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Experimental investigation on the lateral structural performance of a traditional Chinese pre-Ming dynasty timber structure based on half-scale pseudo-static tests

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ABSTRACT

Existing ancient Chinese timber buildings are frequently subjected to seismic or strong wind loads throughout their lifetime, hence their lateral structural performance can undergo significant changes. It is essential to employ tests in the laboratory to study these variations to protect these existing timber buildings. In this paper, a single-layer model of a timber building with a geometrical ratio of 1:2 was fabricated according to the pre-Ming dynasty construction method. Six pseudo-static tests were conducted under three levels of vertical loads. The timber structure displayed visible rocking characteristics during the tests, and the column feet and mortise-tenon joints were the weak links in the structure. The features of hysteresis curves, envelope curves, strength reduction, energy dissipation, and lateral stiffness of the timber structure were obtained, and their variations associated with loading courses were discussed. Moreover, a simplified restoring force model was built for this type of timber structure.

1. Introduction

Existing ancient Chinese architecture, particularly timber buildings, is the carrier of historical memory, cultural development, and civilization progress. Chinese timber buildings have been developed for more than 2000 years, but only about 440 timber buildings constructed before the Ming Dynasty (CE 1368) have been preserved. These buildings have a long history, and their architectural form is much different from that of buildings erected after the Ming Dynasty.

Traditional Chinese timber structures are noted for their excellent seismic performance, as most of them have experienced repeated earthquake action. However, due to environmental erosion, the effect of sustained load, and occasional disasters, a series of negative impacts have been brought upon these pre-Ming dynasty timber buildings. These include the deterioration of wood properties, increasing gaps between components, reducing the effective section of components, etc. which eventually leads to a decrease in the buildings' bearing capacity and to deformability. It is important yet difficult to evaluate the residual structural performance of this type of timber building, especially their capacity to withstand earthquake action.

The major parts of a typical pre-Ming dynasty timber building are shown in Fig. 1 (the main hall of Nanchan Temple on Mount Wutai in Xinzhou city, Shanxi, China). The frame composed of beams, columns, and *Dou-Gong* brackets is the primary load-bearing part, carrying both vertical loads from the roof and horizontal loads caused by earthquake action or wind. Corresponding research on a single element (beam, column, etc.) or a partial structure (beam-column joint, *Dou-Gong* bracket, etc.) of existing timber buildings may partly reflect their local features, while studies on the major load-bearing system, consisting of beam-column frames and *Dou-Gong* brackets, are essential to evaluate their overall structural performance.

Dou-Gong brackets are vital parts of a timber building's load carrying system. Fujita et al. [1] found that the stiffness of the brackets was determined by the theoretical elastic deformation perpendicular to the grain and by the friction coefficient of the timber. Yuan and Shi [2] studied the hysteretic behavior of typical *Dou-Gong* brackets from the Yingxian Timber Pagoda. They found that the lateral stiffness of the *Dou-Gong* brackets increased with the vertical load they carried, and the brackets displayed excellent energy dissipation ability through friction and shear energy dissipation. Ayala and Tsai [3] studied *Dieh–Dou* timber structures in Taiwan, and rotation and pull-out tests were conducted on full-scale *Dieh–Dou* models. It was found that the rotational stiffness of the set joints depended on the applied vertical load, while the translational stiffness was not affected by the applied load. The

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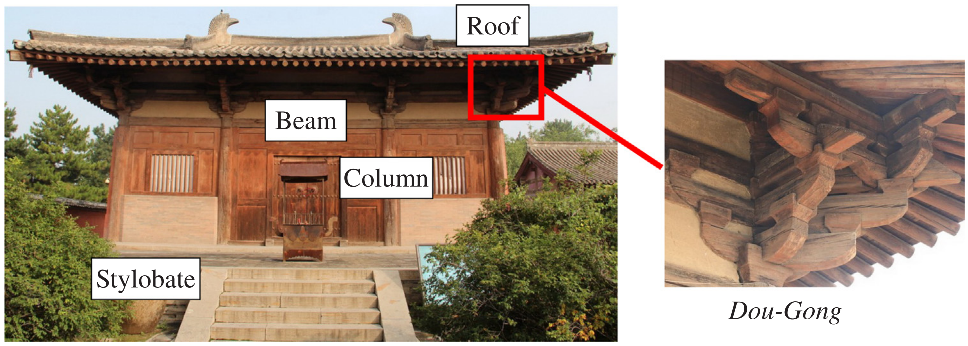

Fig. 1. Composition of a typical pre-Ming dynasty timber building.

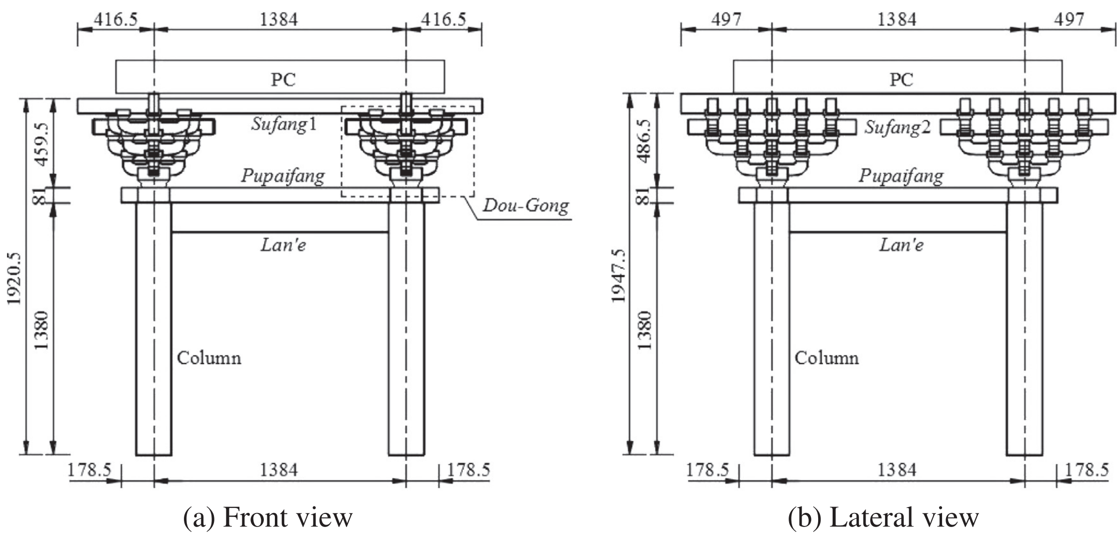

Fig. 2. The test model (unit: mm).

damage behavior of *Dieh–Dou* timber frames under dynamic load was investigated by Yeo et al. [4,5]. Tests were performed on three sizes of typical Japanese bracket complexes to investigate the size effect by Tsuwa et al. [6]. The study showed that rotation was the major cause of horizontal displacement in the small specimen, while slip motion could not be ignored in the medium and large specimens.

The mortise-tenon joints were used as semi-rigid connections in timber frame [7–9], and were proved to be the weak link in beam-column assemblies [10]. In lateral performance testing of mortise-tenon joints [11–16], a vertical load was applied to the top of a column by a jack to simulate a gravity load, and a lateral cyclic load was applied by a horizontal actuator or booster through displacement control. In these tests, the obtained hysteresis curves were relatively full, and the joints displayed good deformation and energy dissipation ability. Moreover, the failure mode of the dovetail mortise-tenon joints was the pulling-out failure of the tenon [14–16].

In the tests conducted by Suzuki and Maeno [17], and by Masaki and Suzuki [18], the lateral structural performance of an overall timber structure consisting of a beam-column frame and *Dou-Gong* bracket was investigated based on the traditional timber buildings in Japan, and precast concrete (PC) panels were used as the vertical load. The results indicated that the ductility of the timber structure is quite good, and column rocking provided the majority of the restoring force when the lateral displacement was small. Hong et al. [19] investigated the hysteretic behavior of traditional timber frames in Korea and found that the lateral resistance of the structure mainly relied on the joint stiffness. Through cyclic horizontal loading tests conducted on traditional *Dieh-Dou* timber frames, Yeo et al. [20] found that the lateral deformation of the entire structure was mainly caused by column rocking, and the vertical load significantly affected the strength and stiffness of the whole structure.

To date, little research has been done to investigate the lateral structural performance of an overall pre-Ming dynasty Chinese timber structure. In this study, a four-pillar half-scale timber structure model with a beam-column frame and *Dou-Gong* brackets was manufactured, and six pseudo-static tests were conducted under three levels of vertical loads. This paper reports on the variation characteristics of hysteretic behavior, strength, lateral stiffness, and energy dissipation of the timber structure. Moreover, a restoring force model that could be widely applied to other studies is developed. These investigations provide a theoretical basis for the monitoring and repair work of existing timber buildings.

2. Test program

2.1. Test model

In this study, a 1:2 scaled timber structure model was made based on the "*caifen* modular system" of *Yingzaofashi* (CE 1103, Song dynasty) [21]. The *caifen* modular system [22] is a technical "code of practice" for the construction of traditional timber buildings of the pre-Ming dynasty. As shown in Fig. 2, the model consists of columns, *lan'es*, *pupaifangs*, *Dou-Gong* brackets, *sufangs* and the dowels between components. The columns are placed directly on a concrete floor, which models the floating pedestal connection of a real timber structure. The area where the column feet are placed had been calibrated to ensure that the friction between the two is the same as that between the column feet and stone base of a real building. The columns and *lan'es* are connected with dovetail mortise-tenon joints. The *pupaifangs* are on the top of the columns with *Dou-Gong* brackets above them. The column, *pupaifang*, and *Ludou* (the component at the bottom of a *Dou-*