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EXPERIMENTAL STUDY OF THE STRENGTH CHARACTRISTICS AND SEISMIC RETROFITTING OF TRADITIONAL JAPANISE HANGING WALLS WITH SLITS

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Abstract

Traditional Japanese houses are made of a wooden framework and a mud wall that is one of the main earthquake-resisting elements of the house. There is a growing tendency toward seismic retrofitting of traditional houses, and while there are choices in the way seismic retrofitting of houses can be realized, for example, increase the quantity of the mud in the wall, the reinforcement of joints, and setting viscous dampers, one effective way is to increase the wall size. Many restoring force characteristics of earthquake-resisting elements have been clarified by experiment; the characteristics of walls in old houses, however, are often different from those of the walls examined in these experiments. For example, the wall above the ceiling of an old house is not considered in structural design. When structural design is executed, the strength of a wall with a slit should be reduced, rather than a wall without a slit. The method for reducing this strength, however, has not yet been clarified. It is thought that such a slit should be filled up at the time of retrofit work. This work, however, is very difficult considering time and cost, since the floor and the ceiling, both sides of the wall need to be demolished and restored when the slit is filled up.

Given this condition, we conducted experiments on mud walls with slits on their upper side, assuming that the wall above the ceiling is not constructed, and clarified their restoring force characteristics. Our experiments comprised static cyclic lateral loading tests. Considering the ease of construction, we examined the seismic retrofit construction method wherein the slit is filled up from one side of the wall; although this method is simple, we hoped that it could provide the required change in strength to make a retrofit practically possible.

We used five hanging mud walls with different specifications, but with common properties as follows: a height of 2.73m, a length of 1.82m, a hanging wall height of 0.91m, a column of 0.105 × 0.105m, a beam of 0.105 × 0.18m, a ground sill of 0.105 × 0.105m, and a wall thickness of 0.06m. The slit width on the wall's upper side was 0.15m. We examined two methods for filling up the slit, one with wall clay and one with wooden boards.

In this paper, we present experimental results of the strength, ductility, and energy dissipating capacity of these walls. The conclusions obtained are summarized as follows. First, the strength of the wall with the slit is 0.875 times less than that of the wall without the slit. Second, if the slit is filled up by wall clay from one side of the wall, a wall with the same strength as that of the wall without a slit is obtained, and a seismic retrofit effect could be expected. Third, if the slit is filled up with wooden boards, the strength does not increase, and a seismic retrofit effect is not expected.

Keywords: Japanese traditional wooden house; Hanging mud wall; Slit; Static horizontal loading test

1. Introduction

Japanese wooden houses constructed before World War II are known as “traditional construction wooden houses.” The structure comprises a framework and mud walls and can resist earthquake motions owing to the strength of the mud walls and toughness of the framework. Various seismic retrofitting methods have been used, such as increasing the strength of the mud walls, retrofitting the framework to improve deformability, and the installation of damping. Calculation of response and limit strength has often been used for seismic diagnosis and retrofit design, and the force characteristics of various earthquake resisting elements have been clarified.

In existing houses, we often see mud walls that do not extend to the attic, as shown in Photo 1. In such designs, the mud wall has slits under the beams. In structural design, these slits are treated as defects and it is considered that the stiffness and the strength should be reduced compared to ordinary designs. However, there have been very few experimental attempts to investigate reduction methods for such designs, and evaluation methods specific to such cases have yet to be clarified.

The simplest retrofitting method is to block the slits by nailing structural plywood to the side of the framework. However, as such an approach will certainly decrease the deformability, a retrofitting method in which the wall is restored would be preferable. On the other hand, this retrofitting method requires work to be carried out from both sides of the wall and is both labor and cost intensive because it requires disassembly and recovery of the surrounding walls and ceiling.

The first objective of our study is to clarify the strength characteristics of a mud wall with slits under the beams through the static horizontal loading test. The second one is to conduct trials of an easy seismic retrofitting method for such walls and verify its effectiveness. In our study, only hanging walls are investigated as they are often used as partition walls and many have slits under the beams.

Photo 1 – Mud wall without wall clay in attic

2. Outline of the Experiment

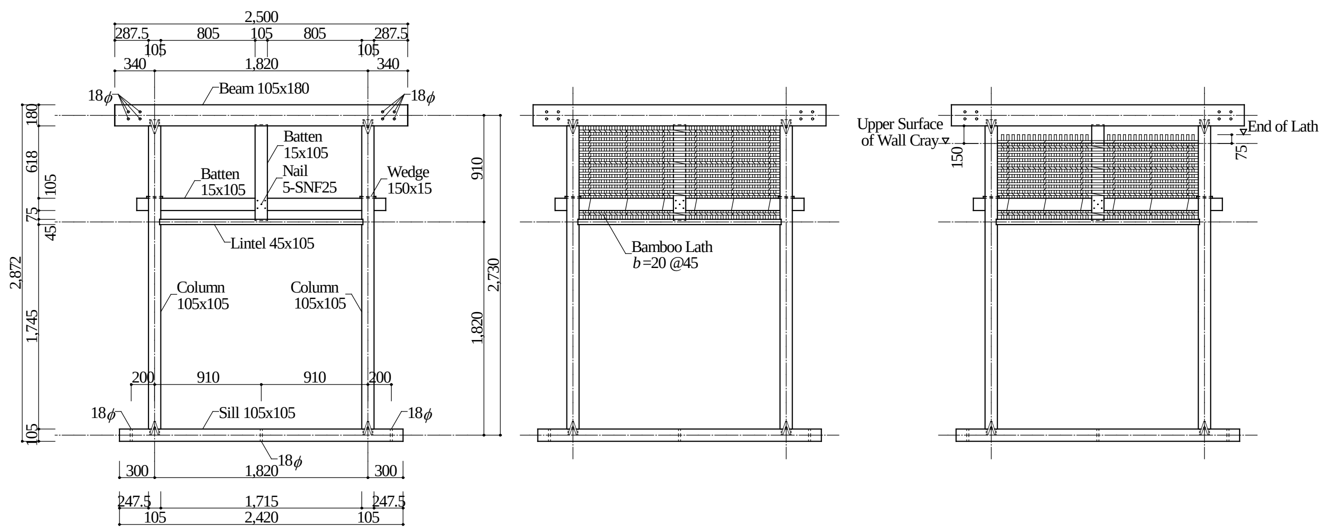
2.1 Specimens

The specimens are designed to match the experimental method for a bearing wall [1]. One specimen of each of the five types is constructed, and these are labeled from No.1 to No.5. They are listed in table 1.

Specimen No.1 has a framework with neither bamboo lath nor wall clay. The other specimens No.2 to No.5 are used to investigate the stiffness and the strength of a mud wall. Specimen No.2 is an ordinary hanging wall with no slits under the beam and is used as the standard specimen in our study. Specimen No.3 is a hanging wall with 150mm slits under the beam and is used to investigate the first objective of our study. Specimens No.4 and No.5 are also hanging walls with 150 mm slits under the beam, and a different retrofitting method is applied to each specimen. The retrofitting processes are described later.

Table 1 – Specifications of specimens

Specimens		Specification
No.1	Framework	Only framework without wall clay and bamboo lath
No.2	Hanging wall	Standard hanging wall
No.3	Hanging wall with slit	Hanging wall with 150mm slit under beam
No.4	Retrofitted wall (1)	Easy retrofitting of No.3 (Wet construction process)
No.5	Retrofitted wall (2)	Easy retrofitting of No.3 (Dry construction process)



(a) No.1 (common framework) (b) No.2 (no slits under beam) (c) Nos.3–5（slits under beam）

Figure 1 – Framework of specimen

All the specimens shared a common framework design. As shown in Figure 1, the center distance between columns is 1820mm, the center distance between the beam and the sill is 2730mm, and the height of the wall is 1/3 of the frame. In cross-section, the columns and sills are 105 × 105mm, the beams 105 × 180mm, and the batten 15 × 105mm, respectively.

The woods are Oregon pine of no grade for the beams and Japanese cedar of no grade for the other members. The walls had a double coating of the “Nakanuri-kabe” clay and the “Ara-kabe” clay over the bamboo lath, with a thickness of 60mm. For the laths of the wall, bamboo of 20mm width are arranged at intervals of 45mm or less. The bamboos with 10mm edges are inserted into the columns and beam at intervals of 300mm or less and fixed with hemp-palm ropes. According to the Japanese Building Standard Law, the wall clay of Ara-kabe is comprised of straw fibers and Arakida-tsuchi clay, Ara-tsuchi clay or Kyo-tsuchi clay, or similar materials of equivalent strength. The wall clay of Nakanuri-kabe is comprised of straw fibers, sand and Arakida-tsuchi clay, Ara-tsuchi clay or Kyo-tsuchi clay, or similar materials of equivalent strength.

The tenons 30 × 85mm and with a depth of 52.5mm are used for the head and the bottom of columns. A V-shaped plates are fixed from both sides of the sill and beam.

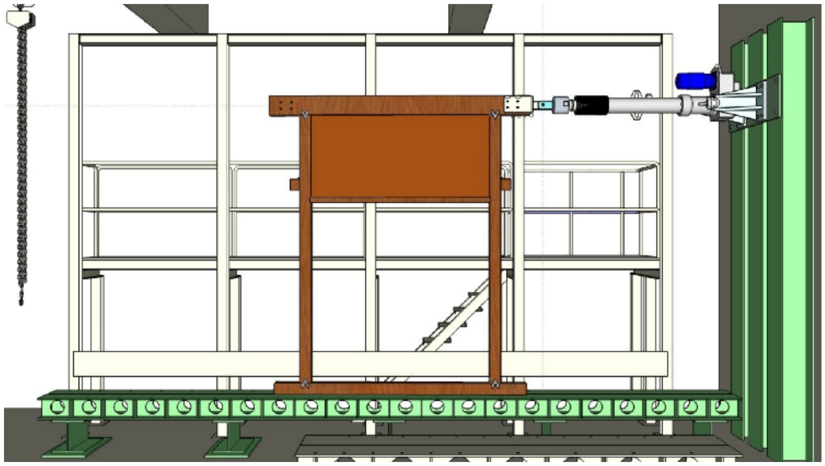


Figure 2 – Image of experiment

	a	b	c	d	e	f	g	h	i
Drift Angle (rad)	1/450	1/300	1/200	1/150	1/100	1/75	1/50	1/40	1/30
Relative story displacement(mm)	6.1	9.1	13.7	18.2	27.3	36.4	54.6	68.3	91.0

	j	k	l	m	n	o	p
Drift Angle (rad)	1/25	1/20	1/15	1/12	1/10	1/8	1/7
Relative story displacement(mm)	109.2	136.5	182.0	227.5	273.0	341.3	390.0

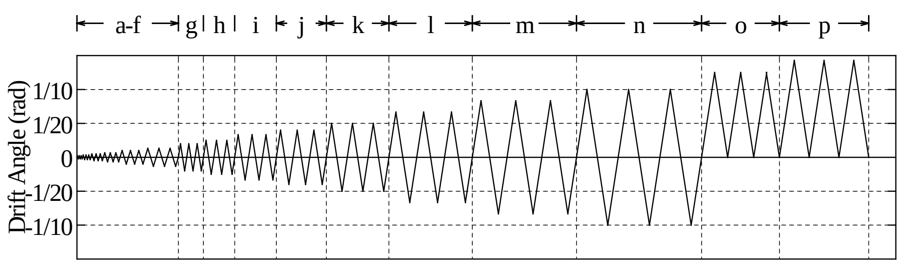


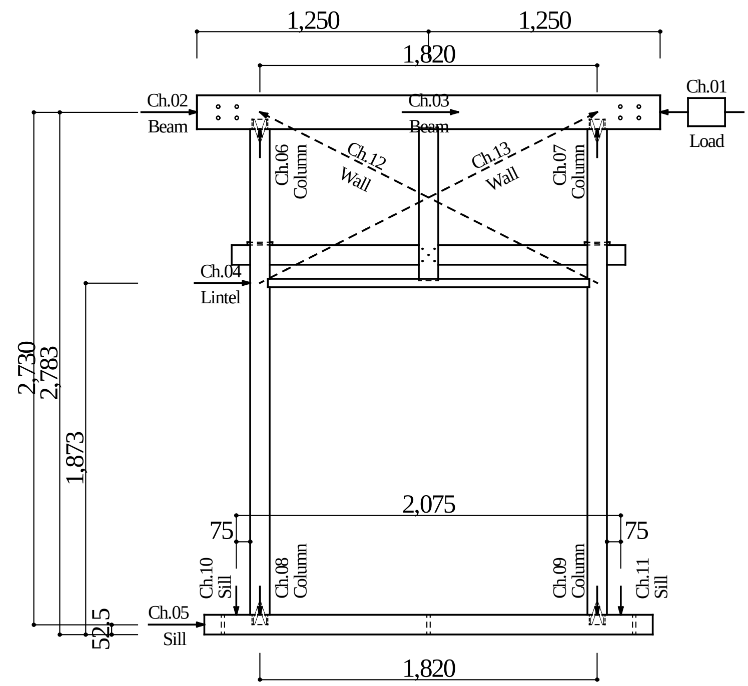
Figure 3 – Loading plan

2.2 Loading procedure

Both sides and center of the sill are fixed to the steel frame by bolts. Cyclic lateral loading is applied to the beams in a horizontal direction by a motor cylinder, and hysteresis of superficial shear deformation angles are 1/450, 1/300, 1/200, 1/150, 1/100, 1/75, 1/50, 1/40, 1/30, 1/25, 1/20, 1/12, and 1/10rad. At each deformation angle, positive and negative loading is applied three times. The cylinder is then pulled to its stroke limit. No loading is applied in the vertical direction as interior walls form partitions and are assumed not to support a vertical load. The experimental setup is shown in Figure 2 and the loading plan in Figure 3.

2.3 Measurement procedure

To measure the displacement of the specimens in the vertical, horizontal and diagonal directions, vertical displacement gauges are installed at four connections on the head and the bottom of the columns, and at two points on the edges of the sill, horizontal displacement gauges are installed at two points on the beam, one point on the sill and other on the lintel, and diagonal displacement gauges are installed at two points on the walls. Figure 4 shows the arrangement of the instruments.



Ch.	Measuring equipment
Ch.01	Load cell
Ch.02-04,12,13	Potentiometer-type displacement transducer
Ch.05-11	Displacement transducer

Figure 4 – Arrangement plan of measurement instruments

3. Experimental Results

3.1 Physical property test of materials

(a) Bending strength and Young's modulus of wood materials

We tested the physical properties of three specimens of Japanese cedar and Oregon pine. The dimensions of the specimens are 30 × 30 × 480mm, and the distance between the supporting points is 420mm [2]. The bending strength and Young's modulus are shown in Table 2. Using the mean value and standard deviation of bending strength from this table, the 5% lower limit that corresponds to the referenced bending strength F_b is obtained by Eq.(1) [3].

$$F_b = \overline{x} - 3.152\sigma \tag{1}$$

The obtained strength of the Japanese cedar and Oregon pine are 59.2 and 94.3N/mm^2, respectively. They are much higher than the 22.2 and 28.2N/mm^2, which is prescribed in the Japanese Building Standard Law. The Young's modulus of the Japanese cedar and Oregon pine are also 1.3–1.4 times higher than the 7000 and 10000N/mm^2 of no grade wood material.

(b) Compressive strength of the wall clay

We conducted compression test of the Ara-kabe and Nakanuri-kabe clays. The dimensions of the specimens are 55 × 150 × 150mm, and they are compressed in the standing position. The compressive strength of the wall clay obtained experimentally is shown in Table 3. It can be seen that the compressive strength of the Ara-kabe clay is 0.73N/mm^2 and that of the Nakanuri-kabe clay is 0.80N/mm^2, which is 1.5–2.4 times greater than the strength specified in the standard strength (Ara-kabe 0.30N/mm^2, Nakanuri-kabe 0.55N/mm^2).

Table 2 – Bending performance of wood material

Specimens	Material	*h*	*b*	*l*	*Z*	*P* max	*M* max	Bending stregth N/mm^2			Young's modulus N/mm^2		
		mm	mm	mm	mm^3	kN	kNm	Test results	Aaverage	Standard deviation	Test results	Aaverage	Standard deviation
C1	Japanese ceder	30.1	30.1	420.0	4539	3.04	0.32	70.3	72.1	4.1	8973	8943	195
C2		30.2	29.9	420.0	4536	3.36	0.35	77.8			9164		
C3		30.1	30.1	420.0	4548	2.96	0.31	68.3			8690		
P1	Oregon pine	30.2	29.8	420.0	4522	4.31	0.45	100.1	100.0	1.8	14522	14328	645
P2		30.0	30.4	420.0	4565	4.25	0.45	97.8			13459		
P3		30.2	30.2	420.0	4574	4.45	0.47	102.2			15002		

Table 3 – Compressive strength of wall clay

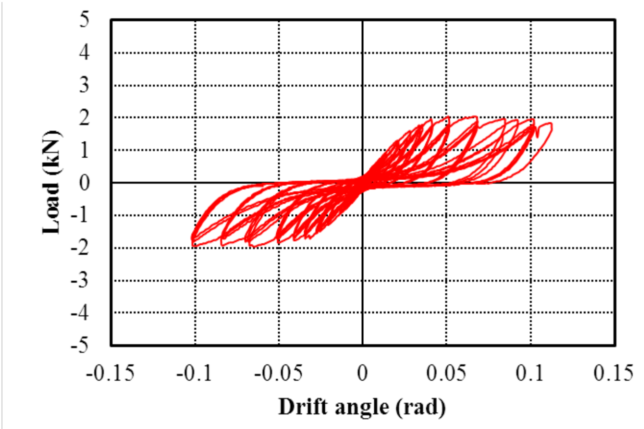
Specimens	Material	Height	Width	Depth	Weight	Maximum load	Compressive Strength N/mm^2		
		mm	mm	mm	kgf	kN	Test results	Aaverage	Standard deviation
A1	Ara-kabe	145.75	150.13	56.86	2.01	5.61	0.66	0.73	0.05
A2		150.33	145.25	58.10	2.12	6.60	0.79		
A3		153.28	146.18	57.08	2.04	6.26	0.75		
N1	Nakanuri-kabe	149.10	153.75	55.60	2.00	6.25	0.75	0.80	0.05
N2		149.85	153.15	57.70	2.03	6.51	0.78		
N3		148.40	154.70	57.60	2.06	7.20	0.87		

3.2 Results of horizontal loading test

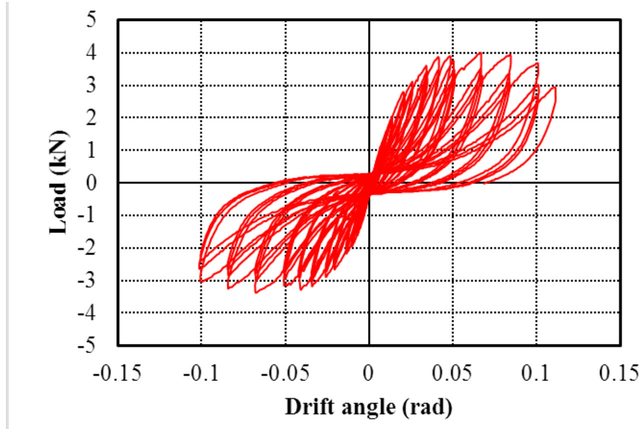
Figures 5(a)–(c) show the relationship between drift angles and loads for specimens No.1–3, respectively. Where, the value of the drift angle is the horizontal deformation of the beam divided by the height of the center distance between the beam and the sill. The vertical displacement of the connections and the sill could be ignored as they were very small.

The maximum strength of specimens Nos.1, 2, and 3 were approximately 2.1, 4.0, and 3.5kN respectively, with all values determined at the pull side (the first quadrant of the figure). The maximum strength at the push side is slightly smaller than that at the pull side (the third quadrant of the figure). For specimen No.1, the column-beam connection began creaking at 1/100rad, and an antiplane deformation occurred on the V-shaped plate at 1/15rad. Numerical calculations of the maximum strength following [5] and taking four points of the tenons of columns and one rung of the batten gave a value of approximately 1kN, while the experimental result was double that value.

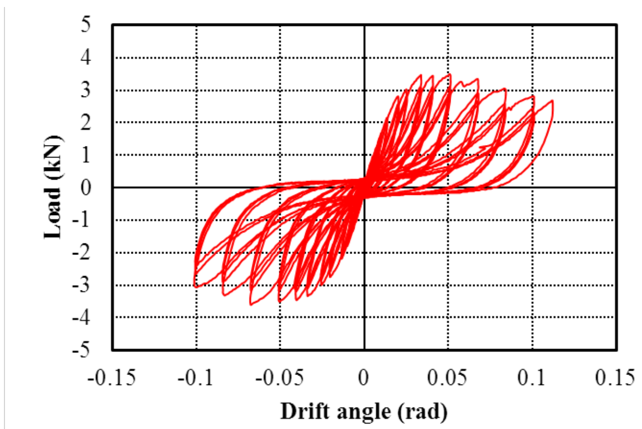
For specimens Nos.2–5, the column-beam connection started creaking at 1/150rad, and the wall clay of the corner section peeled and fell in a powdery state at 1/50rad. The corner of the wall partially collapsed and the lintel slipped out of the column at 1/40rad. The sound of the crack was heard and the restoring force decreased slightly at 1/30rad. The wall of the corner section peeled and fell at 1/25rad. The V-shaped plate was deformed out-of-plane and the wall started separating from the vertical batten. The wedge of the horizontal batten broke at 1/20rad. The wall separated markedly from the vertical batten and the nails of the V-shaped plate slipped out at 1/15rad. The sound of the crack formation was heard and the wall separated from the lath at 1/10rad.



(a) No.1



(b) No.2



(c) No.3

Figure 5 – Restoring force diagrams

The calculated strength of specimen No.2 is 4kN according to the reference [5]. While our results were consistent with the values in the reference at the pull side, those recorded at the push side were slightly lower than previously reported values [6]. Overall, our experimental results were in reasonable agreement with previous studies.

The maximum strength of specimen No.3 was approximately 0.5kN lower than that of specimen No.2. The strength ratio of specimen No.3 to No.2 was 0.875. Therefore, the strength is affected by the slits under the beam. We conclude that the hanging walls with slits under the beam should be evaluated in the relatively lower strength than ordinary hanging walls. However, because of the limited number of specimens, it was therefore difficult to determine whether these differences could be attributed to the dispersion of values in the experiment or to the effects of the slits.

4. Trial of Seismic Retrofitting Designs and Verification of the Retrofitting Effect

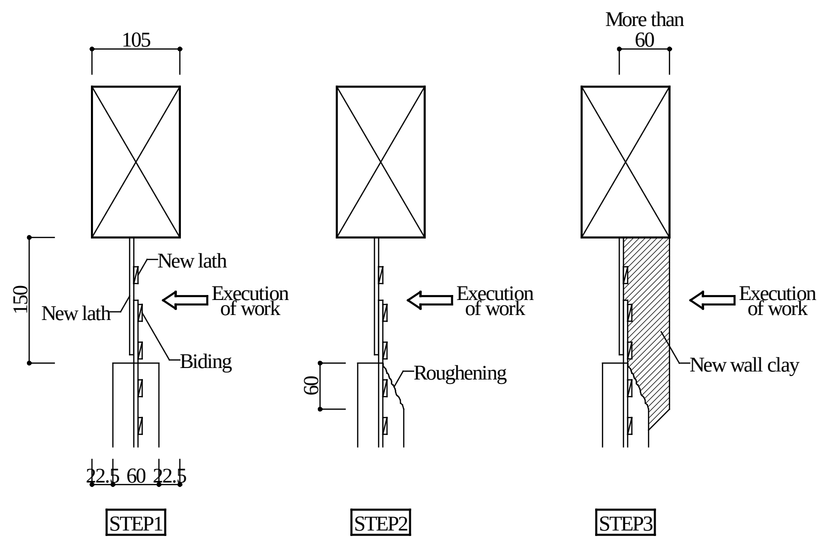
Specimens Nos.4 and 5 has 150mm slits under the beam, similar to specimen No.3. We investigated the effect of blocking the slits using a simple construction method.

Figures 6(a) and (b) show the main points of the retrofitting method applied to specimens Nos.4 and 5, respectively. Both specimens are retrofitted from one side of the wall since we assumed that the cost of retrofitting of the wall are reasonable from the point of view of labor.

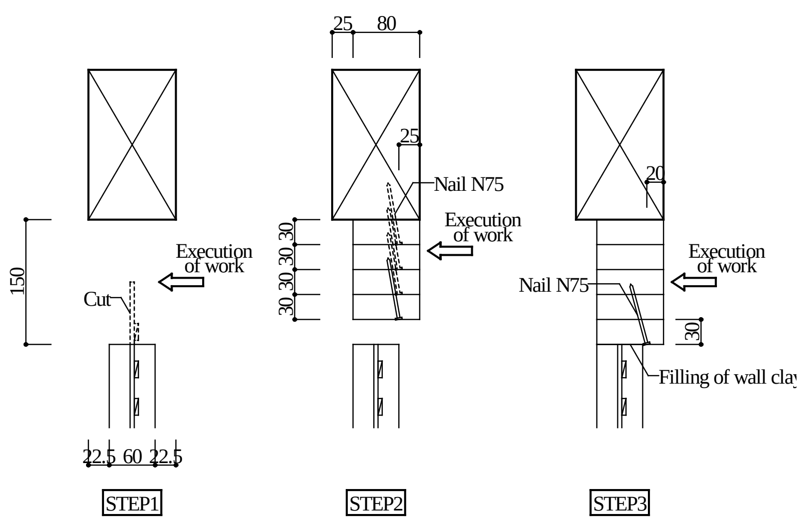
For specimen No.4, we adopted wet construction process, which achieves a state close to the state of the original wall by arranging new bamboo laths to the slits under the beam and filling the Ara-kabe and Nakanuri-kabe clay on one side only. For specimen No.5, we adopted dry construction process, which we considered to be simpler than the technique used for specimen No.4. The slits under the beam were blocked by nailing wood plates piled from the undersurface.

The results of the horizontal loading test are shown in Figures 7 (a) and (b). Form Figure 7 (a), it is recognized that the maximum strength of specimen No.4 is approximately 3.9kN (the first quadrant), which was approximately 11% greater than that of specimen No.3 and almost the same as that of specimen No.2.

The strength of specimen No.5 increased by only 0.1kN compared to specimen No.3. Therefore it is showed no apparent retrofitting effect. We attribute this result to the disconnection between the walls and retrofitting plates as the slits were created at the contact surface due to vertical upward pressure on the beam from the corner of the column. We therefore assumed that the presence or absence of vertical load on the column also affected the experimental results.

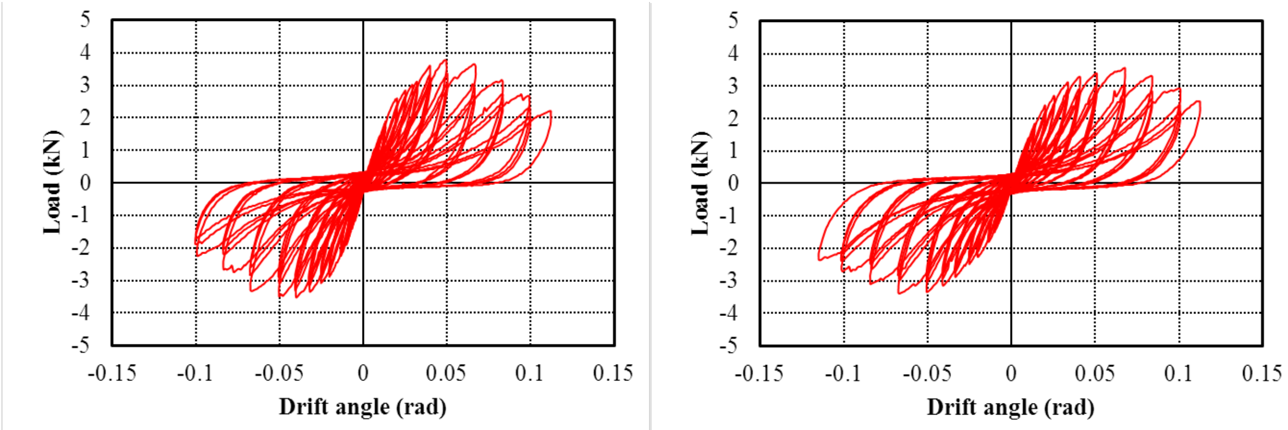


(a) No.4 (Wet construction prosess)



(b) No.5 (Dry construction prosess)

Figure 6 – Main points of blocking of slits under beam



(a) No.4 (b) No.5

Figure 7 – Restoring force diagrams

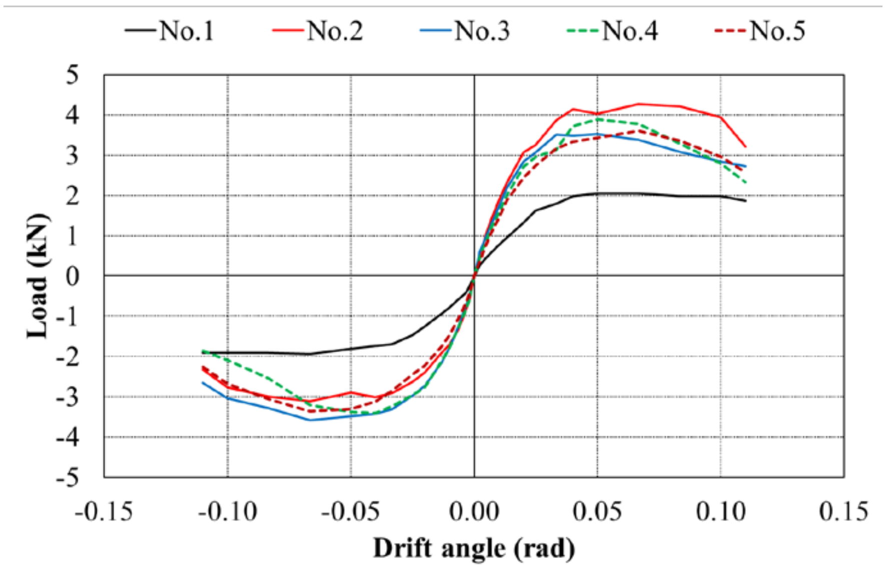


Figure 8 – Envelope curves

5. Envelope Curve and Wall Ratios

The envelope curves of restoring force diagrams for specimens Nos.1–5 are shown in Figure 8. The figure shows that specimens No.2 and No.4 showed almost the same characteristics up to approximately 1/15rad. The retrofitting method used for specimen No.4 has a deformability of 1/15rad.

The wall ratios are shown in Table 4. These calculations are based on the wall ratio evaluation standard [1]. As only one specimen of each test specimen was used, the reduction coefficient due to variation was ignored and only the results under positive force application are shown. In terms of wall ratio, results suggested that the presence or absence of slits under the beam can be ignored, assuming a ratio of approximately 0.4.

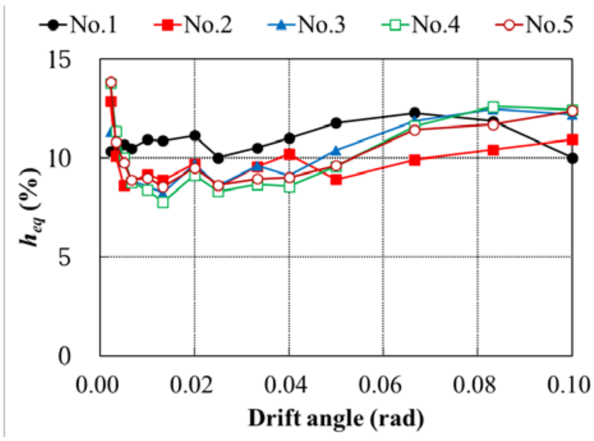
To confirm the change in damping performance with drift angle, the equivalent viscous damping factor h_{eq} is evaluated from Eq.(2).

$$h_{eq} = \frac{1}{4\pi} \cdot \frac{\Delta W}{W} \quad (2)$$

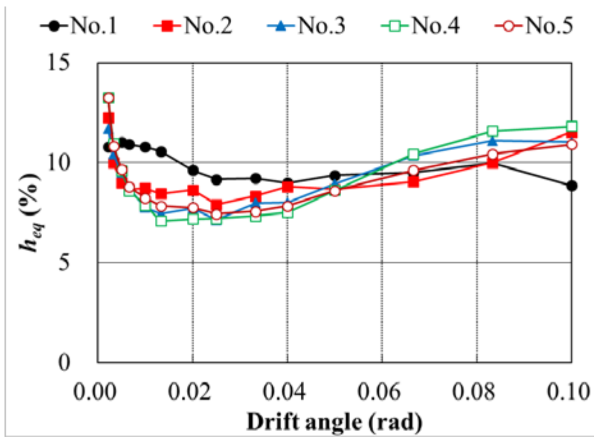
Where, W and ΔW show the equivalent potential energy and one cycle area of the hysteresis loop, respectively. The results are shown in Figures 9 (a)–(c). It is recognized that h_{eq} does not change after the second force application. In general, h_{eq}=7.5–12.5%. The h_{eq} value of specimen No.1 is larger than those of specimens Nos.2–5. In cases of second and third force applications, the magnitude correlation of the results for test specimens Nos.2–5 is reversed.

Table 4 – Wall ratios for positive force application

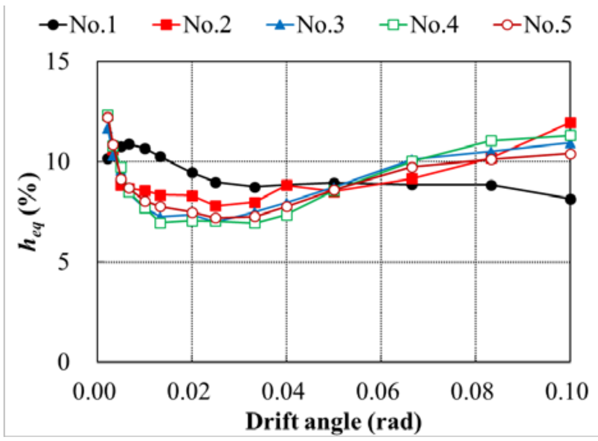
Specimens	P_1 (kN)	P_2 (kN)	P_3 (kN)	P_4 (kN)	Wall ratio
No.1	1.19	0.73	1.37	0.65	0.18
No.2	2.62	2.18	2.84	1.53	0.43
No.3	2.31	1.53	2.35	1.46	0.41
No.4	2.49	1.48	2.59	1.34	0.38
No.5	2.14	1.32	2.38	1.21	0.34



(a) First force application



(b) Second force application



(c) Third force application

Figure 9 – Equivalent viscous damping factor, h_{eq}

6. Conclusions

In this paper, we conducted experiments on mud walls with slits on their upper side, assuming that the wall above the ceiling is not constructed, and clarified their restoring force characteristics. We presented experimental results of the strength, ductility, and energy dissipating capacity of these walls. The results obtained are concluded as follows:

1) While horizontal stiffness was not reduced by the slits in the upper side of walls, the maximum strength was reduced by 0.875. The strength of such walls should be evaluated accordingly.

2) When simple blocking of the slits by wall clay from one side was performed, the maximum strength became almost the same as in the case without slits, demonstrating that retrofitting effects could be achieved.

3) When the slits were blocked only by plate materials, the maximum strength did not increase and no retrofitting effects were observed. This may be due to the impact of vertical load conditions of the columns.

4) The equivalent viscous damping factor was 7.5%–12.5%, the magnitude correlation of the results for test specimens Nos.2–5 reversed at a threshold value of 1/20rad.

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