EXPERIMENTAL ANALYSIS ON SEISMIC PERFORMANCE EVALUATION OF TRADITIONAL TIMBER FRAME STRUCTURES WITH LARGE HANGING WALLS

Saki Ohmura¹, Yasuhiro Nambu², Yoshihiro Shibuya³, Mina Sugino⁴, Yasuhiro Hayashi⁵

ABSTRACT: In Japan, there are a lot of traditional timber buildings. In our investigation of the traditional timber houses, the structures which consist of tall hanging walls and beams called “Sashigamoi” in Japanese were found. The purpose of this study is the demonstrative investigation of the mechanical characteristics of the timber frame structures with large hanging walls aiming for construction of a reasonable and practical seismic evaluation method. In this paper, we performed the static loading tests of the historical timber frames with large hanging walls and analyze the test results in detail. As a result, it is revealed that there is room for improvement on the current method of seismic evaluation on the frames with hanging walls as for evaluation on the restoring force characteristics and the possibility of breakage of columns.

KEYWORDS: Traditional timber buildings, Static loading tests, Large hanging wall, Seismic performance evaluation

1. INTRODUCTION

In Japan, there are a lot of traditional timber buildings. In our investigation of the traditional timber houses, the mud plaster walls which have various specifications such as the thickness of crosspieces called “Nuki” in Japanese and the structures which consist of tall hanging walls and beams called “Sashigamoi” in Japanese (hereinafter referred to as large hanging wall) were found. Figure 1 shows an example of structures with large hanging wall in Wakayama, Japan. Timber frame structures with hanging walls are an important factor for the seismic safety of timber buildings because timber frames with hanging walls can lead to collapse of the whole buildings by breakage of columns at joints of the lower end of hanging walls.

The current method of seismic capacity evaluation on frames with hanging walls in Japan (hereinafter referred to as the current method) is proposed by Agency for Cultural Affairs [1] and the Japan Building Disaster Prevention Association [2]. However, it is not enough to confirm the evaluation by the loading tests in detail of the mechanism such as the shear force of columns and the deformation form of whole structures (refer to such as [3]). The purpose of this study is the demonstrative investigation of the mechanical characteristics of the timber frame structures with large hanging walls aiming for construction of a reasonable and practical seismic evaluation method. In this paper, we perform static loading tests of the historical timber frames with large hanging walls and analyze the test results in detail. Then, it is revealed that there is room for improvement on the current method of seismic evaluation on the frames with hanging walls as for evaluation on the restoring force characteristics and the possibility of breakage of columns.

![Figure 1: Example of structures with large hanging wall](image)

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2. STATIC LOADING TESTS

2.1 SPECIMENS

We made three specimens of timber frames with full walls (full wall specimens) and five specimens with large hanging walls and beams called Sashigamoi (large hanging wall specimens [4], [5]). Figure 2 shows the elevations of the specimens and Table 1 shows the details of the specimens. The specification of the walls and the number of the spans are the experimental variables.

The full wall specimens consist of columns, cross beams, ground sills and mud walls. The large hanging wall specimens consist of columns, cross beams, ground sills, Sashigamoi and mud walls. The height of the full wall specimens is 2700mm. The height of the large hanging wall specimens is 3870mm and that of the hanging wall is 1800mm. The span length between each adjacent columns is 1820mm. The section size of the columns and the ground sills is 120x120mm, that of cross beams is 240x120mm, and that of the Sashigamoi is 270x120mm. The columns and the ground sills are made of Japanese cedar (E90 in Japanese Agricultural Standard). The Sashigamoi and the cross beams are made of oregon pine. The capital and base of the columns is stub tenons with VP joint metals on the both sides. Cotters (Hanasen or Komisen in Japanese) that join the columns and the Sashigamoi are made of oak. The configurations of the tenons of the Sashigamoi are shown in Figure 3. The wall materials are mud plaster or dry mud-panels.

The specimens with mud plaster walls whose thickness is 60mm have the horizontal and vertical crosspieces called Nuki inside the frames and bamboo laths in a lattice shape inside the wall. The number of the horizontal Nuki is three in each full wall specimen and two in each large hanging wall specimen. The number of the vertical Nuki is one in each area of the wall. The Nuki is made of Japanese cedar. The section size of the

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![Figure 2: Examples of specimens (Unit : mm)](image)

**Table 1: Details of specimens (X: Breakage of column)**

<table>
<thead>
<tr>
<th>Wall material</th>
<th>Frame</th>
<th>Specimen</th>
<th>Thickness</th>
<th>Weight (kN)</th>
<th>Location</th>
<th>MOE (kN/mm²)</th>
<th>MOR (N/mm²)</th>
<th>Breakage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full wall</td>
<td>F12#12N</td>
<td>60 40</td>
<td>5.0</td>
<td>Left</td>
<td>9.7</td>
<td>51.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F12#12</td>
<td>60 15</td>
<td>4.6</td>
<td>Left</td>
<td>9.7</td>
<td>59.1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Large Hanging wall</td>
<td>2P12#12N</td>
<td>60 40</td>
<td>3.9</td>
<td>Left</td>
<td>6.8</td>
<td>47.3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2P12#12</td>
<td>60 15</td>
<td>4.2</td>
<td>Left</td>
<td>7.7</td>
<td>38.5</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Dry mud panels</td>
<td>4P12#12#12N</td>
<td>60 40</td>
<td>7.5</td>
<td>Left</td>
<td>6.8</td>
<td>41.8</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Large Hanging wall</td>
<td>F12-12</td>
<td>26 18</td>
<td>1.6</td>
<td>Left</td>
<td>7.7</td>
<td>56.9</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2P12-12</td>
<td>26 18</td>
<td>2.1</td>
<td>Left</td>
<td>7.9</td>
<td>45.7</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4P12-12-12</td>
<td>26 18</td>
<td>3.5</td>
<td>Left</td>
<td>8.6</td>
<td>51.7</td>
<td>X</td>
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</table>
horizontal Nuki is 120x40 or 120x15mm and that of the vertical Nuki is 120x15mm. The difference of the thickness of the horizontal Nuki expresses whether the Nuki is exposed to a surface of the wall or not. On the other hand, the specimens with dry mud-panels [6] whose thickness is 26mm have the horizontal Nuki inside the frames. The section size of the Nuki is 105x18mm. The full wall specimen has four Nuki and five mud-panels. The large hanging wall specimens have two Nuki and three mud-panels in each area of the wall. All the sides of each dry mud-panel are screwed on the Nuki and corbels inside the frames. The specimens are named in the following rules. The initial is "F" of the full wall specimens or "2P", "4P" of the large hanging wall specimens which is the width of the specimen. The numbers are the section size of the columns. As the mud wall, the mud plaster wall is "#" and the dry mud-panel is ".-". The last character "N" of the mud plaster wall specimens indicates the specification of the 40mm thickness horizontal Nuki.

We obtained the bending Young's modulus MOE and the bending strength MOR of all the columns by the three-point bending tests performed after the static loading tests. The distance between the support points is 1680mm (fourteen times as long as the section size of the columns) in full wall specimens and 1440mm (twelve as long as the section size of the columns to avoid a defect due to breakage) in large hanging wall specimens. The material constants of each column are shown in Table 1.

2.2 LOADING SETUP

Figure 4 shows the loading setup of the static loading tests and the location of strain gauges at the columns of the large hanging wall specimens. We performed the static loading tests by loading the both ends of the cross beam of the specimen through load cells not to bind in the vertical direction. To prevent pullout of the column bases, the capital and base of each column are fixed in metal fittings, and each specimen is weighted on the capitals of each column with the vertical load W like Figure 4. Furthermore, we set hold down hardware at the capital and base of each column in the full wall specimens. The reversed cyclic loading in the horizontal direction is conducted by increasing the amplitude of the rotational angle.

![Figure 4: Loading setup](image)

The rotational angle R is given by Equation (1).

\[ R = \frac{\delta}{h} \]  

(1)

where \( \delta \) is the horizontal relative displacement between the cross beam and the ground sill (top displacement of specimen), and \( h \) is the inner height (the full wall specimens : \( h=2700mm \), the large hanging wall specimens : \( h=3870mm \)). In this paper, the hanging wall of the large hanging wall specimen is defined as the part which is lower the cross beam and upper the Sashigamoi including the walls and the columns. The rotational angle of the hanging wall \( \delta_h \) is given by Equation (1).

\[ \delta_h = \frac{R}{h} \]  

(2)

where \( \delta_h \) is the horizontal relative displacement between the cross beam and the Sashigamoi, and \( h_2 \) is the inner height between the cross beam and the Sashigamoi \( (h_2=1800mm) \).

The restoring force \( P \) is measured by the load cells, and the bending moment and shear force of each column are obtained by the strain gauges. The shear force of the columns \( Q \) is calculated by Equation (3).

\[ Q = \frac{M_U - M_D}{l_s} \]  

(3)

where \( M_U \) and \( M_D \) are the bending moment at the upper and lower positions of the strain gauges, respectively, and \( l_s \) is the length between the two position (=900mm) as shown in Figure 4. The \( M_U \) and \( M_D \) are calculated by using the bending Young's modulus MOE and the geometrical moment of inertia \( I \) considering the partial loss of the area by a back split.

In this paper, the front column is defined as the column of the loading direction side, and the rear column is as the column of the loading direction opposite side. For example, the left column is the front column and the right column is the rear column when loading to the plus direction (the left of the sheet).

2.3 TEST RESULT

2.3.1 RESTORING FORCE CHARACTERISTICS AND DAMAGE

Figure 5 shows the loading state of 4P12#12#12N. Figure 6 shows the relationship of the restoring force \( P \) and the rotational angle \( R \) (hereinafter referred to as restoring force characteristics) of each specimen and Table 2 shows the maximum restoring force \( P_{max} \) and breakage of the columns in the large hanging wall specimens. The damage of the walls in each mud plaster wall specimen is shown in Figure 7.
First, we mention the full wall specimens. In F12#12N, shear cracks in the wall occurred on the front surface and the restoring force $P$ reached a maximum at 1/120 rad. After that, the cracks developed between the vertical Nuki as shown in Figure 7 (a). In F12#12, the restoring force $P$ reached a maximum at 1/30 rad, then out-of-plane deformation and collapse at the corners of the wall were observed. Compared with F12#12N, F12#12 had few crack of the wall and different in how to crack as shown in Figure 7 (a), (b). However, the maximum restoring force $P_{\text{max}}$ has about the same value in the both full wall specimens. In F12-12, shear cracks occurred

<table>
<thead>
<tr>
<th>Table 2: Maximum Restoring force $P_{\text{max}}$ and breakage of column (★: $P_{\text{max}}$, ▼: Breakage of columns)</th>
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</thead>
<tbody>
<tr>
<td>Frame</td>
</tr>
<tr>
<td>Full wall</td>
</tr>
<tr>
<td></td>
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<tr>
<td>Large wall</td>
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<tr>
<td>Hanging wall</td>
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</tbody>
</table>

- Figure 6: Restoring force characteristics (▼: Breakage of column)
- Figure 7: Damage of wall in mud plaster wall specimen
- Figure 8: Bending moment diagram (4P12#12#12N)
and the restoring force reached a maximum at 1/20 rad. Then the shear cracks developed and out-of-plane deformation of the Nuki and the panels occurred at 1/15 rad.

Next, we mention the large hanging wall specimens (refer to [4, 5]). The damage modes of the large hanging walls specimens were roughly classified into the damage of the hanging walls and the breakage of the columns. In this paper, we define breakage of columns as when the columns crack at the joint for the first time. Figure 8 shows the bending moment diagram and Figure 9 shows a picture of the breakage of the center column in 4P12#12#12N. In the large hanging wall specimens, the breakage of the columns were caused by the large bending moment at the lower end of the hanging wall as shown in Figure 8. The columns did not lose the effective area of the cross section of the joint just after breakage (Figure 9 refers) and the cracks gradually developed as the deformation of the whole structure become larger. In 2P12#12N, the cracks in the wall developed as shown in Figure 7 (c) and the columns did not break until the restoring force P was lost. In 2P12#12, the cracks in the wall are few compared with 2P12#12N and all the columns broke in order of the left(rear) column and the right(rear) column. In 4P12#12#12N, there is few cracks in the wall and all the columns broke in order of the center column, the right(front) column and the left(front) column. In 2P12-12, the cracks of the dry mud-panels were few and columns did not break until restoring force P was lost. In 4P12-12-12, the damage of the hanging wall was little and all the columns broke in order of the center column, the right(rear) column and the left(rear) column.

2.3.2 RESTORING FORCE CHARACTERISTICS OF HANGING WALLS

In the current seismic evaluation methods, the load-displacement relationship of the mud wall is modeled with the shear force proportional to the thickness and the width of the wall. Furthermore, the current method use the restoring force characteristics of the model whose restoring force P reduced by Equation (4) for the restoring force characteristics of the hanging walls.

\[ P = \frac{h_1}{\bar{h}} P \]

where \( P \) is the reduced value of the restoring force \( P \).

On the other hand, we use the test results of the full wall specimens instead of the mud wall model and calculate the reduced value \( P' \) by Equation (4).

Figure 10 shows the comparison between the restoring force characteristics of the hanging wall of the large hanging wall specimens and the reduced values of the mud wall model and the full wall specimens. Besides, 2P12-12 shows only the test results because the wall made of dry mud-panels is not defined in the current method. Compared with the test results, the reduced value \( P' \) of the mud wall model is low in the specimens with mud plaster walls as shown in Figure 10 (a) and (b). In short, the current method estimates the restoring force of the mud wall lower than that of the test result. On the other hand, the reduced value \( P' \) of the full wall specimens generally corresponds with the test results including the specimen with dry mud-panels.

In addition, Figure 11 shows the comparison between the maximum restoring force \( P_{\text{max}} \) in the large hanging wall specimens and the reduced values of the maximum restoring force \( P'_{\text{max}} \) in the full wall specimens. In 2P12#12N and 2P12-12 whose columns did not break, it is considered that the hanging wall exert the shear strength because the restoring force \( P \) of the whole frames decreased by the damage of the hanging wall. As shown in Figure 11, the reduced value \( P'_{\text{max}} \) in the full wall specimens is 1.3 times as much as the value of \( P_{\text{max}} \) in the two specimens. It shows that the shear strength of the hanging wall in the large hanging wall specimens can be estimated comparatively by the test results of the full wall specimens.
2.3.3 SHEAR FORCE OF COLUMNS

The current method assumes the following. Each column in the frames with the hanging walls bears the hanging walls of the length which is the sum of a half of the distances to the adjacent columns. The restoring force characteristics of the whole structure is calculated as the sum of the restoring force characteristics of each independent column with hanging walls. According to the current method, the length of the bearing hanging wall of each column of the 4P large hanging wall specimen is 1P (=910mm) in the side columns and 2P (=1820mm) in the center column as shown in Figure 12. Thus, the shear force of each column is in the ratio in 1:2:1 from left to right. In other words, the current method assumes that the shear force of each column is independent and the center column shares the shear force twice as much as that of the side columns. Furthermore, the current method take zero for the shear force of the broken columns after breakage.

Figure 13 shows the relationship between the shear force of the columns $Q_c$ and the rotational angle $R$ in the plus loading in the three specimens whose columns broke. From Figure 13, it can be seen that the broken columns did not lose the shear force just after breakage but kept the shear force to some extent. In the three specimens, shear force of the rear column was lower than that of the other columns until breakage of the columns occurred. The same tendency is shown in the minus loading although the front column and the rear column exchanged.

As shown in Figure 14, the shear force of each column is given by Equation (5) assuming a pin joint of the column base.

$$Q_c = \frac{3EI}{h_1} x_c$$  \hspace{1cm} (5)

where $E$ is the Young's modulus of the column, $h_1$ is the inner height between Sashigamoi and the ground sill and $x_c$ is the bending deformation of the column under the Sashigamoi. If the bending deformation is the same in all the columns, the ratio of the shear force of each column is depend on the bending rigidity $EI$ of each column.

In this paper, we define the ratio of the shear force of each column to the sum of the shear force of all the columns as the sharing ratio. Figure 15 shows the relationship of the sharing ratio of the columns and the
rotational angle $R$ in 4P12#12#12N in the plus loading. As shown in Figure 15, it can be seen that the share ratio was generally constant until the center column broke and changed after then. Figure 16 shows the comparison between the share ratio calculated by Equation (3) of the test result about just before breakage of column and the ratio of the bending rigidity calculated by the bending Young's modulus $MOE$ and the previously mentioned geometrical moment of inertia $I$. As shown in Figure 16, the shear ratio in the test is not determined by the bending rigidity of the columns.

As stated above, it is considered that the current method different from the test results in that the current method take the approach dividing a frame with hanging walls into each independent column with hanging walls.

Next, as shown in Figure 17, we define the points of the heights of the column capital, the upper and lower end of the Sashogamoi and the column base as the point A, B, C and D, respectively. The relative heights are $h_2=1800\text{mm}$ between A and B, $h_1=270\text{mm}$ between B and C, $h_r=1800\text{mm}$ between C and D and $h=3870\text{mm}$ between A and D. The rotational angles of the columns such as $R_{AB}$, $R_{BC}$ and $R_{CD}$ are calculated by dividing the relative horizontal displacement between any two points by the inner height. Besides, the horizontal displacements of A and D are equal to those of the cross beam and the ground sill, respectively. In all the large hanging wall specimens, the values of the rotational angles of the columns shows the relationship of $R_{AB} < R_{BC} < R_{CD}$.

As shown in Figure 18 (a), the bending deformation of the column $\delta_s$ is defined by the Equation (6).

$$\delta_s = u_{\text{CD}} - R_{\text{BC}} \cdot h_1$$  \hspace{1cm} (6)

where, $u_{\text{CD}}$ is the horizontal displacement of the column at the height of the lower end of the Sashigamoi (the relative displacement between C and D). Figure 19 shows the relative horizontal displacement $u_{\text{CD}}$ and Figure 18 shows the bending deformation $\delta_s$ of the columns in 4P12#12#12N. Although there is little difference between $u_{\text{CD}}$ of each column, $\delta_s$ is remarkably various and large in order of the center column, the front column and the rear column. The reason is considered that the restraint of the columns at the joint by the Sashigamoi is different due to the location against the loading direction and the $R_{\text{BC}}$ of each column is various at Equation (6).

Using the bending deformation of column $\delta_s$ obtained by Equation (6), we calculate the shear force of the columns $Q_s$ by Equation (7) assuming that the load-displacement relationship of the columns is linear and the column base is a pin joint.

$$Q_s = \frac{3MOE \cdot I}{h_1} \delta_s$$  \hspace{1cm} (7)

Figure 20 shows the comparison of the shear force $Q_s$ between Equation (3) and Equation (7) in 4P12#12#12N. Equation (7) generally evaluates Equation (3) until each column breaks in the center column and the rear column (Figure 20 (b) and (c) refer). Although there is a difference in large deformation, Equation (7) generally
evaluates Equation (3) until almost 0.03 rad in the front column (Figure 20 (a) refer).

From the above, it is considered that the shear force of the columns in the large hanging wall specimens is different until breakage due to the rotational angle at the height of the Sashigamoi $R_{BC}$, that is, the restraint of the columns at the joint by the Sashigamoi. In particular, we can guess that the reason why the shear force of the rear column is lower than the other columns is that a gap between the column and the lower end of the Sashigamoi occurs, the rotational angle of the column at the height of the Sashigamoi become large and the bending deformation is smaller than the other columns.

2.3.4 DEFORMATION OF COLUMNS

As shown in Figure 17 (b), the top displacement of the large hanging wall specimens $\delta$ is expressed by Equation (8) ~ (11).

\[
\delta = \delta_w + \delta_r + \delta_i \\
\delta_w = R_{AB} \cdot h \tag{9} \\
\delta_r = (R_{BC} - R_{AB}) \cdot (h_i + h_t) \tag{10} \\
\delta_i = (R_{CD} - R_{BC}) \cdot h_t \tag{11}
\]

where, $\delta_w$ is the horizontal displacement by the shear deformation of the hanging wall, $\delta_r$ is the horizontal displacement by the rotational deformation at the height of the Sashigamoi and $\delta_i$ is the bending deformation of the column under the lower end of the Sashigamoi. The current method calculates the top displacement $\delta$ by the sum of the horizontal displacement by the shear deformation of the hanging wall $\delta_w$ and the bending deformation of the column $\delta_i$. That is, the current method do not consider the horizontal displacement by the rotational deformation at the height of the Sashigamoi $\delta_i$ and estimate the top deformation $\delta$ lower by $\delta_w$.

Figure 21 shows the value of $\delta/\delta$ in 4P12#12#12N. It can be seen that $\delta/\delta$ is about 40% in the side columns and about 20% in the center column. Thus, it is consider that the rotational deformation at the height of the Sashigamoi affect the top displacement of a whole structure.

![Figure 20: Restoring force characteristics of columns (4P12#12#12N, ▼:Breakage of column)](image)

![Figure 21: Value of $\delta/\delta$ (4P12#12#12N)](image)

2.3.5 FLEXURAL CAPACITY OF COLUMNS

This section shows the relationship between the maximum tensile stress and the flexural strength of the columns which broke in the tests. Furthermore, we consider the judgement of breakage of the columns by the current method.

The current method calculates the horizontal force when a column breaks $P_{cr}$ by Equation (12).

\[
P_{cr} = \frac{Z_e F_b}{h_t} \tag{12}
\]

where $Z_e$ is the effective section modulus of the column at the joint that is 0.75Z (the full section modulus Z) and $F_b$ is the flexural strength of the column.

We calculated the $Z_e$ of the columns in the large hanging wall specimens considering the partial loss of areas in the joints. Thereby, the $Z_e$ of the center column and the side column are 0.65Z and 0.68Z, respectively. The $Z_e$ in the tests is less than 0.75Z assumed in the current method.

Next, we calculated the maximum tensile stress at the joint $\sigma_t$ of all the broken columns by Equation (13) ~ (16). Here, the tensile force was set as the positive.

\[
\sigma_t = \sigma_w + \sigma_n + \sigma_m \\
\sigma_w = -W_i / A_e \tag{14}
\]
\[
\sigma_n = \begin{cases}
-(P \cdot h)/(l \cdot A_t) & \text{Left column} \\
(P \cdot h)/(l \cdot A_t) & \text{Right column} \\
0 & \text{Center column}
\end{cases}
\]  

(15)

\[
\sigma_n = \max M / Z_e
\]  

(16)

We assumed that the maximum tensile stress is the sum of the three kinds of stress (the axial force of the vertical load and the self-weight \(\sigma_n\), the axial force varied by the rigid rotation of the whole structure \(\sigma_s\), and the tensile stress by the bending moment at the height of the lower end of the Sashigamoi \(\sigma_m\)). \(W_t\) is the axial force of the vertical load and the self-weight in each column. \(A_t\) and \(Z_e\) are the sectional area and the section modulus at the minimum cross section, respectively. \(l\) is the distance between the both side columns. \(\max M_t\) is the absolute maximum bending moment at the height of the lower end of the Sashigamoi. Moreover, we assumed that the specimens revolve around the center of the ground sill. In calculating, it is confirmed that the values of the \(\sigma_n\) and \(\sigma_s\) are very small and around 10% of that of the \(\sigma_m\).

Figure 22 shows the relationship between the maximum tensile stress \(\max \sigma_n\) and the flexural strength MOR of all the broken columns. The two values of each column are shown in the figure because the two sides of each column in the test were strained by cyclic loading. As shown in the figure, the \(\max \sigma_n\) of the front columns had the tendency to be almost the same value of the MOR. On the other hand, the \(\max \sigma_n\) of the rear columns and the center columns tended to be smaller than the MOR. Also, we confirmed that the columns of the specimens in this test tend to break at the tensile stress which is about the half of the flexural strength MOR in the rear columns because the rear columns have large strain in the corners of the inner part of the joint which lead to a crack [7]. This is one of the reason why the rear column in spite of the smaller shear force broke earlier than the front column in 2P12#12 and 4P12-12-12. However, the current method is possible to fail to correctly judge breakage of column like the rear column in the tests for the above reason (refer to Equation (12)).

### 3. SEISMIC PERFORMANCE EVALUATION

Based on the current method, we evaluate the restoring force characteristics of 4P12#12#12N in the two cases. In the first case which assumes the seismic evaluation on an existing structure, we use the mud wall model of the current method as the hanging wall and the reference strength (Japanese cedar of no grade in Japanese Agricultural Standard [8]) as the material constants of the columns. In the second case which assumes the experimental simulation, we use the hysteresis characteristic of F12#12N until 1/15rad as the hanging wall and the values of MOE and MOR shown in Table 1 as the material constants of the columns. In addition, the column break when the tensile stress at the joint reaches the value of the maximum tensile stress \(\max \sigma_n\) as shown in Figure 22.

Figure 23 shows the evaluation result in the two cases with the test result of 4P12#12#12N in the plus loading. Although all the columns broke in the test, the seismic evaluation case judges only the center column broken and the experimental simulation case judges the center column and the right(rear) column. As shown in Figure 23 (a), the current method generally corresponds with the test result until 0.02rad. After judging breakage of the center column, the restoring force \(P\) is about the half as much as that of the test result. The maximum restoring force \(P_{\max}\) is 0.6 times as much as that of the test result. In the seismic performance evaluation, although it is not necessarily bad to underestimate the restoring force, there is a possibility to fail to judge the breakage of the columns correctly. As shown in Figure 23 (b), the current method generally corresponds with the test result until 0.01rad. After judging breakage of the center column and the right(rear) column, the restoring force \(P\) is about the half as much as that of the test result. The maximum restoring force \(P_{\max}\) is 0.8 times as much as that of the test result. The result of the experimental simulation is different from the test result in judgement of the breakage of the column, the rotational angle \(R\) when the columns break and the restoring force characteristics after 0.01rad. The reasons for that the current method fails to evaluate the test result include the following. The current method divides the frame into the independent columns with the hanging walls, and estimates the shear force of the columns just after breakage at zero. Moreover, it do not consider the horizontal displacement of the whole structure by the rotation deformation at the Sashigamoi joint.

From the above, it is revealed that there is room for improvement on the current method of the seismic evaluation on the frames with the hanging walls as for evaluation on the restoring force characteristics and breakage of the columns. After this, we are going to propose a new method of seismic performance evaluation on traditional timber frame structures with large hanging walls.

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**Figure 22:** Relationship between maximum tensile stress \(\max \sigma_n\) and flexural strength MOR
4. CONCLUSIONS

The major findings obtained from this paper are summarized as follows:

a) The restoring force of mud walls obtained by the current method is lower than that of the test results. The restoring force characteristics of large hanging walls can be calculated by the restoring force characteristics of full walls which have the same specification of wall.

b) Shear force of a column is not depend on only the sum of half of the distances from the column to the adjacent columns on the both sides, because shear force is affected by the sectional performance and Young’s modulus of the column, the location of the column against the loading direction and breakage of the surrounding columns.

c) From the above, it is revealed that there is room for improvement on the current method in evaluation of breakage of columns of timber frames with hanging wall.

d) It is need to consider rotational deformation of columns at joints in evaluation of deformation of timber frames with hanging walls.

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