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To cite this article: Bo Shen et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 397 012034

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Experimental study on seismic performance of Song-style Dou-gong joints in Chinese traditional building

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Abstract. Research on the mechanics performance of Song-style Dou-gong joints is absent currently, especially considering Xiaang and Angshuan in this type of joints. Two different types of Dou-gong joints were experimentally studied by making models in this paper. The Dou-gong joints can maintain good integrity and rotate around the bottom member in the longitudinal plane under horizontal loads, which shows poor seismic performance. The displacement of layers is less, Xiaang and Angshuan can limit slippage between components to some extent, but they had little effect on the seismic performance of the Dou-gong joints.

1. Introduction

In Chinese traditional wooden building, the main connection mode of wooden components is mortise-tenon connection, and the application of this connection type to the extreme is Dou-gong joints. Furthermore, Dou-gong joints are formed by overlapping of crossbars intersecting longitudinally and transversely, which is a necessary structural member in a large-scale building \cite{1,2}. Besides, this structural member is also very common in traditional buildings in Japan and South Korea. At present, there are studies that divide the form of Dou-gong joints into Song-style and Qing-style. Among them, Song-style Dou-gong joints represents the peak of the development of Dou-gong in traditional Chinese architecture \cite{3}. (The basic construction of the Song-style Dou-gong joints is shown in Figure 1)

Because of the complicated construction, there is less research on Dou-gong joints. At the begining of this century, the restoring force model and the calculation method of vertical stiffness and lateral stiffness for Japanese Dou-gong joints was proposed in Japan \cite{4}. In the shaking table test, the deformation of Dou-gong joints is complex and can be roughly divided into shear deformation, overall rotation and interlayer slippage \cite{5}, but the joints is greatly simplified in the experiment. However, the joints without simplified only showed overall rotation in another experiment \cite{6}. The fork-column Dou-gong joints is a kind of Dou-gong joints which mainly used in the pavilion architecture. By partially changing the structure of fork-column Dou-gong joints, the energy consumption capacity of different joints is basically the same \cite{7}.The Taihe Temple of the Forbidden City is one of the largest existing timber frame structures in China, and three types of Dou-gong joints were selected for research, and results that showed obvious sliding characteristics\cite{8}, but all models of the joints was Qing-style in this experiment. In fact, Qing-style’s structural performance is almost lost compared with Song-style.

The above research on Dou-gong joints has achieved certain results, but it is mainly aimed at regular Dou-gong joints with specific layer, but lacks the research on irregular joints which is interrupted layer by Xiaang (see number 11 in Figure 1). What’s more, as a concealed connector, the Angshuan (see number 13 in Figure 1) is not taken into account in the joints.
2. Experiment

According to the relevant literature data [1, 2], two different types of Song-style Dou-gong joints are produced at a ratio of 1:3.52 in prototype using second-class materials. In Figure 2(a), the layers of crossbars are stacked to form an inverted triangle construction, which is symmetrical in the plane, so that it is regarded as regular joints. In Figure 2(b), Xiaang breaks obviously the layered features of regular joints, which makes the joints structure asymmetric in the plane, so it is called irregular joints. Angshuan runs through the entire Dou-gong joints (see number 2 in Figure 5). Hence, Considering Angshuan’s function on Dou-gong joints, that Angshuan was removed in regular joints in another set of trials. For experimental safety, there was no trial to remove Angshuan in irregular joints. As shown in Figure 2, although the internal construction of the joints is different, a complete plane is still formed through the splicing of diverse components in longitudinal direction.

The vertical load of \( N = 17.5 \) kN was applied to the model, and horizontal low cyclic repeated loading tests were performed using displacement control loading. Loading from 1mm, the peak value of horizontal displacement is 8mm, 16mm and 24mm respectively, loading three times per stage. Vertical loads and horizontal loads are imposed by jack and hydraulic fluid actuator, respectively. In the horizontal direction, sliding device (shown in Figure 2) achieves the gliding of the joints.

Before the test, the vertical loads of 5kN were applied to the model of Dou-gong joints respectively and held for 15 minutes and then completely unloaded. This measure was mainly used to eliminate gaps formed by component processing errors and assembly errors. In order to prevent Dou-gong joints from sliding freely, the joints connects with fixed wooden block by wooden hidden dowel (see number 1 in Figure 5).
3. Results and Discussion

3.1. Xiaang
During the test, both joints showed good integrity and they mainly showed in-plane rotation centering on the bottom Ludou (see number 1 in Figure 1). The maximum displacement between the layers was about 4mm and appeared in regular joints. In fact, although Xiaang interrupted the layer, the oblique components hindered the movement of the layers in the horizontal direction to some extent.

The hysteresis characteristics of two models in Figure 3 (a) and (b) are basically similar, and they all show anti-“S” type, and the skeleton curve in Figure 4 is also very close. And these indicate that two Dou-gong joints exhibit the similar characteristic of force under horizontal loads. The hysteresis curve is always not smooth, which is mainly caused by the gaps between components. Although the entire curve is relatively symmetrical but not saturated, the equivalent viscous damping coefficients of the model of regular joints and irregular joints are about 0.11 and 0.10, which shows that the energy dissipation capability is not superior.

Under the vertical load, the integrity of Dou-gong joints weakens the influence of the internal construction irregularity, so that the existence of Xiaang has no significant influence on the seismic performance of the joints. Certainly, the inverted triangular shape of Dou-gong joints results in relatively weak energy dissipation capacity due to the ease of rotation.

![Figure 3](image1.png)
**Figure 3.** Load-displacement hysteresis curves of regular joints (a), the curves of irregular joints (b)

![Figure 4](image2.png)
**Figure 4.** Skeleton curves of regular joints and irregular joints

![Figure 5](image3.png)
**Figure 5.** The position of Angshuan in regular joints, and the position of connection at the bottom of Dou-gong joints

3.2. Angshuan
The specific position of Angshuan can be seen from Figure 5. During the test, the maximum relative displacement of layers of regular joints without Angshuan was approximately 10 mm. Due to lack of Angshuan, the restriction between layers is reduced, resulting in increased displacement between layers. The hysteresis curves of regular joints without Angshuan is still not saturated but has poor symmetry. Although the integrity can still be maintained, it is obviously inferior to regular joints with
Angshuan. The skeleton curve is relatively close, and the equivalent viscous damping coefficient obtained by calculation is about 0.10, which is basically the same as that of the joints with Angshuan. And these indicates that this degree of slippage is within ignorable range, it has little effect on the mechanical properties of Dou-gong joints although the slippage of layers increases.

The joints is mainly performed overall rotation, which is not changed after removing Angshuan, because there are other structural measures in the Dou-gong joints that have the ability to maintain its integrity. Therefore, the impact of Angshuan on seismic performance of regular joints is not prominent.

Figure 6. Load-displacement hysteresis curves of regular joints without Angshuan

Figure 7. Skeleton curves of regular joints without Angshuan

4. Summary
In the Song-style Dou-gong joints, the use of Xiaang and Angshuan is the requirement of traditional architecture, and their use is not only based on structural performance, it also considers other factors such as decorative factors and etiquette factors. The following conclusions are obtained from structural factors. 1) Dou-gong joints can always maintain good integrity under vertical loads; 2) Xiaang and Angshuan changes the construction of joints, but has little effect on seismic performance; 3) Under the action of horizontal loads, because of the inverted triangles features of Dou-gong joints, it exhibits the characteristics of rotation, so its seismic performance is not superior.

Acknowledgement
This study was financially supported by the National Natural Science Foundation of China (No. 51678298).

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