Lateral Resistance Performance of Hybrid Shear Wall According to Structural Insulated Panel Installation Location

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In the post and beam structure, the post and beam play a crucial role in directly supporting and transmitting loads, thus making them essential elements in structural design. In cases where the moment resistance performance of the post-beam joint is inadequate, a shear wall and bracing are frequently installed to provide support for horizontal load on the posts and beams. The structural insulated panel (SIP) is increasingly utilized and studied as shear walls alongside light-frame timber construction, owing to its insulation properties as well as its high shear strength. In this study, when using SIP as a shear wall between post and beams, three composite wall structures were considered based on the installation location of the SIPs on the post-beam structure and lateral resistance performance of the hybrid shear wall was evaluated according to the SIP installation location. Depending on the installation location SIPs on the posts and beams, shear strength for I-SIP 150, E-SIP 150, and M-SIP 150 were 23.2, 24.6, and 26.0 kN, respectively. In case of the shear stiffness, I-SIP 150, E-SIP-150, and M-SIP 150 were found to be 4.32, 3.99, and 2.74 kN/mm, respectively.

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Keywords: Hybrid Shear Wall; SIP; Post and beam; Light-frame wall; Shear resistance; Lateral load

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INTRODUCTION

Wood structures can be broadly divided into light frame timber and heavy timber structures. In the case of a light frame timber structure, the shear wall is formed using lumber framing, sheathing panels, and nails, while in the case of a heavy timber structure, it is based on a post and beam framework. Post and beam structures have the advantage of being processed in advance using the pre-cut method and using steel connections, which allow for high precision and easy construction, reducing the amount of constructions period required on site. Post and beam structures can have wide interior spacing by installing column spacing widely, and it can create a natural interior effect by exposing the posts and beams.

In the post and beam structure, post and beam play a crucial role in directly supporting and transmitting loads, thus making them essential elements in structural design. In the post-beam joints, horizontal and vertical loads act simultaneously, leading to load concentration. Joints consisting of brackets, pins, or bolts are usually used in post-beam joints, so achieving moment-resistance performance can be difficult. In cases where the moment resistance performance of the post-beam joint is inadequate, shear wall or bracing are frequently installed to provide support for horizontal load on the posts and beams.

Structural insulated panels (SIP) are increasingly used and studied as shear walls alongside light-frame timber construction. This is due to their insulation properties and high shear strength. Khademibami *et al* (2023) evaluated flexural testing of structural insulated panels before and after creep testing. Kochkin *et al*. (2015) conducted a study evaluating the cyclic performance of SIP shear walls based on aspect ration and openings. Yeh *et al*. (2018, 2019) assessed the lateral load resistance of a fully bearing SIP and researched on the test protocol, nail size and spacing for SIP connections, and spline types. Rammer and Williamon (2020) evaluated the performance against seismic load of various SIP connected with block splines. Additionally, SIPs have higher insulation properties compared to other materials. Liu *et al.* (2020) measured the heat transfer coefficient when EPS (expanded polystyrene) and XPS (extruded polystrene), which are used in SIPs, were used as external insulation on wood frame walls with bracing. Lee *et al*. (2012) evaluated the fire resistance and insulation performance of structural insulated panels for application to low-energy house. It was concluded that SIPs can be employed as construction materials for low-energy houses, meeting the fire resistance and insulation performance requirements of wooden structural materials that fulfill both structural and insulating functions.

In a study by Sim *et al*. (2010), the lateral load resistance of a hybrid shear wall with SIPs infilled between posts and beams was evaluated. The SIP hybrid wall system demonstrated higher maximum shear strength, initial stiffness, ductility, and yield strength compared to those of a post and beam with a light-frame wall system. Except for the study by Sim *et al*. (2010), to the authors' knowledge, there has been a lack of research on SIP hybrid walls. In this study, therefore, three composite wall structures were based on the installation location of the SIPs on the post-beam. The objective was to assess the lateral load resistance of hybrid shear walls according to installation positions and propose optimal SIPs installation configuration.

EXPERIMENTAL

Shear Wall Material

Post and Beam

The post, beam, and sill plate were made by using glued laminated timber (glulam) with the cross-section dimension of 140 × 140 mm^2. The glulam was manufactured four layers of spruce (*Picea jezoensis*) laminations. The cross-sectional lamination was 35 (thickness) × 140 (width) mm^2. The machine grade of four laminations were GL24h and the specification of GL24h grade is shown in Table 1.

SIP

The SIP's facing material used 11.1 mm thickness performance category wood structural panels composed of oriented strand board (OSB) in accordance with DOC PS 1 or DOC PS 2 of ANSI/APA PRS 610.1 (2023). The SIP's foam core material was expanded polystyrene (EPS) of 140 mm thickness, which complied with ASTM C 578 (2023) type 1. The total thickness of SIPs was 162 mm with 140 mm EPS core and two 11.1 mm OSB facing. The top and bottom plates of SIPs used 2 × 6 structural lumber having cross-sections of 38 (thickness) × 140 (width) mm^2. Figure 1 shows a perspective view of a SIP. In the case of spline that joints both shear wall together, two 2 × 6 structural lumbers were used with 16 d nails. The SIP manufactured in this study was 2440 (width) × 2440 (length) $mm^{2.}$

Table 1. Mechanical Properties of GL 24h (Unit: N/mm^2)

Bending	Tension Grain Direction		Compression Grain Direction		Shear	Modulus of Elasticity Grain Direction		Shear Modulus
	//[1)]	⊥[2)]	//	⊥		//	⊥	
$f_{m,k}$	$f_{t,0,k}$	$f_{t,90,k}$	$f_{c,0,k}$	$f_{c,90,k}$	$f_{V,k}$	E_0	E_{90}	G
24	19.2	0.5	20	2.5	3.5	11500	9600	650

Notes: 1) Parallel Direction, 2) Perpendicular Direction

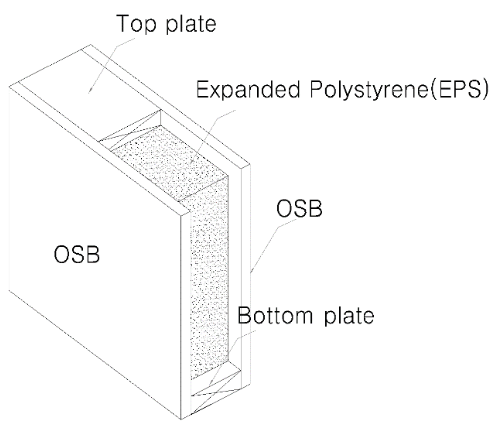


Fig. 1. Perspective view of a SIP

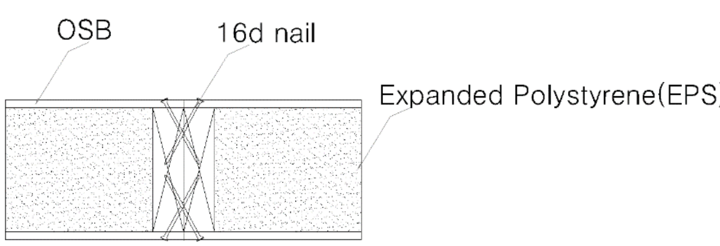


Fig. 2. Schematic diagram of lumber spline

Table 2. Specifications of Hybrid Shear Walls

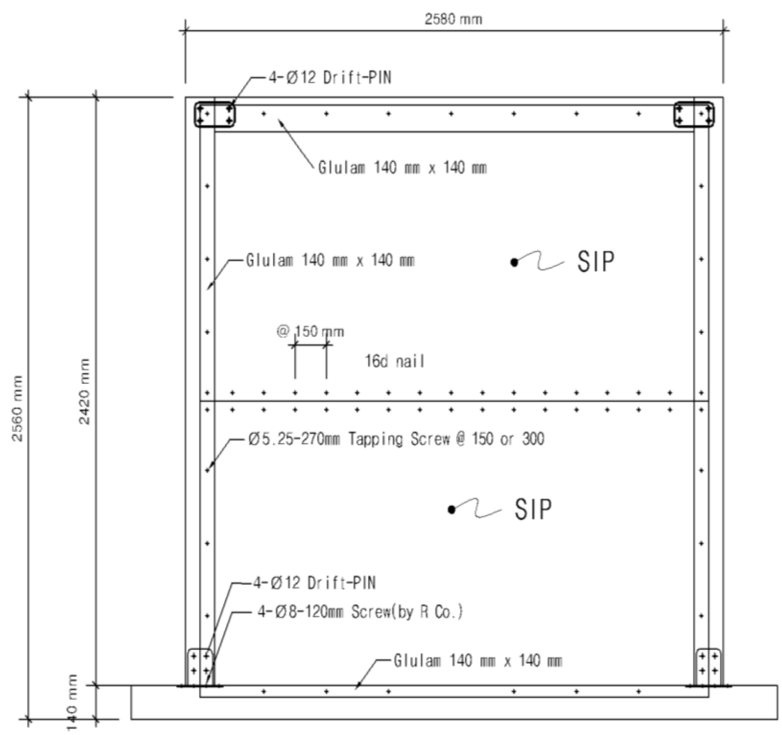
Type	Installation location of SIP	Fastener		
		Type	Size	Spacing
E-SIP 150	External	Tapping screw	Ø5.25mm-270mm	150mm
E-SIP 300	External	Tapping screw	Ø5.25mm-270mm	300mm
M-SIP 150	Middle	Tapping screw	Ø5.25mm-180mm	150mm
M-SIP 300	Middle	Tapping screw	Ø5.25mm-180mm	300mm
I-SIP 150	Inner	16d nail	Ø4.11mm-88.9mm	150mm

Hybrid Shear Wall Type

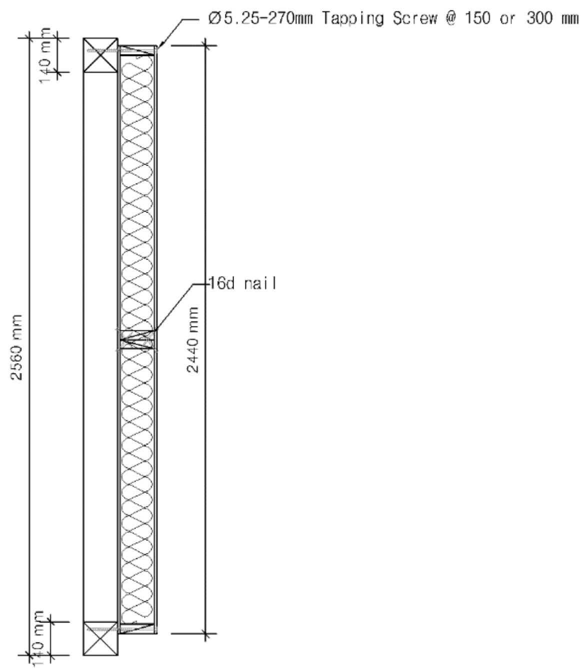
The five types of hybrid shear walls were prepared, depending on the relative position where SIPs were installed on post and beam, as well as the type and spacing of fasteners used to connect SIPs. The number of repetitions per type was three. Specifications of the five shear walls are shown in Table 2.

E-SIP 150 or E-SIP 300

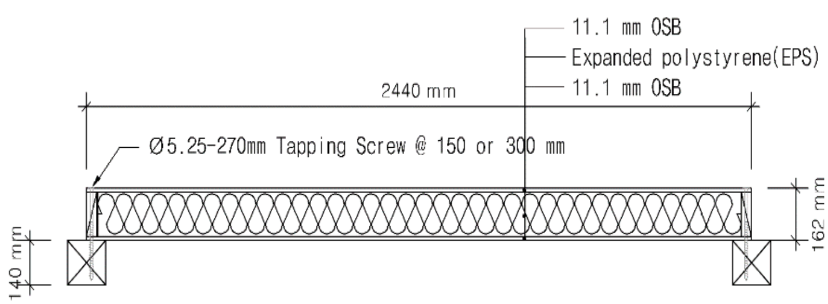
Figure 3 provides information about the E-SIP 150 and E-SIP 300 used in this study. E-SIP represented a hybrid shear wall in which SIPs were positioned externally on the posts and beams (Figs 3(b) and 3(c)). The post and beam were joined using a steel connection having 6 mm thickness (type A) with four drift pins with a diameter of 12 mm and a length of 80 mm as shown in Fig. 4. The steel connection using the drift pin fastener was one of the simplest methods for constructing heavy timber structures (Sim *et al*. 2010), so the connection was applied in this study. Another steel connection (type B) between the post and sill is shown in Fig. 5. In the steel connection, the post was joined with a drift pin fastener, similar to the post and beam joint, while the sill was connected by using TBS EVO 8120 screw (Rothoblaas, Italy) fastener with a diameter of 8 mm and length of 120 mm. When SIPs were attached to two posts, beam, and sill, tapping screws (Myunghwa metal. Co., Ltd, Republic of Korea) fastener with diameter of 5.25 mm and a length of 270 mm were used. If spacing between adjacent tapping screws of 150 or 300 mm, the hybrid shear wall was denominated as E-SIP 150 or E-SIP 300, respectively.



(a) Plan



(b) Vertical section



(c) Horizontal section

Fig. 3. Schematic illustration of E-SIP 150 or E-SIP 300

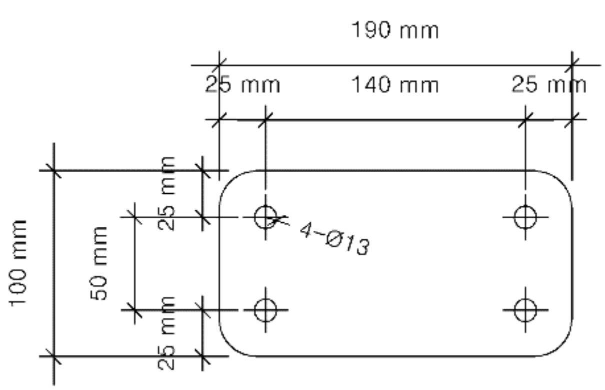


Fig. 4. Post-Beam joint steel connector plate (type A)

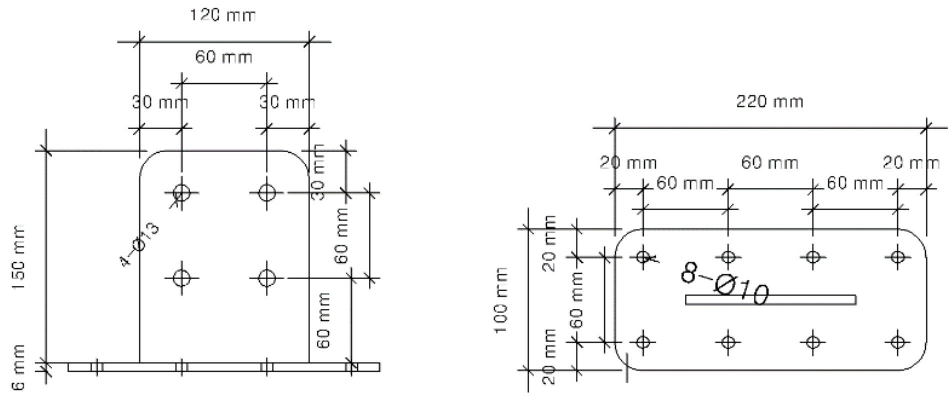
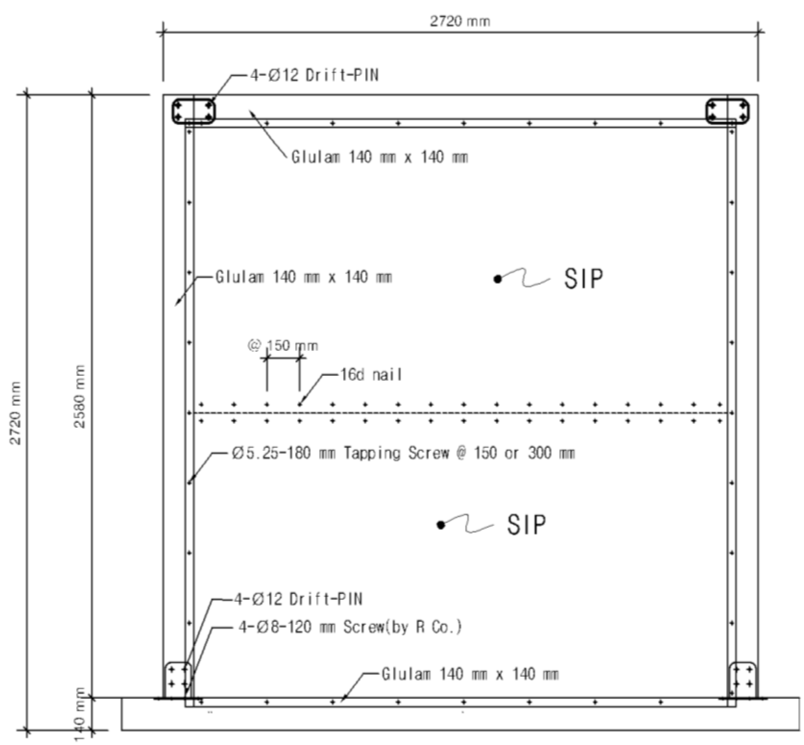


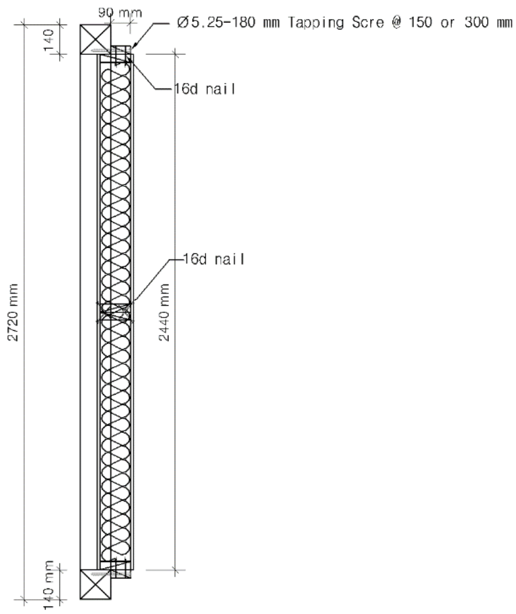
Fig. 5. Post-Sill joint steel connector plate (type B)

M-SIP 150 or M-SIP 300

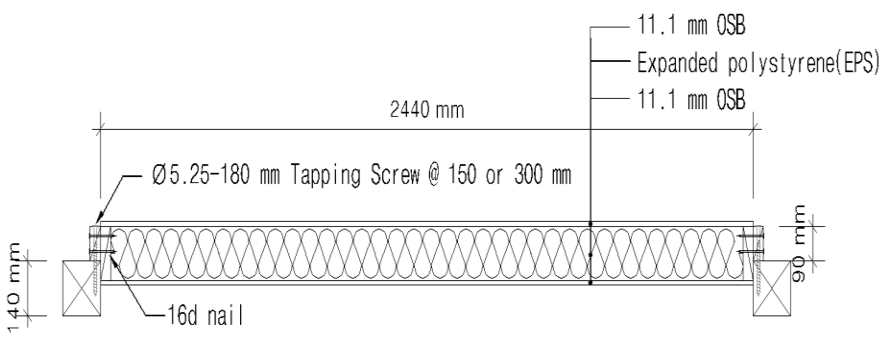
M-SIP represented a hybrid shear wall in which SIPs were positioned in the middle of the posts and beams. For joints between post and beam or post and sill, the same steel connections (type A and B) were used to make post and beam structure. To install SIPs to the middle of posts and beams, 2 × 4 structural lumber was fastened to four sides of the SIPs using 16d nails. The SIPs having structural lumbers were connected to the posts, beams, and sill using tapping screws (Myunghwa metal. Co., Ltd, Republic of Korea) with a diameter of 5.25 mm and a length of 180 mm, as shown in Fig. 6. If spacing between adjacent tapping screws of 150 or 300 mm, the hybrid shear wall was denominated as M-SIP 150 or M-SIP 300, respectively.



(a) Plan



(b) Vertical section

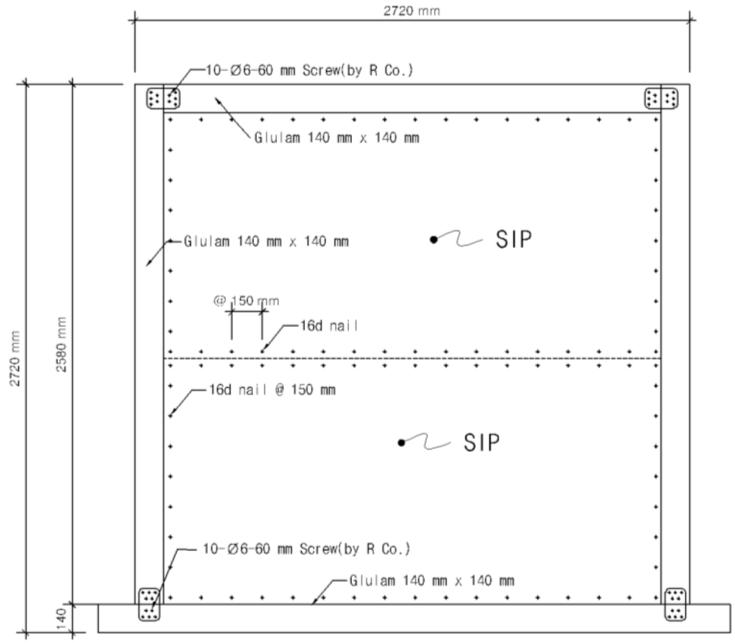


(c) Horizontal section

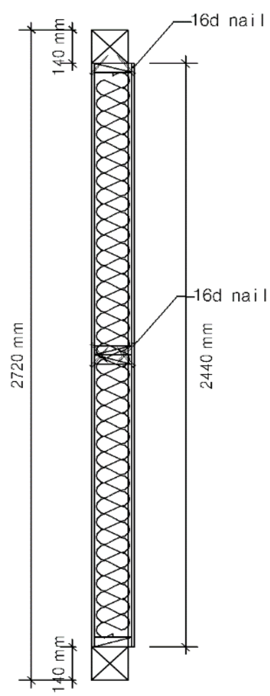
Fig. 6. Schematic illustration of M-SIP 150 or M-SIP 300

I-SIP 150

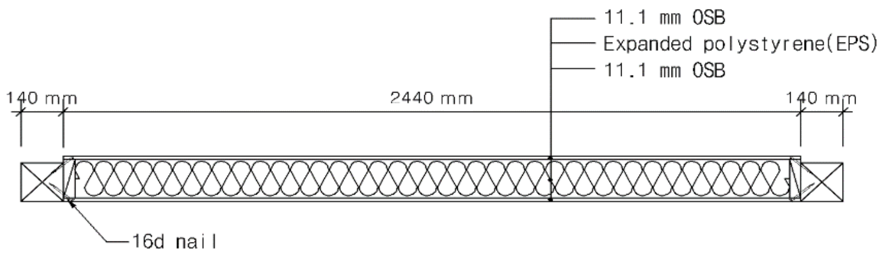
Figure 7 shows information about the I-SIP 150 specimen used in this study. I-SIP was a hybrid shear wall in which SIPs were positioned inside the posts and beam. The SIPs were inserted into the posts and beam, and then the post-beam and the SIP were joined by toe nailing using 16d nails, with an inclination angle of about 30 degrees on both sides and 150 mm spacing. In this case, a steel connection with 4 mm thickness and TBS EVO 660 screws (Rothoblaas, Italy) with 6 mm diameter and 60 mm length, which was different from previous steel connections (type A and B), was installed on the frame outside to assemble the hybrid shear wall (Figs. 7 and 8).



(a) Plan



b) Vertical section



(c) Horizontal section

Fig. 7. Schematic illustration of I-SIP 150

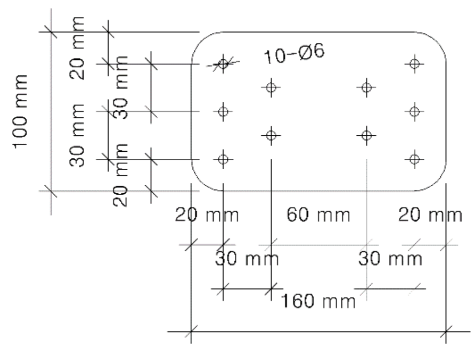


Fig. 8. Post-beam and post-sill joint connection (type C)

Test method

Test set-up and procedure

A lateral load resistance of five types of hybrid walls was measured in accordance with ASTM E 2126 (2019), as shown in Fig. 9.

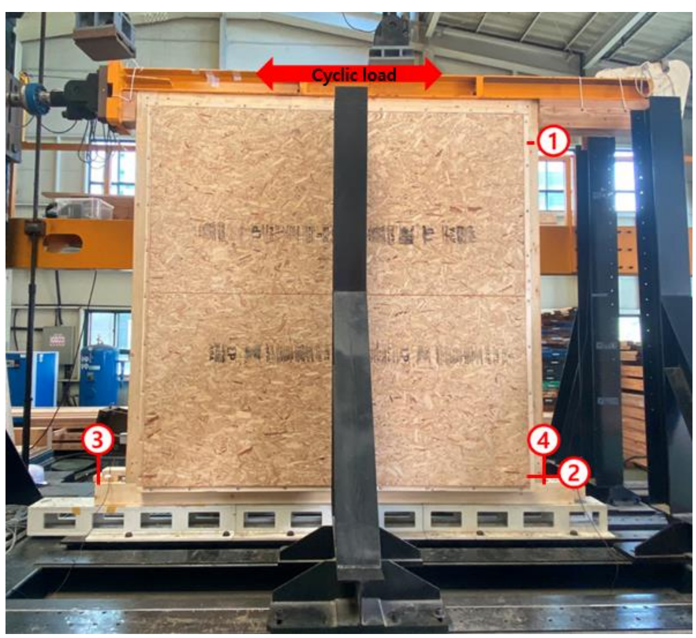


Fig. 9. Test set-up for testing lateral load resistance of hybrid shear wall specimen

The loading block was fixed to the top of wall to deliver the lateral load uniformly *via* the top length of the specimen. To measure displacement during the test, four linear variable differential transformers (LVDTs) were installed according to ASTM E 564 (2018). The LVDT located at position 1 was used to measure the horizontal displacement at the top of the specimen, while the LVDT located at position 2 was used to measure the base slip at the bottom of the specimen. Additionally, LVDTs located at positions 3 and 4 were utilized to measure the vertical displacement caused by tensile force from the overturning moment at the base of the specimen (Lee and Jang 2023).

The loading protocol developed as part of the amplitudes of the reversed cycles was used to subject the specimens to cyclic loading in this study. The protocol procedure was composed of a displacement-controlled loading function involving 11 loading steps. The ultimate displacement used in this study was 83.33 mm. The first five loading steps consisted of one loading cycle to allow the specimen to adjust before testing, while the 6th to 11th loading steps consisted of three loading cycles. The cyclic frequency was 0.2 Hz for all loading steps (ASTM E 2126, 2019). The specification of the protocol is presented in Table 3.

Table 3. Amplitudes of the Reversed Cycles

Pattern	Step	Min. Number of cycles	Amplitude, % (Δ_m)	Displacement (mm)
1	1	1	1.25	1.04
	2	1	2.5	2.08
	3	1	5.0	4.16
	4	1	7.5	6.25
	5	1	10.0	8.33
2	6	3	20.0	16.66
	7	3	40.0	33.33
	8	3	60.0	50.00
	9	3	80.0	66.66
	10	3	100.0	83.33
	11	3	120.0	100.00

Hysteresis curves were converted to envelope curves and Equivalent Energy Elastic-Plastic (EEEP) curves by identifying the peak points of the second loading cycles in the three loading cycles of each loading step and connection them. The shear strength (v_{peak}), secant shear modulus (G') at 0.4 P_{peak}, and ductility (D) were calculated based on the test results using Eqs. 1, 2, and 3 in accordance with ASTM E 2126 (2018), respectively.

$$v_{peak} = \frac{P_{peak}}{L} \tag{1}$$

where v_{peak} is shear strength (kN/m), P_{peak} is maximum load resisted by specimens in the given envelope curve (kN) and L is length of specimens (m).

$$G' = \frac{P}{\Delta} \times \frac{H}{L} \tag{2}$$

In Eq. 2, G' is shear modulus at 0.4 P_{peak} (kN/mm), P is applied load measured at the top edge of the specimens (kN), Δ is displacement of the top edge of the specimen based on test (mm), H is height of specimen (m), and L is length of specimen (m),

$$D = \frac{\Delta_u}{\Delta_{yield}} \tag{3}$$

where D is ductility ratio, Δ_u is ultimate displacement (mm), and Δ_{yield} is yield displacement (mm)

RESULTS AND DISCUSSION

Effect of Tapping Screw Spacing

Figures 10 and 11 show the hysteresis and envelop curve resulting from the lateral load resistance test for E-SIP (E-SIP 150 and E-SIP 300) and M-SIP hybrid shear wall (M-SIP 150 and M-SIP 300), respectively. It was confirmed that the E-SIP 150 shear wall had a higher lateral resistance than the E-SIP 300 shear wall. In the case of the M-SIP specimens, the lateral resistance of the M-SIP 150 shear wall was also a little higher than that of the M-SIP 300 shear wall. Adding more nails increased the lateral resistance of the hybrid shear wall. The results were similar to those of nailing spacing, which was used to fix sheathing panels and studs, on lateral resistance of light frame shear wall. McCutcheon (1985), Wang (2009), and Germano *et al*. (2015) reported that the nails between studs and sheathing panel in a light-frame structure affected the stiffness and lateral resistance performance of the shear wall. Additionally, Lee and Jang (2023) and Shadravan and Ramseyer (2018) reported in light-frame timber shear wall, as the nailing spacing was reinforced, the lateral resistance performance of the shear wall increased.

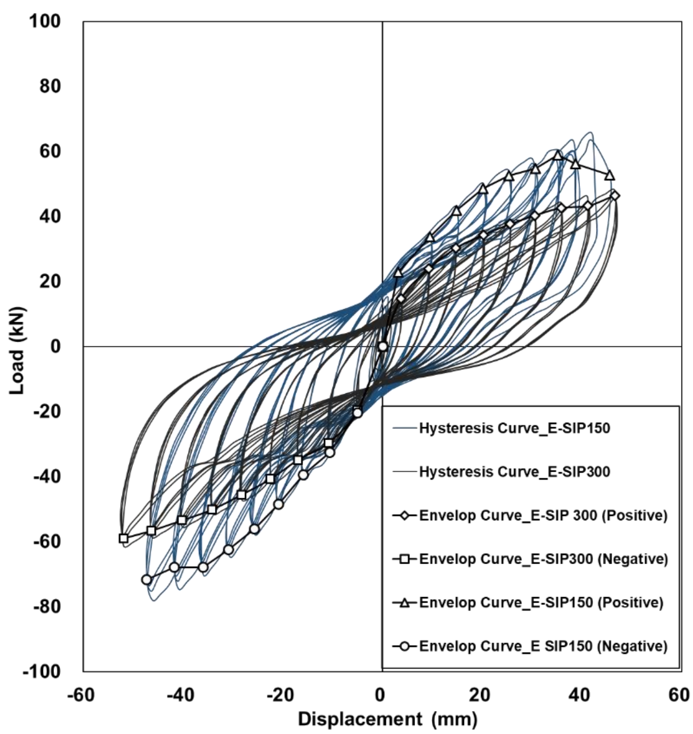


Fig. 10. Load-displacement hysteresis and envelop curve obtained from lateral-load resistance test for specimens E-SIP 150 and E-SIP 300

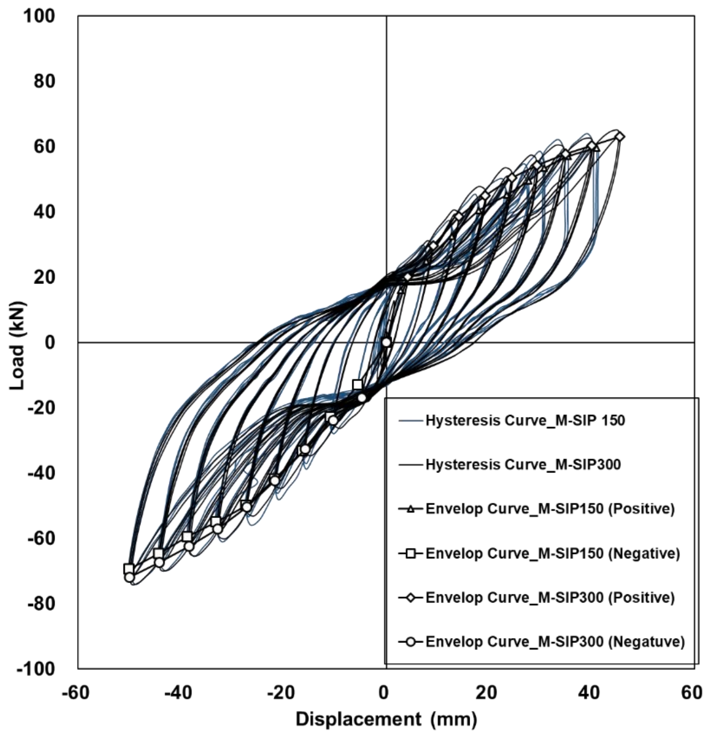


Fig. 11. Load-displacement hysteresis and envelop curve obtained from lateral-load resistance test for specimens M-SIP 150 and M-SIP 300

Effect of SIP installation location

To assess the effect of the SIP installation location, the load-displacement envelop curves for the hybrid shear walls (E-SIP 150, M-SIP 150, and I-SIP 150) were investigated, as shown in Fig. 12. These walls were assembled using the same fastener spacing. The maximum loads for E-SIP 150, M-SIP, and I-SIP 150 were found to be 63.39, 67.16, and 59.96 kN, respectively. In Fig 12, it can be seen that the initial slope, which indicates the initial stiffness of M-SIP 150, was lower compared to the other hybrid shear walls. The Analysis of Variance (ANOVA) results for maximum load indicated that there was no significant difference between E-SIP 150, M-SIP 150, and I-SIP 150, as the p-value (0.076) was greater than 0.05. The analysis of ANOVA results for the initial stiffness showed that p-value (0.008) was lower than 0.05. In case of stiffness of E-SIP 150 and I-SIP 150, there was no significant difference (p-value: 0.28 > 0.05). The ANOVA results indicated that the p-values for E-SIP 150 and M-SIP 150, as well as M-SIP 150 and I-SIP 150, were 0.015 and 0.03, respectively, both of which were less than 0.05.

The lower initial stiffness of M-SIP 150 might be attributed to the incomplete assembly between the structural lumber and SIP during the process of connecting the SIP to posts and beams. The failures between the structural lumbers and the SIP after testing also were consistent with an assumed incomplete assembly in case of M-SIP 150 (Fig. 13a). while, as shown in Fig 13b. By contrast, failure in the other hybrid shear walls (E-SIP 150 and I-SIP 150) occurred in the sill member. This failure was induced by the process of overturning the shear wall under lateral load. Therefore, it was concluded that the lateral resistance of the hybrid shear wall, based on the SIP installation locations, had slightly different initial stiffness. There was no significant difference in the maximum loads.

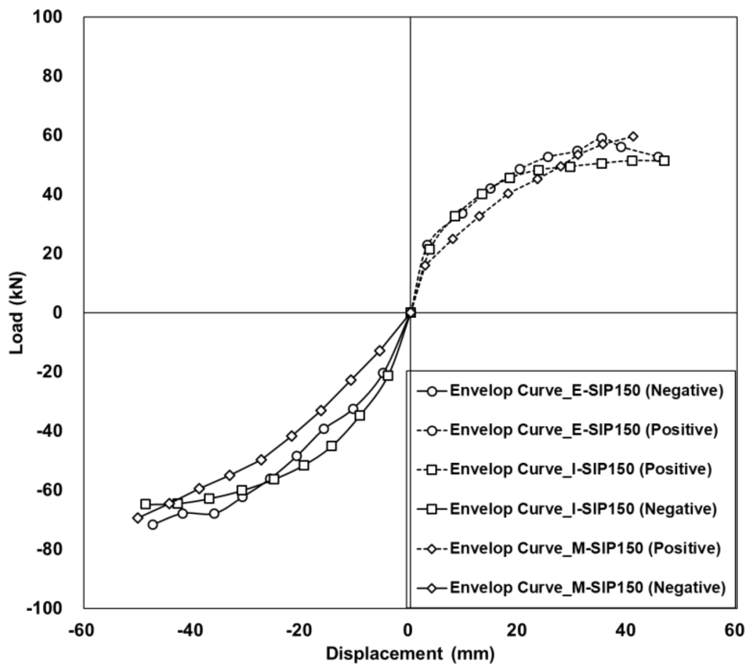


Fig. 12. Envelope curve obtained from lateral-load resistance test for E-SIP 150, M-SIP 150 and I-SIP 150

(a) Failure mode of M-SIP 150

(b) Failure mode of E-SIP 150

Fig. 13. Failure mode in lateral resistance test for M-SIP 150 specimen and E-SIP 150 specimen

Comparison of shear strength of hybrid shear wall and conventional light-frame shear wall

Figure 14 shows the EEEP curves, which were obtained by averaging the positive and negative values of load and displacement, to determine lateral resistance properties for calculating the shear modulus, shear strength, and ductility using Eqs. 1, 2, and 3, respectively. Table 4 shows the results of lateral resistance properties for five types of hybrid shear walls. The shear strength (v_{peak}) increased in the order of E-SIP 300, I-SIP 150, E-SIP 150, M-SIP 300, and M-SIP 150. On the other hand, shear modulus at 0.4 peak load increased in the order of M-SIP 300, M-SIP 150, E-SIP 300, E-SIP 150, and I-SIP. 150.

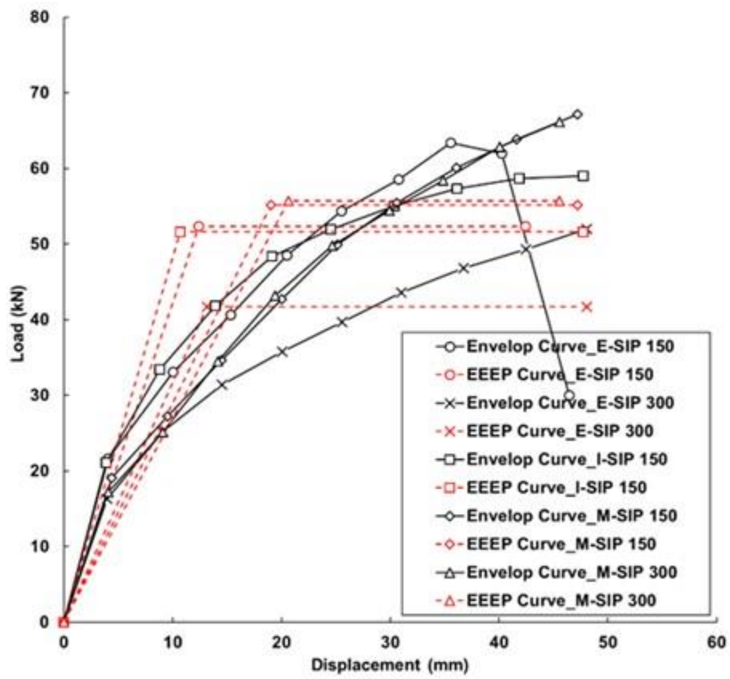


Fig. 14. Combined envelop and EEEP curves for five types of hybrid shear walls.

Table 4. Lateral Load Resistance Properties of the Hybrid Shear Walls

Specimen	v_{peak} (kN/m)	G'(kN/mm)		Ductility
		0.4Peak	Peak	
E-SIP150	24.57	3.99	1.69	3.69
E-SIP300	20.16	2.99	1.02	3.66
M-SIP150	26.03	2.74	1.35	2.48
M-SIP300	25.64	2.55	1.37	2.21
I-SIP150	23.24	4.32	1.19	4.22

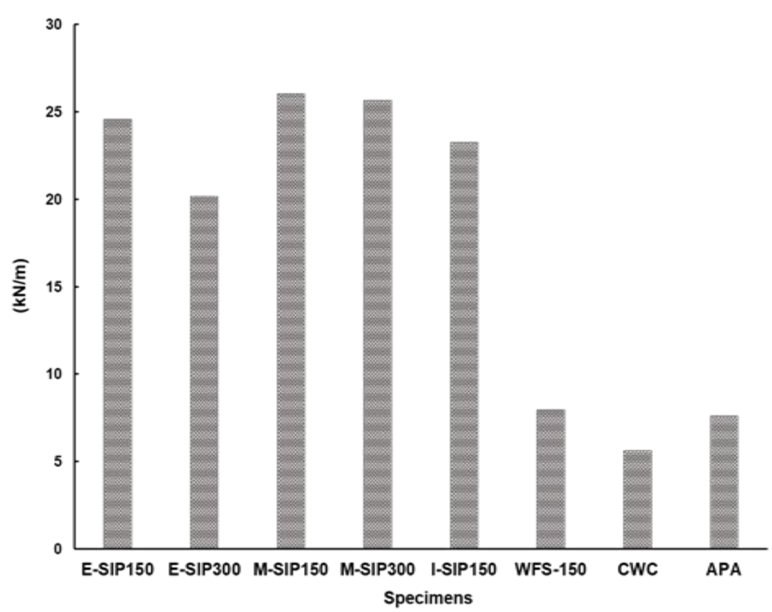


Fig. 15. Comparison of shear strength of hybrid shear walls and conventional light-frame shear walls

Figure 15 shows the shear strength of hybrid shear walls in this study and conventional light-frame shear walls with a nail spacing of 150 mm on the edge of sheathing panel, as reported by APA (2007), CWC (2020), and WFS-150 (Lee and Jang 2023). When comparing the shear wall strength of the hybrid shear wall (E-SIP 300) with the conventional light-frame shear wall (WFS-150; Lee and Jang 2023, CWC 2020, and APA 2007), the hybrid shear wall showed 2.5 to 3.6 times higher strength than light-frame shear walls.

CONCLUSIONS

1. By implementing the tapping screws reinforcement (*i.e.*, decreasing the tapping screws spacing), the lateral-resistance of the composite wall structure increased
2. The shear strengths did not vary significantly depend on the installation location of structural insulated panels (SIPs) on the posts and beams, but in terms of shear stiffness, SIPs installed midway between posts and beams showed the lowest value.
3. When comparing the shear strength of the hybrid shear wall with the conventional light-frame shear wall, the hybrid shear wall showed about 2.5 to 3.6 times higher strength than a corresponding light-frame shear wall.
4. Considering the overall lateral resistance properties and construction aspects of the hybrid shear wall, it was judged that it will be most effectively for SIPs to be installed externally on the posts and beams.

ACKNOWLEDGMENTS

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