Shear Resistance for Lateral Force of Light-frame Wall Sheathed with Structural Particleboard (PB)

Chul-Ki Kim,* Hyung Woo Lee, Min Lee, and Sang-Joon Lee

The shear resistance of a structural particleboard (PB) wall was evaluated as a means to utilize recycled wood and low-grade logs for long periods. The wall was composed of spruce-pine-fir (SPF) lumber, nails, and structural PB, which was developed by improving the water resistance of default PB. Structural PB has a higher density than OSB, which is a commonly used covering material for light wooden structural walls, so a longer end distance for nailing at edge of sheathing is needed for structural PB. In this study, it was confirmed that structural PB walls sufficiently resisted lateral load when the end distance was 15 mm. In this case, the shear strength, shear modulus, and ductility of the structural PB wall for lateral cyclic load were confirmed as 9.2 kN/m, 2.0 kN/mm, and 6.2, respectively. When compared to the design value, the shear strength value was higher than that of the OSB wall and the plywood wall. The shear modulus was lower than that of OSB walls, but higher than plywood walls. Based on the above results, it was considered that structural PB light-frame wall could be used in residential load-bearing applications.

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Keywords: Structural PB; Light-frame wall; Shear resistance; Lateral load

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INTRODUCTION

In line with the carbon neutral era, interest in mass timber building is increasing. However, buildings using light-frame construction still occupy a high proportion of timber buildings. Light-frame construction is widely used in low-rise residential, commercial, and industrial buildings in Northern Europe and North America because of the low cost to build them and their relatively high resistance to earthquake and wind loads (Liu *et al*. 2021). In Korea, the proportion of timber construction is small in the whole construction market, but timber building using the light-frame construction is steadily commencing. Since the method of light-frame construction was introduced in Korea in the late 1990s, approximately 10000 buildings per year using light-frame construction have been steadily been constructed, starting from 2011 (Lee *et al*. 2020).

The shear wall is one of the most important components affecting structural performance in light-frame construction. This component transmits earthquake and wind loads generated from the roof or upper floors to the foundation. The shear wall is usually composed of a frame, sheathing, exterior finishing material, fasteners, and anchors (Peng *et al*. 2020). Anchors serve to prevent buildings made by light-frame construction from overturning or sliding by directly connecting the wall and foundation. A role of the shear wall in light-frame construction is to resist horizontal loads such as earthquakes and wind loads. To play this role, sheathing wood-based panel materials such as plywood or Oriented Strand Board (OSB) are required. These are typically nailed to the wood frame.

Research on the structural performance of shear walls in light-frame construction began in 1927 (Peterson 1983). Bagheri and Doudak (2020) reported that shear strength of the wall is greatly affected by nail diameter and nail spacing. Dhonju *et al*. (2017) examined the effects of nail spacing in panel, wall length, arrangement and configuration of studs and floor members, and vertical load on the shear performance of OSB shear walls. Demir *et al.* (2023) used Artificial Neural Networks (ANN) to estimate the maximum load and displacement of shear walls sheathed with plywood according to various nail spacing and revealed the effect of nail size and spacing on the shear resistance of plywood shear walls in light-frame construction. Doudak *et al*. (2006) experimented to find the effects of openings in light-frame shear walls such as windows and doors, on the shear modulus and strength characteristics of the wall. Comparing experimental results using the Canadian design code and finite element analysis, it was revealed that the design code was able to predict the shear performance of walls with openings with high accuracy.

In this way, the shear resistance of walls in light-frame construction has focused on the influence of fasteners. To the best of the author's knowledge, research rarely has been done on the types of sheathing materials for shear walls in light-frame construction. Limited research on bamboo sheathing has been conducted to replace OSB and plywood in light-frame shear walls (Varela *et al*. 2013; Xiao *et al*. 2015; Wang *et al*. 2017). Xiao *et al*. (2015) conducted shear wall tests, which was made of bamboo sheathings and Spruce-Pine-Fir (SPF) lumber, and Wang *et al*. (2017) experimented with shear resistance test using not only the sheathings but also the frame of a light-frame wall made of bamboo. The results concluded that walls made of bamboo ensure excellent seismic performance and the ability to meet design requirements.

Particleboard (PB) is widely used as furniture and interior materials due to its reasonable price and applicability for various purposes. Additionally, PB can use low-grade logs such as tree branches, bent or twisted trees, along with by-products of wood and wood product waste as raw materials. Therefore, considering the supply and demand situation of wood in Korea, PB is one of the efficient ways to utilize wood. Accordingly, structural PB having resistance to high moisture during short-term was developed to use PB as structural members (Lee *et al*. 2023). Additionally, the rot fungi and termite resistance of structural PB was evaluated. In this study, the structural PB referred to PB having performance that exceeded the performance requirements for structural panels in ISO 16893(2016), ISO 16894 (2009), and JIS A5908 (2015).

This study examined whether structural PB can be used as a sheathing material for shear walls in light-frame construction. When applying lateral cyclic load to the structural PB light-frame wall, the shear resistance was evaluated by analyzing the obtained load and compared to the shear resistance of the Oriented Strand Board (OSB) light-frame wall.

EXPERIMENTAL

Materials

Wood framing materials

To make a wood frame of shear wall, 2x6 lumber pieces were used. The actual cross-sectional size of the lumber was 38 (thickness) × 140 (width) mm^2. The species was SPF from North America. The grade of lumber was 2 by visually grading, and it was graded according to the Canadian National Lumber Grading Authority (NLGA) standards. Ten test pieces of size 38 (thickness) × 140 (width) × 20 (length) mm^3 were gathered randomly from some of the lumbers used in the tibia wall frame. The oven-dry method was applied to the gathered test pieces to evaluate air-dry density and moisture content. The air-density and moisture content of the lumbers were 0.42 ± 0.05 g/cm^3 and 15.3 ± 1.0%, respectively.

In this study, structural PB and OSB were used as sheathing materials for light-frame wall. Structural PB was manufactured by utilizing wood chips obtained from recycled wood products similar to PB. The manufacturing conditions and adhesive information used for structural PB were described by Lee et al. (2023) in detail. In addition, the mechanical properties of structural PB were higher than the properties of wood-based panel listed in ISO 16894 (2009) and, unlike OSB, they were not affected by machine direction (Lee *et al*. 2023). OSB was also used for comparison with structural PB. The OSB as sheathing material was manufactured by Tolko Industries Ltd. (Canada), and the exposure and span ratings determined by the American Plywood Association (APA) were Exposure 1 and 24/16, respectively. The size of structural PB and OSB was 1220 (width) × 2440 (length) mm^2. The thicknesses of structural PB and OSB were 12.0 and 11.1 mm, respectively. The structural PB and OSB used in this study are shown in Fig. 1.

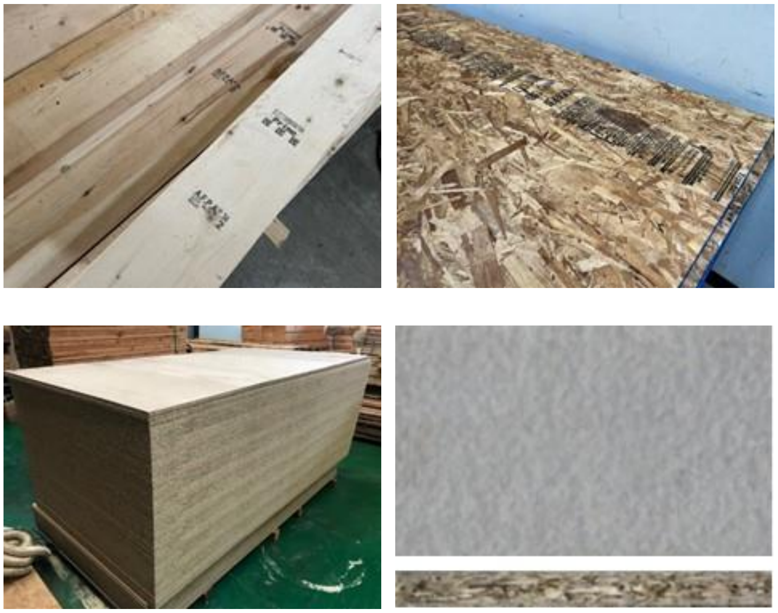


Fig. 1. Picture of wood framing materials (Top-left: 2 × 6 lumber, Top-right: OSB, Bottom-left: Structural PB, and Bottom-right: Surface and cross section of structural PB)

Light-frame wall assembly

Figure 2 provides information about the light-frame shear wall used in this study. The spacing between studs within the walls was 406 mm, and the upper plate and outmost studs were double-layered. 12d nails were used to assemble the plate and stud. The final size of the shear wall frame was 2440 (height) × 2440 (length) mm^2.

The 8d nails were used to fix the shear wall frame and sheathing materials without pre-drilled holes. The nail spacing between center and center at the edge of the sheathing material was 150 mm, while the nail spacing between centers was 300 mm in the middle of the sheathing material. In general, when driving nails into a sheathing panel, the end distance from the edge of the sheathing is 10 mm at least (Fig. 2). The OSB light-frame shear wall was manufactured with an end distance of 10 mm. In the case of structural PB light-frame shear wall, on the other hand, the experiment was conducted with two kinds of the end distance from the edge of the sheathing: 10 and 15 mm. Size information of the 12d and 8d nails is shown in Table 1, and both nails were full round head nails with galvanized manufactured by Kyocera Senco Industrial Tools, Inc (USA). Finally, there were three types of light-frame shear walls, and the number of repetitions per type was two.

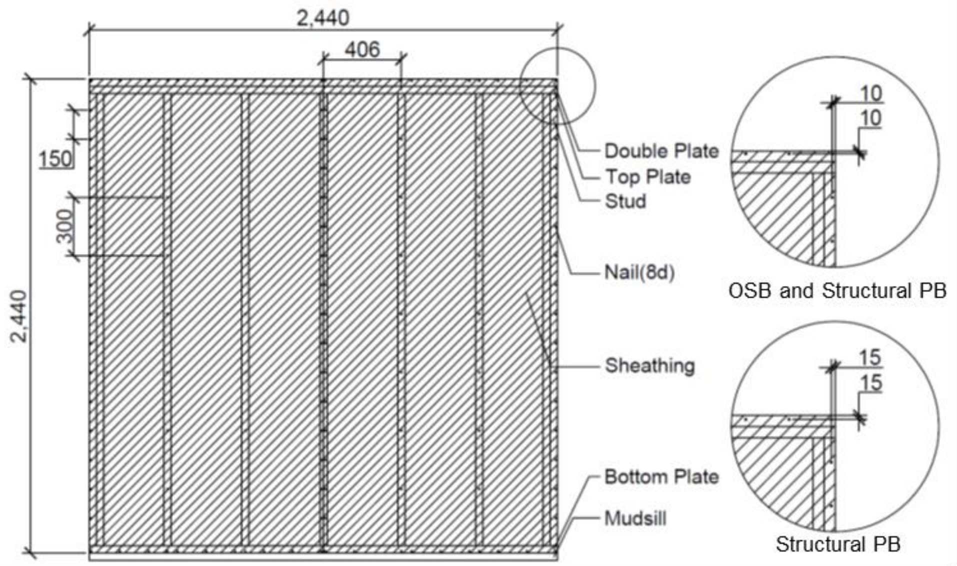


Fig. 2. Schematic picture of nailing for light-frame wall with OSB or structural PB (Right: nailing distance from the edge of each panel) (Unit: mm)

Table 1. Specification of Nail for Light-frame Wall Assembly (Unit: mm)

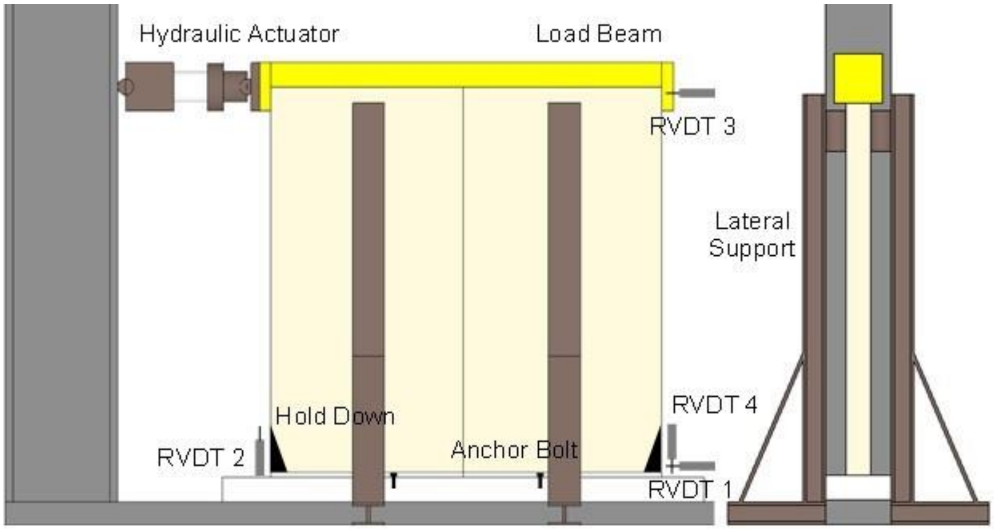
Type	Shank		Head	
	Length	Diameter	Thickness	Diameter
8d	63	2.9	1.0	7.0
12d	74	3.05	1.0	7.0

Experimental Method of Shear Resistance Test

Test set-up

A shear force tester (Dongyang, Korea) was used to evaluate the shear resistance of three types of light-frame shear walls against horizontal loads. The maximum load of the shear force tester and the maximum stroke length of the actuator were 225 kN and 210 mm, respectively. The 2 × 6 lumber as mudsill was fixed with two anchor bolts to secure the test specimen to the shear force tester. Both ends of the wall were fixed with hold-downs after placing the shear wall on the mudsill. After that, two 12d nails were driven around the studs to fasten the shear wall with the mudsill.

A load beam was fixed with a wooden block on the top of the wall to apply a horizontal load. Four rotary variable differential transformers (RVDT) were installed according to ASTM E564 (2018) to measure displacement during lateral cyclic load. Among the four RVDTs, the RVDT at position 3 was installed to measure the horizontal displacement of the edge of the wall. RVDTs at positions 2 and 4 were installed to measure the uplifting and vertical displacement of the end point of the wall due to rotation, respectively. The LVDT at position 1 was installed to measure the base slip at the bottom of slip of wall. The test set-up is shown in Fig. 3. Four lateral supports were installed to prevent buckling during the evaluation of the shear resistance as shown in Fig. 3a.



(a) Schematic picture

(b) Test picture of Structural PB light-frame wall

Fig. 3. Test set-up for evaluating shear resistance

Evaluation of shear resistance for lateral cyclic load

Shear resistance was evaluated by applying a lateral cyclic load, which is ISO 16670 protocol presented in ASTM E2126 (2018), to the wall. The ultimate displacement used in this study was 83.33 mm, and the displacement was obtained through previous static experiments. The ISO 16670 protocol is presented in Table 2. In steps 1 to 5, one fully reversed cycle was performed for each displacement, and in further steps, three fully reversed cycles were performed for each displacement.

Table 2. Amplitudes of the Reversed Cycles in ISO 16670 Protocol

Pattern	Step	Min. Number of Cycles	Amplitude (%)	Displacement (mm)
1	1	1	1.25	1.04
	2	1	2.50	2.08
	3	1	5.00	4.16
	4	1	7.50	6.25
	5	1	10.00	8.33
2	6	3	20.00	16.66
	7	3	40.00	33.33
	8	3	60.00	50.00
	9	3	80.00	66.66
	10	3	100.00	83.33
	11	3	120.00	100.00

The envelope and EEEP (Equivalent Energy Elastic-Plastic) curve were derived using a hysteresis curve obtained through the experiment. Since three fully reversed cycles were repeated in 6 or more stages in the ISO 16670 protocol, shear resistance was evaluated for each cycle. The shear resistance of the wall against lateral cyclic load was evaluated by shear strength, secant shear modulus at 0.4 peak load and peak load, and ductility ratio. The formula for calculating each resistance was as follows,

$$\text{Shear Strength: } v_{peak} = \frac{P_{peak}}{L} \tag{1}$$

$$\text{Secant Shear Modulus: } G^{'} = \frac{P}{\Delta} \times \frac{H}{L} \tag{2}$$

$$\text{Ductility Ratio: } D = \frac{\Delta_u}{\Delta_{yield}} \tag{3}$$

where v_{peak} is shear strength (kN/m), P_{peak} is maximum load resisted by wall in the given envelope (kN), L is length of wall (m), $G^{'}$ is shear modulus of wall obtained from test (kN/mm), P is applied load, 0.4 of peak or peak load, measured at the top edge of the specimen (kN), Δ is displacement of the top edge of the specimens according to applied load based on test (mm), H is height of specimen (m), L is length of specimen (m), D is ductility ratio, Δ_u is ultimate displacement (mm), and Δ_{yield} is yield displacement (mm). Detail calculation for shear resistance for lateral cyclic load of light-frame wall can be found in ASTM E2126 (2018).

RESULTS AND DISCUSSION

Table 3 presents the average results of shear resistance for all specimens. For the OSB light-frame shear wall, the shear strength and shear modulus at 0.4 peak load in the first cycle were found to be 9.6 kN/m and 2.7 kN/mm, respectively. In the case of the OSB light-frame shear wall, it was confirmed that the shear strength decreased and the shear modulus increased as the number of cycles increased at the same step.

The maximum shear strength of the OSB light-frame shear wall was 9.6 kN/m, and the shear modulus was 3.4 kN/mm. The maximum ductility was 12.5 in the second cycle. Cassidy *et al*. (2006) reported that the maximum load in the first cycle under similar light-frame wall assembly to this study was 22.0 kN, which was slightly lower than the 23.4 kN in this study, but there was no significant difference.

Table 3. Shear Resistance for Lateral Force According to Type of Sheathing Panel and End Distance

Type	ED$^{1)}$ (mm)	Cycles	Displacement (mm)				Load (kN)			
			Yield	Peak	Ult$^{2)}$	0.4Peak	Yield	Peak	Ult	0.4Peak
OSB	10	1	7.9	55.1	72.7	3.6	20.6	23.4	18.7	9.4
		2	5.9	48.4	67.6	2.7	18.2	20.7	16.6	8.3
		3	5.2	40.5	64.5	2.3	17.1	19.5	15.6	7.8
SPB$^{3)}$	10	1	11.6	49.7	77.9	5.2	19.1	21.5	17.2	8.6
		2	9.2	49.8	75.6	4.1	17.1	19.1	15.3	7.7
		3	8.1	42.1	72.8	3.7	16.0	18.0	14.4	7.2
	15	1	12.3	44.7	64.7	5.7	22.4	26.0	20.8	10.4
		2	9.6	45.1	59.3	4.5	19.3	22.6	18.1	9.0
		3	8.2	45.3	53.6	3.8	17.9	20.6	16.5	8.3

Type	ED (mm)	Cycles	$v^{4)}$ (kN/m)	$G^{'5)}$ (kN/mm)		Ductility
				0.4Peak	Peak	
OSB	10	1	9.6	2.7	0.4	9.2
		2	8.5	3.1	0.5	11.4
		3	8.0	3.4	0.5	12.5
SPB	10	1	8.8	1.6	0.4	6.7
		2	7.8	1.9	0.4	8.2
		3	7.4	2.0	0.4	8.9
	15	1	10.7	1.8	0.6	5.3
		2	9.2	2.0	0.5	6.2
		3	8.5	2.2	0.5	6.6

Notes: 1) End distance, 2) Ultimate, 3) Structural PB, 4) Shear strength, 5) Secant shear modulus

In the case of the structural PB light-frame shear wall, it was confirmed that the shear performance against lateral load varies depending on the end distance from the edge of the sheathing. It was confirmed that as the end distance increases, the shear performance against horizontal load increases in the structural PB light-frame shear wall (Fig. 4). When the end face distance was 10 mm, the shear strength and shear modulus at 0.4 peak load in the first cycle of the structural PB light-frame shear wall were found to be 8.8 kN/m and 1.6 kN/mm. However, the shear strength and shear modulus at 0.4 peak load in the first cycle of the PB tibial wall were 10.7 kN/m and 1.8 kN/mm, when the end distance was 15 mm. Regardless of the end distance, in the case of the structural PB light-frame shear wall, the shear strength decreased and the shear modulus increased as the number of cycles increased in the same step in company with the results of the shear resistance of OSB wall. When compared to the light-frame wall made of bamboo plate material, the shear strength was higher and the shear modulus was similar. Varela *et al*. (2013) reported that the shear strength and shear modulus in the first cycle walls were 6.7 kN/m and 1.82 kN/mm in case of bamboo light-frame shear wall.

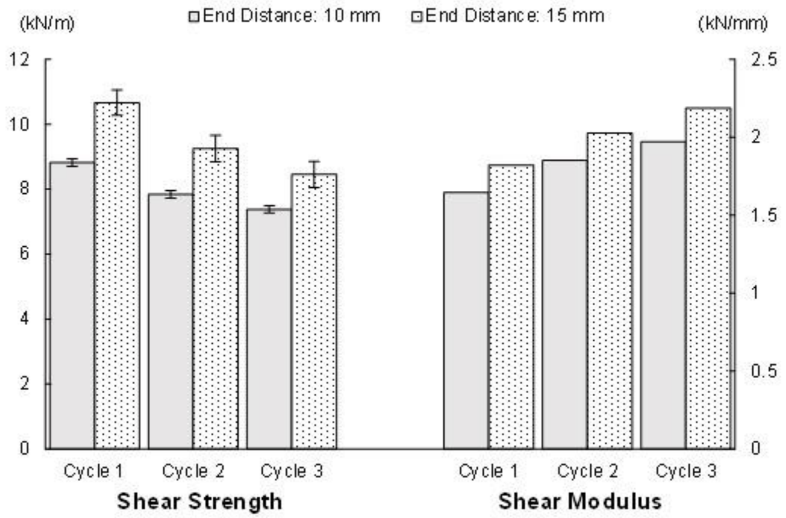
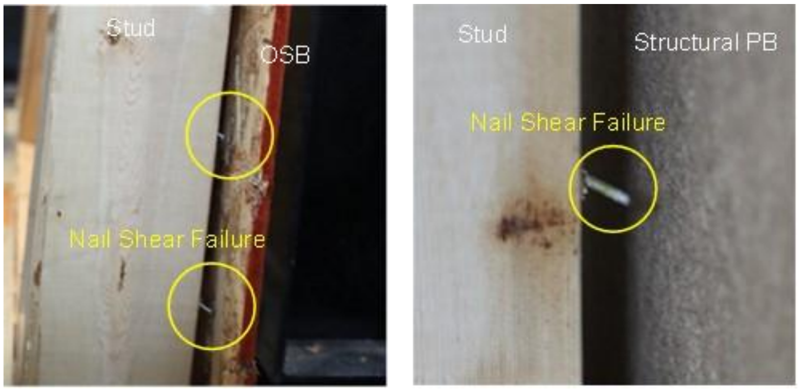
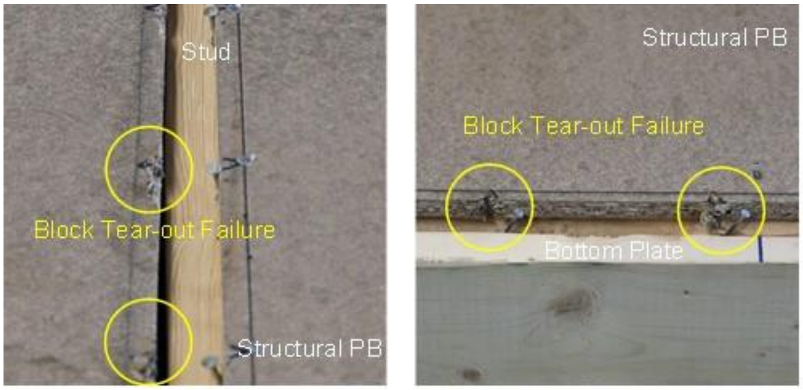


Fig. 4. Shear resistance of structural PB light-frame wall in two kinds of end distance.

Figure 5 shows the failure mode of the test specimen after applying lateral cyclic load. Two major failure modes could be identified. One was the shear failure of a nail located on the edge of sheathing, and the other was a block tear-out failure that also occurred at the edge of sheathing.



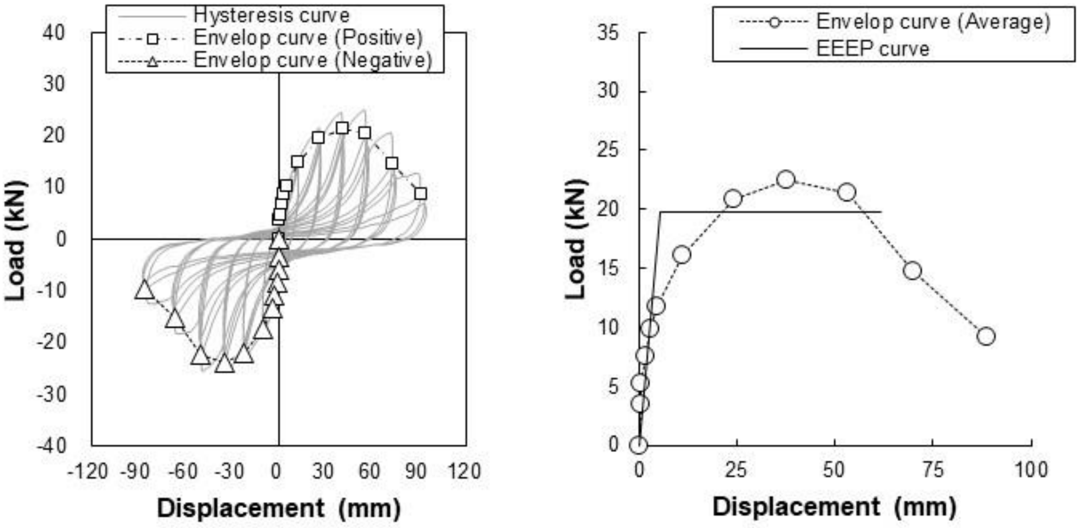
(a) Nail shear failure in OSB light-frame wall and structural PB wall with end distance of 15 mm



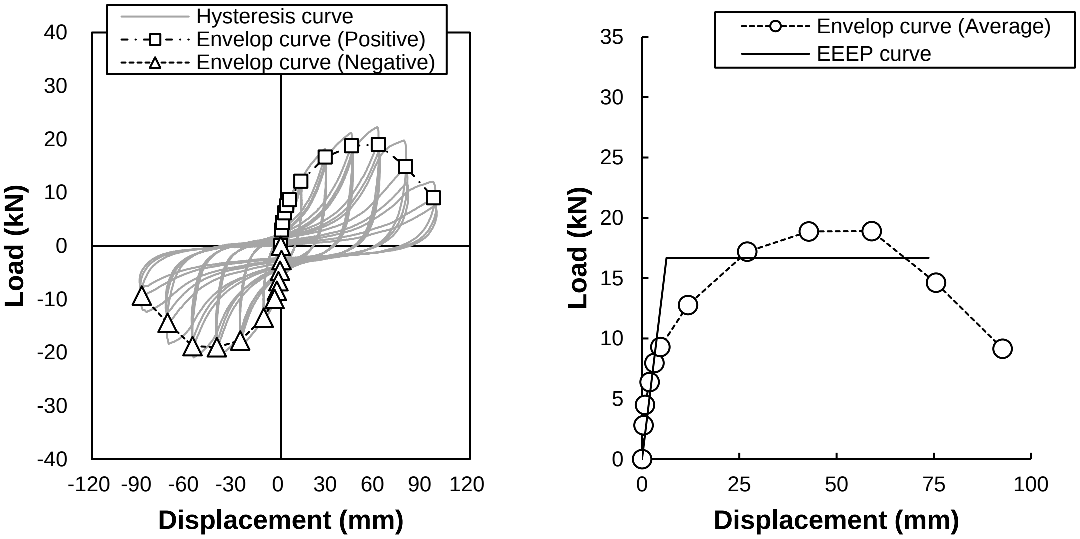
(b) Block failure in structural PB wall with end distance of 10 mm

Fig. 5. Mainly developed failure mode after applying lateral force to each specimen

Figure 5a shows the failure modes that mainly occurred in the OSB light-frame shear wall and the structural PB light-frame shear wall with an end distance of 15 mm from the edge of the sheathing. In Fig. 5a, it can be seen that shear failure of the nail located at the edge of the sheathing occurred. On the other hand, Fig. 5b shows the failure mode that mainly occurred in the structural PB light-frame shear wall with an end distance of 10 mm, and the block tear-out failure at the edge of structural PB can be confirmed. Therefore, it was confirmed that the shear resistance to later load appeared low in case of block tear-out failure occurred mainly.



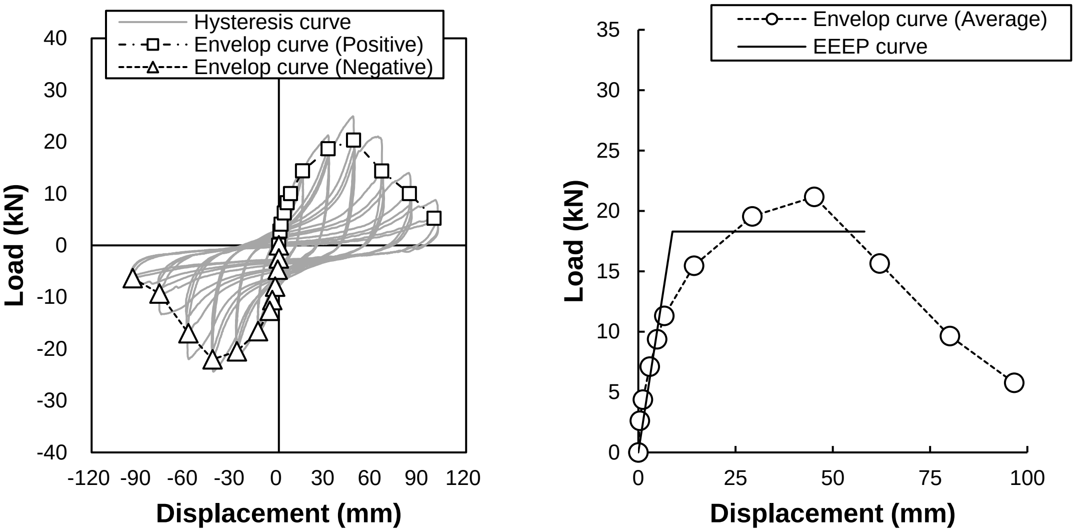
(a) Specimen 1



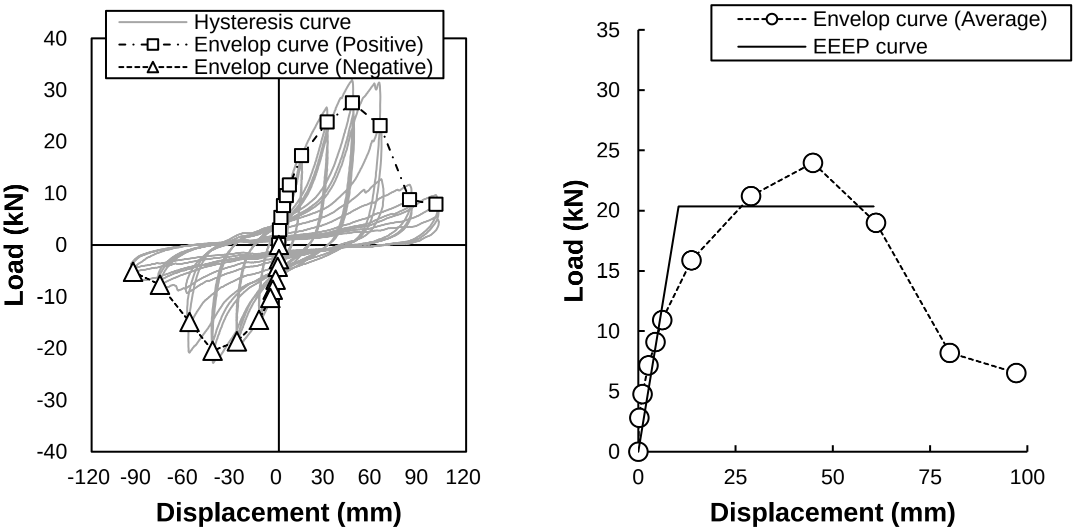
(b) Specimen 2

Fig. 6. Hysteresis, Envelop, and EEEP curve of OSB light-frame wall

There were some reports that the block tear-out failure occurred at wood causing decrease of joint properties (Jensen *et al*. 2012; Stapf *et al*. 2012; Zarnani and Quenneville 2014; Mahlknecht and Brandner 2019). Additionally, it was reported that block tear-out failure occurred more easily in stiff materials (Miyoshi *et al*. 2018). For this reason, it was considered that the structural PB light-frame shear wall with the end distance of 10 mm where block tear-out failure in sheathing occurred showed the lowest shear resistance against lateral load. From the above results, it was confirmed that it is necessary to secure a longer end distance compared to OSB to use structural PB as a sheathing material for the light-frame wall.



(a) Specimen 1



(b) Specimen 2

Fig. 7. Hysteresis, envelop, and EEEP curve of structural PB light-frame wall with 15 mm end distance

Figures 6 and 7 show the results of the hysteresis, envelope, and EEEP curves for the OSB light-frame wall and the structural PB light-frame wall with the end distance of 15 mm. The envelope and EEEP curves were calculated as average values of positive and negative envelop curve using the second cycle at each step of the protocol. The shear strength, shear modulus at 0.4 peak load, and ductility of the OSB wall were determined as 8.5 kN/m, 3.1 kN/mm, and 11.4, respectively. In the same order, the shear resistance of the structural PB wall was calculated as 9.2 kN/m, 2.0 kN/mm, and 6.2, respectively. When comparing the structural PB wall and the OSB wall, it was confirmed that the shear strength of structural PB wall increased by 8%. It was considered that the shear strength of structural PB was high because of higher density of structural PB. It was reported that the properties of nail joint shear were proportional to density of members (Smith *et al*. 2001; Sawata *et al*. 2008; Sandhaas and Görlacher 2018). Therefore, the entire shear strength of wall might increase because the shear property of the nail joint used in structural PB will be high. It was known that the influence of nail joints on the shear strength of a light-frame wall is approximately 65 to 75% (Wang 2009).

In contrast, the shear modulus of structural PB light-frame shear wall was lower than that of OSB light-frame shear wall. There was a positive relationship between the density of the wood-based material's surface layer and the nail joint's stiffness (Sawata *et al*. 2008). Therefore, additional research might be needed to increase the shear modulus of structural PB walls considering the stiffness of the nail joint. It was confirmed that the shear modulus of structural PB wall was 30% lower than that of OSB wall shown in AWC (2015) on seismic load. The shear modulus of the structural PB wall was higher than that of the structural plywood wall (Thickness of plywood: 11.9 mm, Shear modulus: 1.9 kN/mm) in AWC (2015). Caution might be required in designing horizontal displacement of light-frame construction using structural PB wall according to height, because the shear modulus of structural PB was lower than the design value of an OSB wall.

The ultimate displacement after yielding was shorter for the structural PB wall compared to the OSB wall, resulting in lower ductility when examining the EEEP curve of each test piece. However, it was confirmed that there was no problem in using the structural PB wall, since the displacement at which the ultimate load occurs was greater than 50 mm, which is the maximum horizontal displacement to be concerned with light-frame construction structural design.

CONCLUSIONS

1. The shear resistance for the lateral load of structural particleboard (PB) light-frame walls was evaluated, and the structural PB was developed to utilize recycled wood and increase the usage of domestic wood in Korea.
2. The shear strength of the structural PB wall was higher than that of oriented strand board (OSB) light-frame wall. On the other hand, the results of the shear modulus and ductility of the structural PB wall were the converse.
3. It was considered that there would be no problems in the ductility of structural PB wall because the ultimate load of structural PB occurred at a displacement of 50 mm and over. The displacement of 50 mm is used in the structural design of light-frame construction in Korea. The shear modulus of structural PB was lower than the test results and the design value for the OBS wall, and higher than the design value for the plywood wall. Thus, an additional method might be needed to control total horizontal displacement when the structural PB wall is used in mid- or high-rise timber buildings.
4. It was confirmed that structural PB can be utilized as a sheathing material for a wall in light-frame construction if the execution method for the end distance is established so that the structural PB wall can fully resist a lateral load.

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