ABSTRACT

The Chuandou timber frame is a traditional timber structural system widely used for non-engineered residential houses in South China, which features beam-to-column joints with direct penetration tenons. Together with proper infills, Chuandou timber frames exhibited advantageous seismic performance over other non-engineered structures and did not easily collapse in recent earthquakes, although the masonry infills, mortise-tenon connections, timber beams and columns may sustain damage of various extents. To investigate the damage mechanism and the effect of masonry infills on the seismic performance of the structural system, six full-scale Chuandou timber frame subassemblies were subjected to in-plane static cyclic loading, each of which was consisted of two circular sectioned timber columns and a rectangular sectioned timber beam. The specimens were categorized into two groups by their height-to-span ratios of 0.8 and 1.5. In each group, there was a bare frame specimen and two masonry infilled specimens. In the test, the columns rested on top of a concrete grade beam without mechanical anchorage while additional shear keys were provided for infilled specimens to avoid excessive slip at the column base. The test results show that the masonry infills provide most of the lateral resistance in the system and are easily damaged at small lateral drift. Whereas the timber frames can sustain large lateral drift without losing its capacity.
Cyclic loading test of masonry infilled Chuandou timber frames for residences in South China

X. Fu², Z. Qu², S. Kishiki³, Y. Cui⁴, Q. Tang⁵

ABSTRACT

The Chuandou timber frame is a traditional timber structural system widely used in non-engineered residential houses in South China, which features beam-to-column joints of direct penetration tenons. Together with proper infills, Chuandou timber frames exhibited advantageous seismic performance and did not easily collapse in recent earthquakes, although the masonry infills, mortise-tenon connections, timber beams and columns may sustain damage of various extents. To investigate the damage mechanism and the effect of masonry infills on the seismic performance of the structural system, six full-scale Chuandou timber frame subassemblies were subjected to in-plane static cyclic loading, each of which was consisted of two circular sectioned timber columns and a rectangular sectioned timber beam. The specimens were categorized into two groups by their height-to-span ratios of 0.8 and 1.5. In each group, there was a bare frame specimen and two masonry infilled specimens. In the test, the columns rested on top of a concrete grade beam without mechanical anchorage while additional shear keys were provided for infilled specimens to avoid excessive slip at column base. The test results show that the masonry infills provide most of the lateral resistance in the system and are easily damaged at small lateral drift. Whereas the timber frames can sustain large lateral drift without losing its capacity.

Introduction

Masonry-infilled timber frames are widely used in earthquake-prone regions such as Turkey, Greece, Italy, Portugal, Romania, Pakistan and China [1-7]. With a few exceptions, most of the structures are non-engineered and were built following local historical construction practices. In

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some counties, the structures only exist in old buildings, while there are still many countries such as Romania, Pakistan and China where this type of structure is being used in current construction practice.

![Figure 1. Masonry infilled Chuandou frame residences in South China that were damaged in 2013 M7.0 Lushan earthquake [7].](image)

The Chuandou frame system (Figure 1) is one of the two major timber structural systems in China and has a history of approximately 500 years. It is featured by beam-to-column joints with direct penetration tenons, especially in its transverse direction. In the past, Chuandou timber frames were usually infilled with timber panels as partitions, whereas clay brick masonry has been overwhelmingly preferred for the infills in the recent decades, primarily because of its low cost and easy construction. From the field observation [7], the columns of a Chuandou frame were usually put on top of stone footings without anchorage. Together with proper infills, Chuandou timber frames exhibited advantageous seismic performance over other non-engineered structures and did not easily collapse in recent earthquakes, although the masonry infills, mortise-tenon connections, timber beams and columns may sustain various extents of damage. Although Chuandou timber frame houses are widely used in South China, little effort has been made to better understand its seismic behavior and performance, including the commonly seen seismic damage such as column base sliding, pull-out of beam tenons, cracking and collapse of masonry infills.

To this end, six full-scale Chuandou timber frame subassemblies were subjected to in-plane pseudo static loading in an experimental test program at the Institute of Engineering Mechanics. The paper summarizes the details of the specimens, the test method and reports the preliminary results such as the hysteretic behavior, deformation characteristics and damage to the masonry infills.

**Specimens and test setup**

Six full-scale Chuandou timber frame subassemblies were subjected to in-plane pseudo static loading, each of which was consisted of two timber columns and a timber beam. All columns had circular sections of 170 mm in diameter and the beams had rectangular sections of 50 mm in breadth and 150 mm in depth. Pine wood was used for all the beams and columns in the specimens.

The specimens were categorized into two groups by their height-to-span ratios ($H/L$), that is, $H/L=0.8$ to represent narrow span cases and $H/L=1.5$ to represent wide span cases. In each
group, there was a bare frame specimen and two masonry infilled specimens with brick masonry infills of different thicknesses. The parameters of the specimens are summarized in Table 1.

The beam went through the mortises on the columns, which was the same size as the cross-section of the beam. The masonry infills was built after the erection of the timber frame. Following the local construction practice, the masonry infills were connected with the timber columns by plain nails at 300 mm spacing for thick wall specimens and 360 mm spacing for thin wall specimens on both columns (Figure 2(a)) to provide some out-of-plane constraints for the infills.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Height [mm]</th>
<th>Span [mm]</th>
<th>H/L ratio</th>
<th>Wall thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>3100</td>
<td>0.8</td>
<td>×</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2350</td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>1630</td>
<td>1.5</td>
<td>×</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>120</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>120</td>
</tr>
</tbody>
</table>

Because of time and space limitation in the lab, cement accelerator was used in the mortar for the masonry infills. The material tests for the compressive strength of mortar \( f_{m} \) were conducted on 70.7 mm cubes following the specifications in JGJ/T70-2009 [10]. Moreover, average moisture content of the six specimens were obtained by a wood moisture meter. The results are listed in Table.2.

Material tests of timber were carried out, including three-point bending test and compression test perpendicular and parallel to the grain. The Chinese codes for timber material test methods [11-13] were adopted with some revisions to fit the specimens’ dimensions. Three timber cuboids of 120 by 120 by 240 mm were tested for each group of timber compression test in either perpendicular or parallel to the grain direction. The corresponding compressive strengths are 3.53 MPa and 25.92 MPa. The average moisture content of the samples at the time of the
material test are 9.63 % and 9.71 %, respectively. In addition, the results of the timber bending strength are summarized in Table 3.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>( f_m ) [MPa]</th>
<th>Average moisture content [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>7.87</td>
</tr>
<tr>
<td>2</td>
<td>7.30</td>
<td>7.56</td>
</tr>
<tr>
<td>3</td>
<td>8.21</td>
<td>10.24</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>7.65</td>
</tr>
<tr>
<td>5</td>
<td>5.58</td>
<td>8.06</td>
</tr>
<tr>
<td>6</td>
<td>6.19</td>
<td>8.30</td>
</tr>
<tr>
<td>Average</td>
<td>6.82</td>
<td>8.28</td>
</tr>
</tbody>
</table>

Table 2. Average moisture content on test specimens.

Table 3. Average bending strength and Young’s modulus.

<table>
<thead>
<tr>
<th>Sample dimensions [mm]</th>
<th>Sample No.</th>
<th>( \sigma_B ) [MPa]</th>
<th>( E_B ) [GPa]</th>
<th>Average moisture content [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B1</td>
<td>28.98</td>
<td>4.37</td>
<td>14.20</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>36.11</td>
<td>4.86</td>
<td>14.87</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>35.23</td>
<td>3.96</td>
<td>10.00</td>
</tr>
<tr>
<td></td>
<td>B4</td>
<td>33.18</td>
<td>3.22</td>
<td>14.97</td>
</tr>
<tr>
<td></td>
<td>B5</td>
<td>18.78</td>
<td>2.70</td>
<td>16.60</td>
</tr>
<tr>
<td></td>
<td>B6</td>
<td>30.01</td>
<td>4.11</td>
<td>17.10</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>30.39</td>
<td>3.87</td>
<td>14.62</td>
</tr>
</tbody>
</table>

Figure 3 Test setup for masonry infill specimens (a) mechanical hinge, (b) roughened surface on grade beam, (c) shear keys, (d) and (e) loading jigs.
The test setup is shown in Figure 3. Two pantographs were installed to constrain the out-of-plane degrees of freedom of the specimens through a top steel beam, which was connected to the top of the timber columns with a pair of mechanical hinges (Figure 3(a)). In addition to the self weight of 24kN was placed on the mid-span of the top steel beam to represent the dead and live load [8]. The columns rested on top of a reinforced concrete grade beam which was anchored to the strong floor. There was no mechanical anchorage between the timber columns and the concrete grade beam except that the portions of the top surface of the beam were roughened (Figure 3(b)). For the infilled specimens, additional shear keys were prepared in case the column bases suffered from excessive lateral slip (Figure 3(c)).

The lateral load was applied on the timber columns by a 300kN hydraulic jack along the timber beam axis. The jack was connected to the columns through specially-designed jigs to avoid the push-out of the penetration tenons of beam-to-column joints (Figure 3(d) and 3(e)). The two jigs were connected by a pair of steel rods on both sides of the beam.

Cyclic loading tests were performed with increasing amplitudes of story drift ratios $R$ from 0.125% to 15%. The loading protocol in ISO/TC 165 WD 16670 [9] was adopted with some revisions to fit the masonry infill timber frame test. The amplitude of $R$ was increased from 0.125%, 0.25%, 0.5%, 0.75% to 1% and only one cycle of loading was performed for each amplitude. For larger amplitudes, two cycles of loading were performed for each amplitude. The loading protocol is shown in Figure 4. During the test, the maximum $R$ was 8% in the negative loading direction because of the limitation of the stroke of the jack.

![Figure 4. Loading protocol.](image)

**Experimental result**

Figure 5 shows the hysteresis curves obtained by the static cyclic loading tests. For the specimens of wide span, the lateral strength and stiffness of the bare frame (No.1) is much lower than the two masonry infilled specimens (No.2 with 60 mm thick infill and No.3 with 120 mm thick infill). However, the timber frame can sustain a large displacement without losing its vertical load-bearing capacity. For specimen No.2, the masonry infill started to crack in the middle from +0.25% drift ratio. It collapsed at -3% drift ratio. For specimen No.3, rigid body rotation was observed, and the cracks of the masonry infill concentrated at the bottom. The loading was
terminated at 4% drift ratio because a timber column was pulled out of the shear keys and could not fit back during unloading.

Similar phenomena were observed in the short span specimens. However, the lateral strength of specimen No.4 (short span bare frame) is higher than that of specimen No.1. Rigid body rotation occurred in both masonry infilled specimens (No.5 with 60 mm thick infill and No.6 with 120 mm thick infill). The masonry infill collapsed at +4% drift ratio in specimen No.5, whereas little damage to the wall panel was observed in specimen No.6.

![Hysteresis curves](image)

**Figure 5** Hysteresis curves.

For the timber elements of all six specimens, only some local damage were found at the column bases and the column-beam joints (Figure 6).

![Timber damage](image)

**Figure 6** Timber damage: (a) column base, (b) beam-column rotation.

For masonry infill, twelve displacement transducers were installed horizontally on the timber columns to measure the relative displacement between the columns and the masonry panel. Figure 7 shows deformation of the timber columns and the masonry panel at ±0.5% and ±2% drift ratios and the corresponding crack distributions of specimen No.3. It can be seen that the masonry
panel was separated from the columns at lower left and upper right corners during positive loading, while they were separated at the lower right and upper left corners during negative loading. This indicates that the masonry infill resists the lateral load by a diagonal strut approximately between the two corners that were in contact with the columns.

Figure 7. Relative displacement between column and masonry panel and cracks distribution on specimen No.3: (a) positive direction, (b) negative direction.

To better understand the behavior of different parts in the masonry infilled frame specimens, the overall hysteretic behavior is separated into three parts, that is, column base sliding, rigid body rocking and wall shearing. The column base sliding and rigid body rotation were measured by the displacement transducers installed near the column bases. The wall shearing is deemed to be associated with the beam-to-column joint rotation. As a result, the hysteresis curves of the four masonry-infilled specimens are decomposed into three parts (Figures 8 and 9), where $R_s$ is the column base slip; $R_r$ is the rigid body rotation angle; $R_j$ is the rotation of the beam-to-column joints.
Figure 8. Hysteretic behavior of thin masonry panel specimens: (a) No.2, (b) No.5.

Figure 9. Hysteretic behavior of thick masonry panel specimen: (a) No.3, (b) No.6.

For the two specimens with 60 mm thick masonry walls, the one of wide span (No.2) lost most of its lateral strength when the wall panel collapsed after severe shear cracking. Both the sliding and rigid body rocking are negligible as compared to the shear deformation of the specimen (Figure 8(a)). On the other hand, the specimen of short span (No.5) exhibited considerable rigid
body rocking before it finally failed because of the shear failure of the masonry infill (Figure 8(b)).

For both specimens with 120 mm thick masonry walls, considerable rocking was developed during the loading process. In particular, the deformation of the short span specimen with a 120 mm thick wall panel (No.6) is predominated by rigid body rocking and the wall panel was almost intact throughout the loading (Figure 9(b)). Specimen No.3 exhibited the largest slip at the column base among the four masonry infilled specimens. This is because the shear keys were not installed in the first several load cycles for the specimen.

The rocking resistance of the specimen can be estimated by Equation (1).

\[ V_R = \frac{G}{2H} \times (L + \Phi) \]  

(1)

where \( V_R \) is the limit lateral force when rocking initiates, \( G \) is the total weight of the specimen, \( L \) is the span length, \( \Phi \) is the column diameter and \( H \) is the height of the specimen, that is, the vertical distance between the column base to the beam axis.

According to the Chinese masonry structure design code [14], the shear strength \( V_s \) of unreinforced masonry panels is calculated by Equation (2).

\[ V_s = (f_v + \alpha \cdot \mu \cdot \sigma_0) \cdot A \]  

(2)

where \( f_v \) is the nominal shear strength of the masonry, \( A \) is the horizontal sectional area of the masonry panel, \( \alpha \) and \( \mu \) are the influence coefficients, \( \sigma_0 \) is compressive stress in the masonry and is taken as zero in this test because the wall was a partition.

Both the calculated rocking resistance and shear strength are denoted by dashed lines in Figures 8 and 9. The behavior of the thick wall specimens (No.3 and 6) at large displacement is predominated by the rocking behavior. Their lateral strengths in the test are quite close to the estimated rocking resistance by Equation (1), while they are still much below the estimated shear strength. For specimen No.5, the calculated rocking resistance and shear strength are close to each other, and the specimen exhibited a mixed failure mode of rocking and wall shearing. The lateral strength of Specimen No.2 is much lower than the estimated shear strength although it failed in shear. It is worth noting that the height-to-thickness ratio of 35 for the walls in specimen No.2 and 5 much exceeded the corresponding limit of 22 in the code [14]. As a result, Equation (2) may not be applicable to the thin walls in the test, especially for the wide span specimen because out-of-plane behavior may have a large effect on the collapse of the wall.

Conclusions

This paper reported an experimental test on a traditional Chinese timber structure system, namely Chuandou frames with masonry infills, which is widely used for non-engineered residential houses in South China. Six full-scale Chuandou timber frame sub-assemblage specimens of various aspect ratios and masonry infill thicknesses were subjected to lateral cyclic loading. The hysteresis curves of the specimens were obtained and those of the infilled frames are decomposed, into three parts to investigate the role of three major deformations, that is, column base sliding, rigid body rocking
and wall shearing. The results show that the deformation of the infilled frames with thick walls tended to be dominated by rigid body rocking, while the wall shearing is more significant in thin wall specimens. It is also shown that the masonry infills provided most of the lateral resistance in the system.

Acknowledgements

The research was jointly sponsored by a general grand of the National Natural Science Foundation of China (No. 51478441). The financial support is appreciated. The authors are also grateful for the assistance of Professor Feng Peng in Tsinghua University in conducting the three-point bending test for the timber.

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