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Seismic Performance Evaluation based on Static Loading Tests of Timber Frame Structures with Large Hanging Walls and Full Walls

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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. Fig. 1 shows an example of the structures with large hanging walls in the historical timber houses. Timber frame structures with hanging walls are very important factor to think of seismic safety of timber buildings because the timber frames with hanging walls can lead to collapse of the whole buildings by breakage of the columns at the joints of the lower end of the hanging walls.

The purpose of this study is demonstrative investigation of mechanical characteristics of timber frame structures with large hanging walls aiming for construction of a reasonable and practical seismic evaluation method. In this paper, we show the results of the static loading tests of the historical timber frames with large hanging walls, which have the walls at a part under the hanging walls. We examine the effect of the width of the walls and the number of the columns on the maximum restoring force and the deformation performance in the specimens.

As a result, the following conclusions have been drawn.

1) Maximun restoring force of frames with large hanging walls increased by attachment of full walls. However, in the specimens which collapsed by breakage of the walls in first story and all the columns at the joints, the ultimate rotational angles are from about 1/15 to 1/10rad regardless of the presence or absence of full walls in the first story.

2) Within our static loading tests, the maximun restoring force of the frames with large hanging walls and full walls in the first story is proportional to the width of the wall in the first story and the number of the through columns, and can be estimate roughly by a linear regression equation obtained by the test results.

Keywords: Historical timber building; Hanging wall; seismic performance evaluation; Static loading test

1. Introduction

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. Fig. 1 shows an example of the structures with large hanging walls in the historical timber houses. Timber frame structures with hanging walls are very important factor to think of seismic safety of timber buildings because the timber frames with hanging walls can lead to collapse of the whole buildings by breakage of the columns at the joints of the lower end of the hanging walls.

The purpose of this study is demonstrative investigation of mechanical characteristics of timber frame structures with large hanging walls aiming for construction of a reasonable and practical seismic evaluation method. We had performed the static loading tests of the historical timber frames with large hanging walls[1, 2]. In this paper, we show the results of the additional static loading tests of the historical timber frames with large hanging walls, which have walls at a part under the hanging wall. We examine the effect of the width of the wall and the number of the columns on the maximum restoring force and the deformation performance in the specimens.

Fig. 1 – Example of structures with large hanging wall
(Wakayama, Japan)

2. Static loading test

2.1 Specimens

Fig. 2 shows the elevations of the specimens and Table 1 shows the details of the specimens. We made six specimens of timber frames with large hanging walls and beams called *Sashigamoi* in Japanese(refer to [1]). The width of the walls and the number of the columns are the experimental variables. The names of each member in the timber frames are shown in Fig. 3. The specimens consist of columns, cross beams, ground sills, *Sashigamoi* and mud walls. The inner height between the cross beam and the ground sill is 3.87m and the height of the hanging wall is 1.80m. The span length between the adjacent columns is 1.82m(=2P) or 0.91m(=1P). The section size of the columns and the ground sills is 120x120mm, that of the cross beams is 240x120mm, and that of the *Sashigamoi* is 270x120mm.

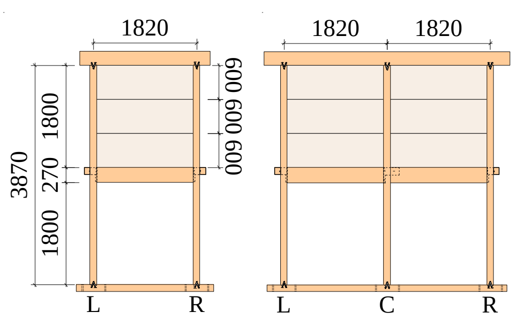
The capital and base of the columns is stub tenon with VP joint metals (refer to Fig. 8) on the both sides. The *Sashigamoi* is inserted into the columns and fixed with cotters (*Hanasen* or *Komisen*). The configuration of the tenon of the *Sashigamoi* is shown in Fig. 4 and the pictures of the joints of the columns are shown in Fig. 5. The specimens have two crosspieces called *Nuki* in Japanese (refer to Fig. 3) and three mud-panels in each area of the walls. The walls are made of dry mud-panels whose thickness are 26mm [3]. All the sides of each mud-panel are screwed on the *Nuki* and corbels inside the frames.

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 *Hanasen* and *Comisen* are made of oak. The *Nuki* is made of Japanese cedar and the section size is 105x18mm.

In this paper, we defined the names of each section of the specimens as shown in Fig. 6. The section above the *Sashigamoi* of the specimens is the *second story section* and the section below the *Sashigamoi* is the *first story section*. The section which have the walls in the both stories is the *multi-story wall*.

The specimens are named in the following rules. The initials such as "2P", "4P" express the width of the specimens. The numbers such as "12" is the section size of the columns (12cm) and "-" is the hanging walls between the columns. The multi-story walls of 1P in width is "f" or that of 2P is "F". The names of each column are "L"(Left), "R"(Right), "C"(Center), "Cl"(Center left) and "Cr"(Center right) as shown in Fig. 2.

We obtained bending the Young's modulus E_b and the bending strength F_b of all the columns by the three-point bending tests performed after the static loading tests. The distance between the support points is 1440mm (twelve as long as the section size of the columns to avoid a defect due to breakage). The material constants are shown in Table 1.



(a) 2P12-12 (b) 4P12-12-12

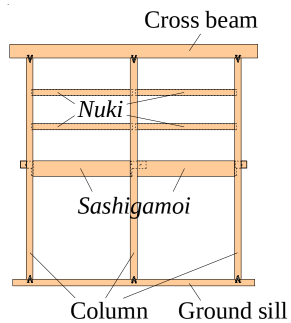


Fig. 3 – Names of each member

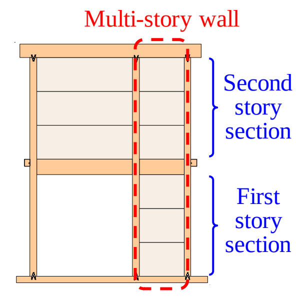
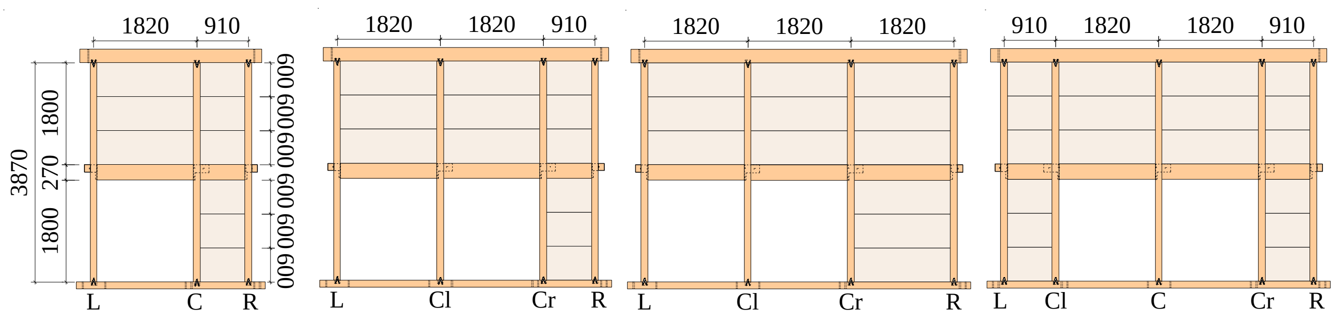
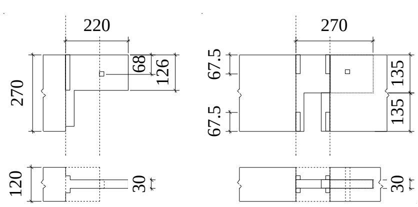


Fig. 6 – Names of each section



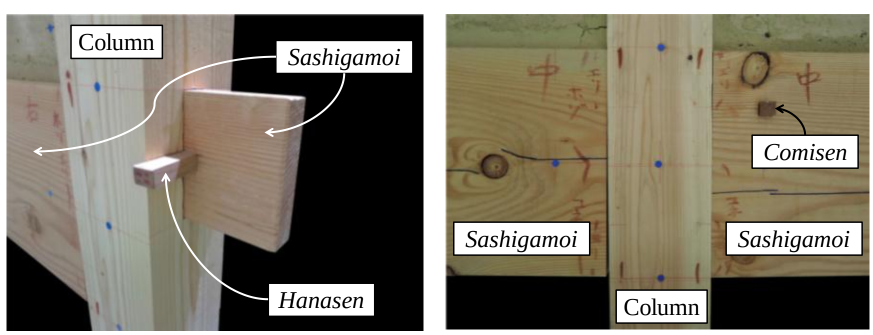
(c) 3P12-12f (d) 5P12-12-12f (e) 6P12-12-12F (f) 6Pf12-12-12f

Fig. 2 – Elevations of specimens (Unit : mm)



(a) L, R (b) C, Cl, Cr

Fig. 4 – Tenons of *Sashigamoi* (Unit : mm)



(a) L, R (b) C, Cl, Cr

Fig. 5 – Joints of columns

Table 1 – Details of specimens (× : Breakage of column)

Specimen	Weight (kN)		Column				
	Specimen	Vertical load W	Location	Density (t/m^3)	E_b (kN/mm^2)	F_b (N/mm^2)	Breakage
2P12-12	2.1	25.7	L	0.44	7.9	45.7	-
			R	0.40	8.3	39.9	-
4P12-12-12	3.5	51.1	L	0.43	8.8	53.2	×
			C	0.39	7.7	43.0	×
			R	0.41	8.1	47.0	×
3P12-12f	2.8	38.6	L	0.39	8.0	-	-
			C	0.46	8.9	-	-
			R	0.40	8.5	-	-
5P12-12-12f	4.1	64.0	L	0.42	8.4	57.3	×
			Cl	0.45	9.6	65.4	×
			Cr	0.42	7.3	52.4	×
			R	0.46	8.0	61.0	×
6P12-12-12F	5.2	75.6	L	0.40	7.9	48.9	×
			Cl	0.46	8.9	59.6	×
			Cr	0.44	7.8	48.9	×
			R	0.41	8.3	56.2	×
6Pf12-12-12f	5.1	77.5	L	0.42	8.5	49.3	×
			Cl	0.43	8.7	49.9	×
			C	0.39	7.3	49.3	×
			Cr	0.47	9.2	57.1	×
			R	0.47	9.5	58.4	×

2.2 Loading setup

Fig. 7 shows the loading setup of the tests and Fig. 8 shows the fixation of the column base. We performed the static loading tests by loading the both ends of the cross beams of the specimens through load cells not to bind in the vertical direction. In order to prevent pullout of the column bases, the capital and base of each column are fixed in VP joint metals, and each specimen is weighted on the capital of each column with the vertical load W like Fig. 7. Furthermore, each column with the adjacent multi-story walls is fixed with hold down hardware at the capital and base, because the estimated pull-out force is larger than the other columns. The reversed cyclic loading in the horizontal direction is conducted by increasing the amplitude of the rotational angle.

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

$$R = \delta / h \tag{1}$$

where δ is the horizontal relative displacement between the cross beam and the ground sill (top displacement of specimen), and h is the inner height between the cross beam and the ground sill (h=3.87m). The restoring force P is measured by the load cells

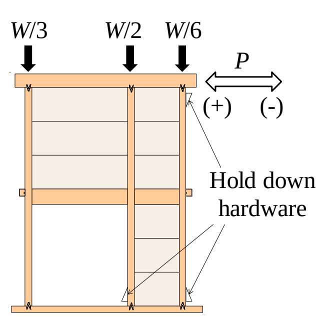


Fig. 7 – Loading setup

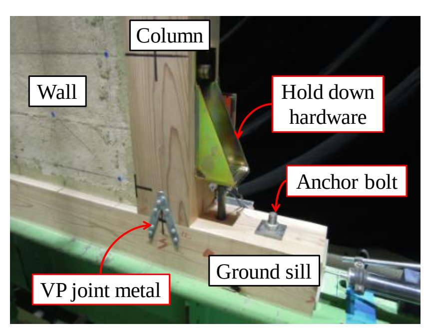


Fig. 8 – Fixation of column base

3. Test results

3.1 Restoring force characteristics and main damage

Fig. 9 shows the relationship of the restoring force *P* and the rotational angle *R* (restoring force characteristics) of each specimen, and breakage of each columns are shown in Table. 1. The test results of the two specimens of 2P12-12 and 4P12-12-12 are detailed in the previous paper [1]. There is little difference between the plus direction and the minus direction in the restoring force characteristics of each specimen. The main damage of the timber frames with large hanging walls were roughly classified into breakage of the columns at the height of lower end of the *Sashigamoi* and the damage of the mud-panels. Fig. 10 shows the examples of the main damage.

As shown in Fig. 9 (b) 4P12-12-12, (d) 5P12-12-12f, (e) 6P12-12-12F and (f) 6Pf12-12-12f, the four specimens lost the restoring force *P* by collapse of the first story due to breakage of all the columns. In 4P12-12-12, the column C broke in *R* = 1/30rad and the column L and R broke in *R* = 1/15rad. In the three specimens of 5P12-12-12f, 6P12-12-12F and 6Pf12-12-12f, the columns C and Cl without wall attached to the first story section broke in *R* = 1/20rad, the columns Cl and Cr with wall attached to the first story section broke in *R* = 1/15rad and the columns L and R broke in *R* = 1/10rad. On the other hand, as shown in Fig. 9 (a) 2P12-12 and (c) 3P12-12f, the columns did not break and the two specimens lost the restoring force *P* by breakage of the walls.

Fig. 11 shows pictures of 6Pf12-12-12f during the test about (a) before collapse and (b) after collapse. As shown in Fig. 9 (f), 6Pf12-12-12f had the restoring force *P* of about 20kN in the first loop of *R* = 1/10rad (refer to Fig. 11 (a)). However, the mud-panels in the first story section fell down and all the columns was fractured by bending at the joints one after the other in the second loop of *R* = 1/10rad (refer to Fig. 11 (b)). As a result, 6Pf12-12-12f lost the restoring force *P* suddenly and collapsed. It is considered as a factor that the shear force of the columns increase by breakage of the walls in the first story section. In the same way, by the columns broken at the joints after breakage of the walls in the first story section, the whole structure caused collapse in 5P12-12-12f and 6P12-12-12F.

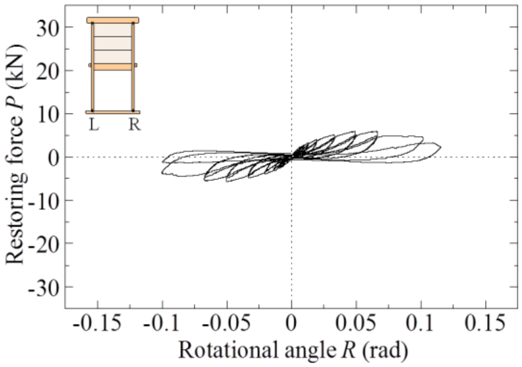
3.2 Comparison between specimens

The maximum restoring force in the plus loading $P_{\max}$ and the ultimate rotational angle R_u of each specimen are shown in Fig. 12 and Fig. 13, respectively. In this paper, the R_u is difined as the smaller one of the rotational angle *R* when the specimen lost the restoring force *P*, and the *R* when the *P* suddenly decrease after all the columns broke.

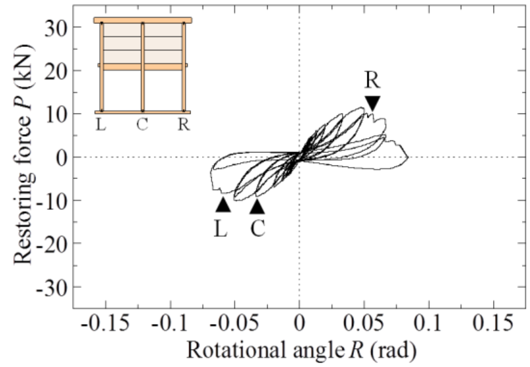
First, we mention the maximum restoring force $P_{\max}$. As shown in Fig. 12, the $P_{\max}$ of the whole structures increase by attaching the multi-story walls to the frames with large hanging walls. It is considerd that $P_{\max}$ often depends on the shear capacity of the first story section because the wall quantity is less in the first story section than in the second story section. Determinant of the $P_{\max}$ will be detailed later in cahpter 4.

Next, we mention the ulimate rotational angle R_u. As shown in Fig. 13, in the two specimens whose columns did not break, R_u in 3P12-12f is larger than in 2P12-12 by attaching the multi-story wall. On the other hand, in the four spesimens whose columns broke, the R_u is from about 1/15 to 1/10rad regardless of the presence or absence of the multi-story wall. The reason that the R_u is almost the same in the specimens whose columns broke is considered as follows. The walls in the first story section break early because the deformation capacity of the walls is small and the wall quantity is less in the first story section than in the second story section. Then, the structure whose walls in the first story broke can be regarded as the frame with large hanging walls without walls in the first story. Furthermore, the columns break at about the same rotational angle *R* as the frames without walls in the first story. As a result, the R_u do not very change by attaching the multi-story wall.

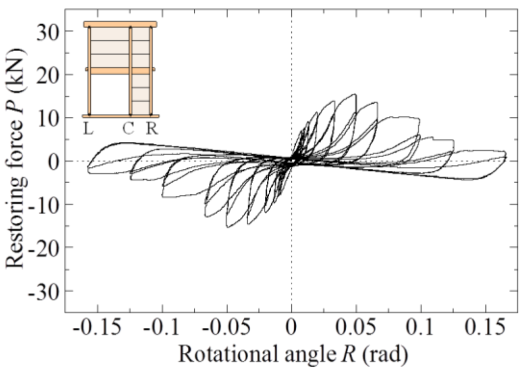
From the above, in the frames with large hanging wall, attachment of the multi-story wall increases the maximum restoring force, but does not necessarily improve the deformation performance.



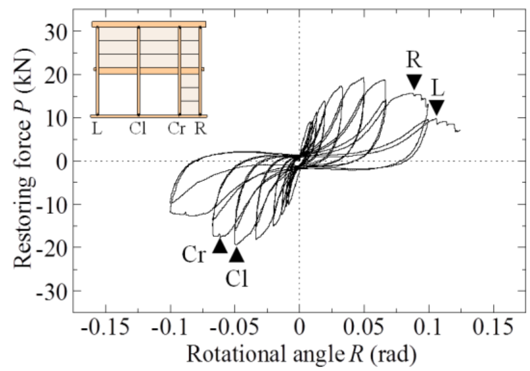
(a) 2P12-12



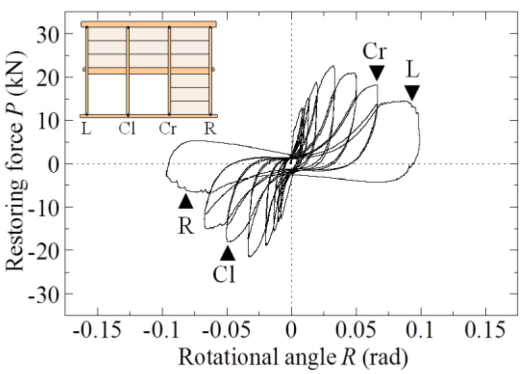
(b) 4P12-12-12



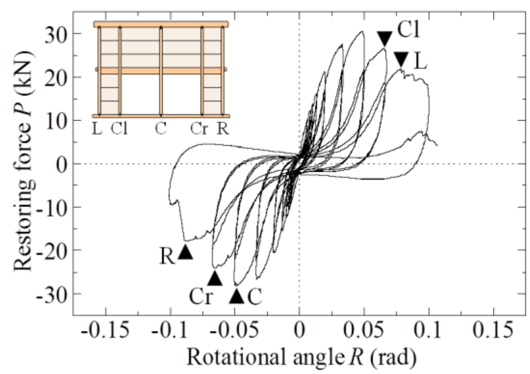
(c) 3P12-12f



(d) 5P12-12-12f



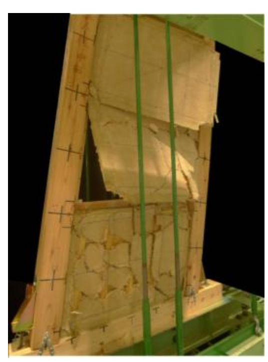
(e) 6P12-12-12F



(f) 6Pf12-12-12f

Fig. 9 – Restoring force characteristics (▼: Breakage of column)

(a) Breakage of column
(5P12-12-12f, Column Cl)



(b) Breakage of wall
(5P12-12-12f, First story section)

Fig. 10 – Examples of main damage

(a) Before collapse
(First loop of R = 1/10rad)

(b) After collapse
(Second loop of R = 1/10rad)

Fig. 11 – Pictures of 6Pf12-12-12f during test

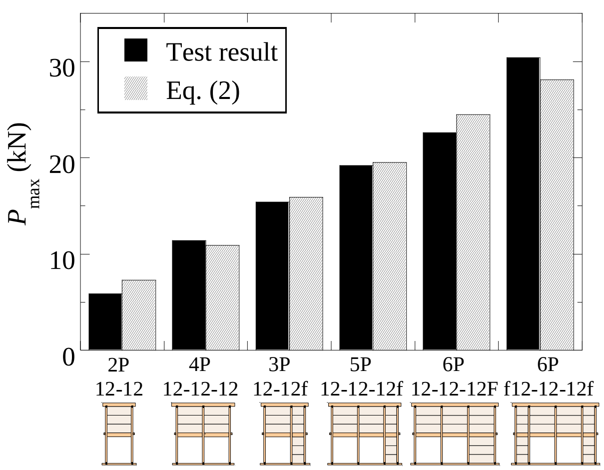


Fig. 12 – Maximum restoring force P_{max}

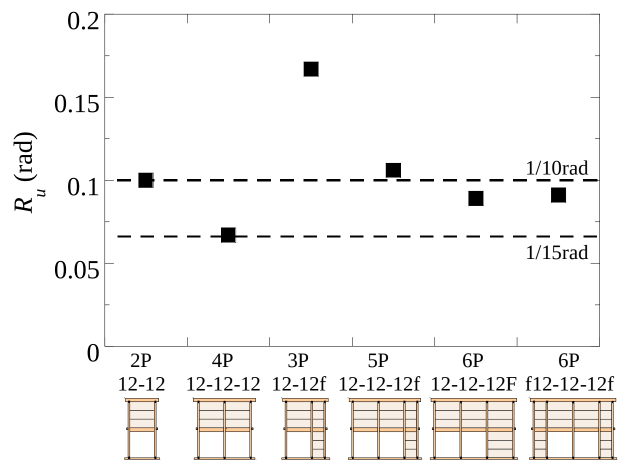


Fig. 13 – Ultimate rotational angle R_u

4. Estimation of maximum restoring force

4.1 Derivation of an regression equation

Based on the consideration in section 3.2, we assume that the maximum restoring force P_{max}(kN) can be expressed by a function of the width of walls in the first story section L_1(m) and the number of through columns N_c as shown in Eq. (2)

$$P_{max}\,(L_1, N) = a_w\,L_1 + a_c\,N \tag{2}$$

where, the coefficients a_w(kN/m) and a_c(kN) are constants.

The width of walls in the first story section L_1(m), the number of through columns N_c and the maximum restoring force P_{max}(kN) of each specimens are shown in Table 2. We performed regression analysis for Eq. (2) by using the experimental values (P_{max}, L_1, N_c) shown in Table 2. As a result, a_w=5.5 and a_c=3.6. The P_{max} calculated by Eq. (2) is shown in Fig. 12 compared with the test results. Eq. (2) indicates a good correspondence to the test results.

From the above, the maximum restoring force P_{max} in our specimens with large hanging walls is proportional to the width of walls in the first story section L_1 and the number of through columns N_c, and can be estimate roughly by Eq. (2).

Table 2 – Values of N_c, L_1 and P_{max} in each specimen

Specimen	Width of wall in first story section	Number of columns N_c	P_{max} (kN)	
			Test result	Eq. (2)
2P12-12	0	2	5.9	7.2
4P12-12-12	0	3	11.4	10.8
3P12-12f	0.91	3	15.4	15.8
5P12-12-12f	0.91	4	19.2	19.4
6P12-12-12F	1.82	4	22.6	24.4
6Pf12-12-12f	1.82	5	30.4	28.0

4.2 Examination of coefficients in regression equation

We consider the coefficients a_w and a_c of Eq. (2) derived in chapter 4.1, where the a_w(kN/m) means the shear capacity of dry mud-panels per one meter in the width of walls in the first story section and the a_c(kN) means the shear force of one column when it breaks.

First, we mention the a_w. The shear capacity of a wall made of dry mud-panels which screwed to crosspieces on one side is 3.8kN in the design value and 6.5kN from the test result of the full wall specimen of 1P in width [3]. The value of the a_w in Eq. (2) is about 1.5 times of the design value and about 0.8 times of the test result.

Next, we mention the a_c. In the large hanging wall specimens, the shear force of one column when it breaks Q_{cr} can be calculated by Eq. (3) according to [4], assuming that the column bases are pin joints.

$$Q_{cr} = Z_e F_b / h_1 \tag{3}$$

where Z_e is the effective section modulus of the column at the joint that is 0.75Z (full section modulus Z), F_b is the flexural strength of the column and h_1 is the inner height between the *Sashigamoi* and the ground sill in the specimens. The Q_{cr} is 4.2kN by using 34.8kN/mm^2 which is the design strength of Japanese cedar (E90 in Japanese Agricultural Standard [5]) as the F_b in Eq. (3). On the other hand, the Q_{cr} is 6.3kN by using 52.2N/mm^2 which is the average of the flexural strength F_b of the columns in the specimens as shown in Table 1. The value of the a_c in Eq. (2) is about 0.9 times of the former Q_{cr} and about 0.6 times of the latter Q_{cr}. It is considered that the value of the a_c in Eq. (2) is lower than Q_{cr} calculated by the material constants of the specimens because the columns in our specimens with large hanging walls tend to break at the tensile stress which is the half of the flexural strength when the side of columns inserted by the *Sashigamoi* at the joint is tension side [6].

5. Conclusions

In this paper, based on the static loading tests, we analyze the maximum restoring force and the deformation performance of the structures with large hanging walls with from about 2m to 6m in width. As results, following conclusions have been drawn;

1) Maximun restoring force of frames with large hanging walls increased by attachment of full walls. However, in the specimens which collapsed by breakage of the walls in first story and all the columns at the joints, the ultimate rotational angles are from about 1/15 to 1/10rad regardless of the presence or absence of full walls in the first story.

2) Within our static loading tests, the maximun restoring force of the frames with large hanging walls and full walls in the first story is proportional to the width of the wall in the first story and the number of the through columns, and can be estimate roughly by a linear regression equation obtained by the test results.

6. References

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