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A Study on the Evaluation of the Earthquake Resistant Performance of Mud-Plastered Walls

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ABSTRACT :

Mud-plastered walls have been acting as earthquake resisting elements in Japanese timber houses from the old times. However, their earthquake resistant performance has been under-evaluated by the design codes, mainly because of the lack of experimental data. This study was carried out to clarify the shear resisting mechanism of mud-plastered walls and propose the numerical analysis model to estimate the earthquake resistant performance of every mud-plastered wall in Japan without shear loading tests. First, shear loading tests of mud-plastered wall specimens with various types were done. From the test results, shear resisting mechanism of mud-plastered walls was clarified. Secondly, numerical analysis model of the mud-plastered wall by means of Rigid bodies-spring model was proposed. The analysis results of the wall specimens showed a good agreement with the failure modes, shear stiffness and shear strengths obtained from the shear loading tests. Therefore, it turned out to be cleared that the proposed numerical analysis model is appropriate for the specimens in the shear loading test.

KEYWORDS: Mud-plastered wall, Numerical analysis, Rigid bodies-spring model, Shear resisting mechanism

1. 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 and gathered around the construction site.

These kinds of walls have been acting as earthquake resisting elements in Japanese timber 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 earthquake resistant performance of the mud-plastered walls in Japan has been under-evaluated by the design codes, because every district in Japan has its own constructing method and the experimental data is insufficient. Additionally, since the mud-plastered walls take long period to be constructed, their constructing cost is higher than sheathed or bracing walls.

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.

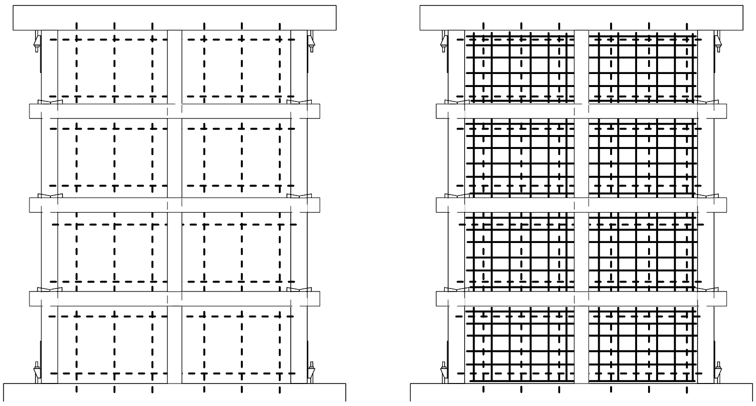
In this study, to clarify the shear resisting mechanism of mud-plastered walls, shear loading tests of mud-plastered walls with various types were carried out. Moreover, the numerical analysis model by means of Rigid bodies-spring model considering the shear resisting mechanism is proposed and the validity of the model is discussed. With numerical analysis, since earthquake resistant performance of mud-plastered walls in every district in Japan can be estimated without shear loading tests of wall specimens, it is efficient to understand adequate earthquake resistant performance of a number of mud-plastered walls in Japan.

2. CONSTRUCTION OF MUD-PLASTERED WALL

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.

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

The first and second layers of mud are called *Arakabe* and *Nakanuri* respectively. *Arakabe* is plastered with *Arakida*-clay that is produced in Tokyo surroundings and suitable for mud-plastered walls. In advance of plastering *Arakabe*, *Arakida*-clay is mixed with water and short cut rice straw. Approximately 3 months later, the clay increased its viscosity by decomposition of the straw. This viscous mud is for *Arakabe*. The mud for *Nakanuri* is commonly obtained from *Arakabe*-mud mixed with additional water and sand. *Nakanuri* is plastered after the *Arakabe* is completely dried. At this time, a lot of cracks are observed on the surface of *Arakabe*. But no crack is observed on the surface of *Nakanuri* even after drying.



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

Figure 1 Arrangement of *Mawatashi*s and *Komai*s
(dashed line:*Mawatashi*, solid line:*Komai*)

Photo 1 Connecting *Komai*s to *Mawatashi*

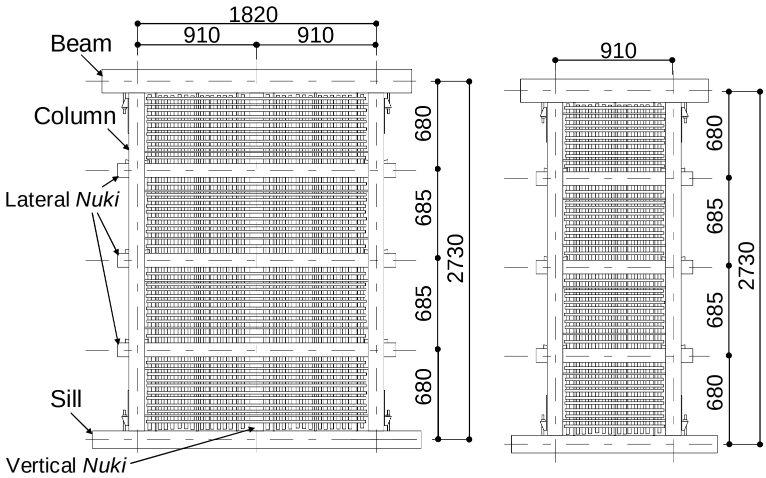
3. OUTLINE OF EXPERIMENT

3.1. Test Specimens of Mud-Plastered Walls

The test specimens were prepared as shown in Figures 2, 3, 4 and Tables 1,2. The parameters were wall length, number of lateral *Nuki*s and thickness of *Nakanuri*-layer. These factors were considered to influence earthquake resistant performance of mud-plastered walls. To avoid pulling-out of tenons from mortises, hold-down connectors (S-HD 15) were fastened to the end of columns by lag bolts and anchored to the horizontal members with anchor bolts. The thickness of each layer of mud after they were completely dried is shown in Figure 5.

3.2. Loading and Measuring Procedure

The wall specimen was fastened to the test apparatus beam at the sill, as shown in Figure 6, 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 7, 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 8.



(a) D-series specimen (b) E-series specimen

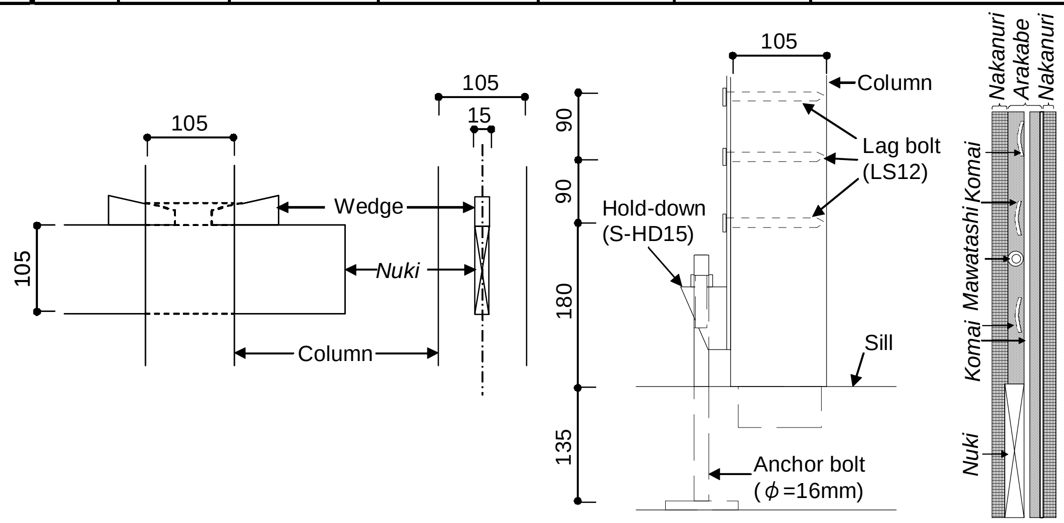
Figure 2 Scheme of specimens (unit : mm)

Table 1 Specifications of members

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

Table 2 List of specimens

	Wall length (mm)	Thickness of plastered mud (mm)			Number of *Nuki*		Features
		Arakabe	*Nakanuri* Lateral *Nuki* side	*Nakanuri* Vertical *Nuki* side	Lateral	Vertical	
D1	1820	30	0	0	3	1	*Arakabe* only
D2			15	15			Standard type
D2N					2		2 lateral *Nuki*s
D2T			25	25	3		Thick *Nakanuri*
D2L			15	0			One side *Nakanuri* only
D2V			0	15			One side *Nakanuri* only
E1	910	30	0	0	3	0	*Arakabe* only
E2			15	15			Standard type
E2N					4		4 lateral *Nuki*s
E2T			25	25	3		Thick *Nakanuri*



(a) Column-*Nuki* joint (b) Column-Sill joint (tenon-mortise joint) (c) Section of wall

Figure 3 Details of specimens (unit : mm)

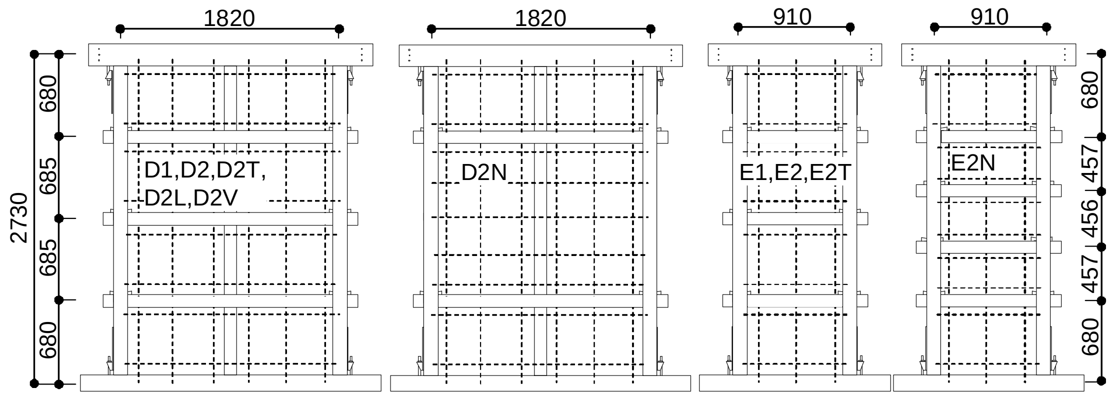


Figure 4 Arrangement of *Mawatashi*s (unit : mm)

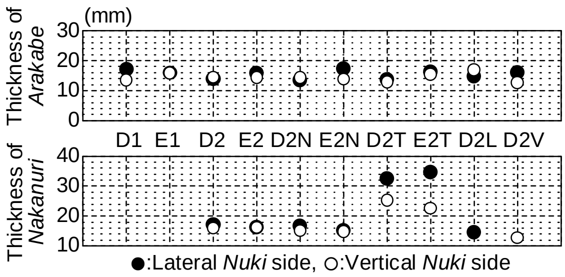


Figure 5 Thickness of *Arakabe* and *Nakanuri*

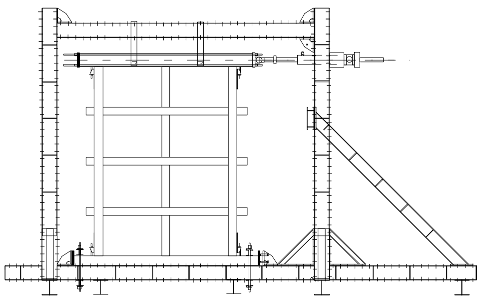


Figure 6 Setup of shear loading test

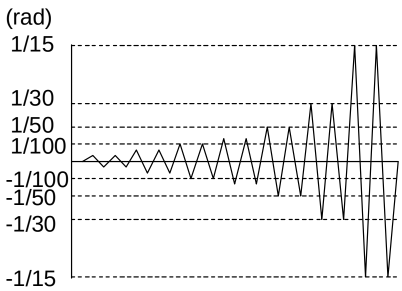


Figure 7 Cyclic history

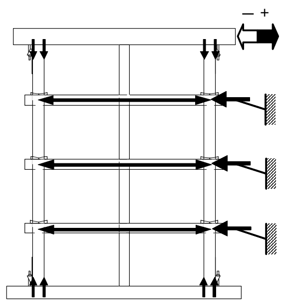


Figure 8 Measured portions

4. RESULTS OF SHEAR LOADING TEST

Figure 9 shows the relation between the drift angle based on horizontal displacement at the beam and the shear force.

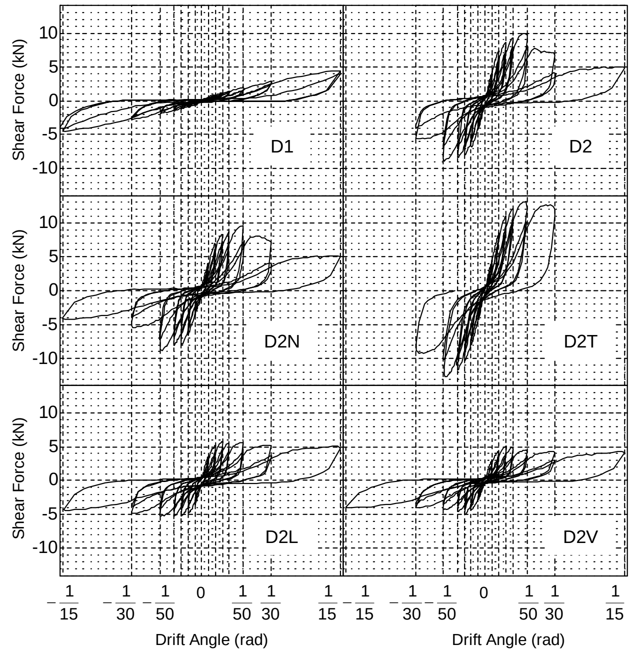
In *Arakabe* specimens, such as D1 and E1, the shear forces increased gradually until the ends of the tests, but showing low shear stiffness. Comparing with frame specimens(Nakao and Yamazaki 2004), a little shear forces are carried by *Arakabe*-layer itself.

In *Nakanuri* specimens with 1820mm of wall length, while in the small deformation level, corners of *Nakanuri*-layer along sill and beam crushed and *Nakanuri*–layer with *Arakabe*–layer rotated together with the increase of the shear deformation of the wood frame. At 1/150rad. of drift angle, in *Nakanuri* specimens except for D2T, shear cracks occurred. It was at 1/75rad. that the shear crack was observed in D2T. The maximum shear force was provided at 1/100 rad. in D2L and D2V while in the other specimens at 1/50 rad. Crack patterns when the maximum shear force was attained are shown in Figure 10. In D2, D2N, D2L and D2V, shear slip failure was observed along lateral *Nuki*s, however, such failure mode was not seen in D2T. In D2T, since *Nakanuri*-layer was swelled out of plane at 1/50 rad. and almost falling down at 1/30 rad., loading was stopped at the moment.

Moreover, since the crush of corners of *Nakanuri*−layer along the end of column occurred in every *Nakanuri* specimen, it is considered that the shear force applied to the specimen is transferred from the top end of column to *Nakanuri*-layer.

In *Nakanuri* specimens with 910mm of wall length, such as E2, E2N and E2T, the crush of corners of *Nakanuri*–layer along sill and beam was remarkable. The rotation angle of *Nakanuri*-layer was larger than the one of the specimen with 1820mm of wall length. About 1/50 rad. of drift angle, *Nakanuri*–layer at the corners and around the joints of columns and *Nuki*s swelled out of plane. The crack along lateral *Nuki* in E2 and E2N occurred due to the swelling out of *Nakanuri*-layer. Such failure mode observed in these specimens, E2, E2N and E2T, is defined as “*Nakanuri*–rocking” failure. In the specimens with 910mm of wall length, shear crack was observed only in E2N at 1/30 rad.

In this experiment, the failure modes of mud-plastered wall specimens were classified into two types, namely, shear slip failure and *Nakanuri*-rocking failure. Figure 11 shows the two failure modes of mud-plastered walls. The failure mode of *Nakanuri* specimens with 1820mm of wall length except for D2T was shear slip failure while the one of the other specimens was *Nakanuri*-rocking failure.



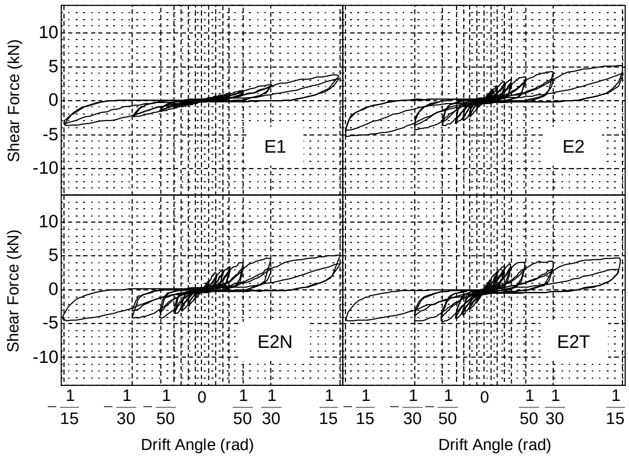


Figure 9 Shear force-drift angle relations

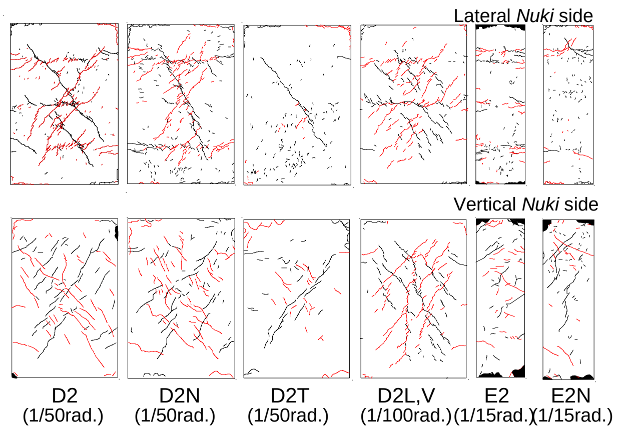


Figure 10 Crack patterns

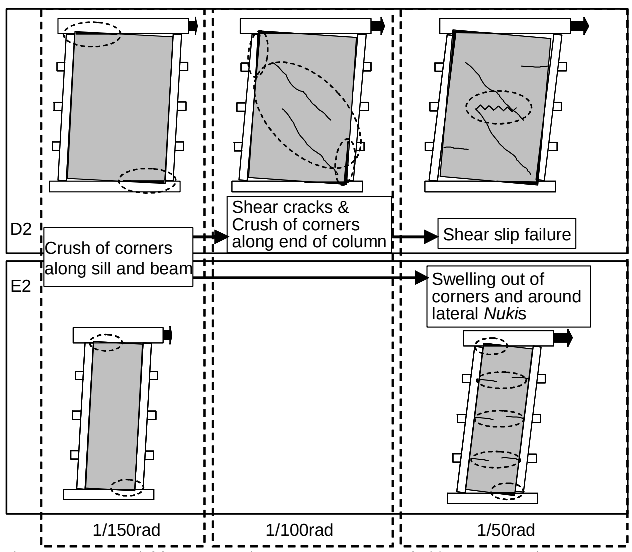


Figure 11 Difference between two failure modes

5. NUMERICAL ANALYSIS

5.1. Analytical Method

In this study, the Rigid bodies-spring model(RBSM)(Kawai 1977) is adopted for the numerical analysis of mud-plastered walls. In RBSM, it is assumed that elements are rigid and two kinds of springs which resist for normal and tangential stress connecting two elements each other has material characteristics. Therefore, simulating failure modes, such as shear crack, shear slip and crush of *Nakanuri*-layer is relatively easy.

The analysis model of the mud-plastered wall specimen with 1820mm of wall length is shown in Figure 12. Wood frame that is assumed to be elastic consists of squared elements, while the shape of mud(*Nakanuri*) element is hexagon. The elastic modulus of Japanese cedar(column, sill and *Nuki*) and Douglas fir(beam) are assumed to be 7kN/mm^2 and 12kN/mm^2 respectively.

Stress-strain curve and shear slip model of *Nakanuri*-mud in this analysis are assumed as Figure 13. *Arakabe*-layer is not contained in this analysis model because the shear force carried by *Arakabe*-layer is much smaller than the shear force carried by *Nakanuri*-layer. For compressive and tensile strength, the average values on compression and tension tests of *Nakanuri*-mud were used. Some of typical test results are shown in Figure 14. The compressive stress of *Arakabe*-mud increased gradually as the displacement increased, while *Nakanuri*-mud reached maximum stress with approximately 2mm of displacement, failing down rapidly after that point.

Lateral *Nuki* elements are connected to both side of columns by pin joint and *Nakanuri* elements. There are link elements between *Nuki* elements and *Nakanuri* elements as shown in Figure 15. The stress-relative displacement relationship of link element is perfectly elastic-plastic, and the yield stress is the equal value with compressive strength of *Nakanuri*-mud and the yield displacement is 4.5mm.

As *Nakanuri*-layer does not stick to wood frame, boundary elements were placed between *Nakanuri* elements and wood frame elements as shown in Figure 16. The normal stress of the spring of boundary element reaches compressive strength of *Nakanuri*-mud when the distance between the wood frame element and the edge of *Nakanuri* element shorten by 2mm. In case the tensile stress is affected, elastic modulus is set to the value near zero. On the other hand, the tangential stress of the spring was controlled not to exceed 30% of the normal stress by switching the shear modulus either the value near zero or the sufficiently large value. This operation aims at considering the coefficient of friction as 0.3 between wood frame and *Nakanuri*-mud.

In the experiment, it was observed that *Nakanuri*-layer inside the wood frame rocked as the lateral load was applied. Since the center of gravity of *Nakanuri*-layer was lifted up through the rock, restoring moment due to the gravity is applied to the *Nakanuri*-layer. To take into account the restoring moment, as shown in Figure 17, shear springs which generate the equal moment to the restoring moment due to the gravity were placed between the wood frame and the edge of *Nakanuri*-layer.

5.2. Comparison between Analyzed and Experimental Results

Numerical analysis models of mud-plastered wall specimens were prepared in the above method and static lateral incremental load was applied to the end of beam until the lateral stiffness was disappeared. For executing this analysis, the program attached to (Takeuchi et al. 2005) is used.

Figure 18 shows load-deformation curves obtained from the analysis and the experiment. In this figure, vertical axes are shear force carried by *Nakanuri*-layer. In most of specimens, load-deformation curves obtained from analyses are close to the ones from the experiment except for D2T. It is considered that the analytical shear force of D2T is larger than experimental force because the failure mode in the analysis is different from the experimental results. In D2T, *Nakanuri*-layer swelled out of plane during the loading in the experiment, however, such failure mode is not able to be shown in the analysis since the analysis model is only 2 dimensions.

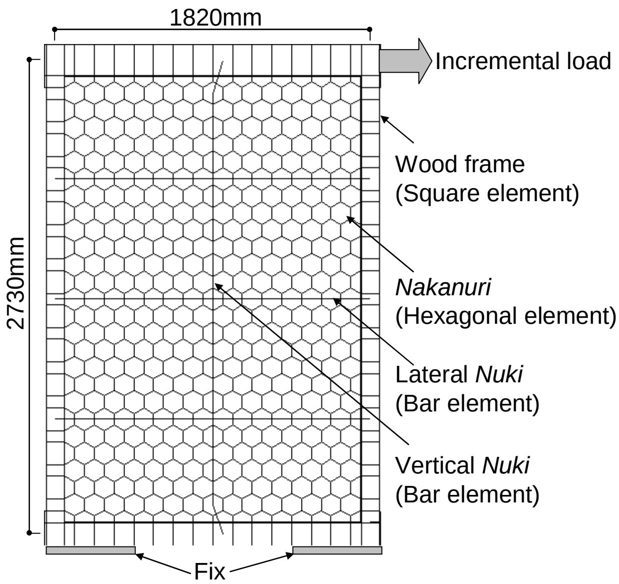
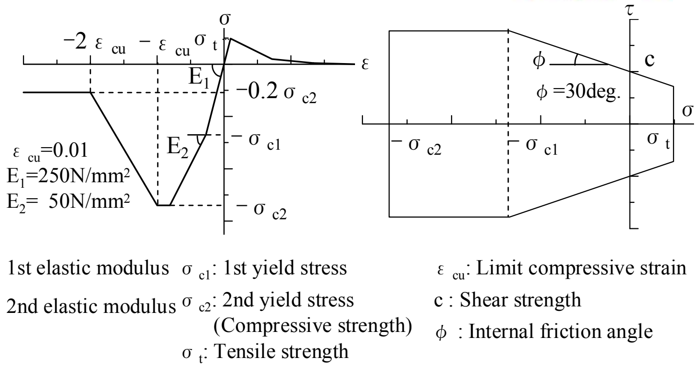


Figure 12 Analysis model



Specimen	σ_{c1} (N/mm²)	σ_{c2} (N/mm²)	σ_t (N/mm²)	c (N/mm²)	ν Poisson's coefficient
D2,D2N, D2L,E2, E2N	0.256	0.513	0.0918	0.243	0.167
D2T,E2T	0.267	0.535	0.0980	0.264	

Figure 13 Stress-strain curve and shear slip model of *Nakanuri*-mud

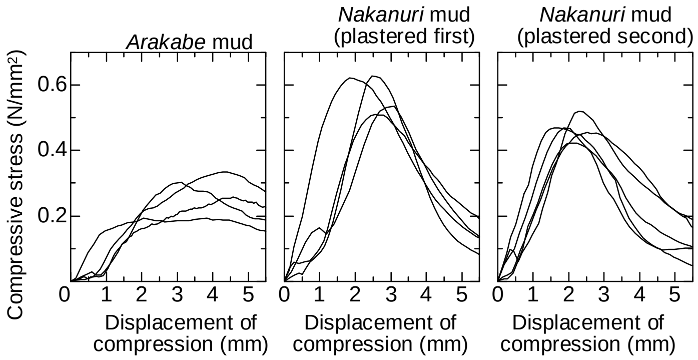


Figure 14 Stress-displacement relationship of mud

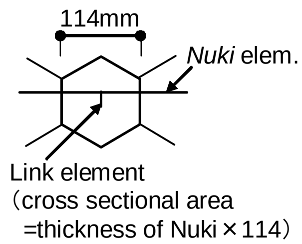


Figure 15 Link element

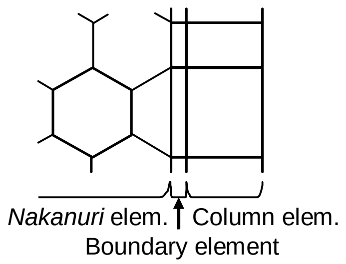


Figure 16 Boundary element

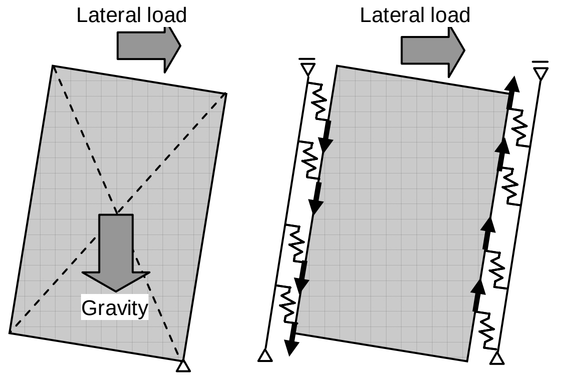


Figure 17 Springs generate restoring moment

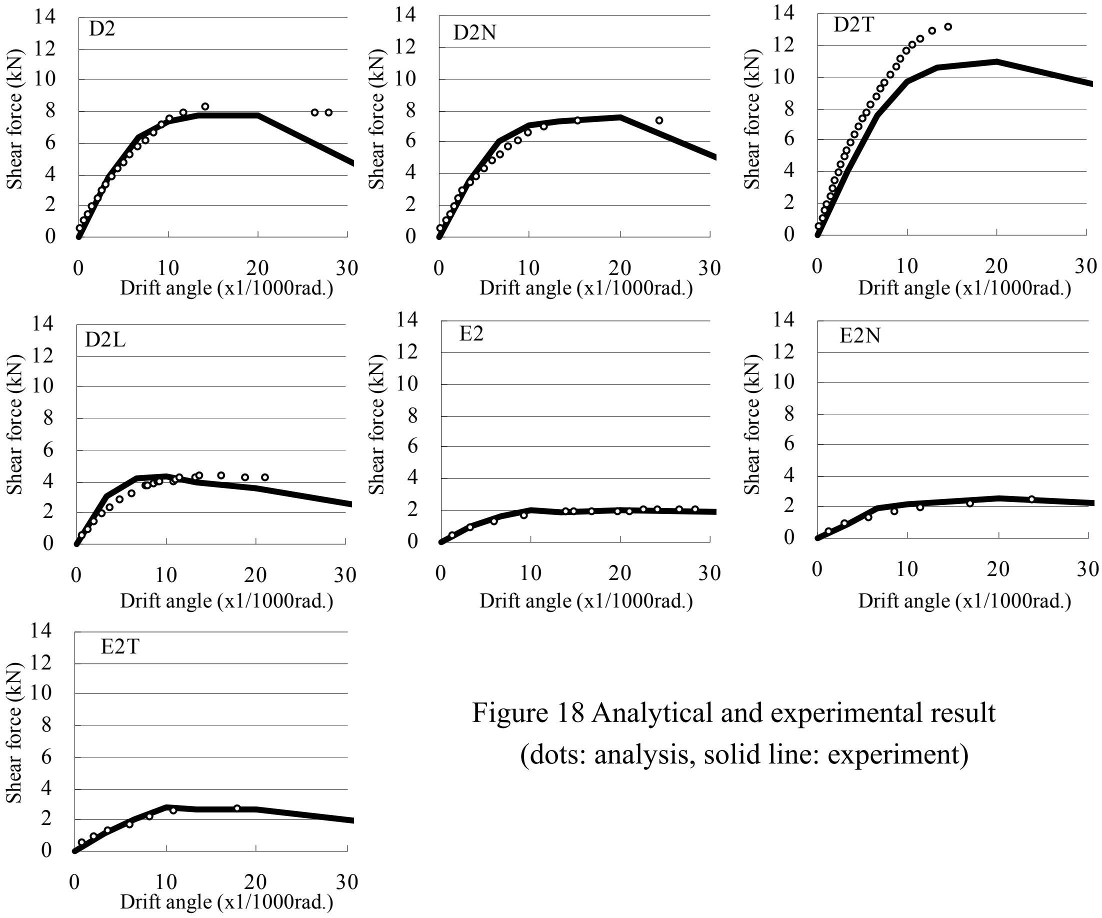


Figure 18 Analytical and experimental result
(dots: analysis, solid line: experiment)

The above analysis model for mud-plastered walls is considered to be adequate for these specimens. However, to construct more accurate analysis model for every mud-plastered wall, more experimental data is needed to adjust parameters of the analysis model.

6. CONCLUSIONS

To clarify the shear resisting mechanism and propose a numerical analysis model for mud-plastered walls, shear loading tests of mud-plastered wall specimens with various types were done. From the test results, failure modes of mud-plastered walls were clarified. Moreover, the numerical analysis model by means of Rigid bodies-spring model was proposed. The analytical load-deformation curves were close to experimental ones for most specimens. The proposed analysis model is adequate for specimens of this experiment, however, more experimental data is needed to adjust parameters of the analysis model for every mud-plastered wall in Japan.

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