomings of difficult formwork support, easy formwork walking, hemp surface, irregular edges and angles, and poor inclination of the bucket arch are avoided in the construction of a large number of concrete bucket archs on site.③ Low cost, follow the characteristics of ancient buildings; ④ Uniform appearance, mass production of prefabricated yards, easy quality control, installation can adjust the verticality and regularity at any time to achieve uniform appearance.

The Difference between Wooden and Concrete Bucket Arches

The wooden bucket arches of ancient buildings are semi-rigid joints, and the structures are joined by tenons and mortises. When the earthquake occurs, the tenons and mortises will become loose but not loose. This rigid and flexible connection method has good energy dissipation and shock absorption effect, as shown in Figure. 5. In the archaized reinforced concrete buildings, the concrete bucket arch joints are cast-in-place rigid joints, as shown in Figure. 6.

The wood structure of ancient buildings is easy to be corroded and fire, and nowadays the society advocates environmental protection, and the wood resources are becoming increasingly scarce; while the reinforced concrete archaized buildings can just make up for the defects of wood structure in anti-corrosion, fire prevention, insect prevention and other aspects, and the concrete structure also has the advantages of saving wood and reducing costs. It has the advantages of good durability and short construction period, which is suitable for our national conditions.
Research Prospects of Bucket Arch in Concrete Structures

With the emergence of antique buildings, prefabricated concrete bucket arch is also widely used. However, there is a lack of in-depth and meticulous research on the force transfer mechanism at the joint of bucket arch and concrete column, the seismic performance of the joint, the reinforcement design of prefabricated concrete bucket arch structure and so on. A lot of experiments and numerical simulation analysis are needed to provide a reference for the design of prefabricated concrete bucket arch structure.

References
