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Lateral performance of mortise-tenon jointed traditional timber frames with wood panel infill

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ABSTRACT

Mortise-tenon jointed timber frames with wood panel infill are commonly used in traditional timber structures of East Asian countries as the primary shear resisting component. This paper presents the test results of three 1:2 scaled Chinese traditional mortise-tenon jointed beam-column frames, one as bare frame, one with partial panel infill accommodating a wide window opening, and the third with full panel infill, considering translational cyclic loading and constant vertical loading. The failure modes, stiffness and strength (including rate of degradation), and energy dissipation capacity of the frames were discussed to quantify the contribution of the panel infill. The results indicated that the frames behaved nonlinearly with good ductility (e.g., 9.72 of the bare frame). The frames with panel infill (with or without a window opening) exhibited higher load carrying capacity (up to 35.3% increase in the peak loads), secant stiffness and energy dissipation capacity. All three frames maintained at least 65% of the peak load of the primary cycles during the trailing cycles, indicating a good endurance against damage accumulation. It was also found that the lateral drift threshold for the panel infill to make a solid contribution to the frames is around 1/70 of the column height. A linear contribution can then be maintained up to 1/30 of the column height, covering the general drift limit for collapse prevention (1/50).

1. Introduction

Wood is one of the oldest construction materials used worldwide in the history of architecture. In China, traditional wooden architecture is very diverse and occupies a large proportion of Chinese ancient structures. Wood has been widely used to build palaces, mansions, temples, and pagodas [1,2]. This major cultural heritage of China however has suffered a lot through the years because of earthquake damage, wind effects, moisture due to heavy rains, and warfare-related damage. Many traditional timber structures are, or will be in a short time, in urgent needs of protection and retrofitting.

To offer an efficient retrofitting plan, it is essential to have an accurate understanding of how the traditional timber structures react to normal loading and, more importantly, to extreme perturbations. It is therefore crucial to understand and to quantify as precise as possible the seismic performance of traditional timber structures, especially multi-story timber pagodas, to provide a reliable basis for quantitative analyses for retrofitting purposes.

In 1100 during the Song dynasty, Li Jie introduced his famous monograph, *Treatise on Architectural Methods or State Building Standards*. With this book, Li provided China's earliest and most influential set of architectural standards for carpenters, craftsmen, and builders [3]. It is the oldest book known to describe the traditional Chinese timber structure details, elements, and basic calculation methods. In the early 1990's, Ma [4] and Wang [5] presented their accounts of the construction technology and mechanics of ancient timber structures, respectively.

More quantitative 21st century studies [6–9] have been conducted on the component level since the fabrication of traditional timber structure models is rather labor intensive and prohibitively complicated. A great deal of attention has been paid on testing timber beam-column frames as they serve as the primary shear resisting elements in traditional timber structures. Chun et al. [6] investigated the traditional beam-column connections of timber frames under dynamic loading with consideration of various geometric configurations. Xu and Qiu [7] tested dovetail connected timber frames and observed that the hysteretic moment-rotation curves were in an inverted "Z" shape and the stiffness of the joints reduces with increased rotation. Fang et al. [8,9] conducted cyclic tests on timber frames, both in the lab and on construction sites, and identified the dynamic properties of the frames. King et al. [10] proved that the static linear characteristics of a traditional timber frame with straight mortise-tenon connections are

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dominated by the characteristics of the connections. Chang et al. investigated the rotational performance of traditional Nuki joints and proposed a theoretical model with good agreements with test results [11].

Study conducted in Korea and Japan are also of reference values since their tested timber structures were constructed with similar craftsmanship. Seo et al. [12] investigated the static and cyclic performance of a mortise-tenon connected Korean timber frame, which exhibited significant inelastic behavior and reduced stiffness with increased loading until shear failure in the joints. Tsuwa and Koshihara conducted tests with Japanese timber frames [13] and reached similar conclusions.

More recently, researchers started to pay more attention on the contribution of infill materials to the stiffness and displacement responses of timber frames, as timber structures are often low in lateral stiffness and their seismic performance is more governed by inter-story and total displacements rather than internal forces. Tests have been conducted with earth in Japanese timber frames [14] and masonry in Portuguese frames [15–17] and Chinese frames [18]. Although wood panels are more frequently used in Chinese traditional timber palaces and pagodas in a pursuit of pure wood structures, no study with wood panel infill and window openings has been reported.

In view of the urgent needs of understanding the seismic performance of traditional timber structures, especially multi-story pagodas, and the complexity of the infilled timber beam-column frames, a series of tests have been conducted, taking the chance of the construction of a seven-story timber pagoda that was designed following the Tang Dynasty style of China. This includes shake table testing of a scaled pagoda model considering strong earthquakes (Fig. 1a), structural monitoring of the construction process (Fig. 1b), and testing of mortise-tenon joints, dou-gong joints (also known as the complicate bracket), infilled beam-column frames, etc. A numerical analysis model has also been planned, using data from component tests, and to be verified against the shake table test data and construction monitoring data.

Being focused on the timber frame component tests, this paper presents the cyclic test results on three frames, which have the same dimension, but different infill parameters: (1) no infill, (2) partial infill as to accommodate a window opening, and (3) a full infill. By comparative studies, the contribution of the infill panels, with or without a window opening, was quantified, based on stiffness, strength, degradation of the two, and energy dissipation capacity.

2. Research significance and limitations

Traditional timber structures are low in lateral stiffness. Excessive lateral displacement often dominates the aseismic capacity of the entire building. The test results of the three otherwisely the same frames can help clarify the contribution of the panel infill to the lateral stiffness and displacement of the frames. The threshold and development of the infill contribution quantified based on the test results in a dimensionless way can also be used as reference for other timber frames with similar configurations and structural behavior.

This study has been based on reduced-scale specimens with no replicates, a limitation that is rather common in this research area [12–15]. The large size wood members used in traditional timber structures of China and other East Asian countries are very expensive and difficult to find, especially for testing purposes. Generally, the influence of no replication on the frame tests is smaller than that on uniformly loaded wood specimens, since the weakest wood may not be in the most stressed areas. However, the assembly gaps in the hand-made joints and frames rely more on craftsmanship than on member size, and can have a variable influence on specimens of different scaling ratios. Thus, the results presented in this paper are not intended to be used directly in design practice. Numerical modeling and parametric studies will be conducted to further address these issues.

Fig. 1. Study of a multi-story timber pagoda: (a) shake table testing of a scaled model and (b) monitoring during construction process.

3. Experimental studies

3.1. Specimen fabrication

Three half-size scale frame specimens were prepared with African rosewood (padauk). The averaged modulus of elasticity, compressive strength and tensile strength and the corresponding coefficients of variation (in parentheses) of the wood in the parallel to grain direction were determined from small clear specimens at 15,207 MPa (0.11), 50.4 MPa (0.08), and 102.0 MPa (0.19), respectively, from nine replicates each [19]. The frames were consisted of beams and columns that were connected using dovetail mortise-tenon joints, as illustrated in Fig. 2.

The span of the frame was 1650 mm and the total height was 1220 mm. The bottom beam had a 110 × 100 mm cross section secured by a lap joint connected to its two round columns, which were 250 mm in diameter and 1100 mm in height. A 170 × 175 mm main beam was leveled with and connected to the columns by mortis-tenon joints. A 230 × 120 mm cover beam was placed on top of the main beam and connected to the columns by a 45 × 45 × 45 mm upward tenon that went into the mortise on the cover beam itself, as shown in Fig. 3.

The frame with full panel infill had two secondary columns that matched the round surface of the columns and the flat surface of the wood panels. These columns simply rested on the bottom beam (with some precut slots) and closed a rectangle with a secondary beam that was placed between the main beam and the wood panels. The wood panels were double layered with wood studs going in between and had a thickness of 100 mm (20 mm of each layer of panel and 60 mm pertaining to the studs) with a width of 150 mm. The panels were connected one by one with tongue-and-groove joints. In the partially infilled frame, the double layered panels went up to mid-height (300 mm) and a 210 × 100 mm lintel, formed by two equal pieces, defined the

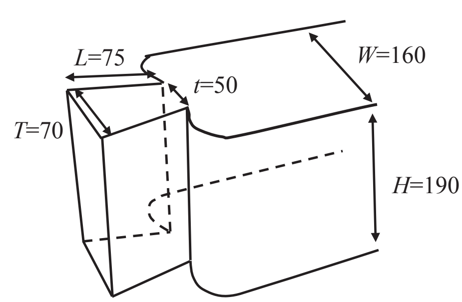

Fig. 2. A typical mortise-tenon joint (mm).