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EVALUATION OF SHEAR RESISTANT PERFORMANCE OF MUD-PLASTERED WALLS ALL OVER JAPAN

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ABSTRACT

In this paper, shear resistant performance of mud-plastered walls with various wall clays was evaluated. Firstly, material testing of 29 kinds of wall clays from all over Japan was conducted to have mechanical characteristics of them. Secondly, mud-plastered wall specimens with three different wall clays were manufactured and shear loading test of these specimens was conducted. Numerical analysis of mud-plastered walls using the results of the material testing of wall clays were also done and it was found that estimating maximum shear force of a mud-plastered wall from material strengths of a wall clay is possible. Finally, a distribution of maximum shear force of mud-plastered walls all over Japan was evaluated.

Introduction

A 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 have been used for Japanese traditional type wooden houses for over one thousand years. They can absorb humidity in damp air and send out in dry air, they are suitable for Japanese climate. Its construction is not efficient to resist for lateral force such as earthquake or wind load, however, through recent studies, it has come to be clear that mud-plastered walls resist lateral force efficiently in Japanese traditional type houses.

Considering the expressed reasons, it is indispensable to clarify the shear resistant performance of mud-plastered walls for seismic design or evaluation of seismic performance of Japanese wooden houses. However, there is a difficulty with the work because the wall clay, which is deeply related to the shear resistant performance of walls, is commonly gathered from a rice field or a hillside near the building site, and so there are too many mud-plastered walls to be evaluated all over Japan.

From the past studies, it has been found that the compressive strength of wall clay is related

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to the shear strength of wall closely. It is considered that there is some possibility of evaluating shear strength of various mud-plastered walls all over Japan by simple material testing of wall clays.

Material Testing of Wall Clay

From the past studies(Nakao and Yamazaki 2004, Nakao and Yamazaki 2007, Nakao and Yamazaki 2008), it has come to be cleared that compressive strength of *Nakanuri*-clay is related to shear strength of a mud-plastered wall. *Nakanuri*-clay is plastered on surface of *Arakabe* after the *Arakabe*-clay is completely dried. Fig. 1 shows substrate and the cross section of a typical mud-plastered wall.

To investigate the range of material strength of *Nakanuri*-clay all over Japan, material testing of 29 kinds of wall clays was conducted. To obtain *Nakanuri*-clays, which are now used for constructing mud-plastered walls in every region, the Japan Plasterers' Association cooperated in Japan with this project. The regions where the 29 kinds of *Nakanuri*-clays were produced are indicated as Fig. 2, *Tohoku* 8, *Kanto* 4, *Koushinetsu* 3, *Tokai* 1, *Kinki* 2, *Cyugoku&Shikoku* 5 and *Kyusyu* 6. The properties of the *Nakanuri*-clay are listed in Table 1. The average of flow values (JIS R 5201) is 139mm and the coefficient of variation (standard deviation / average) is relatively small. As for water content and clay content, the coefficient of variation is 0.172. The most of correlation coefficients of the properties, calculated as Table 2, are small, these properties are considered to be independent of each other.

Testing method of bending strength, compressive strength and shear strength was based on JIS R 5201 which provides 40mmX40mmX160mm specimen. In addition to the test, split test with cylindrical specimen with the size of 50mm in diameter and 100mm in height was also conducted. These testing methods are shown in Fig. 3.

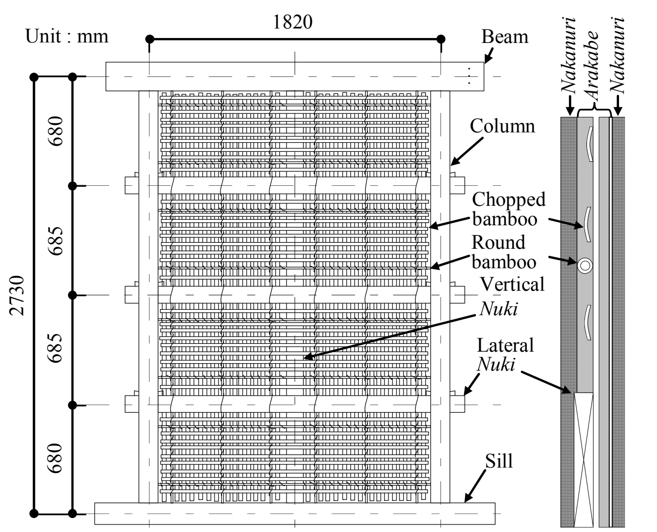


Figure 1. Substrate and cross section of typical mud-plastered wall

Figure 2. Number of *Nakanuri*-clay on every district

Table 1. Properties of *Nakanuri*-clay

	Density (g/cm^3)		Water content	Flow value	Clay content
	Wet clay	Dry clay	(%)	(mm)	(%)
Average	1.83	1.59	32.1	139	29.3
Coef. of variation	0.045	0.074	0.172	0.036	0.172

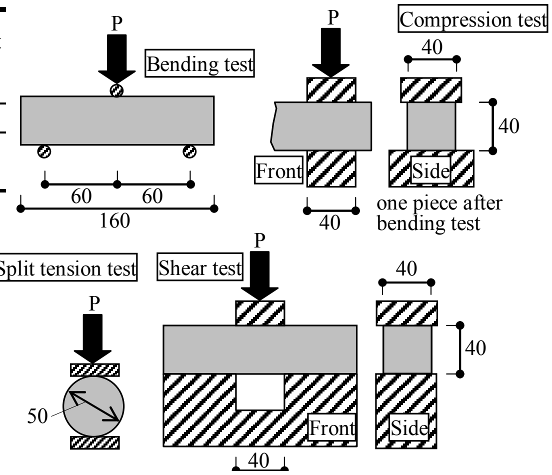


Figure 3. Testing method for *Nakanuri*-clay (unit : mm)

Table 2. Correlation coefficients between the properties of *Nakanuri*-clay

	Density (Dry clay)	Water content	Flow value	Clay content
Density (Wet clay)	0.945	-0.922	-0.201	0.012
Density (Dry clay)	-	-0.922	-0.201	0.012
Water content	-	-	0.210	0.189
Flow value	-	-	-	-0.164

Table 3 shows statistical data of material strengths of 29 kinds of *Nakanuri*-clays. Assuming the average of compressive strengths is 100%, the averages of bending strengths and shear strengths are both approximately 35% and the one of tensile strengths is about 10%. In each material test, 5 specimens were prepared, the word “variation” indicated in Table 3 means the average of 29 coefficients of variation among each 5 specimens. As for the compressive strength, since the “variation” value (0.049) is relatively small, it means the test result is stable.

Fig. 4 is scatter plots between the four kinds of strengths and these properties, namely density, flow value and clay content. And Table 4 indicates the correlation coefficients between the strengths and the properties. Correlation coefficients between the strengths and the properties are less than about 0.5. So it is considered that the strength of *Nakanuri*-clay is not affected by the three properties. As for the relation between the four strengths, the correlation coefficients are more than approximately 0.8, there is close relation between them,. Especially the one between the compressive strength and the shear strength, it is almost 1.0. The reason for such a high correlation coefficient is considered that the failure mechanisms on compression test and shear test are similar. On the compression test, shear slip failure at an angle of 45 degree was observed. Moreover, a correlation coefficient between the bending strength and the tensile strength is also relatively high.

From these results, because it is impossible to estimate material strengths of *Nakanuri*-clay from the properties, namely density, flow value and clay content, to conduct the material strength test is necessary. Although conducting four strength tests will be troublesome, the shear strength and the bending strength are able to be estimated from the compressive strength and the tensile strength respectively because of the high correlation coefficients, so only the compression and the tension tests are necessary to evaluate mechanical characteristics of *Nakanuri*-clay.

Table 3. Statistical data of material strengths of 29 kinds of *Nakanuri*-clays

	Bending	Compression	Shear	Tension
Average(N/mm^2)	0.381	1.107	0.404	0.120
Ratio of average (compression =1.0)	0.344	1.000	0.365	0.108
Coef. of variation	0.294	0.308	0.296	0.321
Maximum(N/mm^2)	0.617	1.787	0.685	0.234
Minimum(N/mm^2)	0.150	0.452	0.171	0.042
Variation	0.100	0.049	0.059	0.073

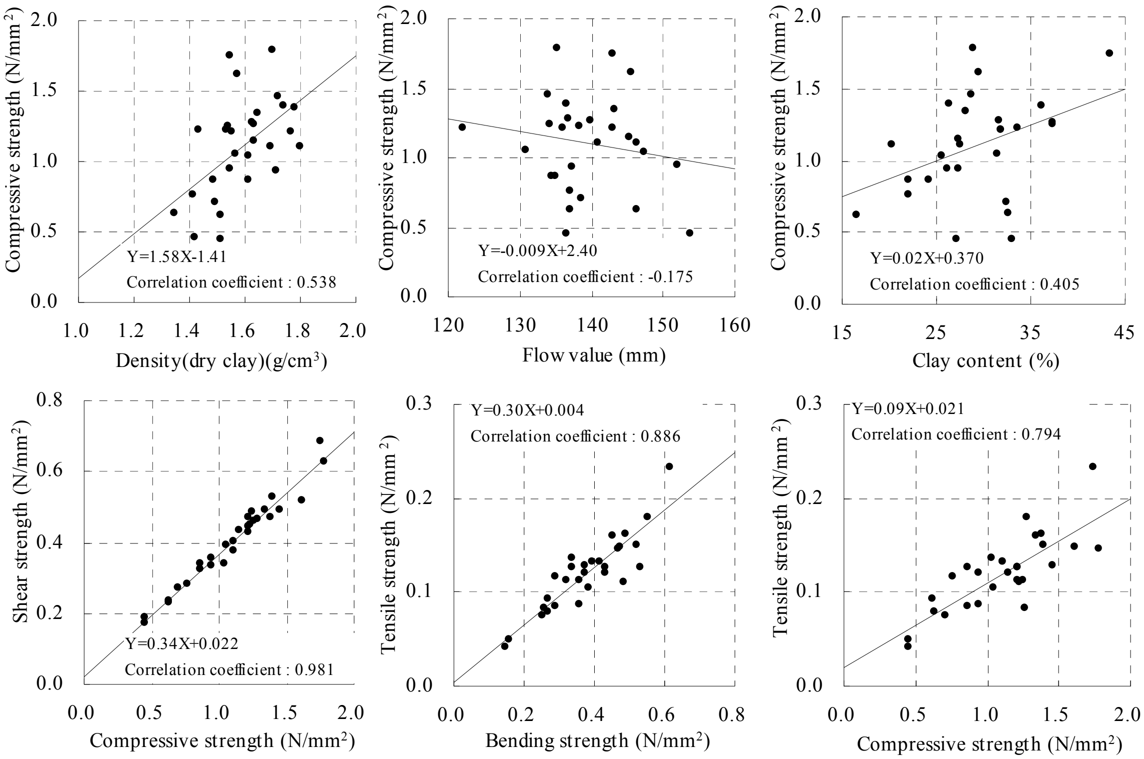


Figure 4. Scatter plots of correlations between three properties and four strengths

Table 4. Correlation coefficients between three properties and four strengths

	Bending	Compression	Shear	Tension
Density (Dry clay)	**0.506**	**0.538**	**0.492**	**0.489**
Flow value	-0.173	-0.175	-0.174	-0.098
Clay content	0.302	**0.405**	**0.460**	0.258
Bending	-	**0.819**	**0.823**	**0.886**
Compression	-	-	**0.981**	**0.794**
Shear	-	-	-	**0.793**

White number :over0.7, Bold number :0.4 - 0.7

Shear Loading Test of Mud-plastered Wall Specimens

Outline of Experiment

Static shear loading test of mud-plastered wall specimens was carried out to examine a relationship between the material strength of *Nakanuri*-clay and the maximum shear force carried by mud-plastered wall. Wall specimens were manufactured with three kinds of *Nakanuri*-clays among 29 clays above mentioned. Compressive strengths of three *Nakanuri*-clays(A, B and C) were 0.63N/mm^2, 1.22 N/mm^2 and 1.28 N/mm^2 respectively. Assuming a distribution of the compressive strengths of 29 clays is normal distribution, a range from 0.63 N/mm^2 to 1.28 N/mm^2 corresponds to 61% of a range of the 29 compressive strengths.

Six wall specimens were prepared as shown in Table 5. There are two types of wall length, namely 1820mm and 910mm, Fig. 1 is the wall specimen with 1820mm of wall length. Three *Nakanuri*-clays(A, B and C) were plastered after *Arakabe*-layer with *Arakida*-clay completely dried. The thicknesses of *Arakabe*-layer and *Nakanuri*-layer were approximately 30mm and 25mm respectively.

A wall specimen was fastened to test apparatus at the sill, as shown in Fig. 5, and lateral static load was applied to the beam of a wall specimen following static cyclic history shown in Fig. 6. While no vertical load was applied, uplift of the beam of a wall specimen was restricted by linear guides.

Table 5. Mud-plastered wall specimens

Specimen	Wall length	Arakabe	Nakanuri
I-1	1820mm	Arakida clay	A
I-2			B
I-3			C
I-4	910mm		A
I-5			B
I-6			C

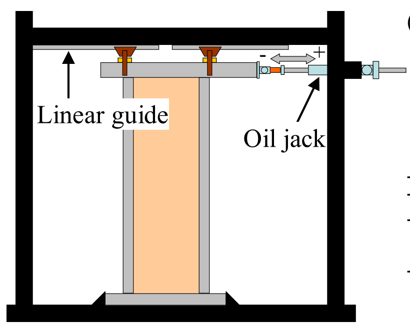


Figure 5. Loading apparatus

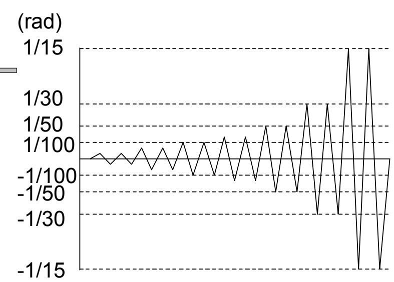


Figure 6. Loading Protocol

Results of Shear Loading Test

Fig. 7 shows relations between drift angle based on horizontal displacement at the beam and shear force. As for the specimens with 1820mm of wall length, while in the small deformation level, corners of *Nakanuri*-layer along the sill and the beam crushed and shear cracks were observed. Maximum shear forces of the specimens with clay A, B and C were 9.6kN, 8.0kN and 9.3kN respectively, they were provided at 1.0% of drift angle. After the maximum shear force, *Nakanuri*-layer was swelled out of plane and shear force carried by the wall specimen declined. As for the specimens with 910mm of wall length, while crush of corners of *Nakanuri*-layer occurred, no shear crack was observed. Maximum shear forces of the specimens with clay A, B and C were 3.2kN, 3.0kN and 3.0kN respectively, and they were provided at 1.3% or 2.0% of drift angle. The swelling out of *Nakanuri*-layer was observed similarly to the specimens with 1820mm of wall length.

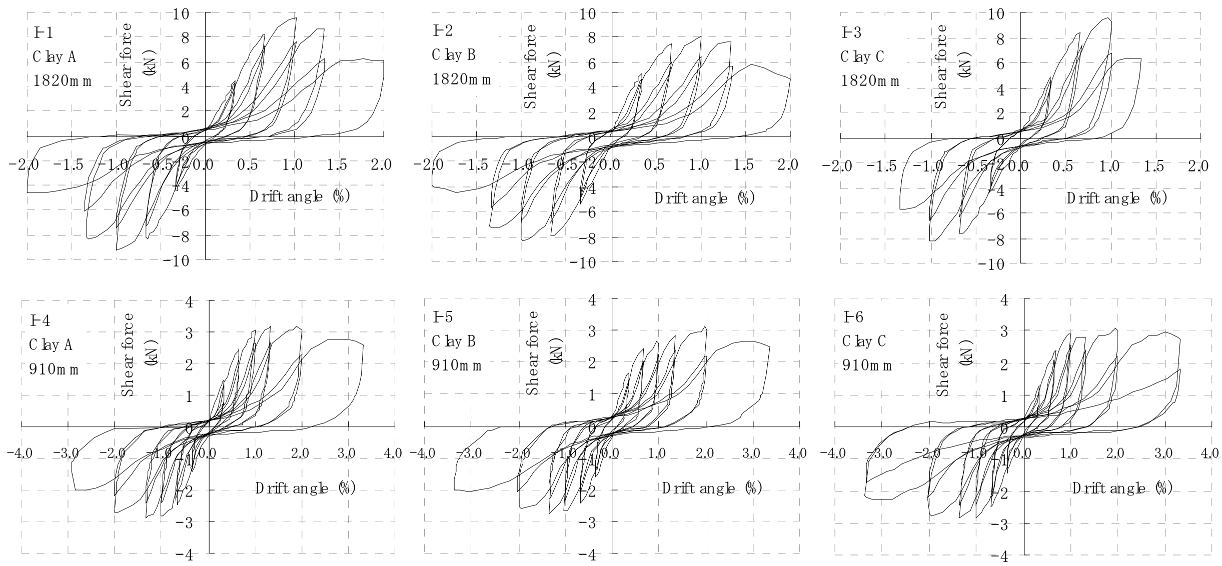


Figure 7. Relations between drift angle and shear force of mud-plastered wall specimens

Material strength test of *Nakanuri*-clays used for plastering the wall specimens was also conducted. Fig. 8 shows the result of this test which is indicated as "2nd test" while the last test result is also plotted in Fig. 8 as "1st test." The material strengths of clay B and C in 2nd test are close to the ones in 1st test, however, the one of clay A in 2nd test is more than twice as much as the one in 1st test. The content of clay A in 2nd test and the one in 1st test were the same, although the density in 2nd test was about 1.2 times as much as the one in 1st test. As for the compressive strengths of clay A, B and C are 1.45 N/mm^2, 0.94 N/mm^2 and 1.32 N/mm^2 respectively in 2nd test. While the ratio of the three compressive strengths is 1.53 : 1.00 : 1.40, the ratio of the maximum shear forces of wall specimens with 1820mm of wall length is 1.20 : 1.00 : 1.15 which is relatively small ratio. As for the specimens with 910mm of wall length, the ratio of maximum shear force is 1.06 : 1.00 : 1.00, there is no influence of the compressive strength of *Nakanuri*-clay.

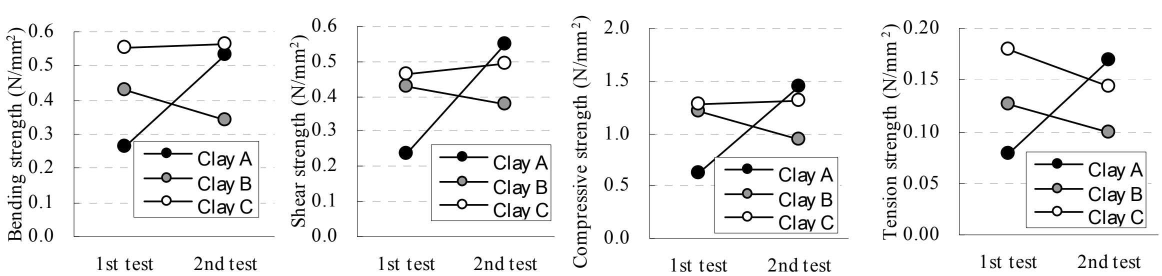


Figure 8. Comparison between 1st and 2nd material strength test results

Fig. 9 shows relations between drift angle and shear stress of *Nakanuri*-layer. For the wall specimen with 1820mm of wall length, maximum shear stresses of the specimens with clay A, B and C are 0.20 N/mm^2, 0.17 N/mm^2 and 0.19 N/mm^2 respectively. On the other hand, for the specimens with 910mm of wall length, they are 0.12 N/mm^2, 0.10 N/mm^2 and 0.11 N/mm^2.

The ratios of the three stresses in 1820mm and 910mm of wall length are almost the same, 1.19 : 1.00 : 1.10 and 1.19 : 1.00 : 1.12 respectively. It is considered that almost the same ratio is derived because the same failure mode was observed.

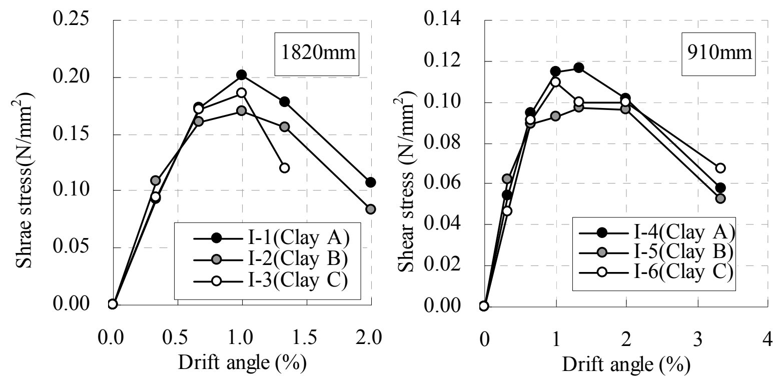


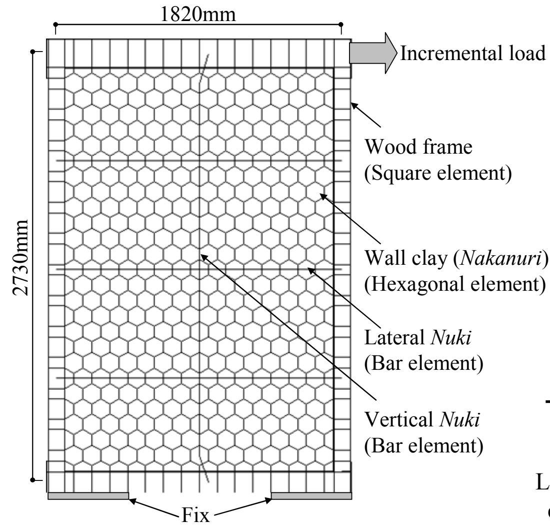
Figure 9. Relations between drift angle and shear stress of *Nakanuri*-layer

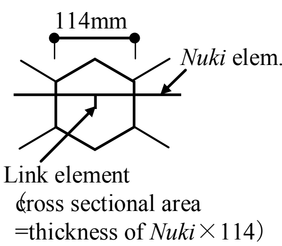
Numerical Analysis of Mud-plastered Walls

Analytical Method

Numerical analysis of six mud-plastered wall specimens was carried out. In this study, the Rigid bodies-spring model(RBSM)(Kawai 1977) was adopted for the numerical analysis of mud-plastered wall specimens. 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 Fig. 10. Wood frame that is assumed to be elastic consists of squared elements, while the shape of wall clay 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 of three *Nakanuri*-clays in this analysis are assumed as Fig. 11. *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, tensile and shear strength, averages on 2nd material test of *Nakanuri*-clay were used. Lateral *Nuki* elements are connected to both side of columns by pin joint and wall clay elements. There are link elements between *Nuki* elements and wall clay elements as shown in Fig. 12. The stress-relative displacement relationship of link element is perfectly elastic-plastic, and the yield compressive or tensile stress was assumed to be 0.6N/mm^2 and the yield displacement was 4.5mm. As wall clay does not stick to wood frame, boundary elements were placed between wall clay elements and wood frame elements as shown in Fig. 13. The normal stress of the spring of boundary element reaches compressive strength of *Nakanuri*-clay when the distance between the wood frame element and the edge of wall clay element shorten by 2mm. In case the tensile stress is affected, elastic modulus is set to the value near zero.





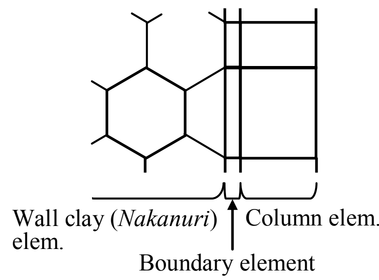


Figure10.

Figure 10. Numerical analysis model of mud-plastered wall

Figure 12. Link element

Figure 13. Boundary element

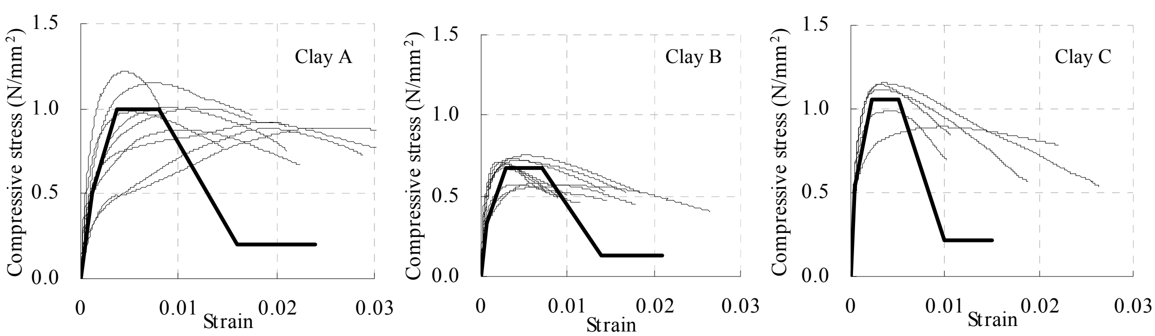


Figure 11. Stress-strain curve model of three *Nakanuri*-clays

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) was used.

Fig. 14 shows the analyzed and experimental relations between drift angle and shear force carried by *Nakanuri*-layer. It is found that there are some differences on shear stiffness between analyzed and experimental results, however, maximum shear forces carried by *Nakanuri*-layer obtained by the analysis are close to the experimental results. From this result, as for maximum shear force, it is considered that estimating maximum shear force of mud-plastered walls from material strength of *Nakanuri*-clays is possible.

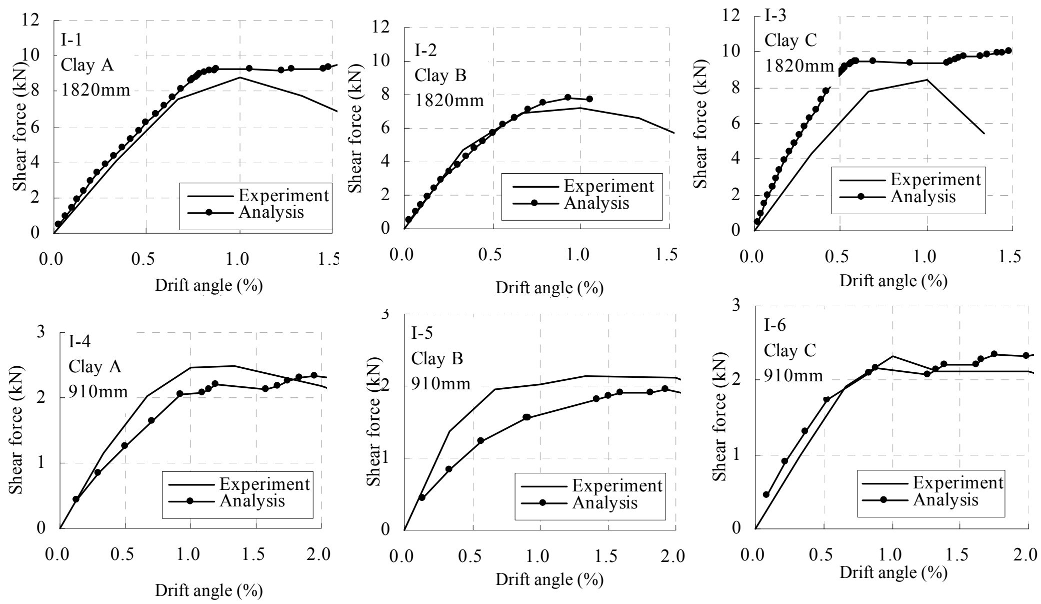


Figure 14. Comparison between analyzed and experimental results

Evaluation of Distribution of Maximum Shear Force of Mud-plastered Wall All Over Japan

Taking account of above experimental and analytical results, a distribution of maximum shear stress of mud-plastered wall was evaluated. Fig. 15 shows relations between maximum shear stress of *Nakanuri*-layer of the wall specimen and compressive strength of *Nakanuri*-clay used for the wall specimen. It is found that the data are able to approximate two liner functions, one is for the specimens with 1820mm and another is for the specimens with 910mm of wall length. Moreover, considering the range of compressive strength of 29 *Nakanuri*-clays(from 0.452N/mm^2 to 1.787 N/mm^2, Table 3), corresponding ranges of the shear stress are from 0.139 N/mm^2 to 0.218 N/mm^2 for 1820mm of wall length and from 0.080 N/mm^2 to 0.127 N/mm^2 for 910mm of it calculated by the liner functions. Assuming thickness of *Nakanuri*-layer is 30mm of mud-plastered wall, maximum shear forces carried by *Nakanuri*-layer all over Japan are estimated from 7.1kN to 11.2kN for walls with 1820mm of wall length and from 1.9kN to 3.1kN for walls with 910mm.

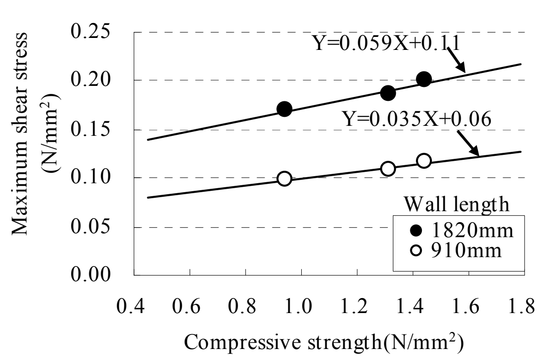


Figure 15. Relations between maximum shear stress of *Nakanuri*-layer of wall specimen and compressive strength of *Nakanuri*-clay

Conclusions

A distribution of mud-plastered walls with various wall clays all over Japan was evaluated by means of material testing of 29 kinds of wall clays, static loading test of wall specimens and numerical analysis. A range of maximum shear force of mud-plastered walls with 30mm of thickness of *Nakanuri*-layer was able to be estimated. However, since it is expected that maximum shear stress of mud-plastered wall varies according to the thickness of wall, studying another case with various thickness is needed.

Acknowledgments

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