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Assessment and retrofitting solutions for an historical wooden pavilion in China

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HIGHLIGHTS

- Measurement data for assessing the ancient timber structure are presented.
- Evaluations on the damages of structural components are described and discussed.
- The strengthening procedure and techniques are described in detail.

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ABSTRACT

Feiyun Pavilion is located in Shanxi Province, China. It is a classic example of ancient wooden pavilions and one of the primary national cultural assets, which was rebuilt more than 500 years ago. During recent years, the structural deterioration and degeneration of Feiyun Pavilion have accelerated due to inefficiencies in maintenance and management. The main structure is apparently off-plumb and in danger of collapse. With special financial required, the state Administration of Cultural Heritage asked the local Cultural Relic Protection Unit to contact historians, researchers, and engineers to restore this particular ancient structure. This paper presents the necessary assessment data, evaluation method, and the preferred solution for retrofitting and strengthening this historical timber building.

1. Introduction

Wooden structures play an important role in ancient architecture. They account for one-third of Chinese cultural relic sites. Wooden pavilions are one of the most common constructions found in courtyard monuments. In ancient times, wooden pavilions in China had multiple uses. People could climb to the top of the pavilion to enjoy a scenic view, or the pavilion could be used as a place to store collected books or even to honor a Buddha. Feiyun Pavilion is located in Wan-rong County, a relic site in south Shanxi Province, famously known for its abundance of ancient wooden pavilions. Feiyun Pavilion, the so-called "Southern Pavilion", shares its reputation as an historic relic of this area with Yingxian Wooden Pagoda, the so-called "Northern Pagoda" (Fig. 1). Feiyun Pavilion was constructed with three floors, with a gable-and-hip roof and double-deck eaves on the top story (Fig. 2). The main structure still retains its original unpainted wooden appearance, while the glamorous tiles and traditional ornaments remain on the roof. The pavilion's plan is shown in Fig. 3.

As shown in Fig. 3, Feiyun Pavilion has only four primary circular columns, referred to as "Yong-ding columns," running across the three floors. Yong-ding columns are tapered, with the diameter varying from 531 mm (top) to 703 mm (bottom). The secondary columns are only one storey high, with the diameter from 150 to 531 mm, the columns transfer the vertical forces of the cross and outrigger beams. Some columns were added during previous repair work, but without considering the plane symmetry, which is located below the cross beam that had experienced considerable deformation. The east and west sides of the first floor have 1-meter thick external walls, which are made of 120 mm thick outer bricks filled with clay. The four stone columns feature dragon carvings and are embedded in each brick wall. According to the historical records, Feiyun Pavilion had originally been built during the Yuan Dynasty (≈1400 A.D.). The pavilion was destroyed during a war and then rebuilt. Based on the inscription which can be found on one table, Feiyun Pavilion was rebuilt at some point between 1506 and 1521 A.D. Other tables which remain at the site indicate

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Fig. 1. Map showing the location of Fei-yun Pavilion and Yingxian Wooden Pagoda.

that the building was repaired a further four times, in 1617, 1746, 1823, and 1858 A.D. Due to the vicissitudes of nearly half a century, human-induced disasters, and a lack of repairs for many years, the main structure currently has serious plumb problems. The Nation's Cultural Heritage Protection Departments have earmarked special funds to carry out urgent repairs. In recent years, the Wan-rong Cultural Relic Protection Department invited the Shanxi Conversation of Historical Building Design Station and Taiyuan University of Technology to participate in the Feiyun Pavilion Restoration Program.

In this study, a range of assessment techniques developed during and based on past experiences [1–4] and the latest research results from Mosoarca and Gioncu [5] and Lourenco et al. [6] are utilized. This article aims to present the structural assessment data of Feiyun Pavilion and the measures used to strengthen the structure.

2. Assessment of the existing structure

When assessing the building, a total station instrument and digital level were used to measure the main structure's deformation, establish the global coordinate system at the building site, obtain the coordinates at the four corners of the flying eaves and at the columns' top and bottom, and measure the deflections of the wooden beams. The measured data was then used to evaluate the safety and reliability of the existing structure, in which clear and present settlement, tilting, and torsion issues were considered. The extent of the damaged condition of individual members was reviewed in detail, followed by a precise description of the damage characteristics and the proposed repairs. In addition, the level of the damage for each component was graded on a storey-by-storey basis [7].

2.1. Observations of settlement and column compression

The relative elevations at the top and bottom of the main bearing columns on the first floor are shown in Fig. 4 (see Fig. 3 for column numbers), in which the relative elevations (top and bottom) of the southwest column (i.e., Column 10) were set as 0.000 m.

The relative elevations at the bottom of the columns depend on factors such as subsoil settlement, decaying of the columns' footing, and installation errors during earlier construction work. An unusual relative elevation of 221 mm at the pedestal of the northwest column was noted. This was caused by the raising of the pedestal during a previous restoration project (as indicated on documented records), while the maximum relative elevation of the other column pedestals is 38 mm. The settlement discrepancy between adjacent column bottoms should not exceed a limits of 0.003 l (l: column spacing in frame), as specified in the Chinese code for the design of building foundations [8]. Nearly half of the calculated values do not fulfill the technical specification requirements. The relative elevations at the tops of the columns are