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EXPERIMENTAL STUDY ON THE EVALUATION OF THE EARTHQUAKE RESISTANT PERFORMANCE OF MUD-PLASTERED WALLS

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SUMMARY

Mud-plastered walls are very suitable for Japanese climate, but their use has declined in recent years because of the construction costs, which in fact are very expensive, and the uncertainly of their shear resistant capacity. This experimental study was carried out with the aim to establish a shear strength evaluation method for mud-plastered walls. Shear loading tests of mud-plastered walls with various shapes were done.

The results showed that *Arakabe* (first layer) is not effective for resisting the shear force, while *Nakanuri* (second layer) is bearing most of the applied shear force. Moreover, the width of the wall affects the failure mode and the shear strength, while the height does not have influence on the shear strength. From the test results, a shear resisting mechanism and a shear strength evaluation method of mud-plastered walls is proposed.

INTRODUCTION

The mud-plastered wall is composed of a substrate woven of bamboos and some layers of mud mixed with straw and sand upon the substrate, consequently they are composed with materials that are completely of natural resources.

These kinds of walls were commonly used as earthquake resisting elements in Japanese traditional houses from the old times. However, because of the collapse of a large number of wooden houses with mud-plastered walls in the recent earthquakes, such as the 1995 Hyogoken-Nanbu Earthquake, it was considered that their earthquake resistant performance is not good enough. Moreover, the seismic resistant performance of the mud-plastered walls in Japan has been under-evaluated by the design codes, mainly because of the lack of experimental data. Additionally, since the mud-plastered walls take long period to be constructed, their manufacturing cost is higher than sheathed or bracing walls.

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Mud-plastered walls have been rejected in the last 30 years for the above expressed reasons, but nowadays there is a movement to recognize that they are suitable for the Japanese humid climate and also because they do not use chemicals which can affect the health of the houses' residents.

This study is to clarify the shear resisting mechanism and to establish a shear strength evaluation method of mud-plastered walls by carrying out shear loading tests of mud-plastered walls with various shapes.

OUTLINE OF EXPERIMENT

Test specimens of mud-plastered walls

The test specimens were prepared as shown in Figure 1, Figure 2, Table 1 and Table 2. The dimensions of wood frames are classified into 3 types, standard (A-type), square shaped (B-type) and slim (C-type). Each type of specimen is provided with 3 kinds of different finishing, no-mud (wood frame only), *Arakabe* (first layer) only and a combination of *Arakabe* and *Nakanuri* (second layer) finishing. Therefore, it is possible to evaluate the influence of the wall shape on the shear strength and estimate the shear force carried by each layer of mud.

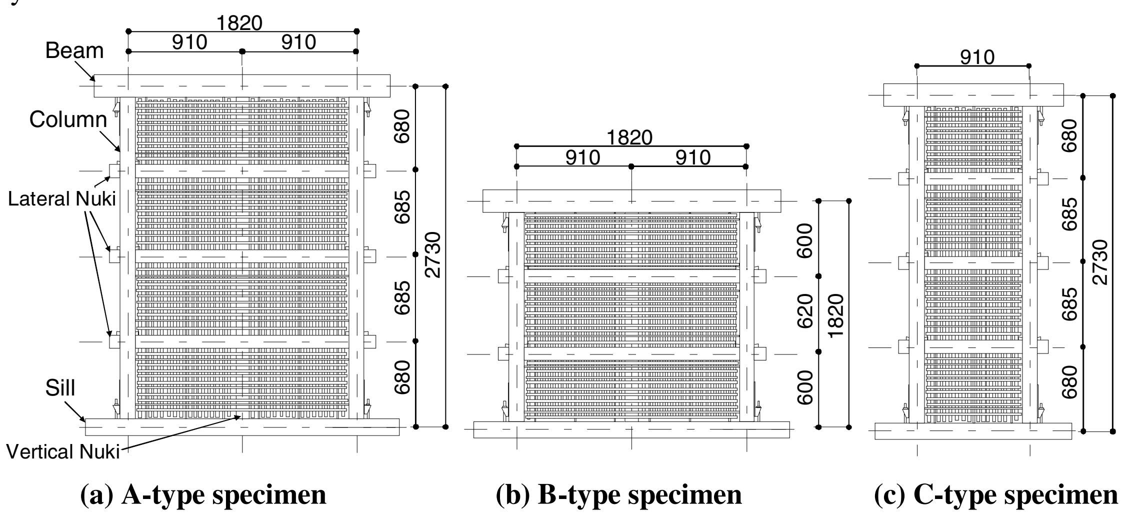


Figure 1: Scheme of specimens (unit : mm)

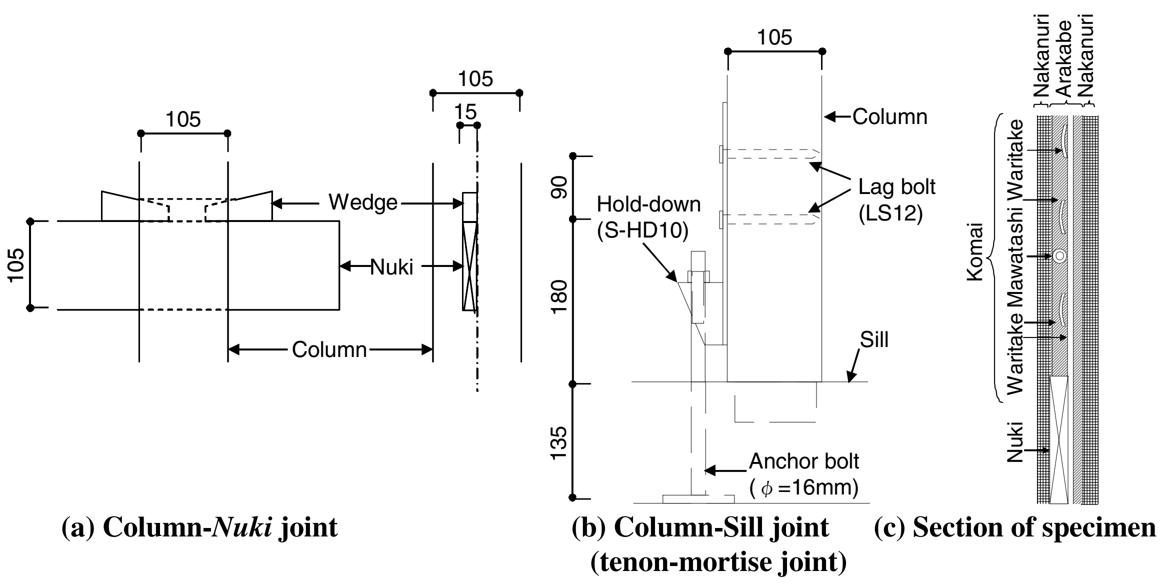


Figure 2: Details of specimens (unit : mm)

Tabel 1: List of specimens

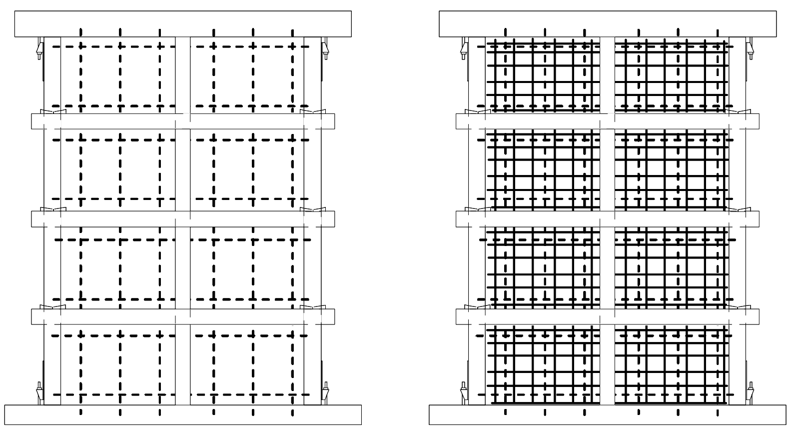
A-type	B-type	C-type	Plastered layers
A0	B0	C0	no mud(Frame only)
A1	B1	C1	Arakabe
A2	B2	C2	Arakabe+Nakanuri

Table 2: Specifications of members

Member	Sizes(mm)	
Column	105x105	
Sill	105x135	Japanese cedar
Nuki	15x105	
Beam	105x180	Douglas fir

To avoid pulling-out of tenons from mortises, hold-down connectors (S-HD 10) were fastened to the end of columns by lag bolts and anchored to the horizontal members with anchor bolts. All specimens have 2 or 3 lateral *Nuki*s arranged at almost regular intervals.

The procedure of constructing *Komai* (substrate) is described as follows. First, *Mawatashi*s which are bamboos of approximately 12 mm in diameter were arranged as illustrated in Figure 3(a). The ends of *Mawatashi*s were stuck in the holes of the frame. Next, *Waritake*s which are chopped into about 20 mm wide were connected to the *Mawatashi*s by straw rope as shown in Photo 1. Figure 3(b) shows the arrangement of *Mawarashi*s and *Waritake*s (*Komai*) from which some *Waritake*s were omitted for simplicity in this illustration.



(a) Arrangement of *Mawatashi*s **(b) Complete *Komai***

Figure 3: Arrangement of *Komai*

(wavy line:*Mawatashi*, solid line:*Waritake*)

Photo 1: Connecting *Waritake*s to *Mawatashi*

Test pieces for material testing

Even though many kinds of local clay are used for mud-plastered walls in Japan, there are not regulations for the material properties testing methods. Therefore, it is imperative to establish a testing method for various kinds of mud used for mud-plastered walls in each part of the country.

In this study, uniaxial compression test was applied to evaluate material characteristics of the mud. The dimension of the test piece is 50mm in diameter and 100mm in height. Molds of cardbord were used because the mud does not dry in metal molds. With cardbord molds, the test pieces dried gradually and the removal of molds was easy. Five test pieces were prepared for each wall specimen, and cured at the same place as the wall specimens. Capping was made with gypsum before the compression test.

Construction of wall specimens

A-type and B-type wall specimens were constructed at the same time, while C-type wall specimens were constructed one year later.

Arakida-clay commonly produced in Kanto area (Tokyo surroundings) was used in this study. It is clayey, suitable for mud-plastered walls. *Arakida*-clay was mixed with water and short cut rice straw at the quantity shown in Table 3. The quantity of water and straw were instructed by an experienced plasterer. Table 4 shows slump values of each mud.

Table 3: Mix proportions of mud

A and B-type specimen						
Date	Mud	Arakida-clay(kg)	Arakabe mud(kg)	Sand(kg)	Water(kg)	Straw(kg)
2001.7.4	Arakabe	964.3		-	340.5	9.8
2001.11.21	Nakanuri(1st)	-	125.8	131.6	proper quantity	0.5
2001.11.21	Nakanuri(2nd)	-	35.3	97.8	proper quantity	0.3
C-type specimen						
Date	Mud	Arakida-clay(kg)	Arakabe mud(kg)	Sand(kg)	Water(kg)	Straw(kg)
2002.5.24	Arakabe	711.7		-	140.6	15.2
2002.10.29	Nakanuri(1st)	-	72.4	27.9	proper quantity	0.4
2002.10.29	Nakanuri(2nd)	41.6	-	43.8	10.2	0.6

Table 4: Slump values of mud

Date	Mud	Slump(cm)	Date	Mud	Slump(cm)
2001.7.4	(Mixture)	19.6	2002.5.24	(Mixture)	15.7
2001.10.13	Arakabe	11.1	2002.9.9	Arakabe	20.4
2001.11.21	Nakanuri(1st)	14.6	2002.10.29	Nakanuri(1st)	20.7
2001.11.21	Nakanuri(2nd)	16.7	2002.10.29	Nakanuri(2nd)	12.0

Approximately 3 months later, *Arakida*-clay mixed with water and rice straw increased its viscosity by decomposition of the straw. This viscous mud is called *Arakabe*-mud. *Arakabe* (first layer) was plastered with the *Arakabe*-mud on the *Komai*. The thickness of *Arakabe* was approximately 30mm at this time.

About fifty days after being plastered the *Arakabe* was completely dried. At this time, a lot of cracks were observed on the surface of *Arakabe*. *Nakanuri* (second layer) was plastered with *Nakanuri*-mud on *Arakabe*. *Nakanuri*-mud is commonly obtained from *Arakabe*-mud mixed with additional water and sand. In C-type wall specimens, however, the second *Nakanuri*-mud was made of *Arakida*-clay instead of *Arakabe*-mud, because rice straw in *Arakabe*-mud was not decomposed completely. The mix proportions and slump values of *Nakanuri*-mud are indicated in Table 3 and Table 4 respectively. Since *Nakanuri* was plastered two times, no crack was observed on the surface even after drying. The thickness of each layer of mud after they were completely dried is shown in Table 5.

Table 5: Thickness of each layer of mud (unit : mm)

Layer	A1	A2	B1	B2	C1	C2
Arakabe	23.1	25.4	23.0	22.4	30.7	30.9
Nakanuri(1st)	-	19.1	-	15.9	-	12.7
Nakanuri(2nd)	-	9.4	-	14.2	-	12.7

Loading and measuring procedure

The wall specimen was fastened to the test apparatus beam at the sill, as shown in Figure 4, and torsion stopping rollers were applied along the beam of the specimen. Lateral static load was applied to the beam of the wall specimen following the static cyclic history shown in Figure 5, while no vertical load was applied. Before starting the test, to prevent the hold-downs being subjected tensile forces, nuts of anchor bolts were loosened but touched hold-downs. In addition, transducers were set to measure the deformation of the wood frame as shown in Figure 6.

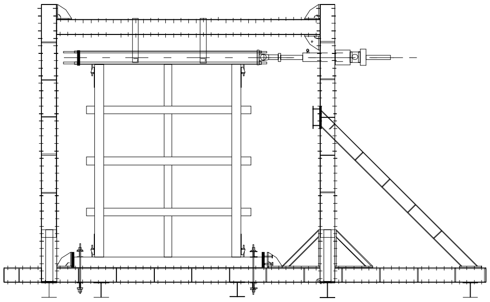


Figure 4: Setup of shear loading test

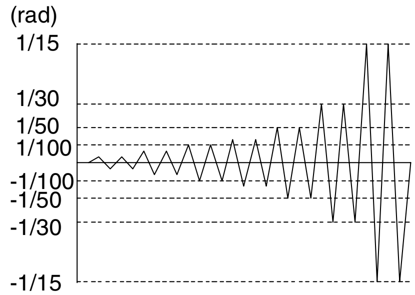


Figure 5: Cyclic history

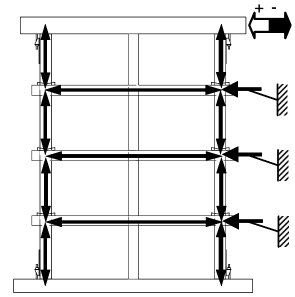


Figure 6: Measured portions

TEST RESULTS

Failure mode of wall specimen

In *Arakabe* specimens, such as A1, B1 and C1, fine clay came down from the cracks which occurred after drying, however, no mud peeled off the *Komai* throughout the tests. For *Nakanuri* specimens, A2 and B2, cracks occurred along *Nuki*s even under relatively low shear stresses. The shear cracks occurred between 1/150-1/100 rad of drift angle, and then the mud at the corners swelled out. Most cracks were observed in the middle part of the wall. Crack patterns at each loading stage are shown in Figure 7. In C2 specimen, no shear crack occurred through the test, because the *Nakanuri* rotated together with the increase of the shear deformation of the wood frame, as shown in Figure 8.

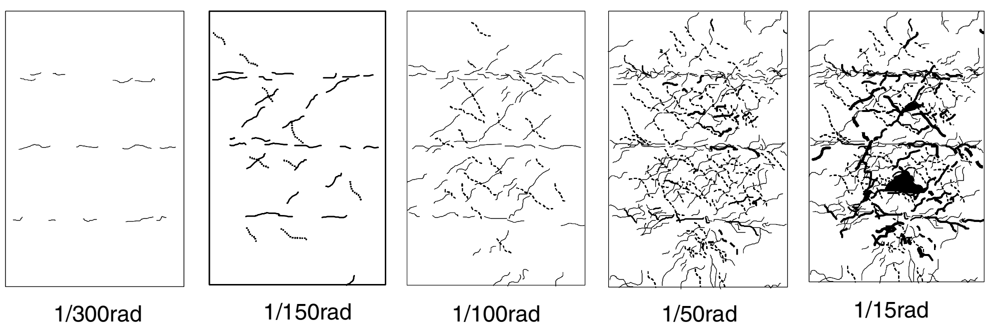


Figure 7(a) Crack patterns of A2 specimen

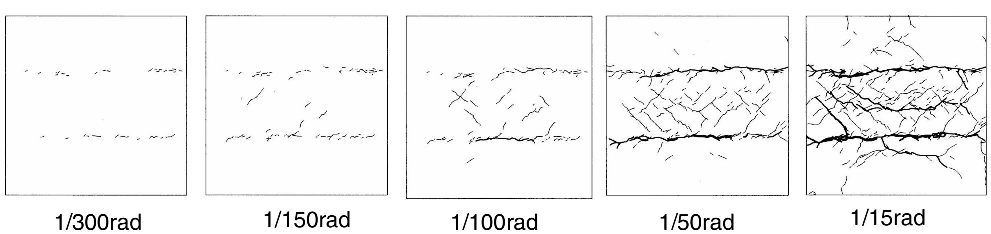


Figure 7(b) Crack patterns of B2 specimen

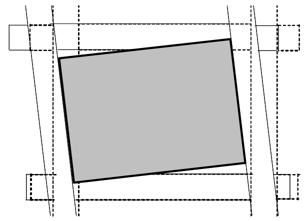


Figure 8: Failure mode of C2

Hysteresis characteristics

Figure 9 shows the relation between the drift angle based on horizontal displacement at the beam and the shear force, and Figure 10 shows the envelope of it during positive loading.

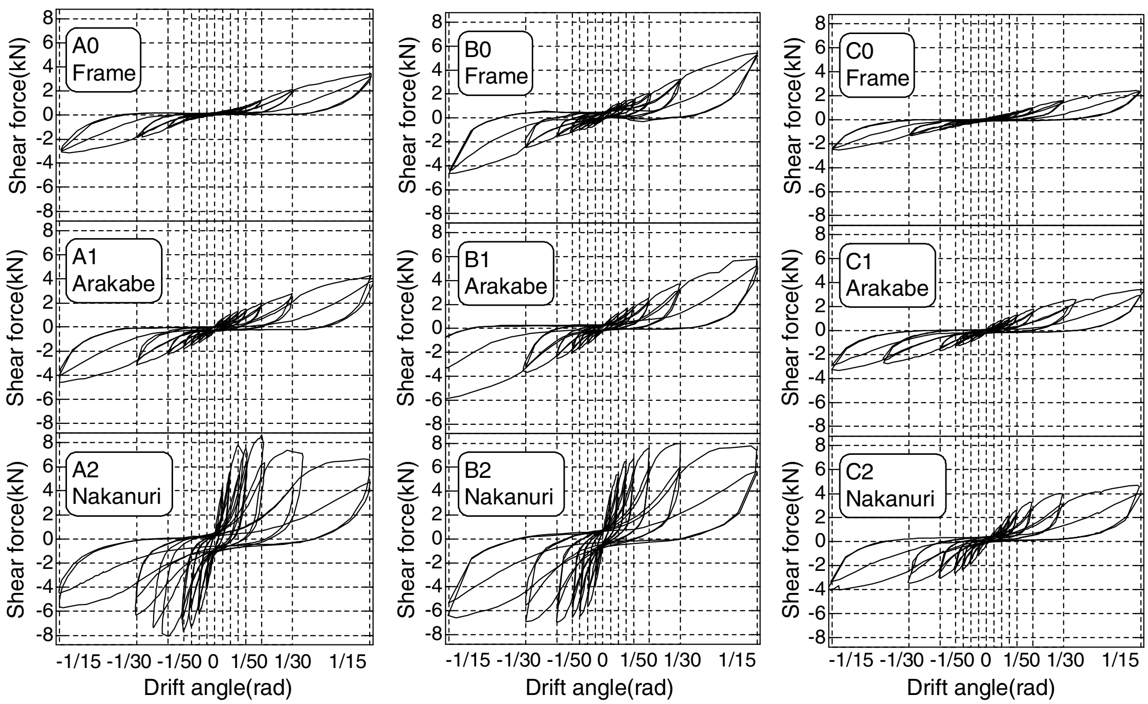


Figure 9: Shear force-drift angle relations

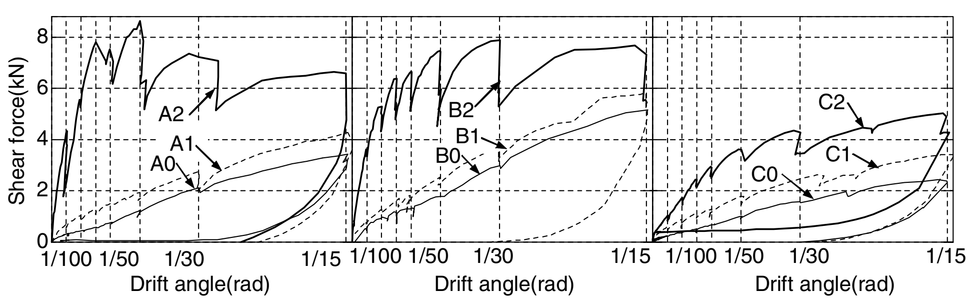


Figure 10: Comparison of envelope curves

In *Arakabe* specimens, such as A1, B1 and C1 the shear forces increased gradually until the ends of the tests, but showing low shear stiffness. Comparing with frame specimens, such as A0, B0 and C0, a little shear forces are carried by *Arakabe*. On the other hand, *Nakanuri* specimens showed higher shear stiffness and the maximum shear force than the provided only with *Arakabe*. *Nakanuri* carries most of the shear force, thus *Arakabe* is considered to be a part of the substrate. In addition, all of the mud-plastered specimens have good ductility capacities.

Deformation of wood frame

The shear deformation angles at each part of the wood frame were derived from measured values. They were divided by the drift angles of the walls. Typical characteristics of this ratio for A-type specimens are shown in Figure.11. In the upper and the lower portion along the wall height, the ratios are less than 1.0 in almost all the specimens, which means the shear deformation angles are less than the drift angles, because ends of columns were fixed by the hold-downs. On the other hand, at mid-height portion the shear deformation angles become greater than the drift angles.

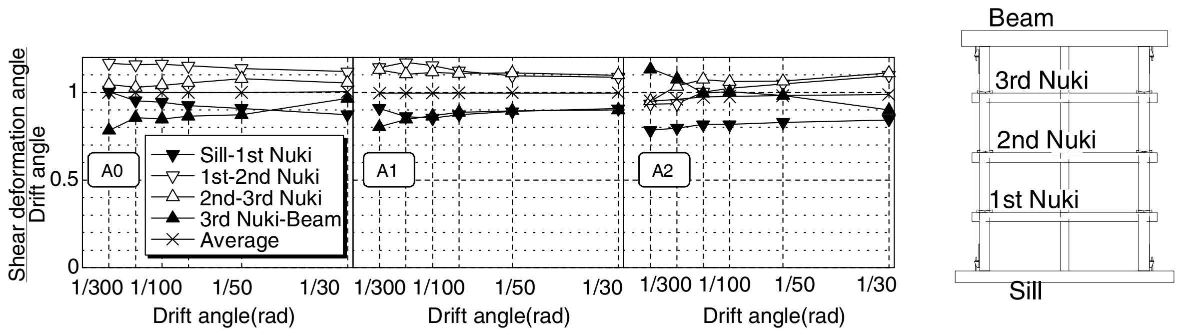


Figure 11: Shear deformations of each portion (A-type)

Figure 12 shows the ratio of the shear displacement to the lateral displacement of wood frames. In *Nakanuri* specimens, such as A2 and B2, the ratio of the shear displacement are lower than those of *Arakabe* specimens, such as A1 and B1, because the higher shear stiffness of *Nakanuri* pulled tenons out of mortises. In C-type specimens, since the proportion of the specimens is slender and the overturning moment is higher than A-type and B-type specimens, the ratios tend to decrease slightly as the deformations progressed. Regardless the ratios are more than 0.9 through the test, it is considered that all wood frames presented shear deformations.

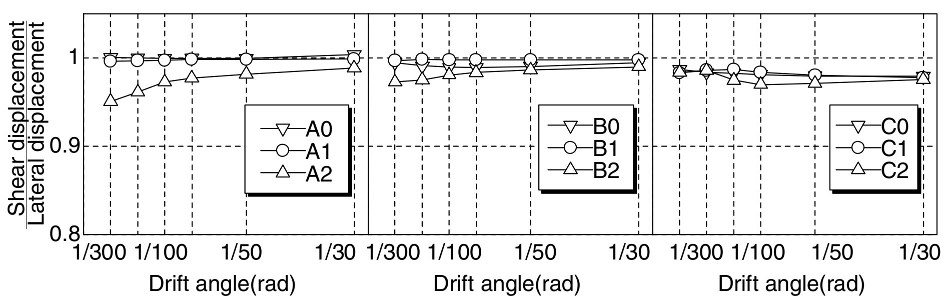


Figure 12: Rate of shear displacement

Result of compression test

Uniaxial compression tests were conducted to evaluate the material characteristics of mud at the same time as the shear loading tests of the walls. Some of typical test results are shown in Figure 13. The compressive stress of *Arakabe*-mud increased gradually as the strain increased. *Nakanuri*-mud reached maximum stress with relatively small strain such as 1-2%, failing down rapidly after that point. Addition of sand provides higher stiffness for mud, but it loses the ductility.

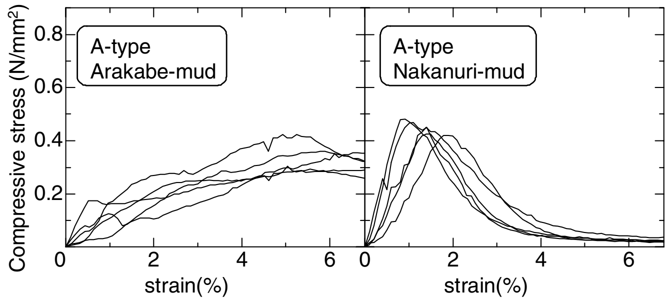
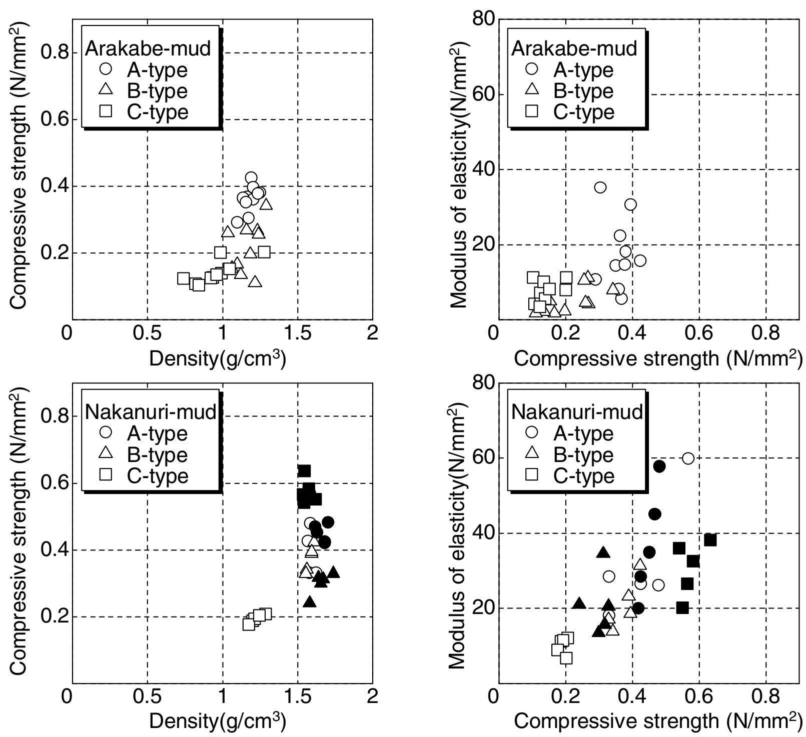


Figure 13: Compression test result

To compare the material characteristics of mud, modulus of elasticity and compressive strength are considered. In this study, modulus of elasticity is defined as the slope of the line passing through the point of zero and the 50% point of compressive strength. Figure 14(a) shows the relationship of the density and the compressive strength. Compressive strengths showed some dispersion even though the mud densities are almost the same on each mud. Little correlation is found between these two values. Figure 14(b) shows the relationship of the compressive strength and the modulus of elasticity. There is proportional relationship between these two values. *Nakanuri*-mud has high stiffness and strength compared with *Arakabe*-mud. In addition, the average compressive strengths of each mud are shown in Table 6. A and B-type specimens were constructed at the same time, however, the compressive strength of *Nakanuri*-mud of B2 is lower than the presented by A2. The reason for this is that B-type specimens were cured outside of the laboratory while A-type specimens were cured inside.



(a) Density-compressive strength (b) Compressive strength-modulus of elasticity

Figure 14: Relations of material characteristics of mud

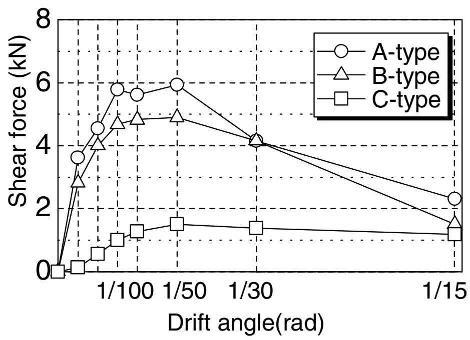
(In *Nakanuri*-mud, white and black dots mean 1st and 2nd *Nakanuri* respectively.)

Table 6: Averages of compressive strengths (unit : N/mm^2)

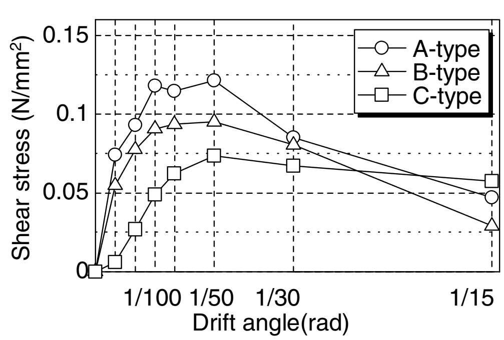
Mud	A-type	B-type	C-type
Arakabe	0.36	0.22	0.14
Nakanuri(1st)	0.43	0.38	0.19
Nakanuri(2nd)	0.45	0.30	0.58

DISCUSSION

To discuss the shear strength of mud-plastered walls, considering the structural behavior of *Nakanuri* is important. The shear force carried by *Nakanuri* in the wall specimens, shown in Figure 15(a), was calculated by subtracting the shear force of the *Arakabe* specimen from the one of the *Nakanuri* specimen. It was assumed that the shear force carried by *Arakabe* in *Nakanuri* specimen was equals to the one of *Arakabe* specimen. Figure 15(b) shows the shear stress of *Nakanuri* that was obtained dividing the shear force by its cross-sectional area. The shear stress carried by *Nakanuri* of A-type specimen is higher than that of B-type specimen due to the difference in compressive strength of *Nakanuri*-mud. Furthermore, as the failure modes are also the same in case of A2 and B2 specimens, it is considered that there is no influence on the shear strength with the variations of the height of specimen. Moreover, in A2 and B2 specimens, the ratio of the maximum shear stress of *Nakanuri* to the compressive strength of *Nakanuri*-mud is approximately 1:4.



(a) Shear force



(b) Shear stress

Figure 15: Shear force and stress carried by *Nakanuri*

In C2 specimen, the failure mode is different from A2 and B2, since no shear crack was observed as the mud rotated together with the shear deformation of the wood frame. The shear stress carried by the *Nakanuri* of C2 is only $0.07N/mm^2$, while for A2 and B2 was $0.09N/mm^2$, when the first shear cracks occurred at 1/150 rad and 1/100 rad respectively. It is considered that the rotation of *Nakanuri* in the wood frame of C2 specimen is caused by the compression failure of *Arakabe* beside *Nuki* prior to the shear clacks.

From above discussions, the shear resisting mechanism of mud-plastered walls is proposed in Figure 16. As the mud is subjected to the shear force Q_N from *Nuki*s, the moment $Q_N h_w$ is generated. The resisting moments against $Q_N h_w$ are $C_N j$ and $Q_M l_w$, where C_N is the compressive force from *Nuki*s and Q_M is the shear force from *Mawatashi*s. It is considered that the C_N and Q_M are able to carry the forces until the compressive failure of *Arakabe* occur at each portion because *Nuki*s and *Mawatashi*s are arranged in *Arakabe*. Therefore, the shear failure of *Nakanuri* that was observed in A2 and B2 specimens can be expressed by the equation(1).

$$Q_{Nu} < (C_{Nu} j + Q_{Mu} l_w)/h_w \quad (1)$$

Q_{Nu} : shear strength of *Nakanuri*
C_{Nu} : compression failure strength of *Arakabe* beside *Nuki*
Q_{Mu} : shear force when compression failure of *Arakabe* beside *Mawatashi* occur

On the other hand, the failure of *Arakebe* which occurs in advance of the shear failure of *Nakanuri* as that was observed in C2 specimen can be expressed by the equation(2).

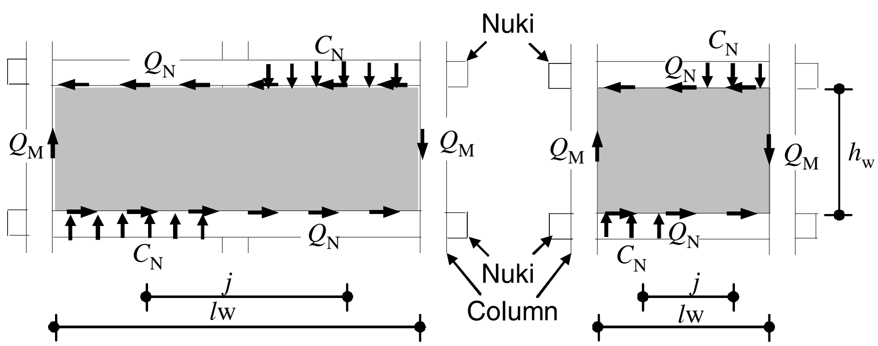
$$Q_{Nu} > (C_{Nu} j + Q_{Mu}\, l_w)/h_w \quad (2)$$

Therefore, based on proposed mechanism, the shear strength of mud-plastered wall V can be expressed by Equation(3).

$$V = \min\{Q_{Nu}, (C_{Nu} j + Q_{Mu}\, l_w)/h_w\} \quad (3)$$

In this equation, the shear force carried by *Arakabe* is neglected because it is much lower than the one of *Nakanuri*. In addition, since the shear force carried by the wood frame is affected by the connectors at the joints, it is also omitted.

Since the shear resisting mechanism and formulations proposed here are based on the limited information obtained from this experiment, more experimental data of wall specimens are necessary to prove the validity of them.



j : distance between both sides of compression resultants(C_N)

(a) A and B-type **(b) C-type**

Figure 16: Shear resisting mechanism

CONCLUSIONS

Shear loading tests of mud-plastered walls with various shapes were done. From the tests, it was clarified that the height of walls does not influence the shear strength, while the length affects the failure mode and the shear strength. A shear resisting mechanism was proposed, however, its validation could not to be proved. To establish the shear strength evaluating method of mud-plastered walls, more experimental data are needed.

ACKNOWLEDGEMENT

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