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STUDY ON ESTIMATION OF SHEAR STRENGTH OF PLYWOOD SHEATHED SHEAR WALLS WITH SMALL OPENINGS

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ABSTRACT: The purpose of this study was to determine the effect of small openings for water supply and drainage boxes, which have been ignored or not considered in residential-scale wood-frame buildings, on the shear performance of plywood sheathed shear walls. Therefore, small openings were installed in plywood sheathed shear walls and the walls were tested for shear. The test results showed that shear failure of the plywood occurred when the maximum strength above a certain level was reached. Since shear failure of the plywood is the main cause of the reduction in bearing capacity, a formula was developed to predict the shear force input to the plywood and an attempt was made to identify the mechanism of shear failure of the plywood. The calculated estimates were in close agreement with experimental values, confirming the validity of the formulas.

KEYWORDS: *Small-openings , Shear wall, Plywood, Shear failure of plywood*

1 – INTRODUCTION

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. 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 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 a method for calculating the capacity of plywood sheathed shear walls with small openings. Portions of this paper are reported in Reference[1].

2 – IN-PLANE SHEAR MODULUS AND SHEAR STRENGTH OF PLYWOOD

To measure the in-plane shear modulus of the plywood to be used prior to the experiment, a dynamic plate shear test shown in Figure 1 was performed. The plywood was suspended from the ceiling by four strings and supported at the center of the four sides. A strike was applied to one end of the plywood. The first-order resonance frequency was measured using the free software Wavespectra. 12-mm-thick plywood was cut into 350-mm squares, and the number of specimens was three. Equation (1) for calculating the in-plane shear modulus G is shown below.

$$G(10^{-14}\ N/mm^2)=0.9\rho(abfr/h\ )^2 \qquad (1)$$

a, b: length of each side of the plate (mm),
h: thickness of the plate (mm)
ρ : Density of the plate (kg/m3),
fr: Resonant vibration male number of the plate (Hz)

From Reference[2], the relationship between the in-plane shear modulus of elasticity and shear strength can be expressed as Equation (2). Table 1 shows the average values of in-plane shear modulus and shear strength calculated using Equations (1) and (2).

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τ_{max} (N/mm^2)=3.49+2.88G (2)

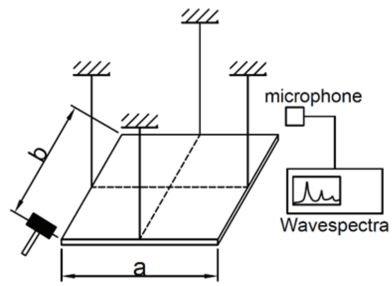

Fig.1 : Dynamic plate shear test

Table 1: In-plane shear modulas

	G(N/mm^2) : in-plane shear modulus
12mm plywood	0.65

3 – SPECIMENS OF SHEAR TEST

Figure 2 shows an example of a test specimen a plywood sheathed shear wall, Figure 3 shows an example of an opening pattern and Table 2 shows the list of test specimens. The wall was 1820 mm high and 910 mm wide; the small openings were in principle square, with diagonal lengths of about 150 mm, with no reinforcement around the openings, and with diagonal lengths of about 450 mm with reinforcement. In some specifications, the shape of the small openings was rectangular (height and width are shown in Table 2) and circle. In addition to the above opening shapes, the parameters were the position of the opening, the thickness of the plywood, the length of the nails, and the pitch of the nails that secured the plywood to the frame. Two structural screws, each 65 mm long, were used at the joint between the frame and the opening reinforcement. The frames were joined to each

Table 2: List of Specimens

Name	Frame Species	Thickness of Plywood (mm)	Nail length (mm)	Nail pitch (mm)	Small Opening Size(mm) Height	Width	Small Opening Position	Numbers of Specimens
s9_50@150_N-S	Japanese cedar	9	50	150	None			1
s9_50@150_s322MM					322		MM*1	3
s9_50@75_N-S			50	75	None			1
s9_50@75_s76MM					76		MM	3
s9_50@75_s76EE							EE*2	
s9_50@75_s322MM					322		MM	
s9_50@75_s322EE							EE	
b9_50@75_N-S	Douglas fir				None			1
b9_50@75_s76EE					76		EE	3
b9_50@75_s322MM					322		MM	
s12_50@75_N-S	Japanese cedar	12			None			1
s12_50@75_s102EE					102		EE	3
s12_50@75_s322MM					322		MM	
s12_50@50_N-S				50	None			1
s12_50@50_s322MM					322		MM	3
s12_65@75_N-S			65	75	None			1
s12_65@75_s322MM					322		MM	3
b12_65@50_N-S	Douglas fir			50	None			1
b12_65@50_s76EE					102		EE	3
b12_65@50_s322MM					322		MM	
b12_65@50_s322EE							EE	
b12_65@50_r644x322MM					644	322	MM	3
b12_65@50_r644x322EE							EE	1
b12_65@50_r150x322MM					150		MM	1
b12_65@50_r150x322EE							EE	1
b12_65@50_r455x150EE					455	150	EE	1
b12_65@50_r150x455MM					150	455	MM	1
b12_65@50_r150x455EE							EE	1
b12_65@50_c455MM					Circle(radius:455)		MM	3

Note: *1 "MM" means center, *2 "EE" means corner

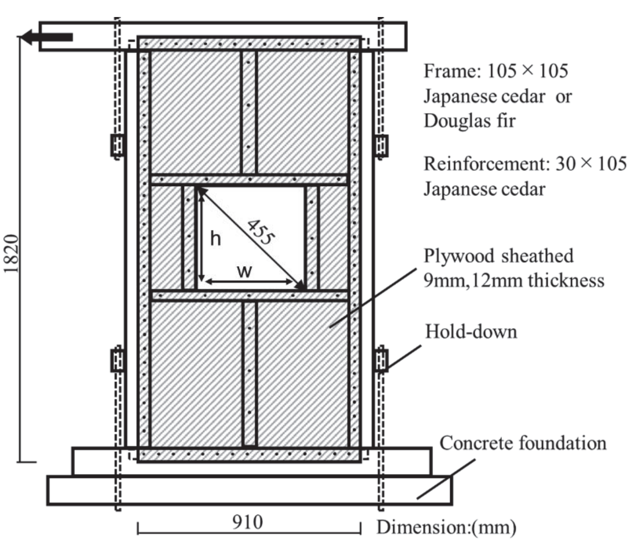

Fig.2 : Example of a test specimen a plywood sheathed shear wall

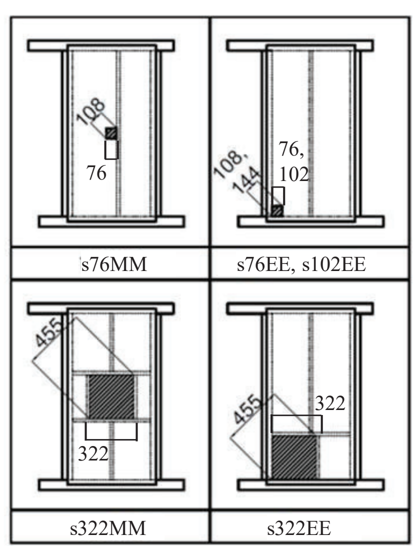

Fig.3 : Example of an opening pattern

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other using mortise and tenon, and the frames and foundation were secured with hold-down connectors.

4 –TEST METHODS AND EVALUATION

The static load test was conducted according to the racking test in "Wood Frame House Construction in Japan"[3]. 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 (Py) was obtained from the intersection of the line connecting 0.1 Pmax point and 0.4 Pmax point and the tangent line to the envelope curve parallel to the line connecting 0.4 Pmax point and 0.9 Pmax point. The stiffness (K) was obtained by dividing the yield strength by the yield displacement (δy). Ultimate displacement (δu)was obtained from the point where the load dropped to 0.8 Pmax after Pmax. Ultimate strength(Pu) 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. Py, K, Pu are obtained as shown in Figure 4. Displacements of the test were measured by transducers shown in Figure 4.

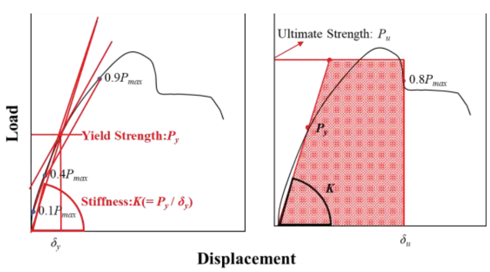

Fig.4 : Evaluation methods on yield strength and ultimate strengt

4 –TEST RESULTS

Figure 5 shows the relationship between load and shear deformation angle, and Table 3 shows the results calculated based on the full elastoplastic modeling. The following trends were observed in the fracture properties, load-deformation angle relationship, and each property value.

4.1 SPECIFICATION WITH NAILS DRIVEN @150mm

The toughness of the specimens was high because the nails yielded and demonstrated shear performance up to the end (1/15 rad) without failure of the opening, regardless of whether the opening was non-opening or opening was present. The shear performance did not decrease due to the small opening, and the reinforcement increased the bearing capacity, although only slightly.

4.2 No openings (N-S) or unreinforced openings with small diameters (s76EE, s76MM, s102EE)

No failure of plywood around the small openings was observed. Nail pullout, shown in Figure 6, occurred in the specification with the lower maximum strength, while nails punched out in the specification with the higher maximum strength. As a result, the load was reduced before reaching 1/15 rad. Shear performance of some specifications (b9_50@75_s76EE) was equal to or about 10% lower than that of the non-openings, but the non-opening was only one unit, and considering the variation, the reduction in shear performance due to small openings that do not require reinforcement can be nearly ignored.

4.3 openings with reinforcement (s322MM, s322EE)

Specification for plywood thickness of 9mm (s9_50@75, b9_50@75)

In s9_50@75_ s322MM, the plywood near the opening began to bulge out of the plane at about 1/30 rad, as shown in Figure 7, and at the same time a crack appeared in the diagonal corner of the compression side of the opening. The out-of-plane buckling of the plywood occurred at about 1/15 rad, and the cracks rapidly developed and the plywood failed in shear, resulting in a drop in load.At this time, the nails at the four corners of the plywood were sheared off, and no punching out, pulling out, or other failure was observed.

In the case of s9_50@75_ s322EE, shear failure of the plywood occurred at about 1/30 rad, as shown in Figure 8, but the load did not decrease. No out-of-plane flaring occurred, the plywood resisted except at the openings, the load increased after shear failure, and the load decreased due to nail pullout.Nail punch-out was virtually nonexistent, indicating high toughness. The reason for this is that although shear failure of the plywood occurred in both specifications, it occurred more slowly than in the specifications with 12 mm plywood thickness (s12_50@75, s12_65@75, s12_50@50, b12_65@50).

In addition, shear failure of the plywood in the two b9_50@75_ s322MM units occurred later, after 1/15 rad, and as shown in the load-deformation angle relationship, the deformation performance was equivalent to that of the non-aperture specimens. However, only the one-piece specimen showed out-of-plane buckling of the plywood near the opening corner at about 1/30 rad, resulting in a sudden drop in load. As a result, the toughness performance decreased. The out-of-plane buckling of plywood with a 9-mm-thick plywood opening is an issue to be addressed in the future.

Specification for plywood thickness of 12mm (s12_50@75, s12_65@75, s12_50@50, b12_65@50)

In s12_50@75_ s322MM, shear failure of the plywood did not occur and the failure behavior was similar to that of the non-opening specification. Therefore, the shear performance of s12_50@75_ s322MM was equivalent to that of the no-opening specification due to the reinforcement effect.

Although the shear failure of the plywood in s12_65@75_ s322MM reduced the load, the performance was improved compared to the no-opening specification due to the reinforcement effect. This was because it occurred later, after 1/20 rad, and did not work against the performance evaluation.

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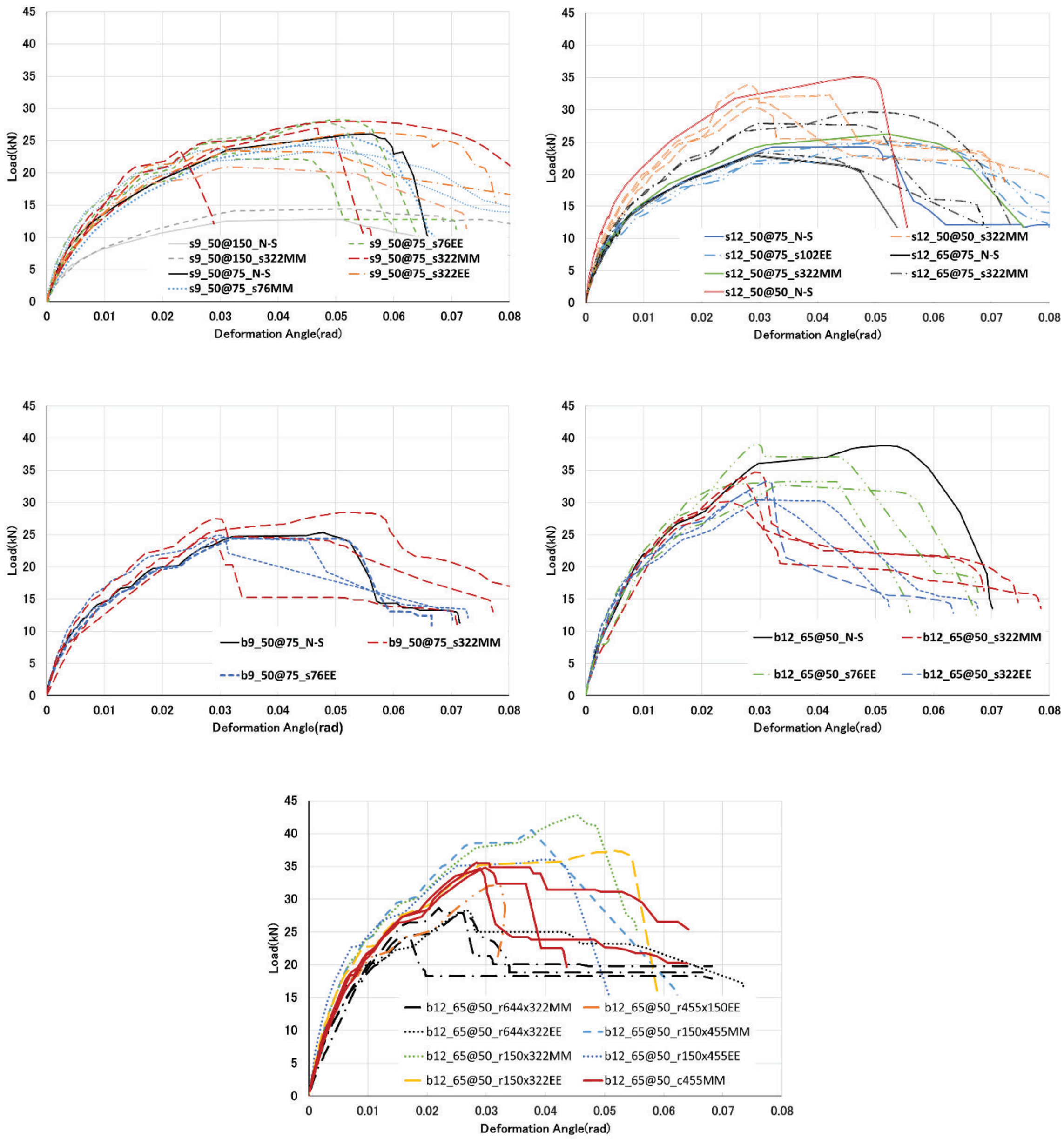

Fig.5 : Relationship between load and shear deformation angle

Table 2: Test results

	s9_50@150		s9_50@75					b9_50@75			s12_50@75			s12_50@50		s12_65@75	
	N-S	s322MM	N-S	s76MM	s76EE	s322MM	s322EE	N-S	s76EE	s322MM	N-S	s102EE	s322MM	N-S	s322MM	N-S	s322MM
K(kN/rad)	1072	975	1555	1711	1567	1402	1467	1741	1854	1577	2218	1779	1774	2748	2302	1858	2012
Py(kN)	6.8	7.2	12.4	13.5	14.3	14.6	14.2	12.8	12.8	13.6	12.8	12.9	14.0	17.7	15.9	12.6	13.9
Pmax(kN)	12.8	14.4	26.1	24.3	26.4	27.5	23.8	25.3	24.8	26.9	24.2	24.2	26.2	35.1	32.5	22.9	27.0
Pu(kN)	11.6	13.1	23.0	22.2	23.7	24.8	22.1	22.8	22.0	23.8	22.2	22.0	23.9	31.3	27.2	20.8	24.4

	b12_65@50											
	N-S	s102EE	s322MM	455EE	r644x322MM	r644x322EE	r150x322MM	r150x322EE	r455x150EE	150x455MM	150x455EE	c455MM
K(kN/rad)	2316	2359	2202	2606	2279	2608	2513	2684	2442	2687	3546	2489
Py(kN)	20.7	19.7	19.1	17.3	15.7	16.9	23.4	19.9	18.0	20.8	19.9	18.3
Pmax(kN)	38.9	35.1	33.2	32.2	26.9	28.4	42.8	37.4	32.2	40.5	36.0	35.0
Pu(kN)	34.9	32.4	29.6	27.6	24.3	24.3	37.3	33.7	27.0	35.4	32.6	30.7

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In the s12_50@50_ s322MM and b12_65@50_ s322MM shear failure of the plywood occurred at about 1/50 rad, and as shown in Figure 9, at 1/30 rad, the load reached the edge of the plywood and dropped rapidly, clearly reducing toughness compared to the no-opening specification. In the specification with a maximum strength exceeding 30 kN, when a small opening with a large diameter was provided that required reinforcement, the shear failure of the plywood starting from the corner of the opening caused a sudden drop in load, resulting in a reduction in the shear performance of the bearing wall.

4.3 THE SPECIES OF THE FRAMING

Comparing the species of the framing, the load on Douglas-fir was lower than that on Japanese cedar due to the earlier shear failure of the plywood. This was attributed to the higher density of Douglas-fir than Japanese cedar. In other words, the higher nail retention was attributed to the higher shear force input to the plywood at the same deformation angle.

4.3 POSITON OF SMALL OPENINGS

Comparing MM and EE, for smaller maximum strength, EE has lower maximum strength. This is due to the fact that the remaining width of the plywood is less due to the openings in the corners, resulting in early plywood failure. On the other hand, when the maximum strength is high, shear failure occurs in both specifications, and the maximum strength tends to be higher in EE, where the plywood is less damaged. It was observed that the narrower the remaining width of the plywood due to the opening, the smaller the maximum strength.

5 –SHEAR FORCE INPUT TO PLYWOOD

The shear failure of the plywood resulted in a sharp drop in the shear strength and a decrease in ductility. The shear force Q was estimated using the Equation (3)

$$Q = \tau \times t \times w \tag{3}$$

τ: Maximum shear stress (N/mm^2) $\tau = G \times \gamma_{max}$
G: In-plane shear modulus(N/mm^2)
γ_{max}: Maximum shear strain from a triaxial rosette gauge placed next to the opening.
t: Plywood thickness (mm)
w: Horizontal length of plywood excluding openings in the short side direction (mm: remaining width of plywood)

Fig.10 shows a comparison of the experimental values of the load on the shear strength wall and the estimated values of the shear force transmitted to the plywood. The estimated values generally agreed with the experimental value, indicating that the remaining width of the plywood bears the shear force in the vicinity of the opening.

Fig.6: Nail pulling through

Fig.7: Out-of-Plane Buckling

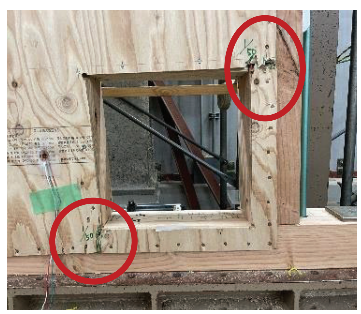


Fig.8: Shear Failure of Plywood (EE)

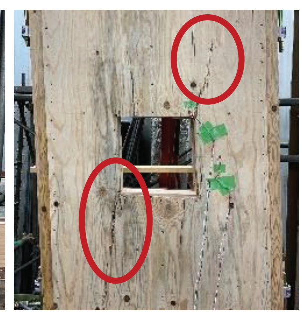
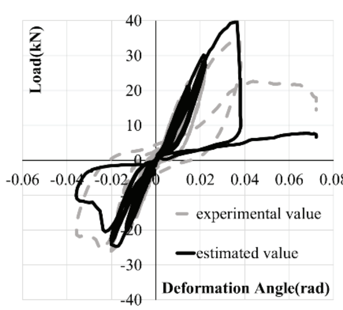
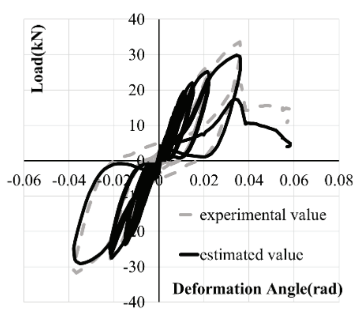


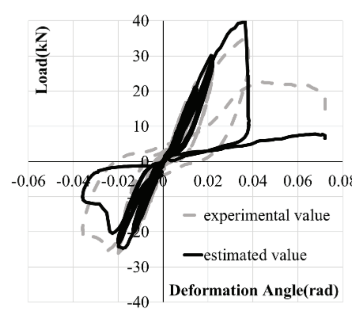
Fig.9: Shear Failure of Plywood (MM)



s12_50@50_455MM



b12_65@50_455EE



b12_65@50_455MM

Fig.10: Comparison of the experimental values and the estimated values.

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6 –CONCLUSION

No reduction in shear capacity due to small openings was observed for walls with low maximum strength on the residential scale or for small openings that did not require reinforcement. On the other hand, shear walls with high maximum strength, such as those used in medium- to large-sized wood-frame buildings, showed reduced shear capacity due to small openings that required reinforcement. Shear failure of the plywood was the primary cause of the reduction in maximum strength. It was confirmed that the remaining width of the plywood bore the shear strength.

7 – REFERENCES

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