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EFFECT OF SMALL OPENINGS ON SHEAR CAPACITY OF PLYWOOD SHEATHED SHEAR WALLS

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ABSTRACT: In plywood shear walls used for interior walls, small openings are provided for the installation of piping. With the increase in the number of medium and large wooden buildings, it is necessary to accurately calculate the earthquake resistance of each member, as the requirements for the earthquake resistance of elements have increased. The purpose of this study is to verify the effect of small openings on the shear capacity of plywood shear walls. 1820 x 910 mm plywood shear walls with small 350 mm wide square openings were used as a preliminary element test. The results indicate that the location of the opening affects the shear failure behavior of the plywood and its ability to resist loads after maximum load. Based on the results of the element tests, full scale plywood shear walls with small openings were developed with the same performance as those without the opening.

KEYWORDS: small opening, racking test, plywood sheathed shear wall, medium- and large-sized wooden buildings

1 INTRODUCTION

In order to prevent global warming and realize a sustainable society, the use of wood is being promoted worldwide. In recent years, the expansion within medium and large scale wooden buildings has received much attention. However, the change from residential scale to medium and large scale brings challenges in various aspects, such as changes in building design methods and preparation of codes. Small openings in plywood shear walls, which are the subject of this study, are one such example. Small openings are made in interior walls to install ducts, outlet boxes, switch boxes, etc. In the past, for small residential buildings, it was not a problem to consider shear walls with small openings as non-shear walls. This was because the entire building had a surplus of earthquake resistance. In fact, in general wooden houses, openings as small as ventilation ducts were allowed in shear walls at the discretion of the building control officer. Therefore, there was almost no research on shear walls with small openings, and no theory for calculating the shear capacity of walls was established. However, as buildings have become larger, the required earthquake resistance has increased. There is no longer a margin for the earthquake resistance of the entire building, and it is necessary to verify the loss of performance due to small openings. In addition, the current standards for small openings have no experimental or theoretical basis, and their applicability to high-strength shear walls is also unclear. It is dangerous to apply the current standards, which are designed for residential buildings, to medium and large timber buildings. It is urgent to establish a new method to accurately calculate the performance of shear walls with small openings in order to promote medium and large wooden buildings and create a sustainable society. Therefore, the purpose of this study is to verify the effect of small openings on the shear capacity of plywood shear walls and to propose small opening size, location, and reinforcement method for a plywood sheathed shear walls with small openings to have the same performance as those with no openings.

2 PRELIMINARY ELEMENT SPECIMEN

2.1 SPECIMENS

Figure 1 and Table 1 shows the preliminary element test specimen and members, a plywood shear wall. The thickness of the plywood is 24 mm, the density is 0.57g/cm^3, and seven layer. The wall size was 1820 mm in height and

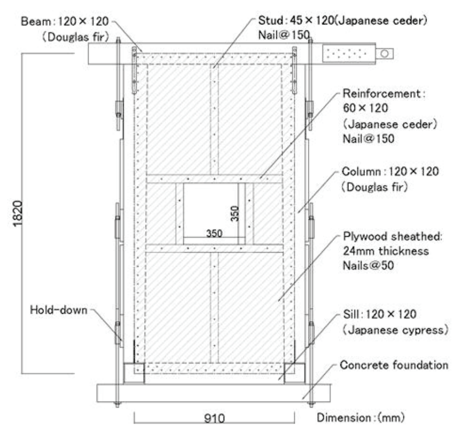

Figure 1: *Preliminary element test specimen*

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910 mm in width, with a small 350 mm square opening, assuming that the pipes used in medium and large wooden buildings have an outer diameter of about 300 mm. When making small openings, holes are drilled at the four corners and then cut in straight lines. The principle of specimen naming and a simplified diagram of each specification are shown in Figure 2. The first half of the specimen name was named after one of the four types of small opening locations (MM, EE, EM, ME), and the second half was named after the reinforcement method (-N, -S, -HS, -SH). The parameters were the location of small openings and the method of reinforcement, and a total of 12 specimens were made, one for each of the 12 specifications. The nails and screws used are shown in Table 2 and Figure 3.

Table 1: *Members of specimens*

Member	Species	Cross-sectional Area(mm)	Dencity (kg/m^3)	Moisture Content(%)
Beam	Douglass fir	120×120	555	13.3
Column			510	15.6
Sill	Cypress		534	16.8
Stud	Ceder	45×120	390	17.0
Reinforcement		60×120	458	19.4

Common 75 mm long nails were used to join the plywood to the framing at 50 mm pitch and for the studs and opening reinforcement at 150 mm pitch. The studs and opening reinforcement were fastened with two 100 mm long structural screws for each joint. Beam-to-column connections were made with mortise and tenon, foundation-to-column connections were fastened with box-type column leg hardware, and foundation-to-base connections were fastened with hold-down connectors.

2.2 TEST METHODS AND EVALUATION

The static load test was conducted according to the racking test in "Wood Frame House Construction in Japan"[1]. The deformation angle was provided by the horizontal displacement height of the specimen. And the three-time cyclic test was conducted at each deformation angle of 1/450, 1/300, 1/200, 1/150, 1/100, 1/75, 1/50, and 1/30. The envelope curve was determined using the load-displacement test data of cyclic loading. Yield strength (P_y) was obtained from the intersection of the line connecting 0.1 P_{max} point and 0.4 P_{max} point and the tangent line to the envelope curve parallel to the line connecting 0.4 P_{max} point and 0.9 P_{max} point. The stiffness (K) was obtained by dividing the yield strength by the yield displacement (δ_y). Ultimate displacement (δ_u)was obtained from the point where the load dropped to 0.8 P_{max} after P_{max}. Ultimate strength(P_u) was obtained from the point where the area of the trapezoid is equal to the area bounded by the envelope curve and the ultimate displacement. P_y, K, P_u are obtained as shown in Figure 5. Displacements of the test were measured by transducers shown in Figure 4.

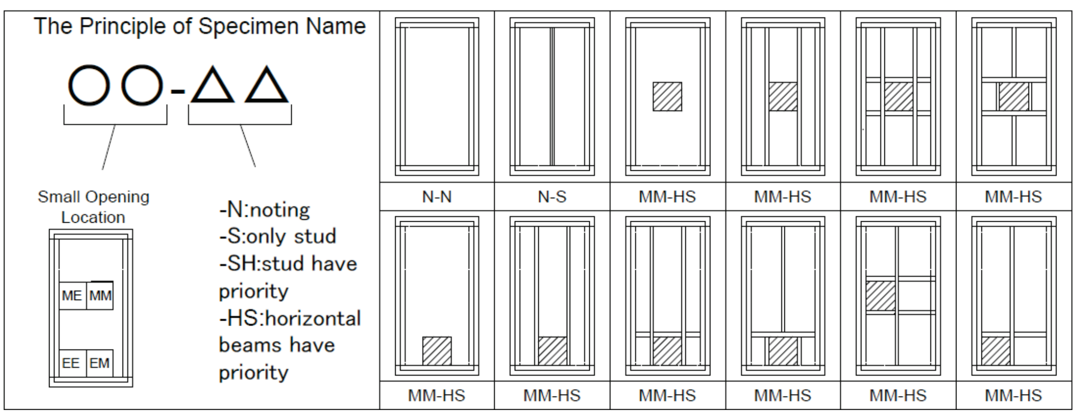

Figure 2: *Preliminary element test specimen*

Table 2: *Detail of Nails and Screws*

	L(mm)	D(mm)	d(mm)	s(mm)
CN75	76.2	7.92	3.76	—
P6-100	100	11.5	6.00	30.0

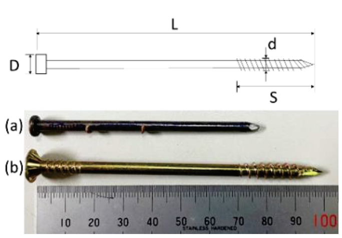

Figure 3: *Nails and Screws*

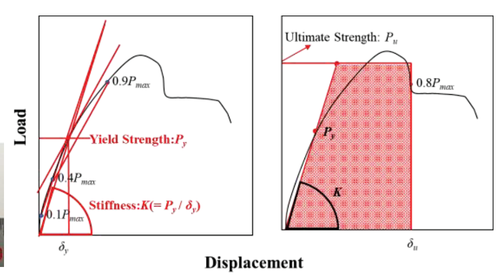

Figure 4: *Evaluation methods on yield strength and ultimate strength*

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2.3 TEST RESULTS AND DISCUSSION

Figure 5 shows the load-deformation angle relationship and Table 3 shows the results. Out-of-plane buckling of the plywood did not occur even in the specification with the lowest ability to suppress buckling. The cause of the decrease in strength in the small opening specifications was shear failure of the plywood, as shown in Figure 6. Cracks started at the corners of the small openings at 1/50 rad and expanded with increasing deformation, reaching the edges of the plywood at about 1/30 rad. In the case where the distance from the opening corner to the plywood edge was short as shown in Figure 7, the cracks starting from the opening corner reached the plywood edge relatively early, but the other parts of the plywood were not damaged and the load continued to increase slowly because the shear force was transferred to the column assembly through the opening reinforcement. On the other hand, when the distance was long as shown in Figure 8, it took time for the crack to reach the plywood edge, so the wall deformation proceeded, but after the crack reached the plywood edge, the plywood was damaged more and the load was maintained while the shear failure zone was crushed.

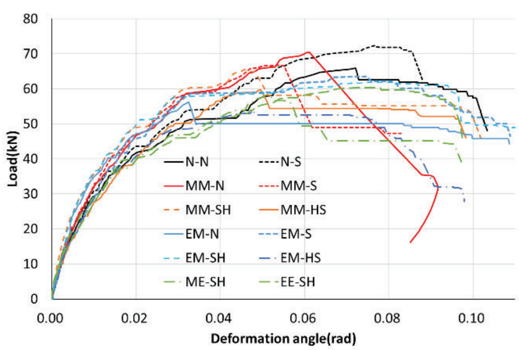

Figure 5: *Load deformation angle relationship of preliminary element test*

Comparing the specification with no openings and those with openings and no reinforcement, it was assumed that the performance of the specification with openings and no reinforcement was lower because of the openings in the plywood. In fact, this trend was confirmed for the EM specification, but the MM-N specification had the highest maximum load of all specifications, an unnatural result that was thought to be due to variation. Therefore, the following discussion is based primarily on the trends in the EM specifications. In comparing the specifications with and without reinforcement, the performance of the specifications with reinforcement was better, confirming the usefulness of the reinforcement. Comparison of the specifications without openings and those with openings and reinforcement indicated that the performance of the specification with openings would be lower, but no significant decrease in stiffness was observed. This is due to the increase in the number of joints because the plywood and the opening reinforcement were fastened with nails, and the opening reinforcement and the frame were fastened with screws. On the other hand, the strength of the plywood was lower because all the openings were

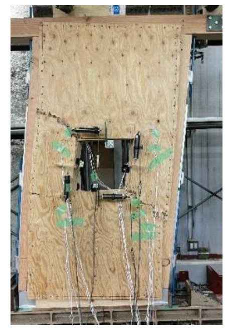

Figure 6: *Failure of entire specimen(MM-HS)*

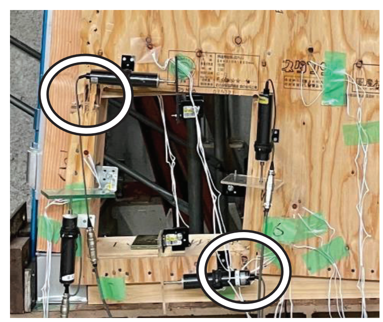

Figure 7: *Short cracks of plywood*

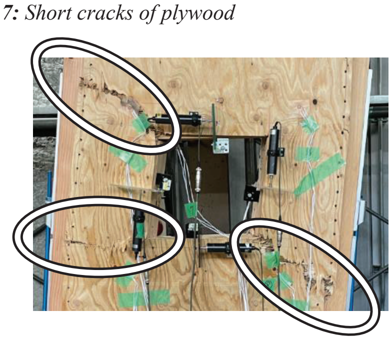

Figure 8: *Long cracks of plywood*

Table 3: *Results of preliminary element test*

	N-N	N-S	MM-N	MM-S	MM-SH	MM-HS	EM-N	EM-S	EM-SH	EM-HS	ME-SH	EE-SH
K(kN/rad)	2462	2775	2541	2918	3887	2391	3989	2763	4114	2558	2642	2447
Py(kN)	35.7	35.8	40.3	38.3	32.1	32.7	29.6	35.5	32.2	31.3	31.3	37.1
Pmax(kN)	65.1	69.9	70.6	66.7	65.5	59.7	56.2	63.3	60.5	54.1	58.2	58.3
Pu(kN)	55.2	58.4	62.8	59.8	57.3	53.2	49.1	57.6	56.1	49.7	50.6	51.0

due to shear failure of the plywood, while those without openings were due to failure at the nail joints. Regarding the method of reinforcement, the -SH specification performed better. It was expected that the short reinforcement would carry the stresses more efficiently. However, contrary to expectations, an extra stud was placed, increasing the number of nails and thus improving the performance of the wall.

3 ANALYSIS

3.1 ANALYSIS MODEL

The analysis was performed to verify the effect of variation in the preliminary test and to confirm the detailed stress state. The analysis was conducted using the SNAP analysis software and the analysis model is shown in Figure 9. The Multi Shear Spring(MSS) model was used for the nails. The restoring force characteristics of the nails were obtained from the results of the nail single shear test, which was carried out as an elementary test through the monotonic loading test of the rocket type shown in Figures 10. As shown in Figure 11, four lines were substituted, including the negative slope after the maximum load. The evaluation of the nail shear test was in accordance with the Wood Frame House Construction in Japan. Each point was set as follows for the average of three specimens based on the element test results.

First point: (P_y, δ_y)
Second point: (P_u, displacement of an arbitrary upper point coinciding with the envelope)
Third point: (P_{max}, δ_{Pmax})
Fourth point: (0.8 P_{max}, δ_u)

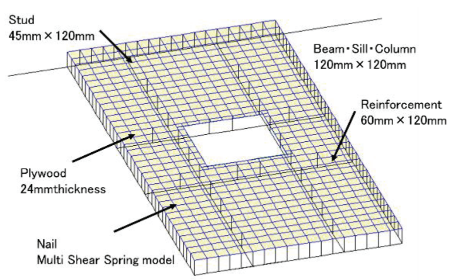

Figure 9: *Analysis model*

Figure 10: *Monotonic loading test of the rocket type*

The boundary conditions were pin supported on one side of the foundation and roller supported on the other. All joints between members were pin joints. The cross sections and nail positions were the same as in the preliminary tests, and only the nails on the four perimeters of the plywood were placed at the edges of the plywood. Physical properties were obtained from the literature. Forced displacement was applied in the positive direction of the x-axis of the beam, with a target displacement of 182 mm and a displacement increment of 0.2 mm per step, for a total of 910 incremental analysis steps.

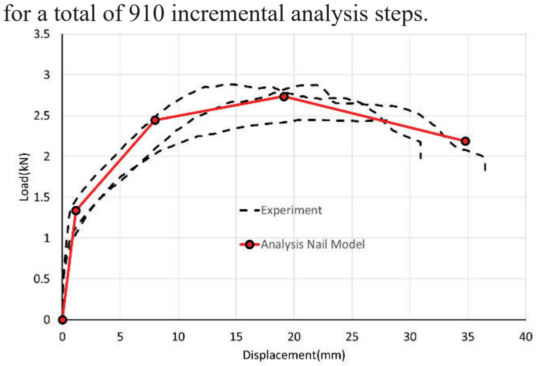

Figure 11: *Load displacement relationship of loading test*

3.2 ANALYSIS RESULT AND DISCUSSION

The load-deformation angle relationships obtained from the analysis are shown in Figure 12, and Table 4 compares each of the analytical values obtained from the analysis with the experimental values. The outline of the curves and the ratio of experimental to analytical values in Table 3 show that, although there are a few large deviations, the overall trend is generally captured.

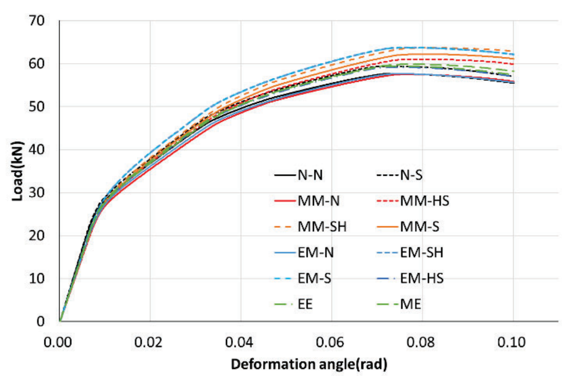

Figure 12: *Load deformation angle relationship of analysis*

The analysis results showed that the specimens with openings and reinforcement had the highest maximum loads, followed by those without openings, and those with openings and no reinforcement had the lowest loads. With no reinforcement, the specimens with openings, which are weak points, had the lowest load capacity. In the case with reinforcement, the load was higher with more nails, supporting that the nails were the main factor in the resistance mechanism.

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Table 4: Results of analysis

	N-N	Ratio*	N-S	Ratio*	MM-N	Ratio*	MM-S	Ratio*	MM-SH	Ratio*	MM-HS	Ratio*
K(kN/rad)	2846	1.16	2744	0.99	2547	1.00	2494	1.00	2524	0.65	2452	1.23
Py(kN)	28.5	0.80	30.2	0.84	28.0	0.70	29.9	0.70	30.3	0.94	29.4	0.93
Pmax(kN)	56.8	0.87	59.4	0.85	56.1	0.79	60.2	0.79	61.5	0.94	59.2	0.99
Pu(kN)	47.9	0.87	49.9	0.86	47.3	0.75	51.0	0.75	51.9	0.91	50.3	0.94

	EM-N	Ratio*	EM-S	Ratio*	EM-SH	Ratio*	EM-HS	Ratio*	ME-SH	Ratio*	EE-SH	Ratio*
K(kN/rad)	2585	0.65	2481	0.90	2634	0.64	2485	1.20	2661	1.25	2662	1.25
Py(kN)	28.4	0.96	32.3	0.91	31.6	0.98	29.8	0.95	29.3	0.94	29.3	0.87
Pmax(kN)	56.5	1.01	62.7	0.99	62.3	1.03	58.3	1.08	58.5	1.01	58.4	1.02
Pu(kN)	47.8	0.97	52.5	0.91	52.8	0.94	49.7	1.00	49.1	0.99	49.4	0.98

Ratio* means 'Ratio to experimental value' (analsis value/experimental value)

The behavior after yielding was considered to be improved by adding appropriate rotational stiffness to the ends of each member in the analytical model instead of pin joints. The plasticity factor tended to have a large error due to its small value. On the other hand, this analytical model does not consider the shear failure of the plywood, so a new method that can estimate the behavior after the end of the phase is needed to predict the overall behavior.

4 FULL SCALE TEXT

4.1 SPECIMEN

To verify the applicability of the preliminary element test results to the actual building, eight 24 mm plywood sheets, four on the front and four on the back, were attached together for a full-scale test of a 3340 mm height and 1820 mm length shear wall as shown in Figure 13. Beam connectors and hold-downs were used for column head connections. Lag screws (ϕ45, 600 mm) was used for the column legs. 110 mm screws were used to fasten the reinforcement to the frame. As in the preliminary test,

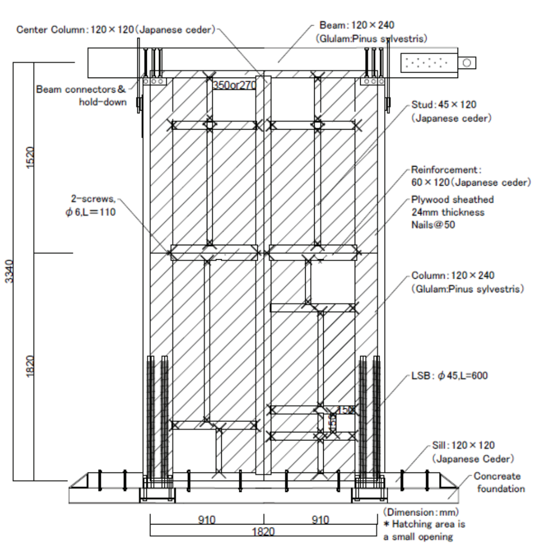

Figure 13: Full scale test specimen

a small 350 mm square opening was made in each faceplate. The number of specimens tested was three for the specimen with no opening and four for the specimen with openings including the preliminary test. The small openings were located at the four corners where performance was estimated to be lowest based on the preliminary element test results, assuming actual construction. An additional 150mm opening for a switch box was provided in the bottom plywood to make the specifications similar to actual installation. Based on the preliminary test results, the size of the small openings in the full-scale test was reduced to 270mm square when small openings are provided at the same height, and the nail pitch to the studs and opening reinforcement was modified from 150mm to 100mm.

4.2 TEST RESULTS AND DISCUSSION

Figure 14 shows the load-deformation angle relationship. The experimental values calculated from them are shown in Table 5. The failure of the preliminary test and the main test are shown in Figure 15 for the entire and in Figure 16 for the upper opening(Left:preliminary,Right:main). Preliminary test results showed that the performance similar to that of the no-opening specification could not be achieved because the center columns failed in bending and the load dropped rapidly. The bending failure of the columns was caused by stress concentration on the columns because the plywood could not resist the shear stress after the cracks from the opening corners reached the plywood edges as in the preliminary test. In this test,

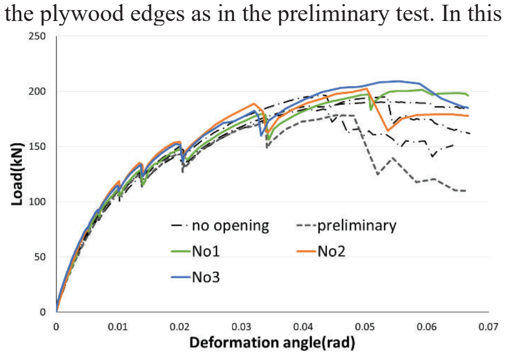

Figure 14: Load deformation angle relationship of full scale test

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crack propagation from the opening corner was suppressed and brittle failure did not occur up to 1/15 rad, confirming that the performance was equivalent to that of the no opening specification. The failure behavior at the end of the test was that the plywood around the opening on the column leg side failed as shown in Figure 17 and the plywood could no longer bear the load, resulting in collective failure of the LSB on the column leg on the tension side and buckling failure of the columns on the compression side as shown in Figure 18 and 19.

Table 5: *Results of full scale test*

	no opening*	opening			
		Prelininary	No.1	No.2	No.3
K(kN/rad)	11924.3	11292	10230	12392	10774
P_{max}(kN)	190.5	178.4	201.3	202.3	209.0
P_y(kN)	102.9	103.8	113.5	111.0	117.1
P_u(kN)	173.3	157.8	181.1	175.4	186.8

*Average of three specimens

Figure 15: *Failure of entire specimen*

Figure 16: *Failure of upper opening*

Figure 17: *Failure of plywood around the opening on the column leg side*

Figure 18: *Collective failure of the Lag screws*

Figure 19: *Buckling failure of the columns*

5 CONCLUSIONS

Preliminary element tests were conducted on a plywood bearing wall 1820 mm high and 910 mm wide with a small 350 mm square opening for a piping. The results indicate that the location of the opening changes the degree of damage to the plywood and may subsequently affect the shear capacity of the wall. In combination with the results of the analysis, it was estimated that the opening positions with the lowest performance were those closer to the four corners. Based on these results, full-scale tests were conducted on an actual medium- to large-sized wooden shear wall. Preliminary tests revealed that shear walls with small openings did not perform as well as walls without openings. When the small openings were horizontally connected, the nail pitch to the opening reinforcement was narrowed by setting a limit based on the opening size. As a result, it was confirmed that the performance of the wall with small openings was equivalent to that of the wall without openings. In this study, the size, location, and reinforcement method of small openings were proposed to ensure that plywood sheathed shear walls with small openings perform as well as those with no openings.

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