Seismic Performance Evaluation on Historical Timber Frame Structures with Large Hanging Walls

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Summary
In this paper, static loading tests of timber frame structures with large hanging walls and beams (Sashigamoi) have been conducted in order to confirm the damage progress and the hysteresis characteristics until the restoring force loses. As the results of the static loading tests, the following results were obtained.

a) Specimens of which walls break before breakage of columns have high deformation performance.
b) Different specification of hanging walls and size of column section give different failure mechanism and bearing force of hanging walls. c) Ratio of shear force of columns given by the results of tests is different from the ratio based on the current code. d) Bearing force of hanging walls is varied by specification of frames such as section size of columns and thickness of crosspieces called Nuki. e) Rear columns are broken at the bending unit stress which is about the half of the flexural strength.

Keywords: historical structures; timber frames; seismic performance; hanging walls.

1. Introduction
In case evaluating the seismic capacity of historical timber frame structures such as Japanese temples and traditional houses, it is very important to investigate the mechanical characteristics of timber frame structures with hanging walls. This is because breakage of the column can lead to collapse of the whole structure.

In this paper, we understand hysteresis characteristics of timber frames with hanging walls and examine difference of the mechanical characteristics due to experimental variables such as section size of columns, specifications of hanging walls and the number of spans.

2. Static loading test
2.1 Specimens
We made eleven timber frames with large hanging walls and beams called Sashigamoi of which height is 270mm. Details of the specimens are shown in Table 1, and elevations of the specimens is in Fig. 1. The section size of columns, the specification of hanging walls and the number of spans are experimental variables. Columns and ground sills of all the specimens are made of cedar (E90 in Japanese Agricultural Standard). Sashigamoi and cross beams are made of Oregon pine. Cotters (Hanasen or Komisen) that joint columns and Sashigamoi are made of oak.

Eight specimens have hanging walls made of dry mud-panels of which thickness is 26mm, and the panels are aligned three on a single side (2P12-12, 2P15-15, 4P12.0-12, 4P12-12-12 and 4P15-12-15) or both sides (2P12=12, 2P15=15 and 4P15=12=15) in the height direction. The hanging walls have two horizontal crosspieces called Nuki of which thickness is 15mm. The dry mud-panels are...
fixed on the frame with nails.

On the other hand, the other three specimens have hanging walls made of clay of which thickness is 60mm (2P12#12N, 2P12#12N and 4P12#12#12N). The hanging walls have two horizontal Nuki of which thickness is 15mm (2P12#12) or 40mm (2P12#12N and 4P12#12#12N), one vertical Nuki of which thickness is 15mm and bamboo lathing. Nuki is internal of the wall in 2P12#12 and exposed from the surface of the walls in 2P12#12N and 4P12#12#12N as shown in Fig. 1.

In Table 1, we use modified Young’s modulus $E_b$ of each column which is calculated by Young’s modulus gotten from the results of bending tests and the water content of columns [1]. Flexural strength $F_b$ of the broken columns is calculated in the same way. Flexural strength $F_b$ of the columns which are not broken in the bending tests is evaluated by the result of non-destructive stress wave velocity measurement[2]. In addition, the not broken frames of the specimens with dry mud-panels on a single side are used again as the frames with dry mud-panels on both sides.

### Table 1: Details of specimens

<table>
<thead>
<tr>
<th>Specification of hanging wall</th>
<th>Specimen</th>
<th>Live load $W$ (kN)</th>
<th>Column Location</th>
<th>$E_b$ (kN/mm²)</th>
<th>$F_b$ (N/mm²)</th>
<th>Section size (mm)</th>
<th>Breakage</th>
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<tbody>
<tr>
<td>Single side Dry mud panels</td>
<td>2P12-12</td>
<td>25.7</td>
<td>Left</td>
<td>7.9</td>
<td>45.7</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Right</td>
<td>8.3</td>
<td>39.9</td>
<td>120×120</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2P15-15</td>
<td>25.7</td>
<td>Left</td>
<td>6.7</td>
<td>31.5</td>
<td>150×150</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Right</td>
<td>9.0</td>
<td>36.5</td>
<td>150×150</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4P12-0-12</td>
<td>25.7</td>
<td>Left</td>
<td>9.4</td>
<td>47.5</td>
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<td></td>
<td></td>
<td></td>
<td>Right</td>
<td>9.2</td>
<td>40.0</td>
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<td></td>
<td>4P12-12-12</td>
<td>51.7</td>
<td>Left</td>
<td>8.6</td>
<td>51.7</td>
<td>120×120</td>
<td>×</td>
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<td></td>
<td></td>
<td></td>
<td>Center</td>
<td>7.6</td>
<td>42.0</td>
<td>120×120</td>
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<td></td>
<td></td>
<td></td>
<td>Right</td>
<td>8.0</td>
<td>45.7</td>
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<td>×</td>
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<td>4P15-12-15</td>
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<td>Left</td>
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<td>36.0</td>
<td>150×150</td>
<td>-</td>
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<tr>
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<td></td>
<td></td>
<td>Center</td>
<td>7.8</td>
<td>46.1</td>
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<td>-</td>
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<td></td>
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<td>Right</td>
<td>8.4</td>
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<td>Both sides</td>
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<td>×</td>
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<td></td>
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<td>Right</td>
<td>8.4</td>
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<td>×</td>
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<tr>
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<td>2P15=15</td>
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<td>4P15=12=15</td>
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<td></td>
<td></td>
<td>Right</td>
<td>6.9</td>
<td>32.8</td>
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<tr>
<td>Internal Nuki</td>
<td>2P12#12</td>
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<td>7.7</td>
<td>38.5</td>
<td>120×120</td>
<td>×</td>
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<td></td>
<td></td>
<td>Right</td>
<td>8.2</td>
<td>44.6</td>
<td>120×120</td>
<td>×</td>
</tr>
<tr>
<td>Exposed Nuki</td>
<td>2P12#12N</td>
<td>25.7</td>
<td>Left</td>
<td>7.4</td>
<td>34.1*</td>
<td>120×120</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Right</td>
<td>7.1</td>
<td>33.3*</td>
<td>120×120</td>
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</tr>
<tr>
<td></td>
<td>4P12#12#12N</td>
<td>51.7</td>
<td>Left</td>
<td>6.8</td>
<td>41.8</td>
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<td>Right</td>
<td>6.6</td>
<td>41.4</td>
<td>120×120</td>
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</tr>
</tbody>
</table>

*the value estimated by non-destructive stress wave velocity measurement
Restoring force $P$ is measured by the load cells, and bending moment and shear force of each column $Q$ are measured by strain gauges. Story shear force is the sum of the shear force of all the columns in the specimen. In fact, story shear force is equal to shear force of hanging walls.

3. Experimental results

3.1 Restoring force and failure mechanism

Figure 4 shows the restoring force $P$ of each specimen. Damage of each specimen with dry mud-panels on both sides and with clay wall is shown in Fig. 5, and pictures of main damage are shown in Fig. 6. In addition, whether each column breaks or not is shown in Table 1. In this paper, out-of-plane deformation of wall is defined as that walls get out of the outer surface of the frames.

First, damage mode of timber frames with large hanging walls is roughly classified into damage of the hanging wall and breakage of the column. Failure mechanism changes due to the magnitude relation of the bearing force between hanging walls and columns.

As shown in Table 1, all the columns in the specimens with dry mud-panels on both sides and with clay wall are broken from near the column-to $Sashigamoi$ joint. Out-of-plane deformation of the dry mud-panels is observed in 2P15=15 as shown in Fig. 6 (b), and cracks in the hanging wall are observed in 2P12#12N as shown in Fig. 6 (c). The columns of 2P15=15 and 2P12#12N are not broken.

The specimens with clay wall of which columns are broken (2P12#12 and 4P12#12#12N) have few cracks in the wall as shown in Fig. 5 (d), (f). The specimens of which walls break before breakage of the columns have high deformation performance.

3.2 Comparison between specimens

We make comparison between all the specimens about the test results.
The not broken columns in the specimens with dry mud-panels on a single side (2P12-12 and 4P15-12-15) are broken in the specimens with dry mud-panels on both sides (2P12=12 and 4P15=12=15). This is because the hanging walls with dry mud-panels on both sides are stronger than the hanging walls with dry mud-panels on a single side, and the columns reach the flexural capacity before breakage of the hanging walls.

Although 2P12#12 and 2P12#12N have the same thickness of the walls, the maximum restoring force of both the specimens are different (2P12#12 is 7.7kN and 2P12#12N is 6.8kN). As the result, the columns are broken in 2P12#12 and the columns are not broken in 2P12#12N. Thus, not only thickness of the hanging wall but also specifications of the hanging wall such as the thickness of Nuki effect on the hysteresis characteristics.

![Fig. 4: Test results of restoring force](image-url)
4. Shear force of columns

4.1 Shear force of each column

In this paper, front column is defined as the column of the loading direction side, and rear column is as the column of the loading direction opposite side.

Figure 7 shows the shear force of each column $Q$ in each specimen. The shear force of the front column is larger than the shear force of the rear column in all the specimens. Furthermore, the shear force of the column at breakage is very different according to the location of the column. In 2P12#12, the rear column breaks first when the rotation angle is $-1/15$rad in spite of the lower shear force compared with the front column. This indicates bearing force of columns varies according to loading direction.

In the specimens of which columns are broken, breakage of the column decreases the shear force. Out-of-plane deformation of dry mud-panels decrease the shear force of the both columns in 2P15=15. This is because that Out-of-plane deformation of panels makes the shear force of the hanging wall lower and the story shear force decreases.

4.2 Ratio of the shear force of each column

On the method of Agency for Cultural Affairs (hereinafter referred to as current code), independent columns bear the shear force of the hanging wall to the half of the distance to the adjacent column$^{[3]}$. Based on the current code, the ratio of the shear force of each column is 1:1 from the left column in the 2P specimens and 1:2:1 in the 4P specimens without an opening.

Figure 8 shows comparisons of ratio of shear force of each column $Q$ between the test results and the current code. The ratio of $Q$ is the value of shear force of each column $Q$ divided by the sum of each $Q$. As told about the specimens with dry mud-panels on a single side$^{[4]}$,$^{[5]}$, the shear force of the columns in the specimens with dry mud-panels on both sides and with clay wall is not divided according to the current code.

Compared 4P15-12-15 with 4P12-12-12, the columns of the both sides in 4P15-12-15 have higher ratio of shear force than the columns of the both sides in 4P12-12-12 as shown in Fig.8 (b). It is considered the larger section size of columns is, the larger ratio of shear force is.
5. Bearing force of hanging wall

5.1 Comparison between specimens

Figure 9 shows the relationship between the story shear force and the rotation angle of the hanging wall $R_h$ in each specimen. The specimens of which columns are not broken are assumed to perform the maximum bearing force of the hanging wall. Thus, the bearing force can be valued by the
maximum of the story shear force.

The maximum of the story shear force is larger in 2P15-15 than in 2P12-12 as shown in Fig. 9 (a). In spite of the same specifications of the hanging walls, the maximum of the story shear force varies due to the section size of the columns.

On the other hand, we can consider the bearing force of the hanging wall does not reach the maximum in 2P12#12 because of breakage of the columns. As Figure 9 (b) shows, the maximum of the story shear force is higher in 2P12#12 than in 2P12#12N. Thus, 2P12#12 is expected to have the maximum bearing force of the hanging wall higher than 2P12#12N.

5.2 Difference due to section size of columns

Figure 10 shows the relation of the gap between the front column and the upper end of Sashigamoi to the rotation angle of the hanging wall $R_h$ in 2P12-12 and 2P15-15. At the same $R_h$, the gap is larger in 2P12-12 than in 2P15-15. The larger the gap is, the larger the relative displacement of the panels and the frame is in the direction of the front column. Thus, fixation degree between panels and frames decreases by movement of the panels, and out-of-plane deformation of the panels occurs. Out-of-plane deformation of the panels makes the bearing force of hanging walls low. Taken together, smaller section size of columns leads to out-of-plane deformation of panels and decrease of bearing force of hanging walls.

6. Bearing force of columns

It has been discussed that the shear force of the column at breakage is very different according to the location of the column.

We get the maximum tensile stress of each column at a height of the lower end of Sashigamoi by calculating the sum of three kinds of stress (the axial force of the live load, the axial force varied by rigid rotation of the whole structure and the tensile stress by bending moment). Figure 11 shows the relationship between the maximum tensile stress and the flexural strength of all the broken columns. The rear columns are broken at tensile stress which is about the half of the flexural strength, although the front columns are broken at tensile stress which is almost the flexural strength.

This result calls for further investigation.
7. **Conclusions**

The major findings obtained from the research are summarized as follows:

a) Specimens of which walls break before breakage of columns have high deformation performance.

b) Different specification of hanging walls and size of column section give different failure mechanism and bearing force of hanging walls.

c) Ratio of shear force of columns given by the results of tests is different from the ratio based on the current code.

d) Bearing force of hanging walls is varied by specification of frames such as section size of columns and thickness of crosspieces called *Nuki*.

e) Rear columns are broken at the bending unit stress which is about the half of the flexural strength.

**References**


