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SIMPLE SHEAR STRENGTH EVALUATION METHOD OF MORTAR FINISHING EXTERNAL WALL WITH OPENING

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Abstract

The shear strength of the external and internal non-structural wall of a wooden house in Japan is relatively high. It is considered that one third of the whole shear force applied to a wooden house is carried by such walls. To understand the whole shear strength of a wooden house, shear strength calculation method of the non-structural walls is needed. In this paper, the incremental analysis of the mortar finishing external wall with one opening was conducted, and then a simple shear strength calculation method was proposed. For developing the analysis model of incremental analysis, static shear loading test of the mortar finishing external wall specimens were performed beforehand, and fundamental failure mode and relationship between shear force and story drift were examined.

There are two major construction systems of the mortar finishing external wall with ventilation space. One is a single layer system and the other is a double layer system. The specimen with unit wall length and the L-shaped specimen were prepared, and a static shear loading test was conducted to examine the fundamental shear force-story drift relationship and the development of crack from the corner of an opening.

To estimate the influence of an opening on the shear strength of the mortar finishing external wall, incremental analysis of the mortar finishing external wall with 4,550mm of wall length which had an opening [1] was conducted. In advance of the analysis, analysis of the unit wall length specimens and the L-shaped specimens were conducted and the validity of the modeling method was confirmed.

While the shear force decreased as the area of opening increases in the double layer system, the one in the single shear system showed little influence of an opening. It was considered that the tensile force around the opening is relatively small in the single layer system the same as the failure mode of the L-shaped specimen.

From the results of the analysis model with 4,550mm of wall length, the relationship between Fr and β was derived. Where Fr is the ratio of the shear force of the wall with an opening to the one with no opening, β is Am/(Am +Ao) (Am: the area of mortar, Ao: opening width × height). Moreover, shear strength of the mortar finishing external wall with no opening Q was defined as C×Nc, where C is a coefficient, Nc is Number of the column. Consequently, the shear strength of the mortar finishing external wall with an opening Q’ was derived as Fr×Q.

Keywords: Mortar; External wall; Opening; Shear strength; Incremental analysis

1. Introduction

The shear strength of an external wall and an internal wall of a wooden house in Japan is relatively high. It is considered that approximately one third of whole shear force applied to a wooden house is carried by such walls. To evaluate the whole shear strength of a wooden house, shear strength calculation method of the walls is needed.

For the external wall, the mortar finishing wall on a plane of structure is considered to be continuous one wall [1]. Because most planes of structure have openings, it is necessary to consider the influence of the openings on the shear strength to develop the shear strength calculation method of the external wall.

In this paper, considering the result of static incremental analysis of the mortar finishing external wall with one opening, simple shear strength calculation method is proposed. To develop the analysis model for the incremental analysis, static shear loading test of mortar finishing external wall specimens with unit wall length and L-shaped specimens was performed and the fundamental failure mode and the relationships between shear force and story drift were examined.

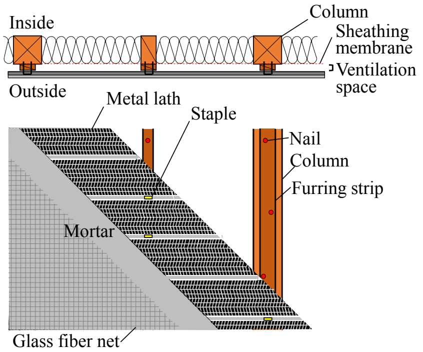
2. Outline of the construction system

There are two major construction systems of the mortar finishing external wall with ventilation space. One is single layer system and the other is double layer system. Fig. 1 shows the schematic of the two systems.

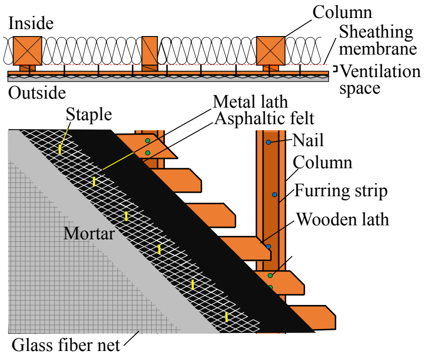
As for the single layer system, vertical furring strips with 15 mm thick are attached to the out face of columns and studs using 65 mm-long nails(N65) at 303 mm spacing to keep ventilation space. Thereafter, ribbed metal lath(155RC800-05) is fixed with 25 mm long staple (L925T) at the rib which is spaced 155 mm. Because duplex asphalt paper is fixed on the back of the ribbed lath by staples, no wooden lath and asphaltic felt is needed. Light weight mortar is plastered on the substrate with 15 mm thick. To avoid shrinkage crack, glass fiber net as shown in Fig. 2 is applied on the surface of the mortar.

As for the double layer system, vertical furring strips with 15 mm thick are attached using 38 mm long nails(N38) at 200 mm spacing to keep ventilation space. Lateral wooden laths are fastened with two 65 mm-long nails(N65) on columns and studs. Asphaltic felt (sheathing membrane) is applied on the wooden laths. Thereafter, wavy metal lath(II W700-06) is fixed with 19 mm long staples(L1019J) spaced 100 mm apart. Light weight mortar is plastered on the substrate same as the single layer system.

Table 1 shows combination of metal laths and staples. Their properties are shown in Table 2 and Table 3. Fig. 3 and Fig. 4 show completed metal lath substrate.



(a) Single layer system



(b) Double layer system

Fig. 1 - Single layer system and double layer system of mortar finishing external wall with ventilation space

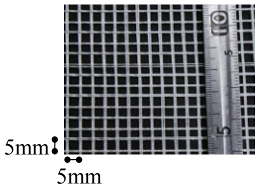


Fig. 2 - Glass fiber net

Fig. 3 - Substrate of single layer system

Fig. 4 - Substrate of double layer system

Table 1 – Combination of metal lath and staple

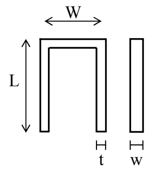
	Metal lath	Staple
Single layer system	Ribbed lath 155RC800-05	L925T
Double layer system	Wavy lath II W700-06	L1019J

Table 2 - Properties of metal lath

Metal lath	Weight (g/m^2)	Thickness (mm)
Ribbed lath 155RC800-05	800	5
Wavy lath II W700-06	700	6

Table 3 - Properties of staple

	Width (W) (mm)	Length (L) (mm)	Shank diameter (t×w) (mm)
L925T	9	25	1.30×1.63
L1019J	10	19	0.60×1.15



3. Static shear loading test

The specimen with unit wall length shown in Fig. 5 was prepared for the static shear loading test to understand the fundamental failure mode and the relationships between the shear force and the story drift of the mortar finishing external wall. L-shaped specimen, another type of specimen, shown in Fig. 6 was prepared to understand the development of cracks from the corner of an opening.

For the specimen with unit wall length, static shear repeated load was applied to the beam of the specimen while one directional shear force was applied to the L-shaped specimen.

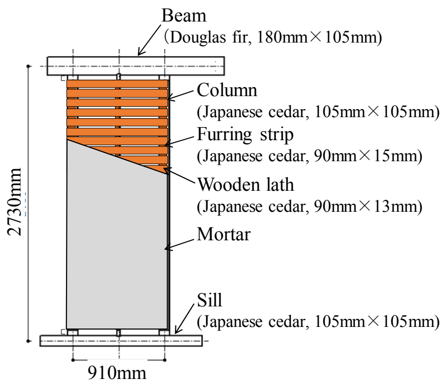


Fig. 5 - Specimen with unit wall length

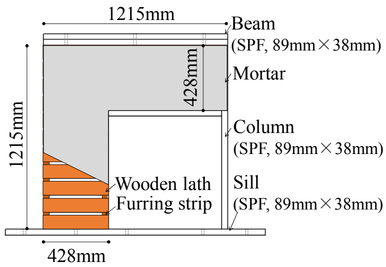


Fig. 6 - L-shaped specimen

Fig. 7 shows relationships between the shear force and the story drift. Fig. 8 shows the specimens at ultimate state.

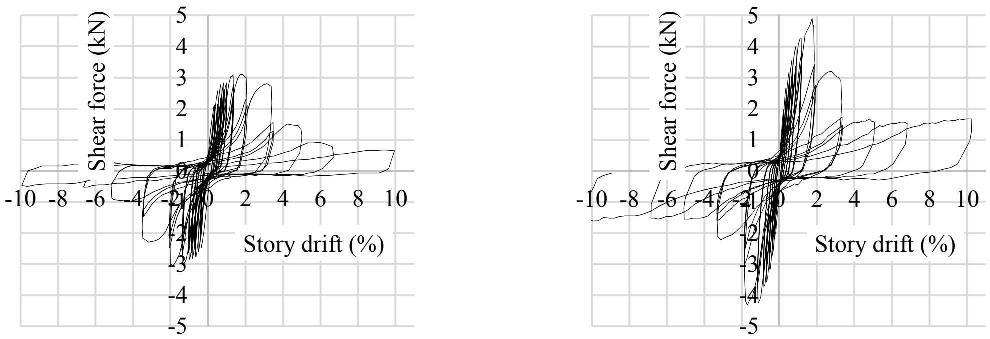
On the specimen with unit wall length of the single layer system, mortar layer rotated together with story drift. At 1.33% of story drift, the specimen reached to maximum shear strength, 3.1 kN. It was almost the same at 2% and decreased slightly at 3.33%. When it reached 5% of story drift, shear strength almost disappeared. On observation after the loading, it was found that the rib around the staple was cut off as shown in Fig. 9.

On the specimen with unit wall length of the double layer system, mortar layer rotated as story drift increased, same as the single layer system. Maximum shear strength was 4.9 kN at around 2% of story drift. It was 3 kN at 3.33% and almost disappeared at around 5%. The staples which fasten the mortar layer to the wooden laths were cut-off as shown in Fig. 10 due to the repeated loading except for the ones around the stud.

Fig. 11 shows relationships between shear force and story drift of the L-shaped specimens. Fig. 12 shows the specimens at ultimate state.

On the L-shaped specimen of the single layer system, initial crack was observed at the corner of the opening at 0.92% of story drift. Length of the crack got longer as the story drift increased. After the maximum shear strength, the ribs at the end of the hanging wall was cut-off and the mortar layer rotated.

On the L-shaped specimen of double layer system, initial crack was observed at 0.47 % of story drift and the crack got longer as the story drift increased. The width of the crack increased to 2 mm at 3.03% and the glass fiber net floated up due to tensile force. The maximum shear strength was 3.1 kN at 3.8% and dropped to 2.4 kN at 10%.



(a) Single layer system (b) Double layer system

Fig. 7 - Shear force-story drift relationship of specimen with unit wall length

(a) Single layer system (b) Double layer system

Fig. 8 - Ultimate state of specimen with unit wall length (6.67% of story drift)

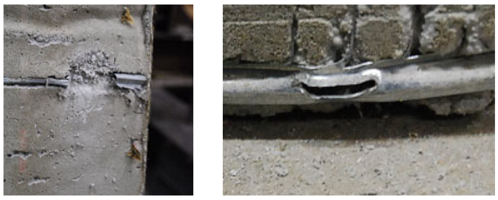


Fig. 9 - Rib around staple after loading

Fig. 10 - Cut staples on wooden laths

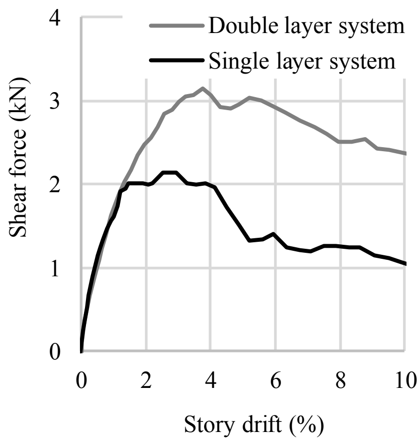
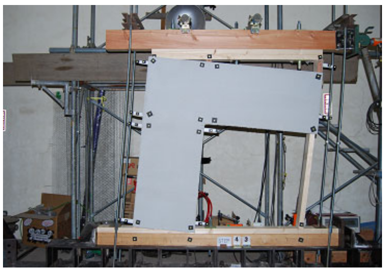
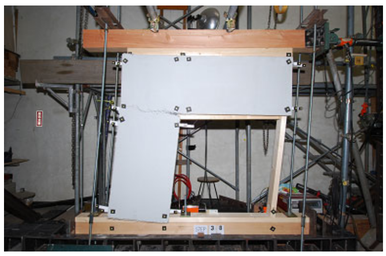


Fig. 11 - Shear force-story drift relationship of L-shaped specimen





(a) Single layer system (b) Double layer system

Fig. 12 - Ultimate state of L-shaped specimen (10% of story drift)

4. Incremental analysis of mortar finishing external wall with opening

4.1 Modeling of each element

For static incremental analysis of the mortar finishing external wall with 4,550mm of wall length, structural models of the each element were examined.

Components of the analysis model are shown in Fig. 13 where it consists of three layers, a wood frame, wooden laths and lath mortar. There is no wooden lath in the single layer system.

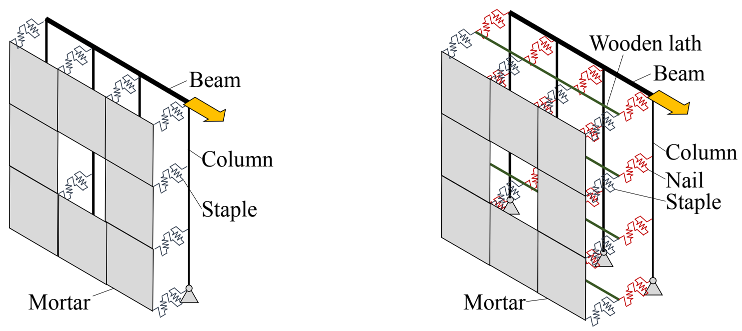
A layer of wood frame consists of a beam element and column elements which take into account axial stiffness and flexural rigidity. The top ends of the column element is connected to the beam element where the joint is pin. Stud was omitted because its flexural rigidity is too low to affect the result. The sill was also omitted because the bottom ends of column elements were restricted as pin directly. The second layer which represents wooden laths is composed of beam elements. Young's modulus of the beam was 10kN/mm^2 while the one of the column and wooden lath was 7kN/mm^2. There is not the second layer, wooden laths, for the single layer system.

Lath mortal layer, the third layer, is modelled as elastic wall elements which take into account axial stiffness, flexural rigidity and shear stiffness within the plane. The Young's modulus was set at 5.3kN/mm^2 based on material testing data.

The first layer and the second layer, namely a layer of a wood frame and a layer of wooden laths, are connected by non-linear spring elements which represents two 65 mm long nails. The shear force-displacement relationship for the analysis model is shown in Fig. 14, which was set based on single shear test of the component.

Another spring elements, which represent staples, connect the first layer with the third layer in the case of the single layer system while the ones connect the second layer with the third layer in the case of the double layer system. The shear force-displacement relationship models of the two staples, namely L1019J and L925T, were prepared as shown in Fig. 15. They were derived from single shear test as shown in Fig. 16. For the staple L925T, decreased shear stiffness was adopted considering the shear stiffness of 65 mm long nail because the staple L925 is anchored to the vertical furring strip that is fastened to the column by 65mm long nails. Fig. 17 shows the shear force-displacement relationship of the 65 mm long nail.

Axial stiffness of the non-linear spring model of the nails and the staples was assumed as rigid. Some 65 mm long nails were concentrated on one spring element to reduce degrees of freedom of the analysis model. As for the staples, same as the 65 mm long nails, one spring element represented some staples.



(a) Single layer system (b) Double layer system

Fig. 13 - Components of analysis model of mortar finishing external wall

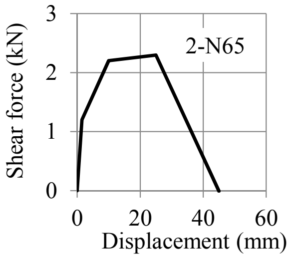
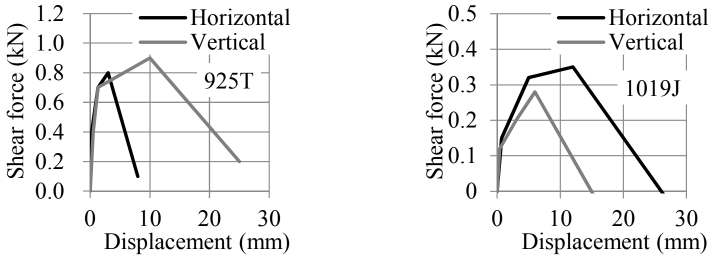


Fig. 14 – Model of N65 nail spring



(a) 925T for single layer system (b) 1019J for Double layer system

Fig. 15 - Shear force-displacement relationship of staples

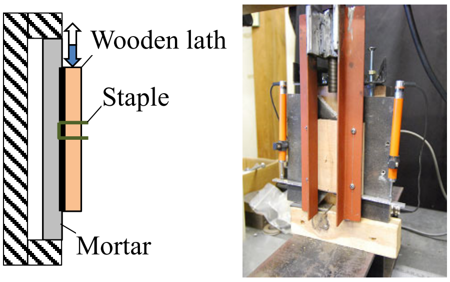


Fig. 16 - Single shear test of L1019J staple

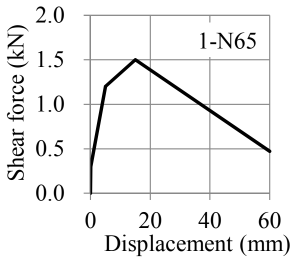


Fig. 17 – Model of 65mm long nail

Compressive, tensile and shear failure of lath mortar affects the shear strength of the mortar finishing external wall with opening greatly. Therefore, non-linear springs were arranged between the wall elements around the opening which express compressive, tensile and shear failure of lath mortar as shown in Fig. 18.

Failure of lath mortar was observed around the opening in the static shear loading test[1], therefore, spring elements were arranged along the line from the corner of opening to the edge of lath mortar. Length of the spring element was set at 5 mm, compressive stiffness was calculated to be equal to Young's modulus(5.3kN/mm^2).

On the tension side, based on the tension test result of lath mortar element specimen as shown in Fig. 19 [2], tensile force-displacement relationship model was derived. Fig. 20 shows axial force-displacement relationship of lath mortar with 100 mm of width. As for the tension side model, two models, namely vertical and horizontal direction, were prepared. Fig. 21 shows compression side of the axial force-displacement relationship. As for the shear force-displacement relationship, it was defined as shown in Fig. 22 from the double shear test of the mortar specimen which contains metal lath and glass fiber net.

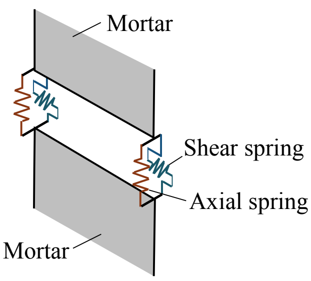


Fig. 18 - Non-linear spring elements

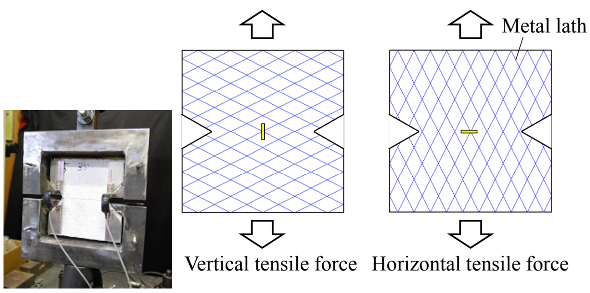


Fig. 19 - Tension test of lath mortar element

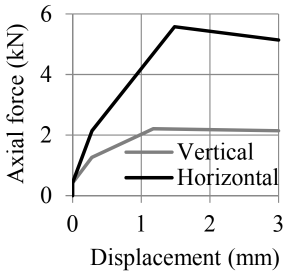


Fig. 20 - Tensile force-displacement relationship of lath mortar (width : 100 mm)

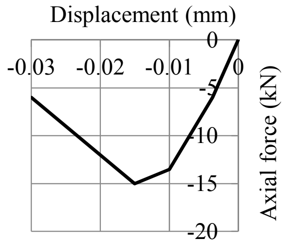


Fig. 21 - Compressive force-displacement relationship of lath mortar (width : 100 mm)

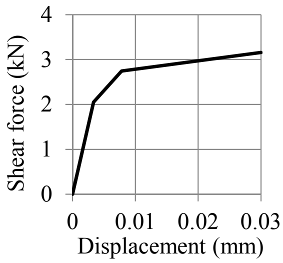
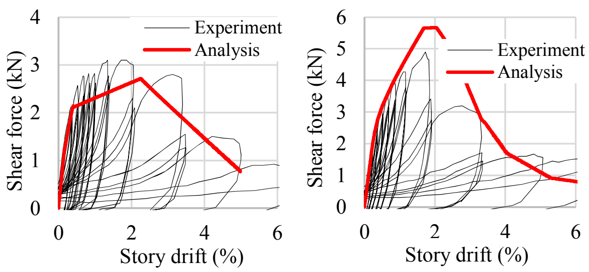


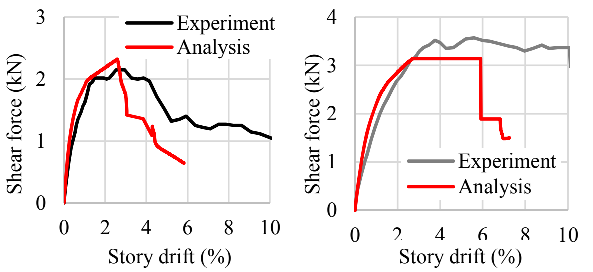
Fig. 22 - Shear force-displacement relationship of lath mortar (width : 100 mm)

4.2 Varification of modeling

To evaluate validity of the modelling method, analysis models of the specimen with unit wall length and the L-shaped specimen were built and static incremental analysis was performed.

Relationships between shear force and story drift of the analysis models were shown in Fig. 23 and Fig. 24. It is found that the analysis results show relatively good correspondence with the experimental results. Fig. 25 and Fig. 26 show global deformation of the analysis models, which show same deformation characteristics as the experimental specimens. Therefore, it is considered that the modelling method is valid to estimate the shear force-story drift relationship and failure mode of the mortar finishing external wall.

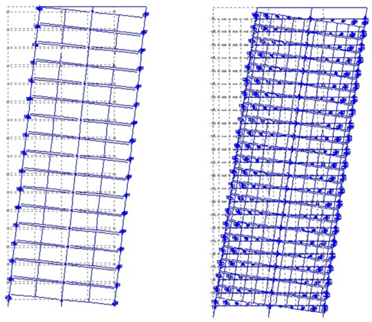




(a) Single layer system (b) Double layer system (a) Single layer system (b) Double layer system

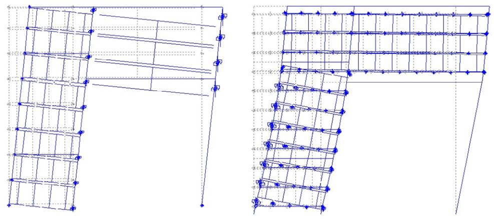
Fig. 23 - Shear force-story drift relationships of specimen with unit wall length

Fig. 24 - Shear force-story drift relationships of L-shaped specimen



(a) Single layer system (b) Double layer system

Fig. 25 - Global deformation of unit wall length specimen (deformation magnification: 2.0)



(a) Single layer system (b) Double layer system

Fig. 26 - Global deformation of L-shaped specimen (deformation magnification: 2.0)

4.3 Incremental analysis of wall with one opening

As for the analysis model with one opening, whose wall length is 4,550 mm of wall length, there were two kinds of opening, namely, door type opening and window type opening. Each type had three opening widths, 910 mm, 1,820 mm and 2,730 mm. In addition to these six models with an opening, the analysis model with no opening was also prepared.

Fig. 27 shows shear force-story drift relationships, and Fig. 28 shows global deformations of the analysis model. While the shear force decreases as the area of opening increases in the double layer system, the one in the single shear system shows little influence of an opening. It is considered that the tensile force around the opening is relatively small in the single layer system the same as the failure mode of the L-shaped specimen.

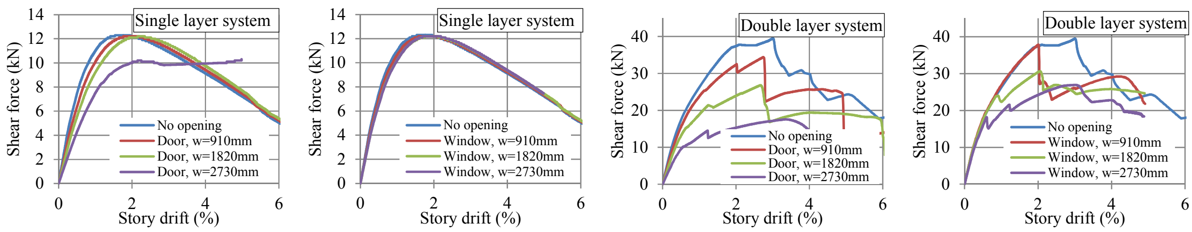


Fig. 27 - Shear force-story drift relationships

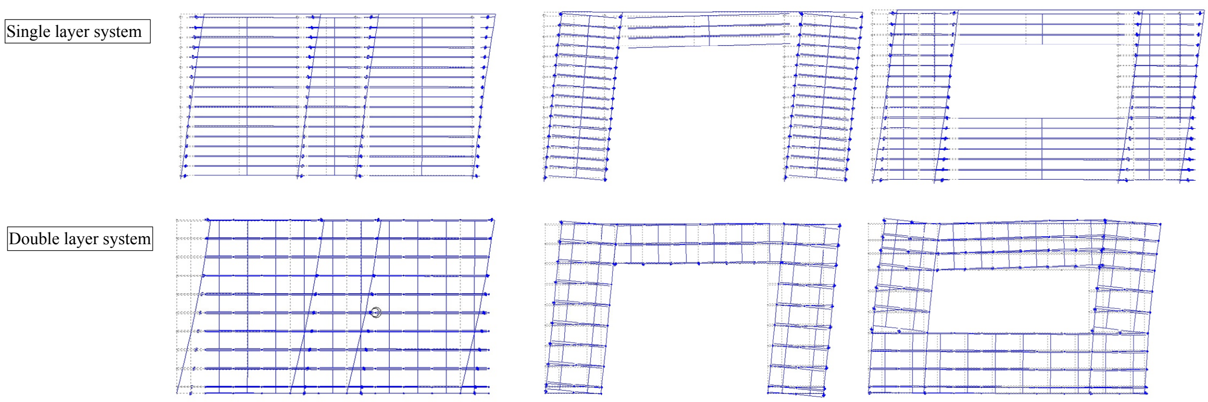


Fig. 28 - Global deformation of analysis model with one opening (deformation magnification: 2.0)

5. Proposal of shear strength calculation method

Based on the result of the static incremental analysis of the analysis model with one opening, simple shear strength calculation method of the mortar finishing external wall with opening is proposed.

First, the shear forces at 0.5% and 2.0% of story drift were picked up from the data of the analysis result, and shear force ratio Fr, which is the ratio of shear force of the wall with opening to the shear force of the wall with no opening at same story drift, was calculated.

Fig. 29 shows relationship between shear force ratio Fr and opening ratio β of the analysis model with 4,550mm of wall length. From Fig. 29, conservative regression lines are derived as Eq. (1) and (2). Eq. (1) and (2) are for single layer system and double layer system, respectively.

$$Fr = \beta \qquad (1)$$

$$Fr = 1.8\beta - 0.7 \qquad (2)$$

where Fr is the ratio of the shear force of the wall with opening to the one with no opening, β = Am/(Am +Ao), Am: the area of mortar, Ao: opening width×height.

Shear strength of the mortar finishing external wall with no opening Q (kN) is calculated using Eq. (3).

$$Q = C \cdot Nc \qquad (3)$$

where C is a coefficient listed in Table 4, Nc is Number of column.

Consequently, the shear strength of the mortar finishing external wall with opening Q’ is derived as Eq. (4).

$$Q' = Fr \cdot Q \qquad (4)$$

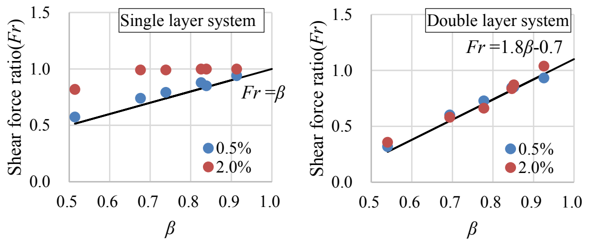


Fig. 29 - Relationship between Fr and β

Table 4 Coefficient C

Story drift	Single layer system	Double layer system
0.5%	1.8	5.9
2.0%	3.0	10.0

6. Conclusions

In this paper, focused on the mortar finishing external wall of single and double layer construction system, static shear loading tests of the specimen with unit wall length and the L-shaped specimen were presented. Considering the results of the tests, analysis model with several types of opening was built and static incremental analysis was performed. Thereafter, simple shear strength calculation method of the mortar finishing external wall with opening was proposed.

Using the proposed calculation method, estimation of the shear force carried by the mortar finishing external wall has become possible. In further study, accuracy of the proposed calculation method will be examined.

Acknowledgements

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References

[1] M. Nakao, Y. Ono, M. Tahara, M. Miyamura, T. Inoue, K. Koga (2014): Experimantal Study on Seismic Performance of Mortar Finishing External Wall, *World Conference on Timber Engineering*

[2] M. Nakao. Evaluation of Seismic Performance of Mortar Finishing External Wall with Ventilation Space (2016): *World Conference on Timber Engineering*

