Shear Resistant Performance of Hanging and Window Back Wall in Traditional Wooden Building

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SUMMARY
Static shear loading tests on single full-height walls, hanging walls and window-back walls with dry-mud-panels were conducted. And then, push-over analysis of combinations of the walls was performed, it was found that summation of shear forces of the single walls is higher than the shear force of combined analysis model except for the range of relatively large deformation. Consequently, to evaluate shear resistant performance of traditional wooden building with dry-mud panel, summation of shear forces of the single walls was found to be adequate

Keywords: Traditional Wooden Building, Hanging wall, Window-Back Wall, Push Over Analysis

1. INTRODUCTION

As the traditional wooden building in Japan has relatively large cross sections of structural members, therefore, not only full-height walls but also columns with hanging walls and window-back walls are able to resist lateral shear force(Shimizu et al. (2006), (2008)). Many hanging and window-back walls are used in traditional wooden building, however, structural design method taking account of the hanging and window-back walls effectively in traditional wooden buildings is not in use for most of designers because of lack of experimental and analytical researches.

In this study, static shear loading test of single full-height walls, hanging walls and window-back walls with dry-mud panels(Sugiyama et al. (2006)) was conducted. And then, analysis models of the specimens were developed for push-over analysis of various combinations of the full-height wall, hanging wall and window-back wall. Through the experimental and analytical investigation, the shear resistant performance of traditional wooden building with not only full-height walls but also hanging walls and window-back walls is discussed.

2. STATIC SHEAR LOADING TEST

2.1. Outline of the test

Figure 1 indicates basic wood frames of static shear loading test specimens. The specimens were post and beam construction, each specimen has a beam, a sill and two or tree columns. A distance between the centers of a beam and a sill was 2730mm. The cross section of a beam was 210mm x 120mm, the one of a column was 120mm x 120mm. Species of these members were Japanese cedar. The cross section of a sill was 120mm x 120mm and the species was Japanese cypress. Column-beam joints were mortise-tenon with cotter-pin as shown in Figure 2. The size of the tenon was 90mm x 120mm x 30mm. A cotter-pin, which was 15mm x 15mm in cross section and the species was Oak, penetrates a tenon and a sill or a beam to prevent a column from pulling out of a sill or a beam. The distance from the upper face of a sill to the center of a cotter-pin was 52.5mm. The one from the lower face of a beam to the center of a cotter-pin was the same, 52.5mm. Figure 3 shows the specimens that vertical and lateral battens were arranged. The dry-mud panels were to be fixed to the battens with wood screws. The species of the batten was Japanese cedar and the cross section was 60mm x 45mm. They were arranged at a distance of 500mm-600mm inside a wood frame and external battens were fixed to the inside face of columns, sills and beams using wood screws. In the specimen which has a hanging wall and/or a window-back wall, lintel and/or window sill was attached. The lintel and the window sill, which were 45mm x 105mm in cross section and the species was Japanese cedar, have tenons which was 15mm x 75mm x15 mm at the both ends of the each member.

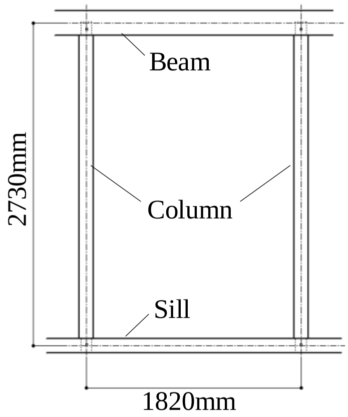


Figure 1. Basic wood frame of specimen

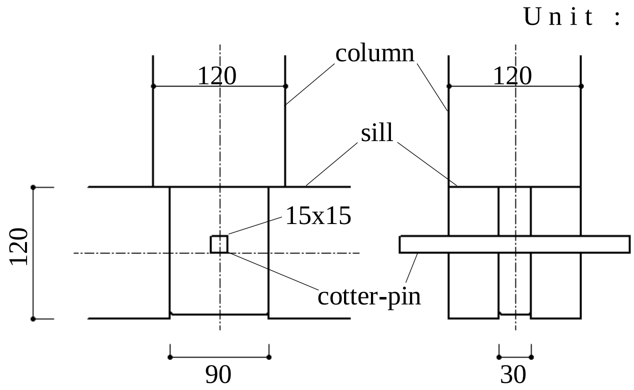


Figure 2. Detail of wood frame joint

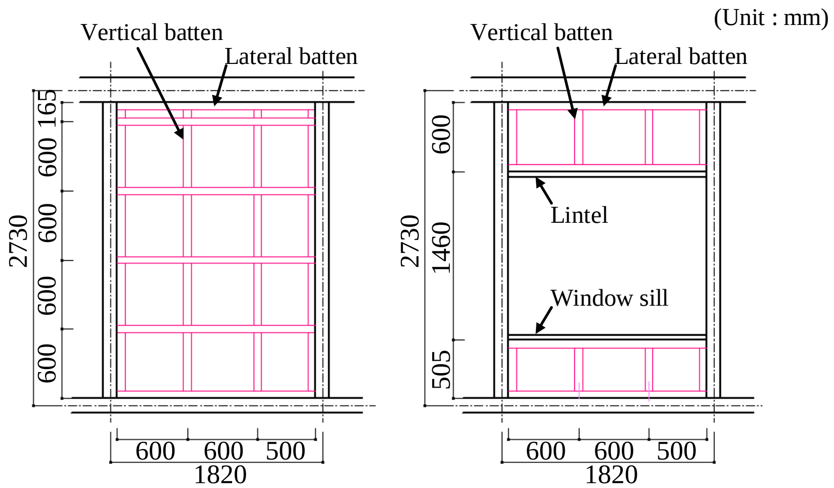


Figure 3. Wood frame with battens

Dry-mud panel was manufactured with natural mud, pieces of thin paper which was used for news paper etc. and chemicals to become solid. They are mixed with water and cast them into a panel. Before the casting, vertical and lateral wooden lattice at a distance of 150mm and 120mm, respectively, were placed in the casting frame to reinforce the mud. To install the panel into a wood frame, the each panel was cut to fit the inside measurement of a wood frame. The cut panel was fixed to vertical and lateral battens with 45mm wood screws spaced 200mm through the wooden lattice of the dry-mud panel as shown in Figure 4 and Figure 5. Original size of the panel is 600mm x 1800mm x 26mm and the weight is approximately 170N.

Figure 4. Specimen under fabrication (2F)

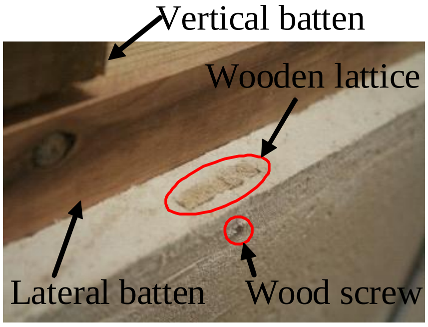


Figure 5. Dry-mud panel fastened by wood screw

There were three types of wall specimen with respect to wall length, namely 1P (910mm), 2P (1820mm) and 4P (3640mm) as shown in Table 1 and Table 2. The 1P specimen is single full-height wall with dry-mud panels. 2P specimens consist of single full-height wall, hanging wall, window-back wall and a combination of hanging wall and window-back wall. The specimen with wall length of 4P is a combination of the 1P and 2P specimen. In each type of 1P and 2P specimen, there were three specimens, while one specimen was prepared for 4P specimen. Average Young's modulus and moisture content of the specimen members were listed in Table 3.

Table 1. 1P&2P specimen for static shear loading test

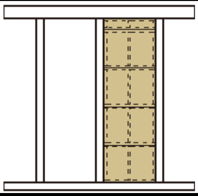
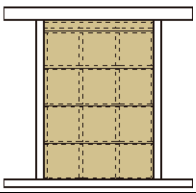
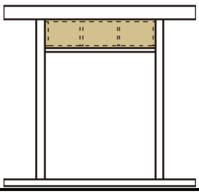
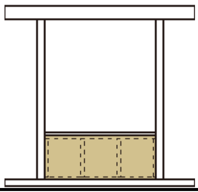
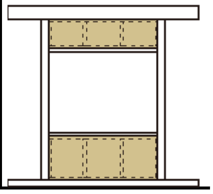
Specimen	1F	2F	2H	$2W_b$	$2HW_b$
Wall type	Full-height wall	Full-height wall	Hanging wall	Window-back wall	Hanging wall & window-back wall
Schematic					

Table 2. 4P specimen for static shear loading test

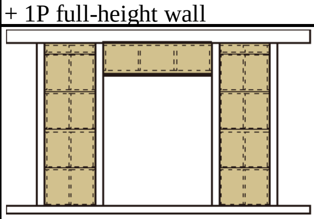
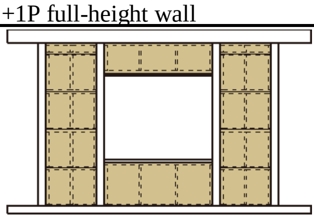
Specimen	1F-2H-1F	1F-$2HW_b$-1F
Wall type	1P full-height wal + 2P hanging wall + 1P full-height wall	1P full-height wall + 2P Hanging & window-back wall +1P full-height wall
Schematic		

Table3. Average Young's modulus and moisture content of wood frame

Member	Species	Average Young's modulus (N/mm^2)	Average moisture content (%)
Beam	Japanese cedar	7528	35.5
Sill	Japanese cypress	10089	32.5
Column	Japanese cedar	7875	25.5

In this static shear loading test, a weight of 10kN was applied to the top of the beam at two outside columns. The amount of the weight was determined from structural inspections of real traditional wooden buildings. No metal fasteners at joints and no tie-rods to prevent column from pulling out of sill were applied. Therefore, uplift of columns is expected to occur when large tensile force is applied to the column. In case an uplift of column occurs, the bottom end of a column was restricted and the loading was continued until at least story drift of 10%. Lateral repeated load was applied to the beam in accordance with the loading protocol as shown in Figure 6. Using displacement transducers, lateral displacement of a beam and relative displacement of the end of a column to a sill or a beam were measured. Additionally, bending strain of the end of a column was measured by strain gauges. Pin markers as shown in Figure 7 were also placed on the wood frame and panels to measure the coordinates.

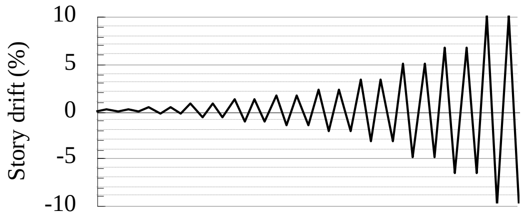


Figure 6. Loading protocol for static shear loading test

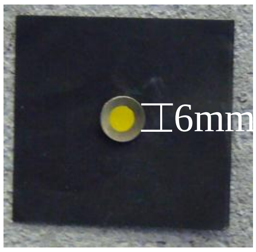


Figure 7. Pin marker

2.2. Test results

Figure 8 shows shear force-drift relationship of the specimens. A mean shear force-drift relationship among three specimens was showed on 1P and 2P specimen. Figure 9 shows average shear forces of the 1P and 2P specimens at each story drift. While uplift of columns was not observed during the loading in most specimens, only in 2F specimen during the drift from 5% to 6.7%, uplift of tensile column was occurred. During the uplift of column occurs, the tensile column was restricted within an uplift displacement of approximately 20mm.

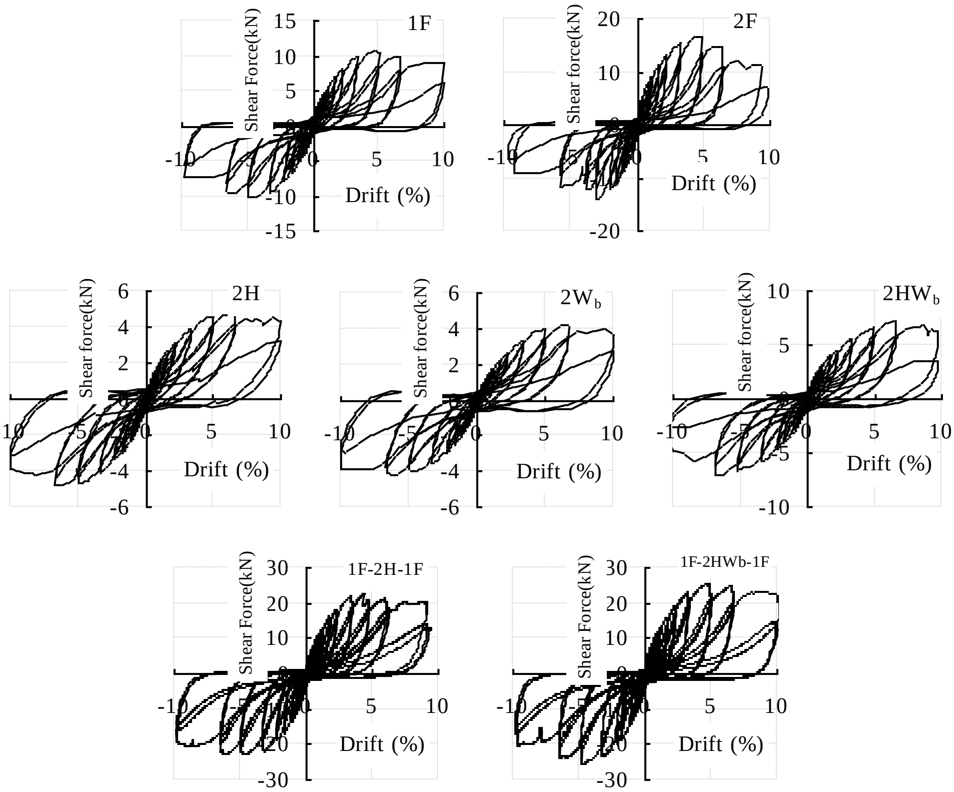


Figure 8. Shear force-drift relationship

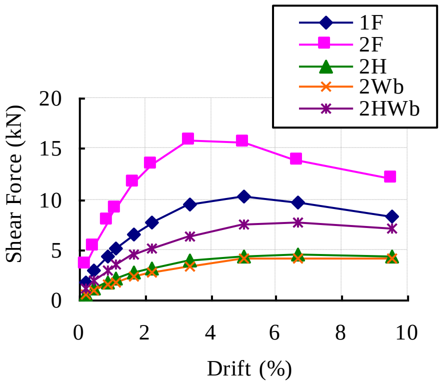


Figure 9. Average shear force-drift relationship

Average maximum shear forces of 1F and 2F specimens were 10.3kN at a drift of 5% and 15.8kN at a drift of 3.3%, respectively. Shear crack was occurred during the drift from 2.2% to 3.3%, and then, a piece of the panel was detached and the panel was swelled out of plane. As for the specimen with a hanging wall and the one with a window-back wall, namely 2H and $2W_b$ specimens, average maximum shear forces were 4.5kN and 4.2kN at a drift of 6.6%, respectively. The specimen with both a hanging wall and a window-back wall showed maximum shear force of 7.7kN at a drift of 6.6%. The ends of lintel and window sill were pulled out of column at a drift of approximately 0.83% as shown in Figure 10 and compressive failure at the corner of the panel and shear cracks on the panel were observed. After the test, the specimens were taken down and damages on each member were inspected. On the inside faces of columns, embedment by the wooden lattice in the dry-mud panel was detected as shown in Figure 11. At the column-sill and column-beam joints, shear failure at the end of the tenon along grain was observed as shown in Figure 12. The damage of the cotter-pins was generally slight. In 4P specimens, same damages as in 1P and 2P specimens were observed. Maximum shear force of 1F-2H-1F was 22.7kN and the one of 1F-2HW_b-1F was 25.7kN.

Figure 10. Joint of window sill-column at a drift of 6.6% (2Wb)

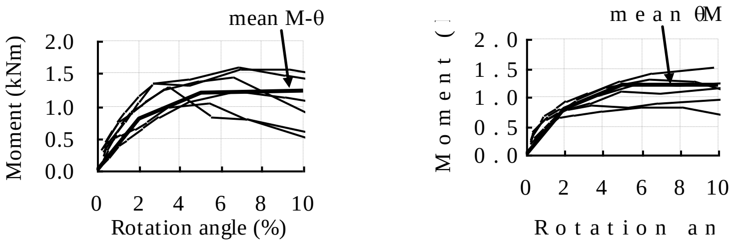
Figure 11. Embedment on the inside face of column (2HWb)

Figure 12. Shear failure of tenon (2HWb)

2.3. Estimation of shear force carried by wood frame

The shear force mentioned above contains the one carried by the wood frame. Calculation of bending moments and rotation angles at the bottom ends of columns of 2H specimens was done, moment-rotation angle relationship of the column-sill joints was shown in Figure 13(a). In the Figure 13(a), mean moment-rotation angel relationship was also indicated. The bending moments were calculated using Young's modulus of the columns and strains measured by strain gauges on the bottom ends of column. From the calculated results, it is found that the bending moment at rotation angles of 3.3% and 6.6% are approximately 1.0kN·m and 1.2kN·m, respectively, therefore shear force carried by a wood frame with two columns at story drift of 3.3% and 6.6% are approximately 1.5kN and 1.8kN, respectively. Consequently, approximately 40% of the maximum shear force of 2H or $2W_b$ specimen is carried by the wood frame. As for 1F specimen, since it has three columns, shear forces of

2.3kN and 2.8kN are estimated to be carried by a wood frame at story drifts of 3.3% and 6.6%, respectively. Moment-rotation angle relationship of the column-beam joints $2W_b$ specimens was shown in Figure 13(b). The tendency was the same as the one of the column-sill joints in 2H specimens



(a) Bottom end of colum (b) Top end of column

Figure 13. Bending moment-rotation angle relationship at joint

3. PUSH-OVER ANALYSIS

3.1. Analysis model

Analysis model for push-over analysis was developed as follows. Though the dry-mud panels were fastened by wood screws through the wood lattice in the dry-mud panel, the ends of wood lattice were split due to shear force. On the other hand, embedment by the wooden lattice was occurred on the surface of column. Considering the observations, each panel transfers a shear force as a compressive force along the diagonal line of the panel. Analysis models of 2P full-height wall and 2P hanging wall are shown in Figure 14. The analysis models have diagonal non-linear springs representing the shear force-displacement relationship of a panel. The shear force carried by a panel was derived by subtracting a shear force carried by a wood frame from a shear force applied to a full-height wall specimen, and dividing the remainder by four. The shear displacement of a panel was calculated from the in-plane coordinates of markers attached on the surface of columns. Using the shear force-displacement relationship, shear force-displacement relationship of a panel was derived and modelled as shown in Figure 15.

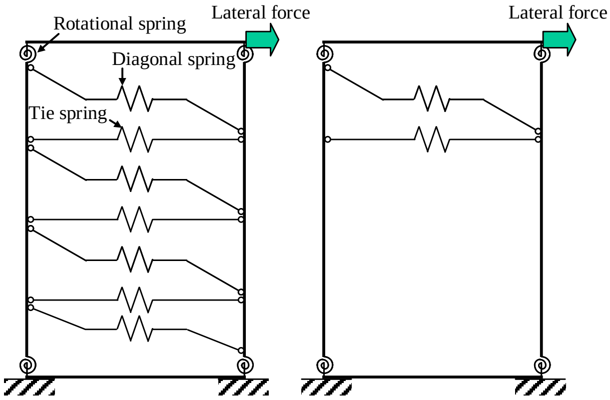


Figure 14. Analysis models

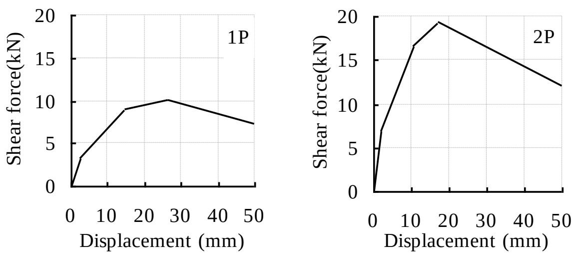


Figure 15. Shear force-displacement relationship of a panel

In addition to the diagonal spring, lateral tie springs were arranged in the models, which connect two columns together. The force is considered to be generated by lateral wooden lattice, lateral battens and a lintel and a window sill. However the magnitude of the force is not able to be estimated from the static shear loading test results, it was defined as 3kN/mm to show good agreement with the test results with respect to shear force-story drift relationship of the specimens.

Figure 16 shows push-over analysis results and experimental results of the specimens in static shear loading test. The total weight of 20kN was applied to the analysis model to consider P-δ effect. Young's modulus of column, beam and sill used in the analysis model were the measured values of the corresponding specimen. The results show good agreement with the experimental results, the analysis model is considered to be adequate.

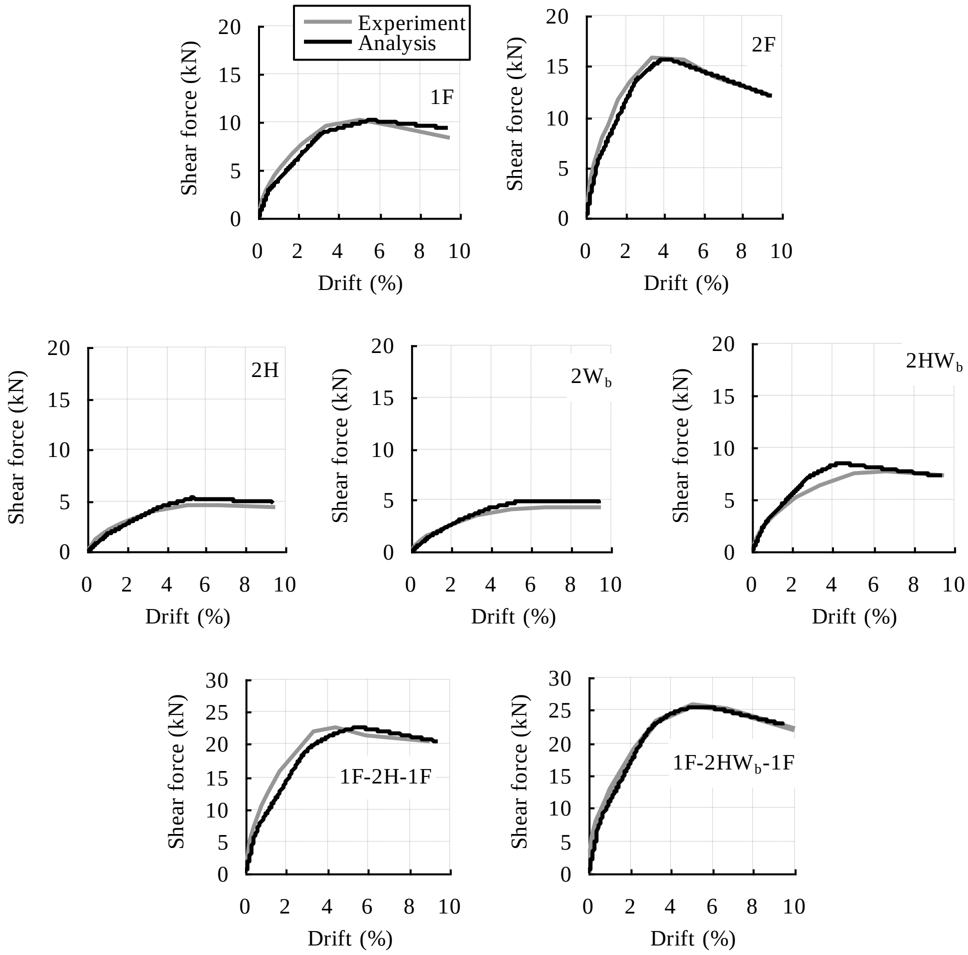


Figure 16. Push-over analysis results and experimental test results

3.2. Evaluation of shear force-displacement relationship of combined walls

To estimate shear force-displacement relationship of hanging and/or window-back wall, not only shear stiffness of the panel itself but also flexural rigidity of column is needed to be considered. In the case of hanging and/or window-back wall adjoining a full-height wall, shear force-displacement relationship is different from the case of single wall because bending deformation of the column with hanging and/or window-back wall is restricted by the full-height wall. Push-over analysis of the combinations of full-height wall and hanging wall as shown in Figure 17 was conducted, and comparison between the analysis results and the summation of shear force-displacement relationships of single full-height wall and single hanging wall was conducted. In this analysis, column-sill and column-beam joints were assumed to be pin, Young's modulus of column and beam was 7kN/mm^2. No vertical weight was applied to the analysis models. Applied shear force on each analysis was one direction. After the one directional loading, analysis under another direction was also conducted. To calculate the summation of the shear forces of single full-height wall and single hanging wall, shear force-displacement relationships of single walls were derived from push-over analysis under above mentioned conditions.

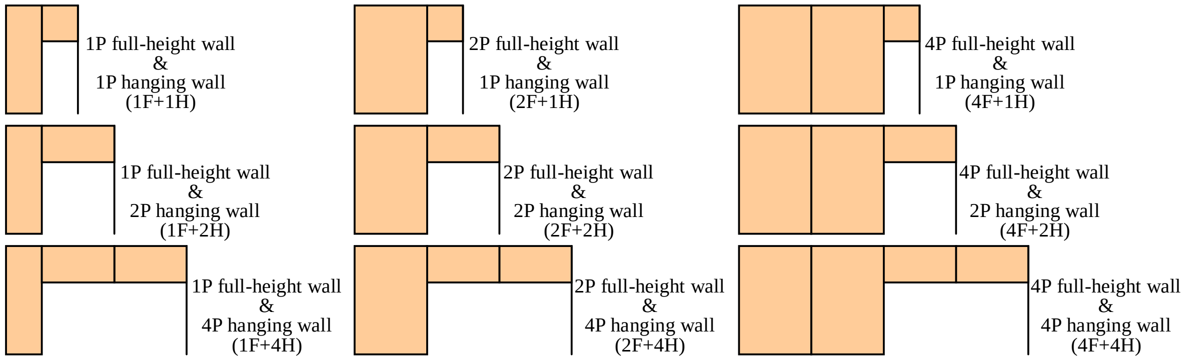


Figure 17. Configuration of combined analysis model

Figure 18 shows the result in the case of columns with cross section of 120mm x 120mm. The value of vertical axis in Figure 18 is derived by dividing analyzed shear force of combined model by summation of shear forces of single full-height wall and single hanging wall. The values were calculated at 1/120rad, 1/60rad, 1/30rad and 1/15rad (story drift of 0.83%, 1.67%, 3.33% and 6.67%). It is found from the figure that the value of vertical axis becomes larger as the wall length of hanging wall increases. Moreover, as the wall length of full-height wall increases, the value of vertical axis decreases. In most of these cases, the values of axial axis were more than 1.0, it is found that analyzed shear force of combined model is larger than summation of shear forces of single full-height wall and single hanging wall except for the values at 1/15 rad(6.67%). It is due to the increase of shear force carried by the hanging wall panel at each displacement.

Figure 19 shows shear forces carried by a hanging wall panel in the case of a combination of 2P hanging wall and 2P full-height wall. Comparing this result to the one in the case of a single 2P hanging wall, the shear force in the former case is higher than the one in the latter case until around 1/20 rad (story drift of 5%).

Figure 20 shows the result in the case of columns with the cross section of 150mm x 150mm. The tendency is the same as the case of 120mm x 120mm column, the values of vertical axial is lower than the case of 120mm x 120mm column because the flexural rigidity of the column is 2.4 times as much as the one of the column with the cross section of 120mm x 120mm. Figure 21 shows the result in the case of a combination of full-height wall and both hanging wall and window-back wall. The cross section of the columns is 120mm x 120mm. Due to presence of both hanging wall and window-back wall at the same columns, flexural rigidity of the columns became higher. Consequently, the values of vertical axis are lower than the above two cases.

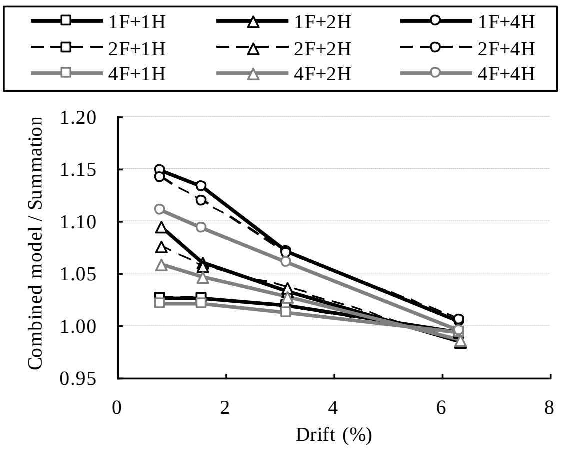


Figure 18. Shear force ratio of full-height and hanging wall in the case of 120mm x 120mm column

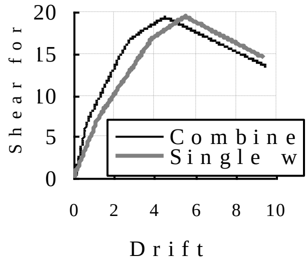


Figure 19. Shear force carried by a panel of hanging wall

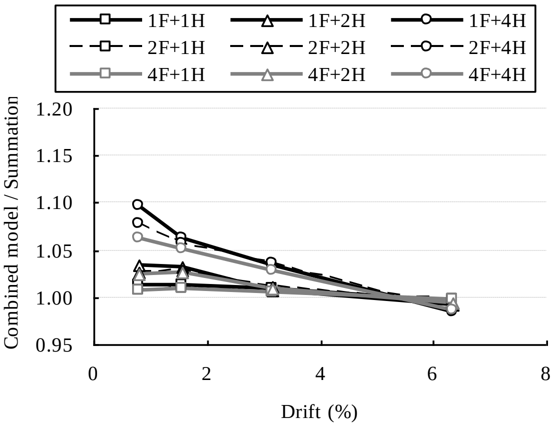


Figure 20. Shear force ratio of full-height and hanging wall in the case of 150mm x 150mm column

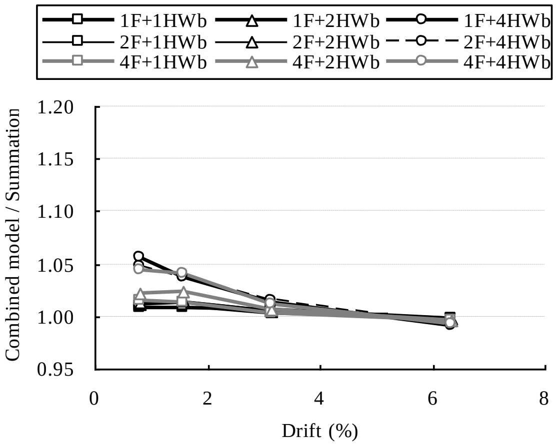


Figure 21. Shear force ratio of full-height, hanging and window-back wall in the case of 120mm x 120mm column

4. CONCLUSIONS

Static shear loading test on single full-height walls, hanging walls and window-back walls with dry-mud-panels was conducted. And then, push-over analysis of various combinations of full-height wall and hanging and/or window-back wall was performed. From the results of the push-over analysis, it was found that summation of shear forces of single full-height wall and single hanging and/or window-back wall is higher than the shear force of combined model except for relatively large deformation range. Consequently, to calculate shear force of a traditional wooden building with dry-mud panel, it is considered that summation of shear forces of single full-height wall, hanging wall and window-back wall gives conservative evaluation. Though hanging wall and window-back wall play a role as effective shear resisting element in traditional wooden building, it is needed to be careful with bending failure of column with the hanging and/or window-back wall in relatively large deformation range.

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