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Performance of cyclic loading for structural insulated panels in wall application

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Abstract. There are few technical documents regulated structural performance and engineering criteria in domestic market for Structural insulated panels in Korea. This paper was focused to identify fundamental performance under monotonic loading and cyclic loading for SIPs in shear wall application. Load-displacement responses of total twelve test specimens were recorded based on shear stiffness, strength, ultimate load and displacement. Finally energy dissipation of each specimen was analyzed respectively. Monotonic test results showed that ultimate load was 44.3 kN, allowable shear load was 6.1 kN/m, shear stiffness was 1.2 MN/m, and ductility ratio was 3.6. Cyclic test was conducted by two kinds of specimens: single panel and double panels. Cyclic loading results, which were equivalent to monotonic loading results, showed that ultimate load was 45.4 kN, allowable shear load was 6.3 kN/m. Furthermore the accumulated energy dissipation capability for double panels was as 2.3 times as that for single panel. Based on results of structural performance test, it was recommended that the allowable shear load for panels should be 6.1 kN/m at least.

Keywords: structural insulated panels; shear wall; monotonic loading; cyclic loading

1. Introduction

1.1 Background and purpose

Structural insulated panels (SIPs), structurally performed panels consisting of a plastic insulation bonded between two structural panel facings, are one of emerging products with a viewpoint of its energy and construction efficiencies. Structural insulated panels excel in terms of thermal perfusion and air-tightness, thus providing ideal conditions for energy savings. They are an eco-friendly material from the viewpoint of relative life cycle cost, because concrete or steel is not used. Only requiring a simple process of assembly, they shorten the duration of construction and are in alignment with the low carbon green growth policy pursued by the Korean government.

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However, SIPs have thus far seen little penetration to the Korean market and no relevant technical guidelines have been established. As for wood building structures, several literatures have been documented since 1988. For example, a large experiment at the University of California, Irvine was conducted where timber shear walls with different configurations were tested under reversed cyclic loading (Pardoen *et al*. 2000). The wood structures project for one-story and two-story shear walls as a part of the CUREE-Caltech woodframe project was in an effort to investigate current design codes for timber structures after the 1994 Northridge earthquake (Filiatrault *et al*. 2000). Mi (2006) conducted full scale tests on unblocked shear walls and blocked walls under monotonic loading and ISO load protocol. Ayoub (2007) studied the project to develop a new model for nonlinear seismic analysis of wood building structures. In the U.S., the National Association of Home Builders conducted a study on a performance evaluation and design standard for residential buildings (2007) and provided allowable loads against shear and axial direction for SIP walls having a thickness of 114 mm and 165 mm and suggested design details for each connection type. APA-the Engineered Wood Association has regularly produced technical reports on the structural performance of SIPs (Edward 2006, Borjen *et al*. 2008, ANSI/APA 2008). Sinha (2009) presented to identify the load sharing aspect between oriented strand board (OSB) and gypsum wall board (GWB) in shear wall assembly during racking load. This paper suggested strain distribution of the load sharing between OSB and GWB after initial loading of 2,440 × 2,440 mm shear wall, but did not reach to search for the proportion of load sharing. Goodall (2011) conducted total fourteen tests to design a wood frame shear wall that could withstand greater displacement before damage occurred to the gypsum wall board. Unlike the case in the U.S., the Korean Building Code simply classifies SIPs into class I and class II based on the composition of the structural panel and wood-based particle panel and categorizes their strength into grade 1 and grade 2 depending on the standard allowable stress that is provided. However, only a paper is documented to evaluate dynamic tests on wood shear wall composed of SIPs in Korea. Little research on design guidelines for structural composite members that contain insulation materials has been conducted. Furthermore, for the purpose of applying shear walls of SIPs, only a study focused on identifying in-plane shear and compressive force under monotonic loading has been reported. (Nah *et al*. 2012).

1.2 Method and scope

It is necessary to produce technical data to design houses with prefabricated SIP walls and flooring and furthermore to verify the structural performance of various SIP members manufactured in Korea. The purpose of this study is to identify the structural behavior of SIPs in wall applications. This will make it possible to domestically manufacture SIPs to be employed in houses and enable more than 30% greater energy efficiency as compared to existing houses. The size of specimens for the shear wall in this study is based on structural insulated panels used in a pilot house in Korea. Among the 6 sizes of panels used in prefabricated wooden structures, the following two sets of dimensions were selected due to the limitation of the size of the panels imported in Korea: 1.2 × 2.4 m and 2.4 × 2.4 m. After choosing a method to test the structural performance and identify the in-plane shear performance under monotonic and cyclic loading, structural tests were performed and load and displacement were measured. Based on the load-displacement relation, the ultimate load, allowable load, and shear stiffness were estimated in order to suggest the allowable shear strength applicable to the design process.

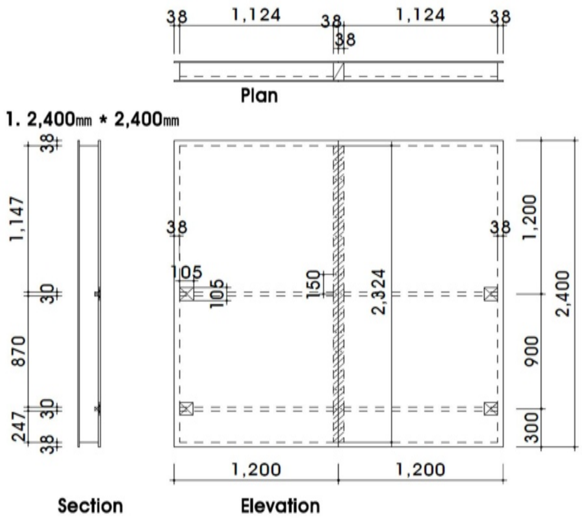
2. Test plan

2.1 Material properties and test method

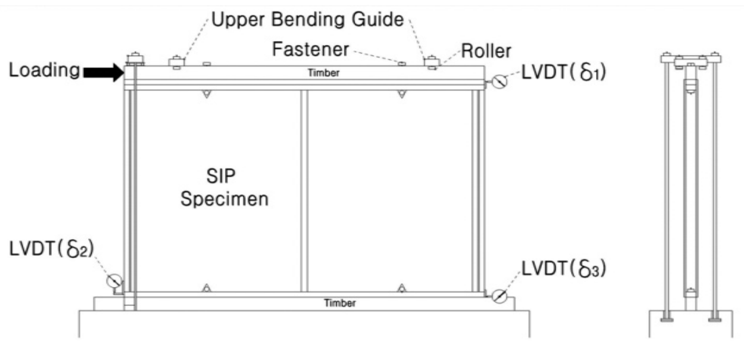
The insulation material, which has a density of 26 kg/m^3 and a thickness of 140 mm, was applied between oriented strand boards for the SIP specimens. The nominal thickness of each oriented strand board as the wooden particle board was 11 mm. The specimens were fabricated at a domestic manufacturer in September 2011. Many test methods, such as ASTM E72, ASTM D4761, ASTM E1803, and KS F2273, as well as the test procedure by APA-the Engineered Wood Association, were examined to determine which steps should be employed in the SIP test.

2.2 Specimens

As shown in Fig. 1, all the edges of insulation were dented 38 mm from the edge of the wooden



(a) Dimension of specimen



(b) Test setup for monotonic loading

Fig. 1 Specimen and monotonic loading

Table 1 Identification of monotonic test specimen

Specimen	Composition of SIP	Dimension (W × H × T)	Quantity
SIPS-R-1	OSB 11 mm	2,400 mm	1
SIPS-R-2	+ Insulation 140 mm	× 2,400 mm	1
SIPS-R-3	+ OSB 11 mm	× 162 mm	1

particle board. A structural header of 50 × 152 mm was placed on center between each 1.2 m wide panel to compose a 2.4 m wide panel. Wooden particle boards were fixed to both sides by screws driven into the panels at intervals of 150 mm. Table 1 shows the dimensions of the specimens consisting of two 1.2 × 2.4 m panels apiece.

2.3 Monitoring loading

Monotonic loading for in-plane shear test was conducted mainly according to ASTM E72. In order to prevent the panel ends from rising when load was applied to one side of the specimen, fixing plates to prevent the specimen from rising were manufactured and positioned on the upper part of the loading jig. The axial force was loaded so as not to exceed 90 N on the top of specimen. Load was applied to the specimens through square headers clamped to the upper part of the panel by bolts. Three loading steps, of 3.5 kN, 7 kN, and 10.5 kN, were applied at a uniform speed. After each loading step, the load was removed and the next loading was applied. The test was terminated when the specimen ruptured or the total strain reached 100 mm. Although the loading was based on load control, the loading speed was set so that the lateral displacement at the upper end of the specimen would not exceed 5×10^{-2} mm/s until 3.5 kN of load, in accordance with KS F2273.

2.4 Cyclic loading

While many research papers on the lateral resistance of shear walls in traditional wooden structures have been written, no study has been conducted in Korea on the dynamic behavior of shear walls made of SIPs. Some researchers in the U.S. and Canada have carried out tests to identify the characteristics of the dynamic behavior. Lam (1997) conducted monotonic loading and cyclic loading tests on 2.4 × 7.2 m shear walls and reported improvement in strength and stiffness of more than 100% when compared with walls of 1.2 × 2.4 m standard size. He (1998) conducted a test with a loading scheme consisting of multiple groups of cycles, each of which had three identical cycles and one group of unidirectional loading, until the test wall failed. He suggested that displacement equivalent to 50% and 80% of the ultimate load obtained from a monotonic loading test be employed for cyclic loading control. Krawinkler (2000) developed the CUREE cyclic test protocol. A simplified cyclic loading test method, one of the CUREE test methods developed by Stanford University, was applied in the test of this study. The basic loading history is as follows. Based on the displacement obtained from the monotonic loading test (Δ_m), which was 80% of the ultimate load, the displacement in the cyclic loading (Δ) was decided. The displacement for cyclic loading was defined according to Eq. (1) (Mosalam *et al*. 2008).

$$\Delta = 0.6\Delta_m \tag{1}$$

Table 2 Displacement amplitude schedule

Loading cycle group	$\Delta = 0.6\Delta_m$	Displacement (mm)
1 Group	0.05Δ 6 Cycle	0.48
2 Group	0.075Δ 7 Cycle	0.73
3 Group	0.1Δ 7 Cycle	0.97
4 Group	0.2Δ 4 Cycle	1.95
5 Group	0.3Δ 4 Cycle	2.93
6 Group	0.4Δ 3 Cycle	3.90
7 Group	0.7Δ 3 Cycle	6.83
8 Group	1.0Δ 3 Cycle	9.76
9 Group	1.5Δ 3 Cycle	14.65
10 Group	2.0Δ 3 Cycle	19.53
11 Group	2.5Δ 3 Cycle	24.42
12 Group	3.0Δ 3 Cycle	29.30
13 Group	3.5Δ 3 Cycle	34.18
14 Group	4.0Δ 3 Cycle	39.07
15 Group	4.5Δ 3 Cycle	43.95
16 Group	5.0Δ 3 Cycle	48.84

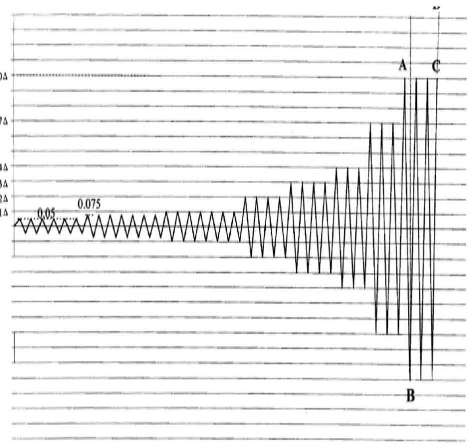


Fig. 2 Cyclic test protocol

Based on the displacement (Δ) obtained from Eq. (1), loading was given at a displacement control speed of 0.02 Hz, as shown in Table 2, for loading groups having different displacement and control cycles.

The specimens to be subjected to monotonic loading were fabricated as listed in Table 3. A 10 ton actuator supplied by Instron in German was used for cyclic loading and jigs were installed to fix the specimens. LVDTs were placed at the upper and lower ends of the specimens to measure lateral and vertical displacement. Test data were obtained at 20 ea/sec. Fig. 3 shows the specimen setting.

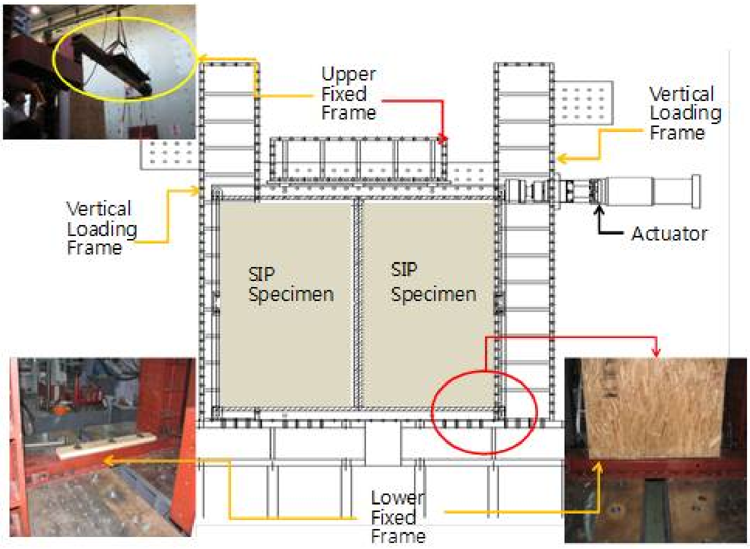
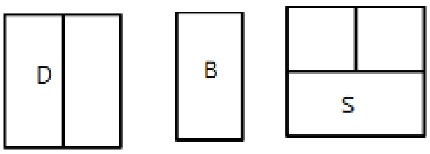


Fig. 3 Test setup

Table 3 Specimens for cyclic loading

Specimen	Composition of SIP	Dimension (W×H×T)	Quantity	Type
SIPC-D-1	OSB (thk.11 mm) + Insulation (thk. 140 mm) + OSB (thk.11 mm)	2,400 mm × 2,400 mm × 162 mm	1	D
SIPC-D-2			1	D
SIPC-D-3			1	D
SIPC-B-1		1,200 mm × 2,400 mm × 162 mm	1	B
SIPC-B-2			1	B
SIPC-B-3			1	B
SIPC-S-1		Upper: (1,200 mm + 1,200 mm) × 1,200 mm × 162 mm Lower: 2,400 mm × 1,200 mm × 162 mm	1	S
SIPC-S-2			1	S
SIPC-S-3			1	S



3. Test results

3.1 Results of monotonic loading test

Eq. (2) for shear deformation (Φ) was formulated in accordance with KS F 2273.

$$\Phi = \{(\delta_1 - \delta_2)/h\} - \delta_3/b \quad (2)$$

Table 4 Shear displacement dependent to load

Specimen	Shear Displacement ($\times 10^{-4}$)		[Unit: mm]
	3.5 kN	7 kN	10.5 kN
SIP-R-1	1.67	6.67	6.46
SIP-R-2	2.92	3.75	2.92
SIP-R-3	4.58	5.42	9.58
Average	3.06	5.28	6.32

In the equation, δ_1, δ_2, δ_3, h, and b denote horizontal pure displacement at the upper side of the specimen at each load step, vertical pure displacement taken from the lower side of the specimen at each load step, horizontal pure displacement at the lower side of the specimen at each load step, and height of the specimen and width of the specimen, respectively. Total displacement at each load step was measured and pure displacement at each load step was obtained from the total displacement. Table 4 shows the displacement in shear at each load step calculated by Eq. (1).

The displacement in shear under 3.5 kN ranged between 1.67×10^{-4} and 4.58×10^{-4} and the average was 3.06×10^{-4}. As the load increased to 7.5 kN and 10.5 kN, the displacement in shear increased to 5.28×10^{-4} and 6.32×10^{-4}, 1.7 times and 2.1 times the shear displacement under the initial load of 3.5 kN. Under 10.5 kN, specimens ruptured before 1.5×10^{-2} of shear displacement, corresponding with the measuring limit of shear displacement prescribed in KS F 2273.

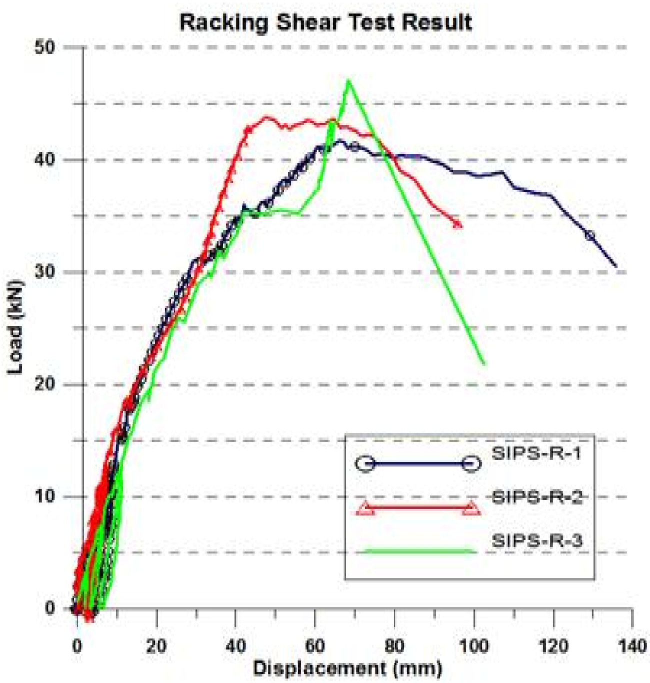


Fig. 4 Load-displacement of racking shear monotonic test result

Table 5 Summary of racking shear monotonic test result

Specimen	Ultimate load (kN)	Ultimate displacement (mm)	Yield displacement (mm)	Shear strength (kN/m)	Shear stiffness (MN/m)	Ductility ratio
SIP-R-1	41.6	67	16	17.3	1.3	4.2
SIP-R-2	43.7	58	17	18.2	1.3	3.4
SIP-R-3	47.1	68	22	19.6	1.1	3.1
Average	44.1	64	18.3	18.4	1.2	3.6

Table 5 shows the total displacement, ultimate load, yield displacement, shear strength, shear stiffness, and ductility at each load step.

For the 3 specimens, the anchor bolts clamping upper structural boards and loading jigs were taken off from the upper headers after testing. As shown in Fig. 4 of the load-displacement relation, separation between the structural board and insulation material, deformation of the lower frame, and separation or rupture of the bolts were observed between plastic behavior and ultimate load. Load transfer was made through the headers connecting the upper and lower parts of the panels as well as the panels themselves. The headers, the weakest members in the panels, were separated from the panels, while the joints of the panels did not rupture or display deformation.

The average ultimate load and displacement of the specimens were 44.3 kN and 64 mm. Yield displacement (Δy) was defined as the displacement at the load equivalent to a half of the ultimate load. The yield displacement of the 1.2 × 2.4 m panels was 9.82 mm (He *et al*. 1999). In the 2.4 × 2.4 m panels, the yield displacement was 9.14 mm or 12.87 mm depending on whether the distance between the screws fixing panel headers was 152 mm or 76 mm (Durham *et al*. 2001). The average yield displacement in this test carried out under the same conditions was 18 mm when the distance between screws was 150 mm. According to the test conducted by APA-the Engineered Wood Association, the average shear strength of 2.4 × 2.4 m panels (165 mm thick) was 14.1 kN/m and that of 2.4 × 3.0 m panels (165 mm thick) was 14.4 kN/m. Shear strength is obtained by dividing the ultimate shear load by the unit width of the panel. In the test carried out in this study, the average shear strength of the shear wall specimens was 18.4 kN/m, which was more than 120% of that obtained from the test conducted by APA-the Engineered Wood Association. The report produced by APA-the Engineered Wood Association (2006) suggested that the ultimate load be three times as much as the allowable load. Thus, the allowable shear strength of the shear walls in this study is 6.1 kN/m. The shear stiffness (G') is defined as follows.

$$G' = (P_{\max} \cdot H) / (2L \cdot \Delta y) \tag{3}$$

The average shear stiffness of the specimens was 1.2 MN/m, which falls into the range of 1.05 to 1.38 reported in previous study (Durham *et al*. 2001). In addition, the ductility index (D) defined as $\Delta u / \Delta y$ was 3.6.

3.2 Cyclic loading test results

3.2.1 SIPC-D specimens

Cyclic loading specimen SIPC-D-1 reached a ultimate load of +45.5 kN at loading cycle group

11. The test was terminated at loading cycle group 16. Fig. 5 shows hysteresis diagram related to loading cycle.

SIPC-D-2 specimen reached a ultimate load of +50.2 kN. The highest load of 6.0 kN at loading cycle group 15 amounted to 12% of the ultimate load and exceeded the estimated allowable load. The effective load strength was 16.7 kN, which was a third of the ultimate load. Fig. 6 shows the load-displacement relationship of cyclic loading specimen SIPC-D-2.

In the SIPC-D-3 specimen, loading was continued until loading cycle group 13. The test was terminated at group 14 when the load was decreased to below a half of the ultimate load. Accordingly, accumulated energy dissipation of this specimen was significantly inferior to that of other specimens. The ultimate load was +40.4 kN, observed at loading cycle group 12, which was 10 kN lower than that of SIPC-D-2 specimen. Fig. 7 shows the load-displacement hysteresis of the specimen, SIPC-D-3. Fig. 8 illustrates a comparison of the hysteretic diagram of specimen D-1 and specimen D-3. Of the SIPC-D specimen series, test result of specimen D-1 shows the best ductile.

3.2.2 SIPC-B specimens

Unlike SIPC-D specimens, which were 2.4 m wide, the panel width of the SIPC-B series specimens was 1.2 m. In the SIPC-B-1 specimen, loading was continued up to group 15. Observed

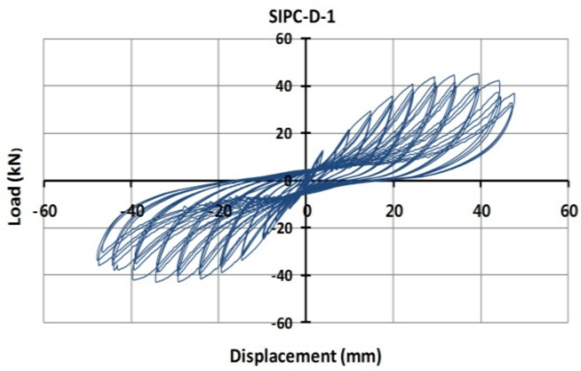


Fig. 5 Load-displacement for SIPC-D-1

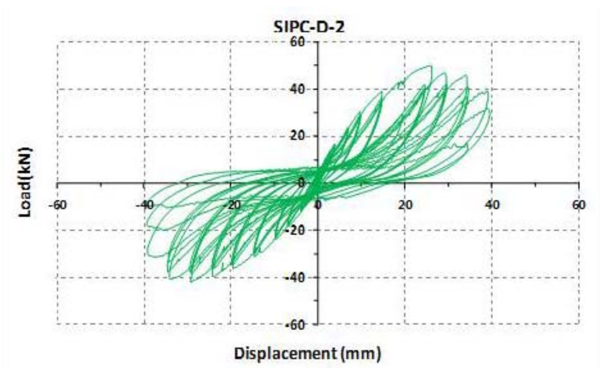


Fig. 6 Load-displacement for SIPC-D-2

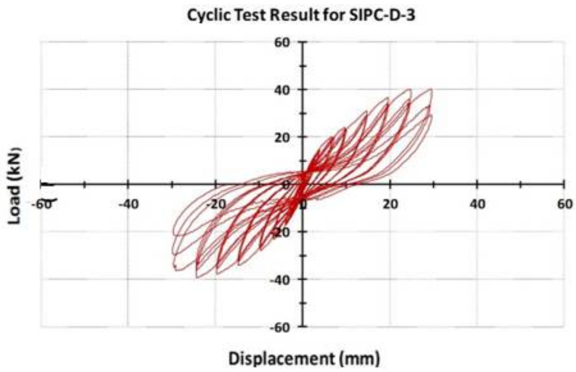


Fig. 7 Load-displacement for SIPC-D-3

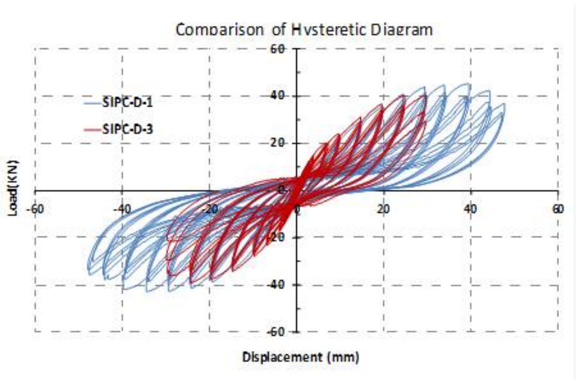


Fig. 8 Comparison between specimens for D-1 and D-3

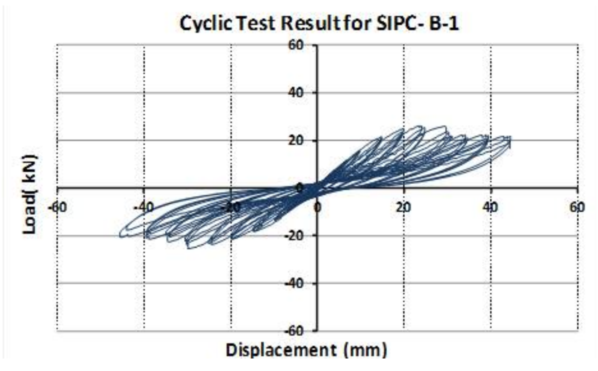


Fig. 9 Load-displacement for SIPC-B-1

at loading cycle group 11 having a displacement of 24.4 mm, the ultimate load of the specimen was +26.1 kN, which was 57% of that in the SIPC-D specimens. Fig. 9 shows the load-displacement relation of the specimen.

In the SIPC-B-2 specimen, loading was continued up to loading cycle group 15. The ultimate load of +27.2 kN was observed at group 12 and the minimum load was -26.5 kN. The ultimate load of the specimen was 4% higher when compared with the SIPC-B-1 specimen. Fig. 10 shows the load-displacement curve.

In the SIPC-B-3 specimen, loading was continued up to loading cycle group 15. The ultimate load of +27.3 kN was observed at loading group 13 and the minimum load was -24.3 kN, observed at loading group 11. The highest load at loading cycle group 15 was 12 kN, which was lower than the estimated allowable load. Fig. 11 shows the load-displacement relation of the specimen. In case of single wide panel, the hysteric diagram of specimen B-1 and specimen B-2 shows similar trend as Fig. 12.

4. Analysis and discussion

In the SIPC-D specimens, the ultimate load was 1 kN to 6 kN higher than the minimum load. In particular, the SIPC-D-3 specimen showed a difference of 20% in the ultimate load and displacement from others. Table 6 shows the results of the cyclic loading test.

According to the results, the ultimate load of 2.4 m wide double panels composed of a 1.2 m wide panel plus a 1.2 m wide panel was 1.6 times when compared with single panel specimens. Since the allowable design load is a third of the ultimate load, an average allowable load of 15.2 kN and an average allowable shear strength of 6.3 kN/m were obtained.

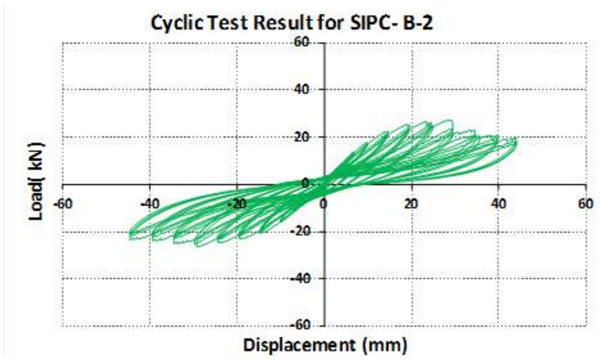


Fig. 10 Load-displacement for SIPC-B-2

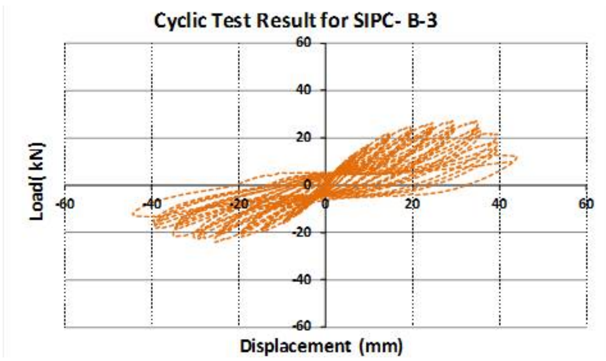


Fig. 11 Load-displacement for SIPC-B-3

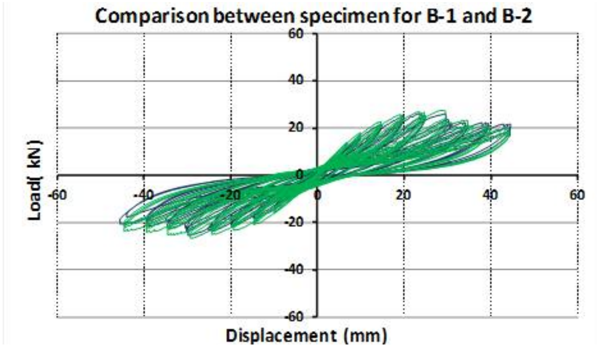


Fig. 12 Comparison between specimens for B-1 and B-2

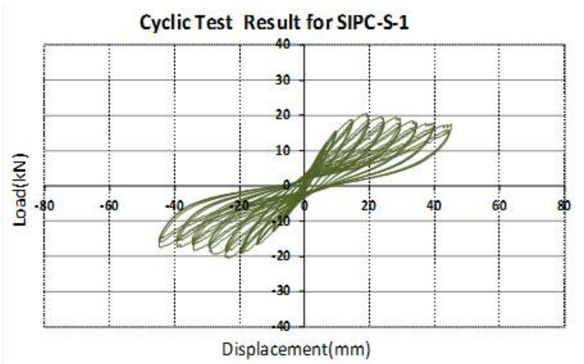


Fig. 13 Load-displacement for SIPC-S-1

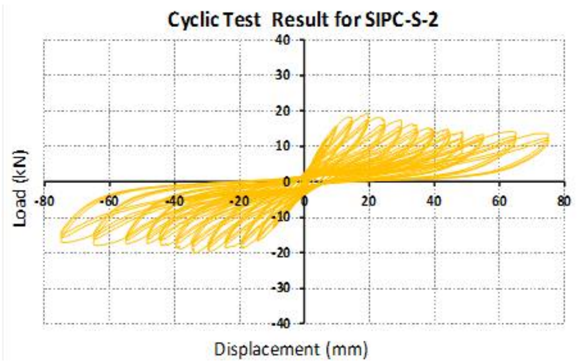


Fig. 14 Load-displacement for SIPC-S-2

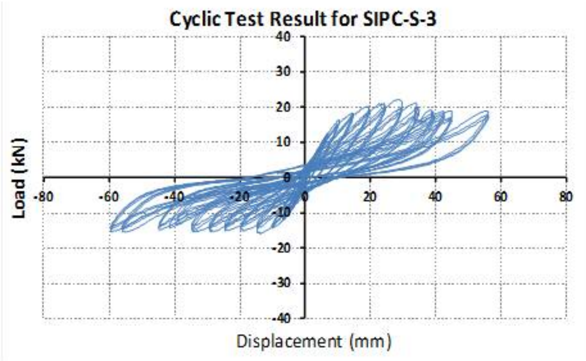


Fig. 15 Load-displacement for SIPC-S-3

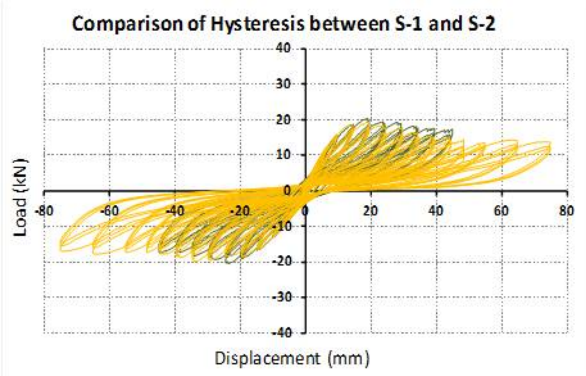


Fig. 16 Comparison between S-1 and S-2

Table 6 Synthetic result for specimen SIPC-D series

Specimen	Ultimate		Minimum		Allowable Load (kN)	Allowable shear stiffness (kN/m)
	Load (kN)	Displacement (mm)	Load (kN)	Displacement (mm)		
SIPS-D-1	+45.5	+48	-42.9	-48	15.2	6.3
SIPS-D-2	+50.3	+43	-42.1	-43	16.8	7.0
SIPS-D-3	+40.5	+29	-39.4	-29	13.5	5.6
Average	+45.4	-	-41.4	-	15.2	6.3

Due to the difference in loading cycle group upon the termination of the test of the 3 specimens, the accumulated energy dissipation capacity also differed considerably. The amount of accumulated energy in SIPC-D-2 and SIPC-D-3 was 62% and 38%, respectively, of that in SIPC-D-1. This difference may be attributable to the variability in construction quality between the two test panels.

Fig. 17 shows the results. The screws connecting two parallel panels were separated or deformed. Some of the screws fixing the lower parts of the panels were separated as lateral displacement increased, which caused abnormality in the load transfer mechanism. Therefore, the accumulated energy dissipation capacity differed significantly among the specimens even though the deviation of average allowable shear load was merely 0.68 kN/m. The ultimate load values for the shear wall under cyclic loading were similar to those in the monotonic loading as shown in Fig. 18. Compared with the monotonic loading, SIPC-D-1 reached an early peak load of 45.5 kN at positive displacement phase. The average ultimate load and minimum load observed in the SIPC-B specimens were 59% and 61% of those in the SIPC-D specimens, as shown in Table 7. The allowable load to the SIPC-B single panel shear specimens was 18% higher than that to the double panel SIPC-D specimens. The average shear strength of the specimens was 7.5 kN/m.

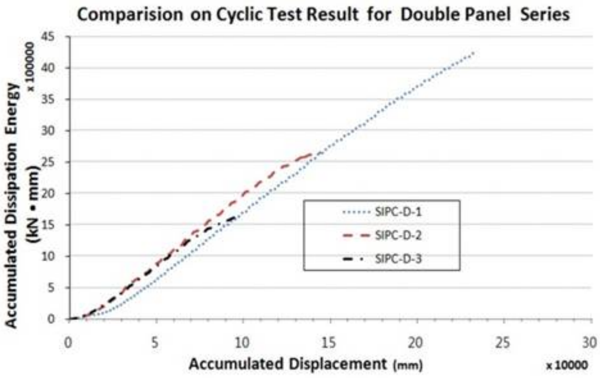


Fig. 17 Accumulated dissipation energy

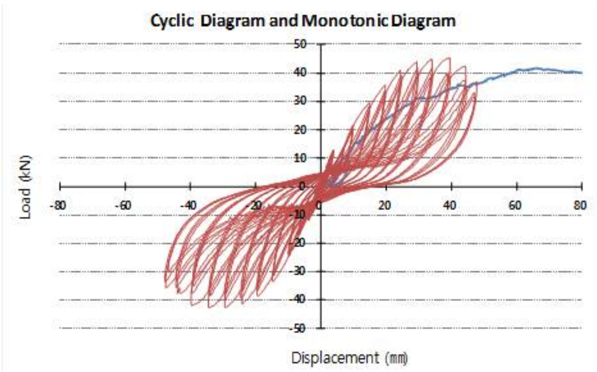


Fig. 18 Cyclic load-displacement with monotonic curve

Table 7 Synthetic result for specimen SIPC-B series

Specimen	Ultimate		Minimum		Allowable Load (kN)	Allowable shear stiffness (kN/m)
	Load (kN)	Displacement (mm)	Load (kN)	Displacement (mm)		
SIPS-B-1	+26.1	+24	-25.5	-29	8.7	7.3
SIPS-B-2	+27.1	+29	-26.5	-29	9.1	7.6
SIPS-B-3	+27.3	+34	-24.3	-24	9.1	7.6
Average	+26.9	-	-25.4	-	8.9	7.5

The comparison of accumulated energy dissipation capacity among the 1.2 m wide single panel specimens provided different results from the SIPC-D specimens. The amount of accumulated energy in SIPC-B-2 and SIPC-B-3 was 99% and 81%, respectively, of that in SIPC-B-1. Fig. 19 shows the results.

The results of the cyclic loading test obtained from SIPC-S specimens are as follows. The average ultimate load of the specimens was 45% and 76% of that obtained from the SIPC-D and SIPC-B specimens. Table 8 shows the results. Since SIPC-S specimens had three panels, the shear capacity was significantly inferior to that of the specimens having a single panel or double panels. The allowable load was 6.8 kN and the average allowable shear strength was 2.8 kN/m, which was 37% of the average shear strength observed at the single panel SIPC-B specimens.

The accumulated energy dissipation capacity differed significantly among the three SIPC-S specimens depending on the displacement control group at the termination of the test. The amount of accumulated energy in SIPC-S-1 and SIPC-S-3 was 47% and 67%, respectively, of that in SIPC-S-2 as shown in Fig. 20. The amount of accumulated energy at loading cycle group 15 was 59,677 kN·mm, 54.948 kN·mm, and 52,326 kN·mm in SIPC-S-1, SIPC-S-2, and SIPC-S-3, respectively. The difference in the amount of accumulated energy among cyclic loading groups was within a range of ±7%.

It was observed from the SIP specimens of shear walls that an increase in the number of panels resulted in a decline of the allowable shear capacity. Among the test candidates, the SIPC-S

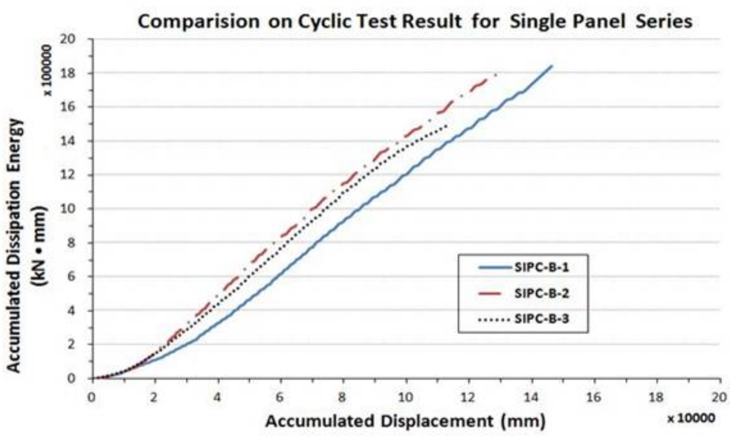


Fig. 19 Accumulated dissipation energy (SIPC-B)

Table 8 Synthetic result for specimen SIPC-S series

Specimen	Ultimate		Minimum		Allowable Load (kN)	Allowable shear stiffness (kN/m)
	Load (kN)	Displacement (mm)	Load (kN)	Displacement (mm)		
SIPS-S-1	+20.3	+24	-20.4	-24	6.7	2.8
SIPS-S-2	+19.4	+34	-19.9	-34	6.4	2.6
SIPS-S-3	+22.1	+28	-15.9	-15	7.3	3.0
Average	+20.6	-	-18.7		6.8	2.8

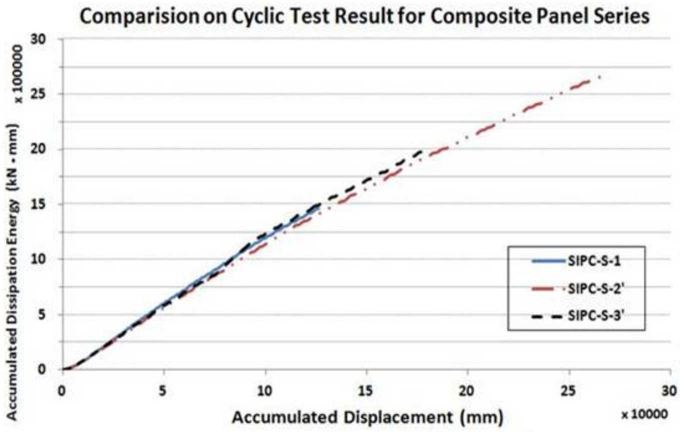


Fig. 20 Accumulated dissipation energy (SIPC-S)

Table 9 Summary of test results under monotonic and cyclic loading

Specimen Identification		Ultimate Load (kN)		Allowable Shear Load (kN/m)	
Monotonic	Cyclic	Monotonic loading	Cyclic loading	Monotonic loading	Cyclic loading
SIP-R-1	SIPS-D-1	41.6	45.5	5.7	6.3
SIP-R-2	SIPS-D-2	43.7	50.2	6.1	6.9
SIP-R-3	SIPS-D-3	47.1	40.4	6.5	5.6
Average		44.4	45.4	6.1	6.3

specimens were the most vulnerable in terms of allowable shear capacity. Therefore, in the design of shear walls using SIPs is important to adhere to the standard size. In the design of shear walls consisting of more than 2 panels it is also necessary to consider incorporating additional structural members such as window frames to secure shear resistance capacity appropriate to the original design conditions and lintel beams to horizontally confine the upper and lower parts of any openings in walls when employing SIPs.

The accumulated energy dissipation capacity of the SIPC-D-1 specimen was 2.3 times greater than that of the SIPC-B-1 specimen. The ultimate load of the SIP-R specimen subjected to monotonic load and the SIPC-D specimen subjected to cyclic load was 44.3 kN and 45.4 kN, respectively, although the two had identical width of 2.4 m. The allowable shear strength was 6.1 kN and 6.3 kN, respectively. The results summarized in Table 9 are similar to those obtained from previous tests using large OSB panels (Durham *et al*. 2001). The trend between monotonic and cyclic loading reveals similar to previous literature (Folz *et al*. 2001).

5. Conclusions

In this study, 162 mm thick structural insulated panel specimens having two different panel sizes of 1.2 by 2.4 m and 2.4 by 2.4 m were fabricated for monotonic loading tests and cyclic loading tests. For the monotonic loading tests to identify in-plane shear resistance capacity, ASTM E73 and KS F2273 were applied. For the cyclic loading tests to observe dynamic behavior and characteristics, one of CUREE's simplified monotonic loading methods was used. The conclusions are as follows.

- The monotonic loading test to evaluate in-plane shear capacity of the 2.4 by 2.4 m specimens provided an average ultimate load of 44.3 kN and an average shear strength of 18.4 kN/m. The allowable shear strength was 6.1 kN/m from the test. This allowable load was 1.2 times greater than that obtained from other test results. The average shear stiffness was 1.23 kN/m and the average ductility ratio was 3.6.
- It was found from the cyclic loading test of 2.4 by 2.4 m specimens for the in-plane shear capacity evaluation that SIPC-D specimens, each of which had two parallel panels, had an average ultimate load of 45.42 kN and an allowable load of 15.14 kN. The allowable shear strength of the specimens was 6.3 kN/m, which was higher than that (6.1 kN/m) obtained from the monotonic loading test.
- From the cyclic loading test of 1.2 by 2.4 m SIPC-B specimens, an average ultimate load of 26.9 kN and an allowable load of 8.96 kN were obtained. The average shear strength of the specimens was 7.47 kN/m.
- The average ultimate load and allowable load of SIPC-S specimens, each of which had two 1.2 by 1.2 m panels and one 2.4 by 1.2 m panel, were 20.6 kN and 6.8 kN. The average shear strength of the specimens was 2.8 kN/m. The cyclic loading test showed that the allowable shear capacity differed among the single, two, and three-panel specimens. Therefore, it is necessary to use identical panels in the design of shear walls or to employ auxiliary structural members such as lintel beams for additional lateral resistance when panels of different sizes are used, as in the case of panels with an opening in the shear wall.
- The accumulated energy dissipation capacity of the single panel specimens was 81% and 99% when compared with the control specimen. However, it declined to 62% and 38% in double panel specimens due to the separation of screws delivering load between panels. On average, the accumulated energy dissipation capacity of the double panel specimens was 2.3 times higher than that of the single panel specimens.
- It is suggested from the monotonic and cyclic loading tests for the shear resistance evaluation that the shear strength of 2.4 by 2.4 m SIPs used in shear walls of prefabricated structures be a minimum of 6.1 kN/m.

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