KSCE Journal of Civil Engineering (2018) 22(9):3579-3591
DOI 10.1007/s12205-018-1197-x

Structural Engineering

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Experimental Study on Existing Reinforced Concrete Frames Strengthened by L-type Precast Concrete Wall Panels to Earthquake-Proof Buildings

Soo Kyoung Ha*, Sung Yong Yu, and Jae Suk Kim*****

Received August 21, 2017/Accepted November 14, 2017/Published Online April 10, 2018

Abstract

The purpose of this study is to investigate the behavior of existing Reinforced Concrete (RC) frames strengthened with L-type Precast Concrete (PC) wall panels under cyclic loads. The idea is to remove the brick walls with windows inside the RC frames and to strengthen the frames using L-type PC wall panels, thus transforming the existing brick infill into a strong and rigid PC infill. Herein, a technique using dowels (i.e. post-installed anchors) to fix a PC wall panel firmly to a RC frame is proposed. This technique is to anchor dowels through pre-installed holes in a PC wall panel. A total of six full-scale, one-bay, one-story RC frames were constructed and tested under reverse cyclic loading. Four L-type PC wall panels with large openings were used for strengthening the RC frames. As a result, the lateral strength, stiffness, and energy dissipation capability of the frame was greatly improved. Specifically, the more dowels that were used to fix the vertical part of a PC wall panel to an RC column and the thicker the PC wall panel, the better the seismic resistance of the frame.

Keywords: *strengthening, retrofit, partial infill, seismic resistant technique, precast concrete, wall panel*

1. Introduction

Throughout the world, many low-rise school buildings with Reinforced Concrete (RC) frames have been constructed without having been designed to be earthquake-proof. Some of these buildings have been severely damaged or destroyed by earthquakes, resulting in the injury or death of many young students. The majority of low-rise RC school buildings currently used in earthquake-prone regions such as China and Indonesia may suffer large-scale earthquake damage at some time or other, and so it is necessary to develop a structurally effective, practical, and economical seismic retrofitting technique that can immediately strengthen them.

There have been many studies on techniques for the strengthening of RC framed structures, especially by using partial or entire RC infill walls (Altin *et al.*, 1992; Sonuvar *et al*., 2004; Turk *et al.*, 2006; Altin *et al.*, 2008; Kaltakci and Yavuz, 2014), a technique which has been studied extensively for practical purposes. This technique substantially increases the lateral strength and stiffness of the frame. However, this method is problematic in that construction takes a long time and requires much fieldwork at construction sites and so is difficult to complete during school vacations. Because of these problems, many researchers consider Precast Concrete (PC) panels (Frosch *et al.*, 1996; Kesner and Billington, 2005; Akin and Sezer, 2016) as an alternative to RC infill walls. The use of factory-manufactured products can save construction time and work without dust and odor because of concrete placement. In addition, they are simple to produce, easy to construct, and durable.

Recently, a technique of bonding thin PC panels to brick infill walls has been widely investigated (Baran *et al*., 2011; Baran and Tankut, 2011a; Baran and Tankut, 2011b; Baran *et al*., 2013; Baran and Aktas, 2013; Baran *et al.*, 2014). The idea is to strengthen an RC frame with an entire infill without providing an opening. However, many low-rise buildings (including school buildings) have windows on the external walls. Furthermore, it has been shown that the members around the windows along the longitudinal side are destroyed by lateral shear cracks when such buildings are shaken by earthquakes.

In a previous study (Yu *et al.*, 2015a; Yu *et al.*, 2015b), we proposed a strengthening technique using an L-type single PC wall panel with an opening. We found that the RC-infill wall technique used on a concrete wall with an opening is more vulnerable than one without in terms of the strength and stiffness of the frame (Kara and Altin, 2006). It has also been researched that using multiple PC panels does not improve seismic resistance compared to using a single PC wall panel (Kahn and Hanson, 1979). Therefore, in order to keep the opening while substantially increasing the strength and stiffness of the RC frame, a single L-type PC wall panel was selected. As a result, the use of an L-type

*Member, Ph.D. Candidate, Dept. of Architectural Engineering, Dongguk University, Seoul 04620, Korea (E-mail: 1992ha@naver.com)
**Member, Professor, Ph.D., Dept. of Architectural Engineering, Dongguk University, Seoul 04620, Korea (Corresponding Author, E-mail: ysy@dongguk.edu)
***Member, Chief Executive Officer, Ph.D., Dept. of Civil Engineering, SDENG Co. Ltd., Gyeonggi 13219, Korea (E-mail: jskim@sdeng.net)

PC wall panel was able to maintain the opening while considerably improving the seismic resistance of the RC frame.

In this study, we propose a dowel-connection technique using post-installed anchors in order to further improve the seismic resistance of the strengthening technique from our previous research. This is a new technique developed in this study for the composite behavior of L-type PC wall panels and RC frames. This technique can be summarized as anchoring a PC wall panel inside an RC frame with dowels through pre-installed holes in the PC wall panel. The main experimental parameters studied in this research were the thickness of the PC wall panels and the arrangement of the dowels, and to this end, the lateral strength, lateral stiffness, energy dissipation capacity, and failure mechanisms of the specimens were investigated. We found that the strengthening technique of L-type PC wall panels by using dowel connections was an effective and convenient technique to improve the seismic resistance of RC frames.

2. The L-type PC Wall Panel Fixing Technique Using Dowels

2.1 The L-type PC Wall Panel Technique

The characteristics of the strengthening technique of an L-type PC wall panel are as follows:

1) Infill technique: This is a partial infill technique of an RC frame. Since it replaces the existing brick wall, the exterior remains the same after the strengthening job. The flexural and shear stiffness of the infilled structure increases so that it is effective against lateral loads as well.

2) Strengthening the exterior wall of the building: A PC wall panel is lifted by crane and installed as an exterior member of the building. It is economical in terms of cost and time saved and is more effective against the torsional force due to lateral loading than the strengthening of an interior member.

3) Maintaining the dimensions of the existing windows: Since the method uses L-type PC wall panels, large windows are maintained and unchanged before and after the strengthening job, as shown in Fig. 1.

4) Construction as a single module PC panel: There is a height-adjustable connection at the top and a width-adjustable connection at the bottom left-hand side of the L-type PC wall panel. These two connections can resolve vertical/horizontal deformation due to aging by up to 50 mm within the RC frame.

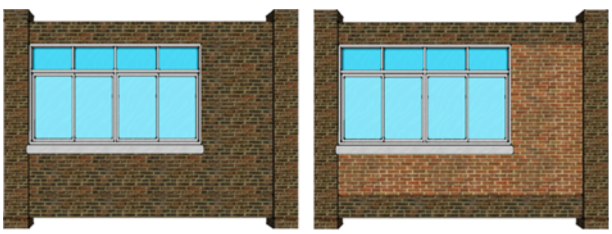


Fig. 1. Exterior View of the Strengthening Job: (a) Before, (b) After

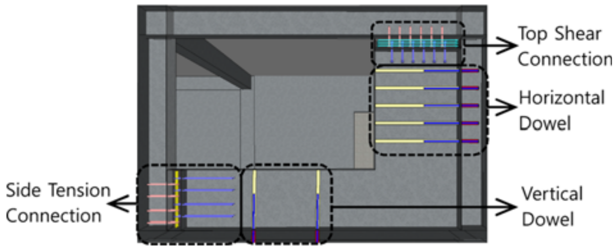


Fig. 2. Connection of the L-type PC Wall Panel

2.2 The Dowel-Connection Technique – use of Post-Installed Anchors

In order to fix the PC wall panel inside the RC frame, a dowel-connection technique was used in order to reduce cost and retain resistance at the same time. The dowel-connections are illustrated in Fig. 2. When manufacturing the PC panels at the PC factory, 50 mm diameter concrete holes were bored into the panels in order to insert the dowels. The holes centered on the faces of the PC members. The adhesive force of the dowels is increased because the holes are made of pure concrete in the interior. In addition, drilling anchor holes into the PC members on site is not required.

A sealing job proceeded through epoxy injection after the PC wall panel was installed inside the RC frame. Additional anchor holes were drilled into the RC frame through the pre-installed vertical and horizontal holes on the PC panel (the dowels anchor the PC panel to the RC frame through these holes). Each dowel consisted of one chemical anchor centered at the face of the PC and RC members. The diameter and length of the dowels was 24 mm and 630 mm, respectively, and the anchorage lengths of the dowels were 420 mm for the PC wall panels and 210 mm for the RC frame. The dowels were then fixed by anchorage injection. Afterwards, the remaining internal holes of the PC panel were filled with non-shrink mortar to complete the anchoring work.

2.3 Other Connections

As can be seen in Figs. 3 and 4, a height-adjustable shear connection at the top and a width-adjustable tension connection at the side of the bottom were provided. The location of the top shear connection is where the largest shear force and displacement are expected under lateral earthquake loading. To resist these

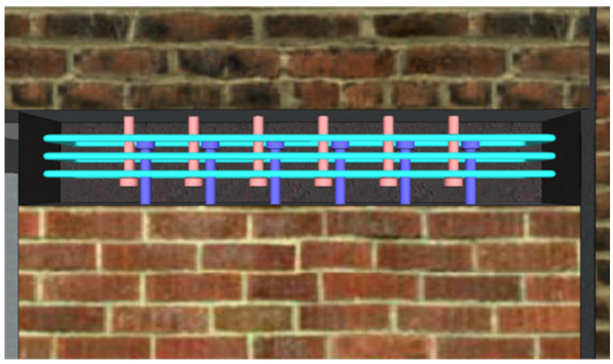


Fig. 3. Top Shear Connection

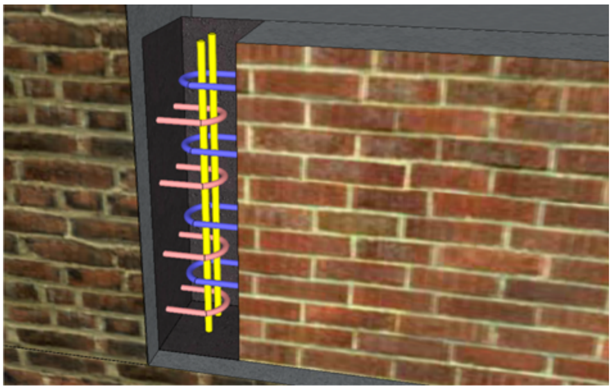


Fig. 4. Side Tension Connection

forces, multiple chemical anchors (ϕ24 × 330 mm) were installed. The six post-installed anchors at the bottom of the RC beam and six cast-in anchors at the top of the PC wall panel were arranged by intersecting one another. Moreover, three 13 mm diameter deformed bars were used as stirrups at the top shear connection. Side tension connections can resist tensile stress while the connection width is adjustable. The connections consist of two straight deformed bars and eight U-bars protruding from the ends of both the RC column and the PC wall panel.

3. Experimental Investigation

3.1 Description of the Test Specimens

A total of six full-scale one-bay, one-story RC frames were designed and tested with cyclic lateral loads. PR1 and LM were designed as reference specimens. The remaining four specimens were strengthened with L-type PC wall panels on bare frames using the dowel-connection technique.

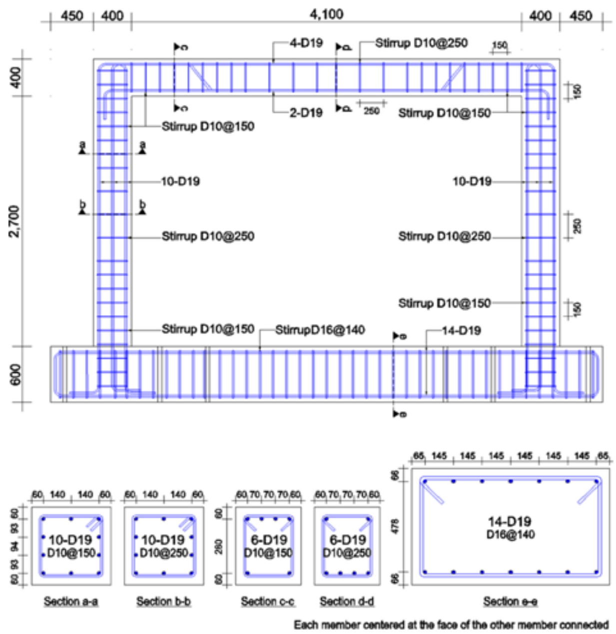


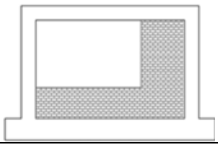
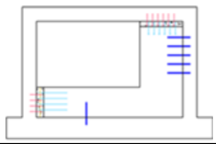
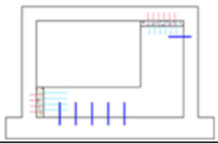
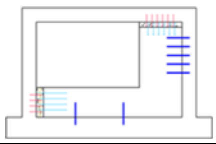
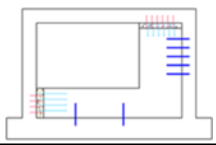
Fig. 5. Dimensions and Reinforcement of the RC Frame for Specimen PR1 (mm)

Specimen PR1 was a bare RC frame produced by modeling an exterior beam-column. It was a section of a school building based on a blueprint of the standard school design from the 1980s provided by the office of education in the Republic of Korea (details of the frame are shown in Fig. 5). The dimensions and reinforcement of the bare frame were the same in all specimens. The sizes of the column and beam were 400 × 400 mm and 330 × 400 mm, respectively. Ten 19 mm diameter deformed bars were used as the longitudinal bars in the columns. Six 19 mm diameter deformed bars were also used as the longitudinal bars for the beam. 10 mm diameter deformed bars were placed as stirrups for the column and beam, and were spaced at 150 mm from the end and 250 mm from the center.

Reference specimen LM was a bare frame with an L-type brick wall. The wall was piled with hollow brick (190 × 90 × 57 mm) in an L-shape with 1B (190 mm) thickness, and English bonding was used. The size of the opening was determined according to the standardized design for schools for which the minimum size of the window was 2,900 × 1,850 mm.

L-type PC wall panels were installed and connected to RC frames using dowel-connections. The location of the dowels (ϕ24 ×

Table 1. Properties of the Specimens

Specimen (1)	Configuration (2)	b_w [mm] (3)*
PR1		-
LM		190
LA1-H5V1		250
LA1-H1V5		250
LA3-H5V2		180
LA4-H5V2		160

*b_w= thickness of PC wall panel.

Table 2. Types of Connection

Specimen (1)	Dowel-Connection Dowels (number/spacing (mm))		Top Connection Anchors (number/spacing (mm))		Side Connection Bars (diameter/spacing (mm))	
	Horizontal (2)	Vertical (3)	At RC beam (4)	At PC panel (5)	At RC column (6)	At PC panel (7)
LA1-H5V1	5/250	1	6/150	6/150	16/160	16/160
LA1-H1V5	1	5/450	6/150	6/150	16/160	16/160
LA3-H5V2	5/250	2/1,350	6/150	6/150	16/160	16/160
LA4-H5V2	5/250	2/1,350	6/150	6/150	13/160	13/160

Notes. The diameters of all anchors and dowels were 24 mm. Anchors and dowels for (2), (3), (4) were post-installed anchors and anchors for (5) were cast-in anchors. Each anchor of (2), (3), and (5) was centered at the face of the member applied. Anchors of (4) were located 34 mm apart at the center. U-bars of (6) and (7) were centered at the face of the member applied in side connection. Two 19 mm diameter bars were installed through the center of the side connection.

Table 3. PC Wall Panel Reinforcement

Specimen (1)	PC wall panel Number and Type of Longitudinal Bar-Stirrup/spacing [mm]	
	Horizontal (2)	Vertical (3)
LA1-H5V1	8ϕ25-D16/100	8ϕ25-D16/100
LA1-H1V5	8ϕ25-D16/100	8ϕ25-D16/100
LA3-H5V2	8ϕ25-D16/100	8ϕ25-D16/100
LA4-H5V2	8ϕ22-D13/100	8ϕ22-D13/100

630 mm) and the thickness of the wall panels were selected as experimental parameters. The properties of the specimens are given in Table 1. The anchorage method and the lengths of the dowels are described in Section 2.2. The number of dowels used and the spacing of the anchors are divided into horizontal/vertical dowels and are assigned as 2(2) and 2(3) in Tables 2. The sizes of the openings of all strengthened specimens were the same as that of specimen LM. In addition, the spaces of the longitudinal bars and the stirrups of the PC panels were identical in all specimens. Deformed bars were used in all of the specimens. In Tables 3(2) and 3(3), the diameters of the bars are divided into those used for the vertical and horizontal parts of PC panels, respectively.

As the positioning of the dowels was the main experimental parameter, specimen LA1-H5V1 and specimen LA1-H1V5 were tested to compare their behavior and resistance. The dimensions and reinforcement of the PC wall panels in the two specimens were the same, as was the thickness (250 mm). In the PC wall panel, eight 25 mm diameter bars were used as compression and tension longitudinal bars in the vertical and horizontal parts. 16 mm diameter bars spaced at 100 mm were used as stirrups. The dimensions and reinforcement details of the PC wall panel of specimen LA1-H5V1 are presented in Fig. 6. This specimen had five horizontal dowels that were placed at a spacing of 250 mm in order to fix the PC panel to the RC column. Fig. 7 shows that specimen LA1-H1V5 mainly used vertical dowels. Five vertical dowels were anchored at a spacing of 450 mm from the internal edge of the PC panel. One horizontal anchor was located 300 mm below the top connection.

Specimens LA3-H5V2 and LA4-H5V2 were tested to compare results according to panel thickness. The thickness of the panel for specimen LA3-H5V2 was 180 mm while that of specimen LA4-H5V2 was 160 mm. The same dowel-connections were used for both specimens with five horizontal dowels anchored at a

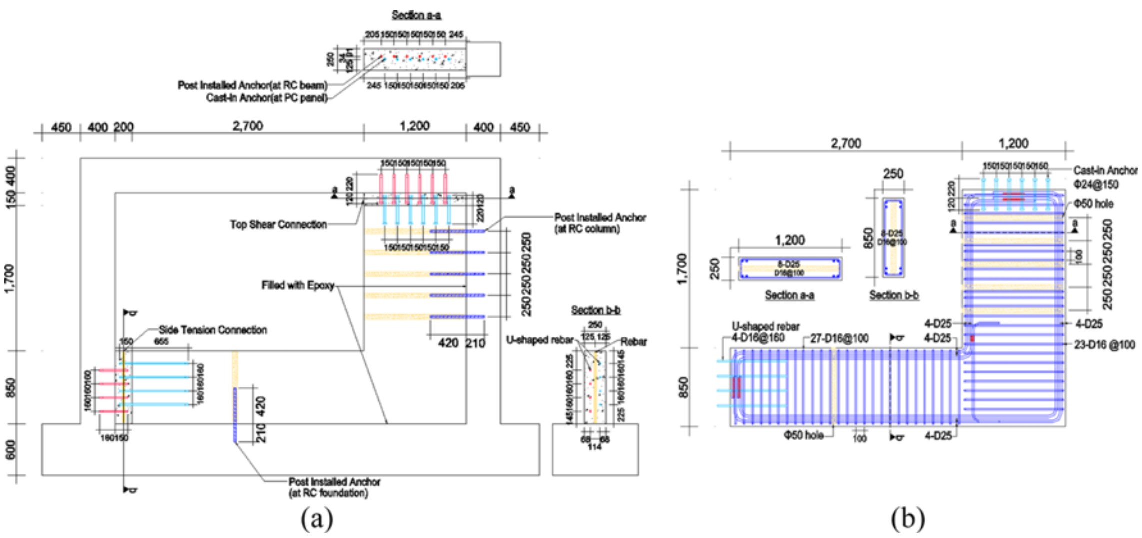


Fig. 6. Dimensions and Reinforcement of Specimen LA1-H5V1 (mm): (a) RC Frame with PC Wall Panel, (b) PC Wall Panel

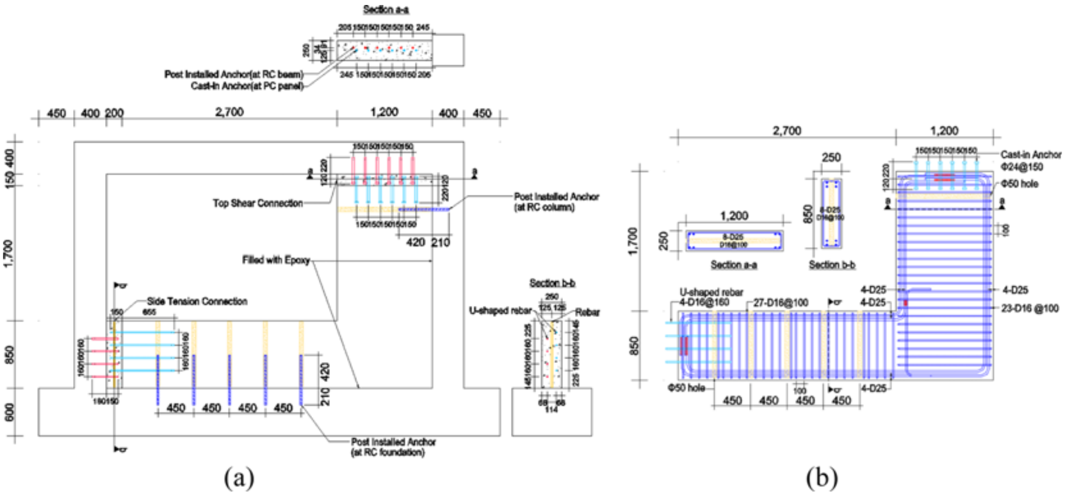


Fig. 7. Dimensions and Reinforcement of Specimen LA1-H1V5 (mm): (a) RC Frame with PC Wall Panel, (b) PC Wall Panel

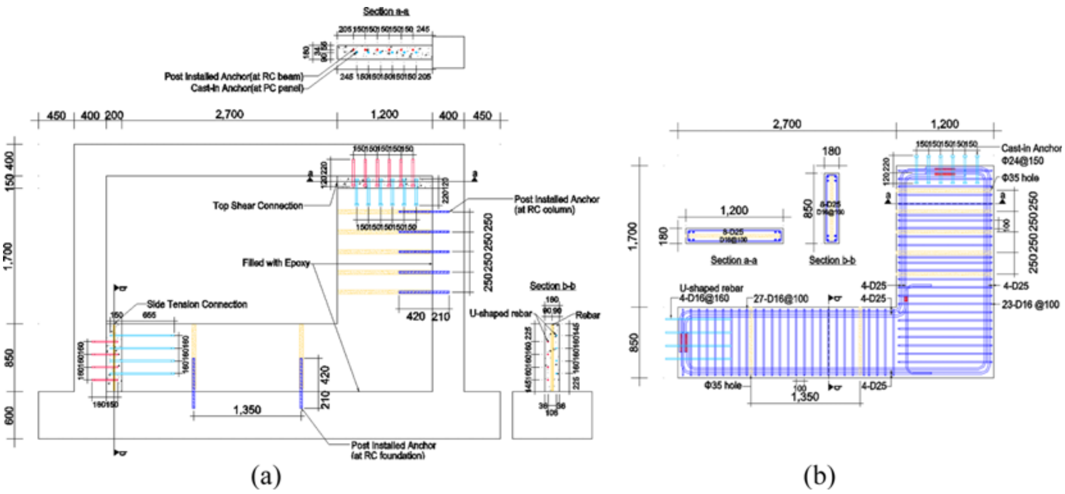


Fig. 8. Dimensions and Reinforcement of Specimen LA3-H5V2 (mm): (a) RC Frame with PC Wall Panel, (b) PC Wall Panel

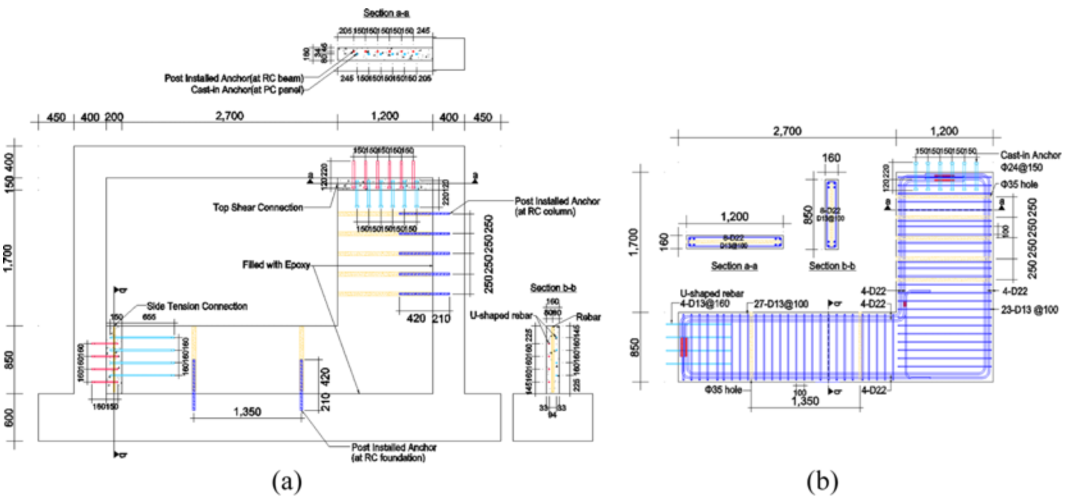


Fig. 9. Dimensions and Reinforcement of Specimen LA4-H5V2 (mm): (a) RC Frame with PC Wall Panel, (b) PC Wall Panel

spacing of 250 mm and two vertical dowels anchored at a spacing of 1,350 mm. Vertical dowel was 450 mm away from the internal edge of PC panel. As can be seen in Table 3, bars with smaller diameters were used in the thin PC wall panel. The reinforcement of the PC panel of specimen LA3-H5V2, which was the same as the previous specimens (LA1-H5V1 and LA1-

H1V5), is illustrated in Fig. 8. The reinforcement details for specimen LA4-H5V2 are shown in Fig. 9. In this specimen, eight 22 mm diameter bars were used as longitudinal bars and 13 mm diameter bars were used as stirrups spaced at 100 mm for the thinner PC panel.

The size and number of the anchors, anchorage lengths, and the spacing of the anchors and the bars at the top and side connections were the same in all of the strengthened specimens. The thickness of the connections matched the thickness of the PC wall panels employed. The top shear connection was constructed as follows with the numbers and the spacing of the anchors provided in Tables 2(4) and 2(5). Six 210 mm-long holes were drilled at the bottom of the top RC beam. Six post-installed anchors (ϕ24 × 330 mm) were then inserted into the holes (at a spacing of 150 mm) by anchorage injection. Afterwards, a PC wall panel with six cast-in anchors (ϕ24 × 330 mm) at a spacing of 150 mm was installed inside the RC frame. Anchors were intersected, as shown in Fig. 3. Finally, high-strength mortar with good flow ability was placed for finishing.

The diameters of the deformed bars and their spacing are listed in Tables 2(6) and 2(7), for the side connection. The anchorage lengths of the U-bars were 180 mm for the RC column and 655 mm for the PC wall panel, and their bonding length into the connection concrete was 150 mm. The U-bars were anchored at a spacing of 160 mm in both the RC and PC members and mutually intersecting. Two 19 mm diameter deformed bars passed through the center of the connection. These were fixed to the U-bars with steel wires. Finally, high-strength concrete was placed to finish the connection construction.

The specimens were constructed under identical conditions including manufacturing environment, date, and materials. Each specimen was tested daily. The gap between the RC frame and the PC wall panel was filled with sealant and medium-viscosity epoxy mortar was tightly injected into the space in between to fix the PC wall panel.

3.2 Materials

Concrete of low compression strength (17.6 ~ 21 MPa) was commonly used for the exterior RC frame in the existing school buildings. Relatively high-strength concrete with a compression strength of between 41.6 and 53.5 MPa was used for the interior PC wall panel, while non-shrink mortar from company S with a compression strength of between 48 and 56.1 MPa was placed at the connection. The compression strength values of the specimen concrete on the date of the tests are summarized in Table 4, and the properties of the rebar used for the specimens are given in Table 5. European company H supplied both post-installed anchors (ϕ24 × 630 mm and ϕ24 × 330 mm) and cast-in anchors (ϕ24 × 630 mm), and their related properties are organized in Table 6.

3.3 The Strength of the Dowel Anchor Connection

The tensile and shear strengths of the dowel-connections calculated according to ACI 318M-11 Appendix D (ACI Committee 318, 2011) are provided in Table 7.

3.4 Test Setup, Loading System, and Instrumentation

As can be seen in Fig. 10, the specimens were installed on the floor of the laboratory. The testing system consisted of a strong floor, a rigid wall, loading equipment, and a data acquisition system. The RC foundations of each specimen were firmly

Table 4. Properties of the Test Specimens Concrete Components

Specimen (1)	RC Frame Concrete [MPa] (2)	PC Panel Concrete [MPa] (3)	Connection Concrete [MPa] (4)	Masonry Mortar [MPa] (5)
PR1	20.5	-	-	-
LM	21.0	-	-	7.1
LA1-H5V1	17.9	41.6	56.1	-
LA1-H1V5	17.6	45.0	56.1	-
LA3-H5V2	19.9	52.2	48.0	-
LA4-H5V2	20.0	53.5	50.8	-

Table 6. Properties of the Anchors

Anchor Type (1)	Property (2)	Effective Section Area [mm^2] (3)	Tensile Strength [MPa] (4)	Yield Strength [MPa] (5)
Stud*	Cast-in-place	353	450	350
Chemical*	Post-installed	353	500	400
Chemical**	Post-installed	353	500	400

*Anchorage for top shear connections
**Anchorage for dowel-connections

Table 5. Properties of the Reinforcing Bars

Bar Type (1)	Bar Diameter [mm] (2)	Location (3)	Tensile Strength [MPa] (4)	Yield Strength [MPa] (5)
ϕ10	9.5	Stirrup for RC beam and column	645.8	516.8
ϕ16	15.9	Stirrup for RC foundation	654.4	536.7
ϕ19	19.1	RC frame longitudinal bars	644.5	508.5
ϕ22	22.2	PC panel longitudinal bars	842.0	705.7
ϕ25	25.4	PC panel longitudinal bars	766.5	627.5
ϕ13	12.7	Stirrup for panel, Anchorage for PC panel-to-side connection-to-RC column	660.7	544.2
ϕ16	15.9	Stirrup for panel, Anchorage for PC panel-to-side connection-to-RC column	675.2	556.4

Table 7. Strength of the Dowel-Connections

Specimen (1)	Horizontal Dowel-Connection [kN]		Vertical Dowel-Connection [kN]	
	Tensile Strength (2)	Shear Strength (3)	Tensile Strength (4)	Shear Strength (5)
LA1-H5V1	86.9	187.1	28.6	63.6
LA1-H1V5	37.8	63.6	65.3	140.6
LA3-H5V2	68.2	205.0	19.7*	62.1*
LA4-H5V2	59.9	206.2	17.3*	59.3*

*Since the spacing between two dowels (1,350 mm) exceeded the limit dowel spacing (1,260 mm), the two dowels were calculated as a single independent dowel.

bolted to the strong floor using twelve 32 mm diameter high-tension steel bars with a tensile strength of over 20 ton each. Two screw jacks that can receive an additional reaction of 400 ton were installed on both ends of the foundations. In order to prevent left/right fall down of the specimen, ball jigs were attached to both sides of the RC columns. Reversed cyclic lateral loading was applied to the center at the end of the upper RC beam using a 200 ton capacity actuator. Finally, the tests were conducted with the displacement control method.

Load control was determined as drift ratios based on ACI 374.1-05. Fig. R7.0 (ACI Committee 374, 2014). Displacement-controlled cycles representative of the drifts expected under earthquake motions were applied. Loading was repeated three times for the drift ratio of each stage, and continuous loading was applied at the same drift ratio. Experiments were continued with gradually increasing drift ratios until they were equal to or greater than 3.5%. However, when the resistance decreased by 20% or more at the maximum load, the specimen was deemed to have been destroyed and the loading was stopped.

All specimens were examined using linear variable differential transformers in order to ascertain the shear displacement of infill, column curvatures, and story drift, as illustrated in Fig. 10. The average shear deformations of infills were measured using diagonally placed wire displacement transducers. Strain gauges were installed on the reinforcement at the critical section to identify the yield of the flexural bars during the test. All cracks in the specimens were marked at the completion of testing after each stage of three cycles. Furthermore, lateral load-story displacement curves were plotted and the failure mechanism was observed and recorded during testing.

4. Experimental Results

4.1 Specimen Behavior and Failure Mechanisms

The load-story displacement ratio curves plotted from the test data are given in Fig. 11, and the maximum loads and the lateral drift ratios at 85% of the maximum load at post peak for each specimen are reported in Table 8. The ductility of the specimens was determined as the lateral drift ratio, and the results were divided into forward and backward cycles. The data from the test results of specimens strengthened with PC wall panels were compared to those of the reference specimen LM with an L- type brick wall used in the actual school buildings, and the ratios are listed in Table 8.

The first reference specimen PR1 (a bare RC frame) showed typical frame behavior during the test and the ductile behavior of flexural failure over a long term at a relatively low load, as is evident in Fig. 11(a). The lateral drift ratio value at 85% of the maximum load was 4.4% in both the forward and backward cycles.

The load-story displacement ratio curve for second reference specimen LM presented in Fig. 11(b) was similar to that of specimen PR1. Specimen LM showed lateral drift ratios of 3.5 and 2.7% at 85% of the maximum load in both the forward and backward cycles, respectively. Although these were 0.9 ~ 1.7% less than that of specimen PR1, they were still high values.

According to the load-displacement ratio curves in Figs. 11(c), 11(d), 11(e), and 11(f), the lateral deformation of the strengthened specimens considerably decreased and the lateral strength and stiffness remarkably increased. Furthermore, they showed an asymmetric curve where strength and stiffness during forward cycles was greater than during backward cycles. The measured lateral drift ratios for the strengthened specimens at 85% of the maximum load were between 0.7% and 1.7% in forward cycles and 0.7% and 1.0% in backward cycles, which was significantly less than that of reference specimen LM (3.5% ~ 2.7%).

The use of horizontal dowels in specimens improved the

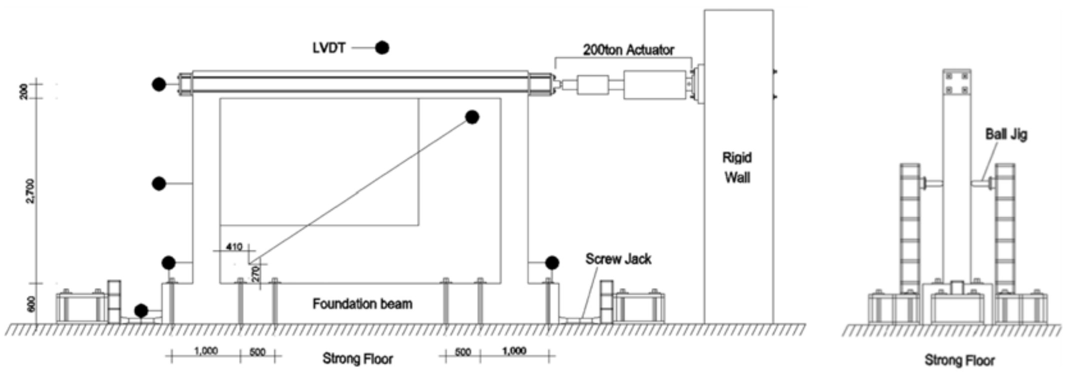


Fig. 10. Test Setup, Loading System, and Instrumentation (mm)

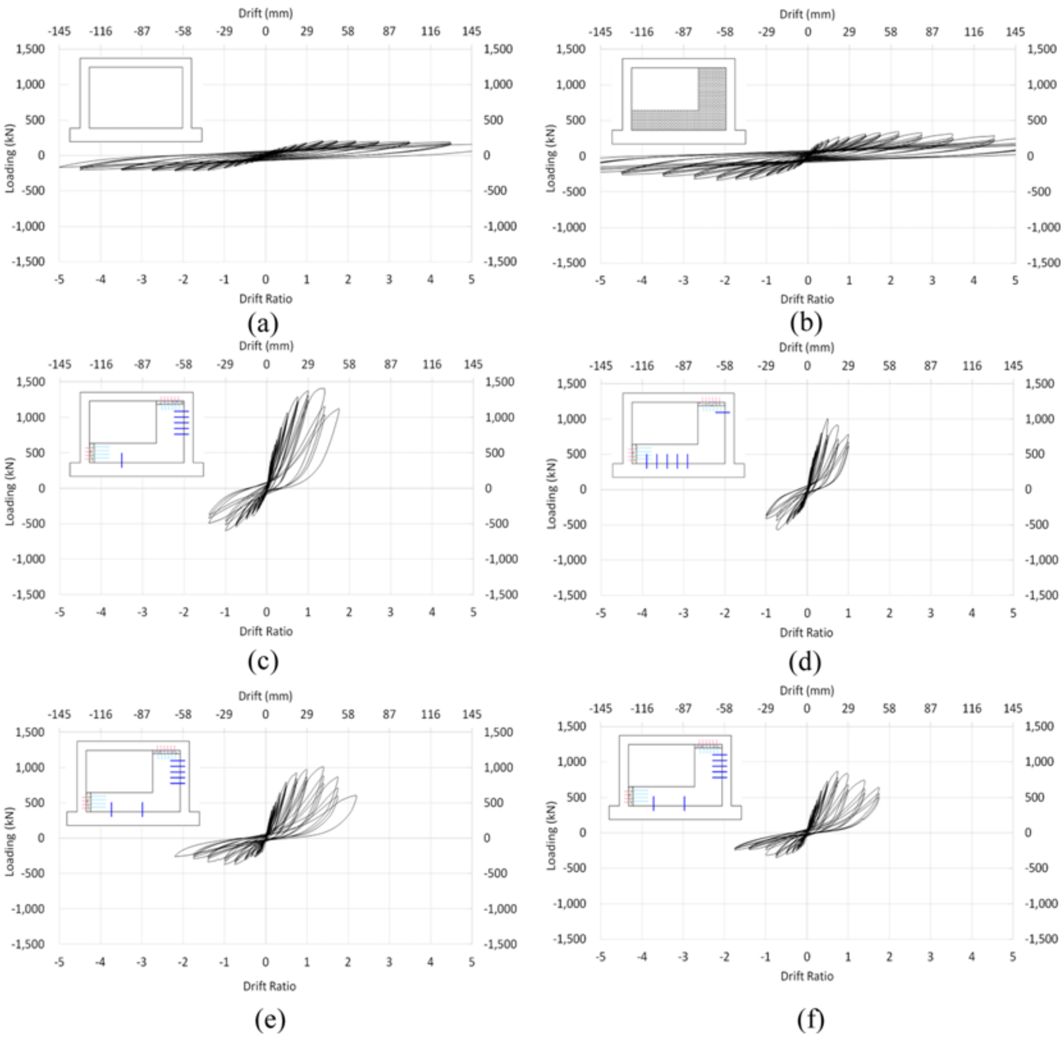


Fig. 11. Load-displacement Ratio Curves for the Test Specimens: (a) PR1, (b) LM, (c) LA1-H5V1, (d) LA1-H1V5, (e) LA3-H5V2, (f) LA4-H5V2

Table 8. Summary of the Experimental Results

Specimen (1)	Forward Cycles			Backward Cycles			Initial Stiffness [kN/mm] (8)	Ratio (9)***	Energy Dissipation Capacity, Joule [kN-mm] (10)	Ratio (11)****
	Maximum load [kN] (2)	Ratio (3)*	Drift Ratio [Drift[mm]] (4)**	Maximum load [kN] (5)	Ratio (6)*	Drift Ratio [Drift[mm]] (7)**				
PR1	207	0.60	4.4 [128.8]	-216	0.64	-4.4 [-128.1]	18.31	0.43	9,489	0.49
LM	346	1.00	3.5 [100.9]	-336	1.00	-2.7 [-77.9]	42.78	1.00	19,334	1.00
LA1-H5V1	1,411	4.08	1.3 [39.1]	-595	1.77	-0.9 [-26.8]	138.12	3.23	62,697	3.24
LA1-H1V5	1,008	2.91	0.7 [21.7]	-568	1.69	-0.7 [-20.6]	114.38	2.67	61,942	3.20
LA3-H5V2	1,016	2.94	1.7 [50.6]	-373	1.11	-0.7 [-20.3]	98.85	2.31	55,336	2.86
LA4-H5V2	871	2.52	1.4 [40.5]	-350	1.04	-1.0 [-28.8]	88.26	2.06	52,844	2.73

*Ratios (3) and (6) are the maximum lateral load compared to reference specimen LM.
**Lateral Drift ratio at 85% of maximum load.
***Ratio (9) is the initial stiffness compared to reference specimen LM.
****Ratio (11) is the cumulative dissipated energy compared to reference specimen LM.

seismic behavior of a frame more effectively than using vertical dowels. The specimen with the largest overall curve was specimen LA1-H5V1 with the thickest (250 mm) PC wall panel on an RC column fixed using the greatest number (five) of horizontal dowels, for which lateral drift ratios of 1.3% during forward cycles and 0.9% during backward cycles were obtained. Therefore, the average drift ratio for the specimen was 1.1%.

The results of the test changed as the arrangement of the dowels did. The lateral drift ratio at 85% of the maximum load for specimen LA1-H1V5 (strengthened with five vertical dowels to fix the PC wall panel to the RC foundation) was 0.7% in both forward and backward cycles. Compared to the specimen LA1-H5V1 (strengthened by using five horizontal dowels), that of specimen LA1-H1V5 slightly decreased by 0.4% on average. Furthermore, as can be seen from the comparison in Figs. 11(c) and 11(d), the load and displacement of specimen LA1-H1V5 significantly decreased overall.

We found that the thicker the PC wall panel was, the greater the load and displacement was during seismic behavior. The difference is evident in Fig. 11(e) and 11(f), which shows that the overall behavior of specimen LA3-H5V2 (with a 180 mm thick PC wall panel) was better than that of specimen LA4-H5V2 (with a thinner (160 mm) one). However, no significant difference was found in their average lateral drift ratios at 85% of the maximum load in both forward and backward cycles when compared to each other or other strengthened specimens. The average lateral drift ratios were 1.2% for specimens LA3-H5V2 and LA4-H5V2.

Figure 12 shows the photographs of specimens after failure. Specimen PR1 ultimately failed due to its column mechanism (Fig. 12(a)); plastic hinge behavior was observed and flexural and shear failure occurred at the beam-column connections and the ends of the columns on the foundation. As can be seen in Fig. 12(b), the behavior of specimen LM with a brick wall was almost identical to the frame with a waist-high wall only. First, a long gap occurred between the RC column and the infill at the sides of the window opening. Afterwards, even though infill at the side of the opening nearly separated from that at the bottom of the opening in the waist-high wall, it did not collapse. The RC frame of specimen LM failed in the same way as specimen PR1.

Photos of the strengthened specimens after the tests are given in Figs. 12(c), 12(d), 12(e), and 12(f). Similar failure mechanisms

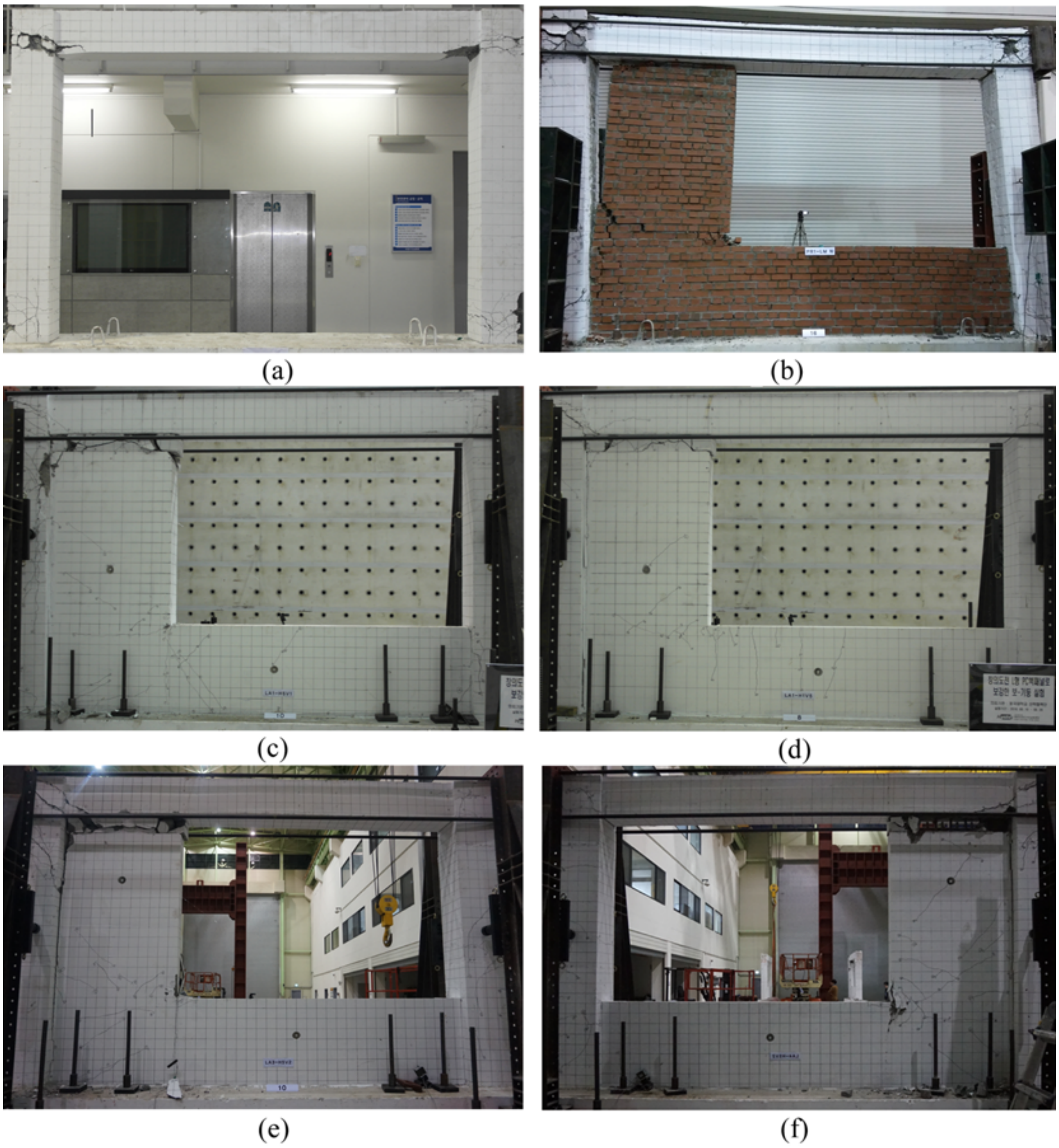


Fig. 12. Specimens after the Test: (a) PR1, (b) LM, (c) LA1-H5V1, (d) LA1-H1V5, (e) LA3-H5V2, (f) LA4-H5V2

were observed in all strengthened specimens in that the internal PC wall panel cracked before the RC frame. On the PC wall panel, flexural or shear cracks started mainly at the corner of window opening (bottom left-hand corner of the opening in the photographs), and numerous cracks occurred across the entire wall. Especially, the thinner the PC wall panel, the more severe the concrete failure at the corner of opening.

After initial cracking of the PC panels, gaps began to occur all over the area between the PC wall panels and the RC columns, and we observed that this gap increased up to around 50 mm by the end of the test. The composite action between the frame and wall panel was reduced because of this gap, thus the lateral force applied to the RC column was subsequently applied directly to the top shear connections fixing the vertical part of PC panels to the upper RC beams, which were ultimately destroyed. The concrete fragments of the top connections shattered and fell down. Separation of the L-type PC wall panel from the RC column and failure of the top shear connections ultimately caused the failure of the strengthened specimens. In other words, when these failures occurred, the strengthened specimens reached their maximum load carrying capacity in both the forward and backward cycles, and such a failure mechanism was verified in the tests of all of the strengthened specimens.

The load in the forward cycles did not increase any further and only decreased after complete separation of the RC column and L-type PC wall panel because the composite flexural resistance between RC column and PC panel dominates the behavior during forward cycles, as illustrated in Fig. 13(a), for the following reasons. The lateral load applied to the top of the RC column pushed the L-type PC wall panel during forward cycles, and the top shear connection exhibited horizontal movement along with the PC wall panel due to flexural deformation. Therefore, no significant shear force developed in the top shear connection.

Figure 13(b) shows the failure behavior of the strengthened specimens in the gap between the PC wall panel and the RC column and the lateral load applied on top shear connections during backward cycles. While the top shear connections failed in the above process, we were able to record the maximum load in backward cycles. Finally, the capacity to the transfer lateral load of the frame decreased.

5. Discussion of the Test Results

5.1 Strength and Stiffness

The test results are summarized in Table 8, from which the lateral strength and initial stiffness of the specimens can be used as a measurement of the effectiveness of the proposed strengthening technique. The strengthening effect of each specimen was determined as the ratio of its effectiveness compared to reference specimen LM with an L-type brick wall. The strength and stiffness characteristics evaluated with the response envelope curves along with the general behavior of the specimens are shown in Fig. 14. Response envelope curves were drawn by connecting the peak points of each forward and backward cycle of lateral load-displacement ratio curves for each specimen.

The brick wall of specimen LM did not have a large strengthening effect on the frame. The lateral forward strength was 207 kN and the lateral backward strength was 216 kN for specimen PR1 (the RC frame). However, the lateral forward strength was 346 kN and the lateral backward strength was 336 kN for specimen LM, which was a slight increased. Therefore, the ratio of lateral strength of specimen PR1 to that of reference specimen LM was 0.6 times. Since the existing RC frame was very vulnerable to seismic activity, the brick wall strengthening alone lacked resistance against an earthquake load.

After strengthening the RC frame with an L-type PC wall

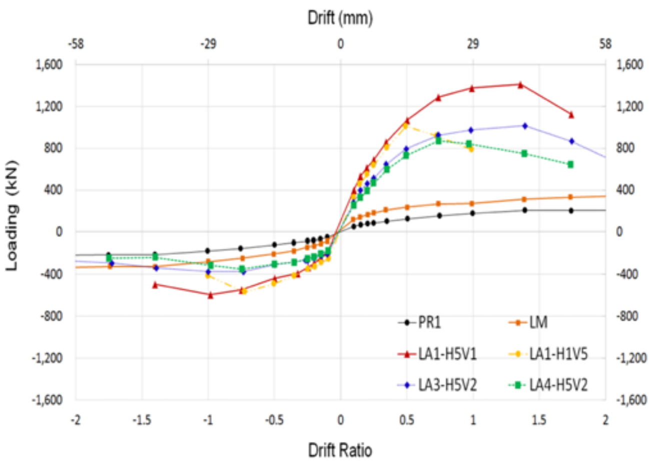
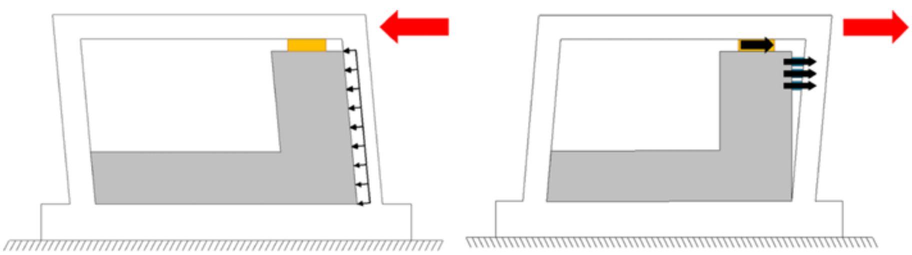


Fig. 14. Response Envelope Curves



(a)

(b)

Fig. 13. Behavior of the Strengthened Specimens: (a) In Forward Cycles, (b) In Backward Cycles

panel, the seismic behavior of the frame was substantially improved. As can be seen in Fig. 14, the strength and stiffness of the strengthened specimens were clearly higher than those of the reference specimen LM with brick wall, and compared to it, the increases in maximum strength were 2.52 and 4.08 times during forward cycles and between 1.04 and 1.77 times during backward cycles. The more horizontal dowels were used and the thicker the PC wall panel was, the more the strength was observed to increase in the strengthened specimens. The lateral forward strength of specimen LA1-H1V5 (with five vertical dowels) was 1,008 kN, and the corresponding value for specimen LA1-H5V1 (with five horizontal dowels) was 1,411 kN, 40% greater than that for specimen LA1-H1V5. However, the lateral strength values for specimens LA1-H5V1 and LA1-H1V5 in backward cycles were 595 kN and 568 kN, respectively, so specimen LA1-H5V1 displayed slightly more strength (5%) than specimen LA1-H1V5 during backward cycles. This seems to be because they used the same top shear connection strategy. The lateral strength values were 1,016 kN and 871 kN in forward cycles and 373 kN and 350 kN in backward cycles for specimen LA3-H5V2 (with a 180 mm thick PC wall panel) and specimen LA4-H5V2 (with a 160 mm thick PC wall panel), respectively. Therefore, specimen LA3-H5V2 exhibited 17 and 7% more strength than specimen LA4-H5V2 during forward cycles and backward cycles, respectively. The PC wall panel of specimen LA3-H5V2 had a larger flexural capacity than that of specimen LA4-H5V2 due to the differences in thickness and reinforcement. Consequently, we confirmed that this affected an increase in lateral strength during forward cycles. The shear strength values of the top connections for these two specimens showed almost no difference because the connection thicknesses were insignificant (20 mm). Hence, we observed that the lateral strength during their backward cycles was similar as well.

The initial stiffness of the specimens was calculated as the initial slope of the load-displacement curve in the first half-cycle in the forward cycles. This was used as a relative index for the improvement in rigidity of the specimen. As can be seen in Table 8(9), the ratio of initial stiffness of specimen PR1 was observed to be 0.43 times less than that of reference specimen LM. The ratios of initial stiffness of the strengthened specimens varied between 2.06 and 3.23 compared to the reference specimen. The ratio of the initial stiffness of specimen LA1-H5V1 was 3.23, and the corresponding ratio for specimen LA1-H1V5 was 2.67, which was 17% less than that for specimen LA1-H5V1. The ratio of the initial stiffness of specimen LA3-H5V2 was 2.31, and the corresponding ratio for specimen LA4-H5V2 was 2.06. Specimen LA4-H5V2 showed 11% less stiffness than specimen LA3-H5V2.

5.2 Energy Dissipation Capacities of the Specimens

Enhancing energy dissipation capacity is an important goal of strengthening techniques and is an important index to further improve earthquake resistance. We measured it as the area inside the hysteresis load-displacement curve for each cycle. The cumulative energy dissipation was calculated up to the point where the hysteresis load test reached 1.75% of the story drift ratio because the load carrying capacities of the specimens were significantly decreased. The cumulative energy dissipations are reported in Table 8.

The increase in energy dissipation capacity for specimens strengthened with L-type PC wall panels occurred in a range between 2.73 and 3.24 times greater than that of the reference specimen LM. Especially, the energy dissipation capacity was increased with an increasing number of horizontal dowels and thicker PC wall panels. This implies that the proposed strengthening technique improved the energy dissipation capacity of the frame and so can effectively improve against earthquake loading.

6. Nonlinear Pushover Analysis of the Specimens

The load-displacement behaviors of the strengthened specimens were evaluated with nonlinear pushover analysis using program Midas Gen (Midas Gen 2017 V860 R3, 2017). It provides an integrated solution system for building or general structures and various analysis functions for linear and nonlinear structural analysis. 'Displacement Control Method' of pushover analysis in the system was used in this study.

The conditions of the analysis model were set as a) similar behavior to the test results, b) initial stiffness and maximum load are similar, and c) its implementation should actually be easy. Based on these three conditions, the analysis model of the specimen strengthened with L-type PC wall panel was modeled as in Fig. 15. The analysis of the test results reflected by the modeling was as follows:

1) The frame failed by plastic hinge behavior at the ends.

2) Cracks occurred on both ends of the L-type PC panel after a certain level of deformation, and the ends of it worked as plastic hinges.

3) In forward cycles, the PC wall panel and RC column exhibited an almost composite behavior.

4) In backward cycles, the PC wall panel and RC column exhibited independent behavior at a low load.

5) The horizontal part of the L-type PC wall did not have a

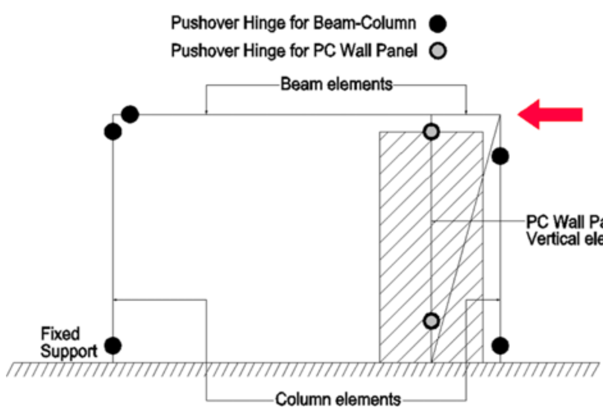


Fig. 15. Analysis Model of the Strengthened Specimens

Table 9. Pushover Analysis and Experimental Results Comparison

Specimen (1)	Maximum load [kN]						Initial stiffness [kN/mm]		
	Forward cycles			Backward cycles					
	Experimental (2)	Analytical (3)	Ratio (4)*	Experimental (5)	Analytical (6)	Ratio (7)*	Experimental (8)	Analytical (9)	Ratio (10)*
PR1	207	184	1.13	-216	-184	1.17	18.31	22.51	0.81
LA1-H5V1	1,411	1,421	0.99	-595	-497	1.20	138.12	98.85	1.40
LA3-H5V2	1,016	947	1.07	-373	-318	1.17	98.85	83.14	1.19
LA4-H5V2	871	891	0.98	-350	-314	1.11	88.26	79.77	1.11

*Ratio of the experimental results to the pushover analysis values.

large influence on the failure mechanism.

Corresponding to this, the analysis model contained the following setup.

1) Nonlinear plastic hinges were defined on both ends of the column and beam.

2) Nonlinear plastic hinges were defined on both ends of the L-type PC wall panel as well.

3) Under load in forward cycles, braces were added to ensure the PC wall panel and the RC column behaved in an integrated manner.

4) Under load in backward cycles, behavior was measured without braces between the PC wall panel and the RC column.

5) For an L-type PC wall panel, only the vertical part was modeled.

First, specimen PR1 was modeled as a base and then the modeling of the vertical part of an L-type PC wall panel was added to that frame. In practice, a PC wall panel with the required thickness would be used, and so the analysis model was made by selecting optimal models with good lateral strength and stiffness for each thickness. The values obtained from the pushover analysis were compared to the test results, and the ratios of maximum load and initial stiffness are exhibited in Table 9.

The results of the pushover analysis for specimen PR1 obtained a ratio of maximum lateral load of 1.15 on average in both forward and backward cycles, and an initial stiffness of 0.81. The ratios of the maximum lateral load measured in the strengthened specimens from the analysis varied between 0.98 and 1.07 in forward cycles, and between 1.11 and 1.20 in backward cycles. The initial stiffness values of the analysis were less than the test values for all strengthened specimens. The ratio of the initial stiffness obtained through testing compared to the values from the analysis varied between 1.11 and 1.40.

7. Conclusions

In this study, we tested and analyzed the behavior of RC frames strengthened with L-type PC wall panels with openings, which were produced as full-scale under reversed cyclic lateral loads. Four strengthened specimens were manufactured with varying thicknesses of PC wall panels and arrangement of the dowels. Based on the results of the executed tests, the following conclusions were obtained.

1. This is an infill technique, so the external appearance of a building does not change much before/after strengthening. The method of fabricating the PC wall panel does not require much fieldwork, thus it has a short construction period and is economical. The proposed seismic retrofitting technique substantially increased lateral strength, stiffness, and energy dissipation capacity while maintaining openings, and so can be effectively used as a seismic retrofitting technique for low-rise buildings with windows.
2. The lateral strengths of specimens strengthened with L-type PC wall panel increased by 2.93 and 1.78 times on average in both forward and backward cycles compared to the reference specimen LM with an L-type brick wall, and the initial stiffness of the strengthened specimens increased by 2.06 and 3.23 times.
3. The increase in the energy dissipation capacity for the frames strengthened with an L-type PC wall panel were 2.73 and 3.24 times greater than that of reference specimen LM. This shows that the proposed strengthening technique can effectively improve the resistance of a structure against seismic loading.
4. All of the specimens infilled with an L-type PC wall panel demonstrated superior strength and stiffness, especially in forward cycles rather than backward ones. According to the test results, the composite flexural resistance of the RC column and L-type PC wall panel dominated the behavior in forward cycles and the strength of the top shear connection dominated the behavior in backward cycle.
5. In the strengthened specimens, two factors mostly influenced the composite flexural resistance of an RC column and an L-type PC wall panel. The first was the effect of horizontal dowel connections in the composite behavior of the RC column and the PC wall panel, and the second was the thickness and reinforcement of the PC wall panel affecting the flexural capacity. Therefore, the more horizontal dowels placed and the greater the flexural capacity of the L-type PC wall panel, the more the lateral strength, stiffness, and energy dissipation capability of the strengthened specimen increased, and thus seismic resistance was further improved.
6. The strengthened specimens were properly modeled using nonlinear plastic hinges, braces, and vertical parts of an L-type PC wall panel. From the results of the pushover analysis with the Midas Gen program, the maximum lateral load in backward cycles was 14% and the initial stiffness 18%

less than the experimental values for strengthened specimens. The maximum lateral load in forward cycles showed no great difference with an error rate of 3%.

7. The design technique was conservative so that the results of the analysis model were less than the experimental values. Furthermore, we expect that design time may be saved in practice because of the simple modeling approach.

Acknowledgements

This research was supported by a grant (16CTAP-C077924-03) from Technology Advancement Research Program (TARP) Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

Notations

b_w: Thickness of PC wall panel (mm)

References

ACI Committee 318 (2011). "Appendix D." 318M-11: *Building code requirement for structural concrete and commentary*, American Concrete Institute, Farmington Hills, Michigan, USA, pp. 417-465.

ACI Committee 374 (2014). *374.1.05: Acceptance criteria for moment frames based on structural testing and commentary,* American Concrete Institute, Farmington Hills, Michigan, USA.

Akin, A. and Sezer, R. (2016). "A study on strengthening of reinforced concrete frames using precast concrete panels." *KSCE Journal of Civil Engineering,* KSCE, Vol. 20, No. 6, pp. 1-8, DOI: 10.1007/s12205-016-0188-z.

Altin, S., Anil, O., and Kara, M. E. (2008). "Strengthening of RC nonductile frames with RC infills: An experimental study." *Cement and Concrete Composites,* Elsevier, Vol. 30, No. 7, pp. 612-621, DOI: 10.1016/j.cemconcomp.2007.07.003.

Altin, S., Ersoy, U., and Tankut, T. (1992). "Hysteretic response of reinforced concrete infilled frames." *Journal of Structural Engineering,* ASCE, Vol. 118, No. 8, pp. 2133-2150, DOI: 10.1061/(ASCE)ST.1943-541X.0001042.

Baran, M. and Aktas, M. (2013). "Occupant friendly seismic retrofit by concrete plates." *Journal of Zhejiang University: Science A,* Springer, Vol. 14, No. 11, pp. 789-804, DOI: 10.1631/jzus.A1200324.

Baran, M., Aktaş, M., and Aykaç, S. (2014). "Strengthening of plastered hollow brick infill walls using strip concrete/reinforced concrete panels." *Journal of the Faculty of Engineering and Architecture of Gazi University,* Celal Bayar Bulvari, Vol. 29, No. 1, pp. 23-33.

Baran, M., Okuyucu, D., Susoy, M., and Tankut, T. (2011). "Seismic strengthening of reinforced concrete frames by precast concrete panels." *Magazine of Concrete Research,* ICE, Vol. 63, No. 5, pp. 321-332, DOI: 10.1680/macr.10.0003.

Baran, M. and Tankut, T. (2011a). "Experimental study on seismic strengthening of reinforced concrete frames by precast concrete panels." *ACI Structural Journal,* American Concrete Institute, Vol. 108, No. 2, pp. 227-237.

Baran, M. and Tankut, T. (2011b). "Retrofit of non-ductile RC frames with Precast Concrete (PC) wall panels." *Advances in Structural Engineering,* Sage, Vol. 14, No. 6, pp. 1149-1166.

Baran, M., ÖZçelik, R., Sevil, T., and Canbay, E. (2013). "Modelling of strengthened hollow brick infills." *Magazine of Concrete Research,* ICE, Vol. 65, No. 4, pp. 257-271, DOI: 10.1680/macr.12.00076.

Frosch, R. J., Li, W., Jirsa, J. O., and Kreger, M. E. (1996). "Retrofit of non-ductile moment-resisting frames using precast infill wall panels." *Earthquake Spectra, Earthquake Engineering Research Institute*, Vol. 12, No. 4, pp. 741-760, DOI: 10.1193/1.1585908.

Kahn, L. F. and Hanson, R. D. (1979). "Infilled walls for earthquake strengthening." *Journal of Structural Division,* ASCE, Vol. 105, No. 2, pp. 283-296.

Kaltakci, M. Y. and Yavuz, G. (2014). "The seismic improvement and control of weak concrete frames with partial concrete shear walls." *Journal of Vibration and Control,* Sage, Vol. 20, No. 8, pp. 1239-1256, DOI: 10.1177/1077546312467220.

Kara, M. E. and Altin, S. (2006). "Behavior of reinforced concrete frames with reinforced concrete partial infills." *ACI Structural Journal, American Concrete Institute*, Vol. 103, No. 5, pp. 701-709.

Kesner, K. and Billington, S. L. (2005). "Investigation of infill panels made from engineered cementitious composites for seismic strengthening and retrofit." *Journal of Structural Engineering,* ASCE, Vol. 131, No.11, pp. 1712-1720, DOI: 10.1061/(ASCE)0733-9445(2005)131:11(1712).

Midas Gen 2017 V860 R3. (2017). *MIDAS Information Technology Co. Ltd.*, Republic of Korea.

Sonuvar, M. O., Ozcebe, G., and Ersoy, U. (2004). "Rehabilitation of reinforced concrete frames with reinforced concrete infills." *ACI Structural Journal, American Concrete Institute*, Vol. 101, No. 4, pp. 494-500.

Turk, A. M., Ersoy, U., and Ozcebe, G. (2006). "Effect of introducing RC infill on seismic performance of damaged RC frames." *Structural Engineering and Mechanics, Korea Advanced Institute of Science and Technology*, Vol. 23, No. 5, pp. 469-486, DOI: 10.12989/sem.2006.23.5.469.

Yu, S. U., Ju, H. S., and Son, G. W. (2015a). "Analysis on the flexural behavior of existing reinforced concrete frame structures infilled with L-Type precast wall panel." *Journal of the Korean Society for Advanced Composite Structures, Korean Society for Advanced Composite Structures*, Vol. 6, No. 2, pp. 52-62, DOI: 10.11004/kosacs.2015.6.2.052.

Yu, S. U., Ju, H. S., and Ha, S. K. (2015b). "Analysis on the shear behavior of existing reinforced concrete frame structures infilled with L-Type precast wall panel." *Journal of the Korean Society for Advanced Composite Structures, Korean Society for Advanced Composite Structures*, Vol. 6, No. 2, pp. 105-117, DOI: 10.11004/kosacs.2015.6.2.105.