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Effect of stay-in-place PVC formwork panel geometry on flexural behavior of reinforced concrete walls

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ABSTRACT

The use of stay-in-place (SIP) formwork has become an increasingly popular tool for concrete structures, providing advantages in construction scheduling and labor reduction. Previous research suggests that PVC provides an enhancement to reinforced concrete strength and ductility. The research herein outlines tests on reinforced concrete walls with a compressive strength of 25 MPa, utilizing two types of PVC panels: flat or hollow, in order to further understand the polymer's contribution to flexural resistance. Variables studied included concrete core thickness (152 mm, 178 mm, and 203 mm), reinforcing ratio (3–10 M bars or 3–15 M bars), and panel type (hollow or flat). The walls were tested in four point bending. Walls failed due to steel yielding followed by concrete crushing, PVC buckling, and/or PVC rupture depending on the reinforcement ratio and panel type. The hollow panel encased specimens also experienced slip of the panels on the tensile face. The PVC encasement enhanced the yield load, ultimate load, ductility, and toughness of the concrete walls. Concrete cores were taken from the tested PVC encased specimens and compressive strength was found to be the same as the control walls.

1. Introduction

Stay-in-place (SIP) formwork is a permanent system commonly used in construction projects throughout the world. As traditional formwork is removed or “stripped” when the hardened concrete has achieved sufficient strength, stay-in-place forms become part of the finished structure. SIP formwork can play a role in providing additional structural capacity to an element. In recent years, polyvinyl chloride (PVC) SIP formwork has been developed as a solution for fast, secure, and convenient concrete construction.

Researchers investigated the flexural behavior of PVC stay-in-place formwork with and without steel reinforcement (Chahrour et al. [3], Rteil et al. [5], Wahab and Soudki [7]). Test variables included the thickness of the concrete core, reinforcement ratio, and the configuration of the PVC connectors (middle or braced). It was concluded that adding PVC SIP forms increased the cracking, yield, and ultimate load of the PVC encased specimens over their respective control walls. The configuration of PVC connectors did not have a significant impact on steel reinforced specimens. It was also concluded that the PVC contribution to flexural strength depended on the reinforcing ratio and section thickness. As the concrete core thickness and/or the internal reinforcement decreased, the enhancement of the PVC encasement to the wall's behavior increased.

The effect of connector's configuration on the mechanical performance of encased concrete walls was explored in depth by Kuder et al. [4]. The effect of the PVC on increasing the flexural capacity and toughness of their specimens varied from 39% to 66% and 41% to 60%, respectively. The PVC connector configuration with the highest quantity of polymer in the cross-section showed the highest increase in ultimate load.

Research is required to further investigate the flexural behavior of PVC encased concrete wall systems and develop an analytical model to estimate the yield and ultimate capacities of these composite members. Depending on the significance of improvement, a reinforced concrete wall that is traditionally formed could have the same capacity as a PVC encased wall with a thinner cross-section. This change in thickness, however small, applied to an entire structural system would result in tangible materials and cost savings. In addition, the concrete compressive strengths of the tested walls in the literature were in excess of 40 MPa. The effect of using concrete strengths more reflective of low rise construction (25–30 MPa) is of interest. Finally, additional PVC panel geometries have been developed. Their influence on the flexural performance of PVC encased walls has not been investigated yet. The discussion of the results of this research is divided into two portions. Part one, discussed herein, will explore the experimental results while part two will present the analytical model and compare its results to the experimental results. The analytical model was also used to predict the behavior of different cross sections. Details of the model are

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reported elsewhere (Scott [6]) and will be published in a separate paper. It is also worth mentioning that the work presented here is a part of a larger experimental program that investigates the behavior of the walls under different types of loading. The behavior of the walls under combined axial load and bending moments has been investigated and is reported elsewhere (Abdel Havez [2] and Abdel Havez et al. [1]).

2. Experimental program

Eighteen specimens were cast in the structures laboratory at the University of Waterloo. Six specimens were cast without PVC encasement to act as control walls. The remaining twelve specimens were cast using the PVC forming system. The test matrix is shown in Table 1. The variables studied were; concrete core thickness: 152, 178, and 203 mm (6, 7, or 8 in, respectively), type of PVC forming panel: flat panel or hollow panel, and tension steel reinforcement: 3–10 M or 3–15 M rebars per specimen.

The specimen notation in Table 1 is as follows; the first letter designates the panel type; control or without PVC encasing (C), flat PVC panels (PF), or hollow PVC panels (PH). The following number reflects the concrete core size in inches. The final number designates the diameter of the reinforcement placed in the specimen; 3–10 M or 3–15 M rebars. For example; the specimen PF-8-15 denotes an 8 in (203 mm) thick PVC encased wall specimen, formed with flat panels and reinforced with 3–15 M rebars.

2.1. Test specimens

All specimens had a rectangular cross-section (Fig. 1), with a constant length of 2440 mm (8 ft) and a width of 610 mm (2 ft). The thickness of each specimen was 152, 178, or 203 mm (6, 7, or 8 in, respectively). Each PVC encased specimen consisted of 4 bottom and 4 top panels. Walls with hollow panels had 5 middle connectors spaced at 152 mm, while walls with flat panels had 9 middle connectors spaced at 76 mm. Each specimen was reinforced in the longitudinal direction with 3 steel rebars (3–10 M or 3–15 M) with a clear cover of 38 mm on the tension side of the wall. The clear cover was measured from the PVC panel and concrete interface. Five transverse 10 M rebars were added to the reinforcement (spaced at 450 mm) to replicate transverse wall reinforcement as seen in practice and to secure the longitudinal rebars into place. The longitudinal and transverse steel rebars were tied together using spiral ties.

Table 1
Test matrix.

Group	Panel	Thickness	Connector type	Reinforcement	Reinforcement ratio
152 mm (6″) thick walls					
C-6-10	None		None	3 – 10 M	0.45%
C-6-15				3–15 M	0.92%
PF-6-10	Flat	152 mm (6 ″)		3–10 M	0.45%
PF-6-15			Middle	3–15 M	0.92%
PH-6-10	Hollow			3–10 M	0.57%
PH-6-15				3–15 M	1.17%
178 mm (7″) thick walls					
C-7-10	None		None	3–10 M	0.36%
C-7-15				3–15 M	0.74%
PF-7-10	Flat	178 mm (7 ″)		3–10 M	0.36%
PF-7-15			Middle	3–15 M	0.74%
PH-7-10	Hollow			3–10 M	0.44%
PH-7-15				3–15 M	0.90%
203 mm (8″) thick walls					
C-8-10	None		None	3–10 M	0.31%
C-8-15				3–15 M	0.62%
PF-8-10	Flat	203 mm (8 ″)		3–10 M	0.31%
PF-8-15			Middle	3–15 M	0.62%
PH-8-10	Hollow			3–10 M	0.36%
PH-8-15				3–15 M	0.73%

For walls of the same thickness, the resulting reinforcement ratio for the hollow panel encased wall was higher. This increase is due to the thicker hollow panels (11 mm on average) compared to flat panels (2 mm on average), reducing the depth of concrete to the reinforcement. Comparatively low reinforcing ratios were selected in order to best observe the effects of the SIP PVC system as testing occurred.

2.2. Material properties

Typical concrete compressive strengths used in PVC encased walls varied between 20 and 32 MPa based on data provided by PVC supplier. A mix was selected with a nominal compressive strength of 26 MPa. The concrete mix had a maximum aggregate size of 10 mm. Super plasticizers and retarders were used to provide a workable concrete. The recorded slump for the mix was 210 mm.

Compressive strength tests were conducted on concrete cylinders cast from the mix. The average compressive strength represents the average strength of six tested cylinders. The concrete strength was 21.8 ± 0.7 MPa and 24.0 ± 0.3 MPa at 28 and 56 days, respectively. The testing of the walls began at 56 days. Cylinders were tested after the wall testing was completed (116 days). The average strength of the concrete at this time was 27.6 ± 0.7 MPa.

Reinforcing steel rebars sizes 10 M and 15 M were used. The yield strength was 480 MPa and the ultimate strength was 580 MPa as indicated by the steel manufacturer. The polyvinyl chloride (PVC) had a tensile strength of 45.9 MPa and tensile modulus of 2.9 GPa as provided by the manufacturer.

2.3. Instrumentation and test procedure

Prior to casting, two steel strain gauges were mounted at mid-span of each wall on two longitudinal rebars (outer and middle). Once the walls were cast, additional strain gauges were mounted on the compression side prior to testing. For the control specimens, two concrete strain gauges were placed on the compression face of the wall; one at the centerline of the cross section and another close to the edge of the cross section. For the PVC encased specimens, cuts were made through the PVC panel in the compression zone in order for a strain gauge (60 mm long) to be adhered to the concrete surface. Also, high elasticity strain gauges (5 mm long) were mounted on to the tension and compression faces of the PVC panels. A minimum of four PVC strain gauges were used to monitor the behavior of each PVC encased specimen, with at least two adhered to the tension side and two adhered to the compression side.

The walls were tested in four-point bending using a servo-hydraulic actuator controlled by an MTS-Digital GT controller. The shear span was 770 mm and the constant moment region was 600 mm as shown in Fig. 2. The load was applied at a rate of 2.5 mm/min. The duration of the tests varied between 60 and 120 min. The wall was supported on a hinge support at one end and a roller support at the other end. The hinge support was a cylindrical bar welded to a flat plate and the roller support was a steel cylinder between two curved plates. The load was measured using a 500 kN load cell. The deflection of the wall at midspan was measured using two external string pots attached to the sides of the specimen. The test was stopped when the load dropped by more than 20% of the peak load or if the specimen shifted on the supports, resulting in a change in the loading conditions (encountered with one specimen).

3. Test results

All test results are presented in Tables 2 and 3, with typical load deflection plots presented in Fig. 3. The results from the flat panel encased sections and hollow panel encased sections will be discussed followed by a focused comparison between the panel types.

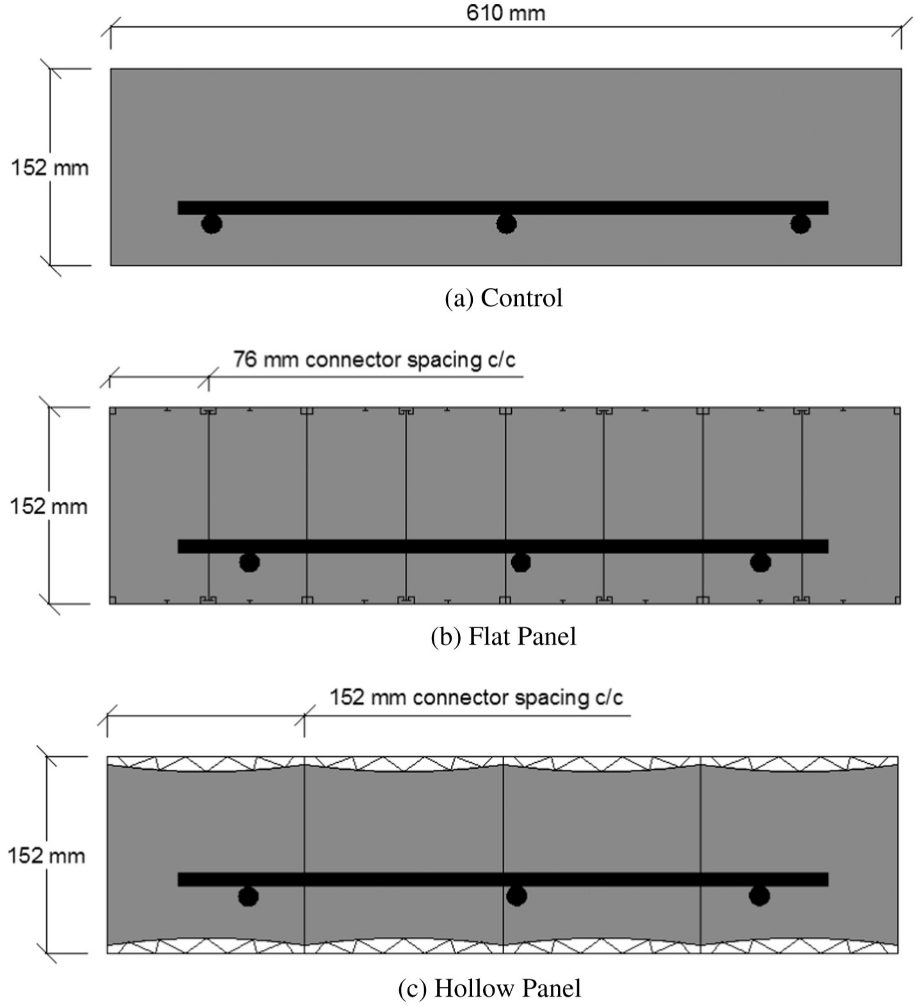


Fig. 1. Concrete wall cross-sections.

3.1. Modes of failure

The control walls failed due to steel yielding followed by concrete crushing. All the PVC encased specimens showed similar behavior when tested. The first concrete cracks appeared on the tension side at midspan in the constant moment region. As the load increased, several more cracks appeared just outside of the constant moment region. After the steel yield point was reached, the cracks at the midspan began to widen and propagate towards the compression face as the wall continued to deflect. As the load was increased further, one or two cracks in the constant moment region continued to widen excessively. At these crack locations, the concrete crushed then the flat PVC panels on the compression side of the wall buckled in case of flat panels or "bubbled" in case of the PVC hollow panels (Fig. 4(c))

The final failure for the specimens with flat panels was dependent on the area of the steel reinforcement. For specimens reinforced with 10 M rebars, the panels on the compression side of the wall buckled, followed by a PVC panel on the tension side of the wall rupturing (Fig. 4(b)). For

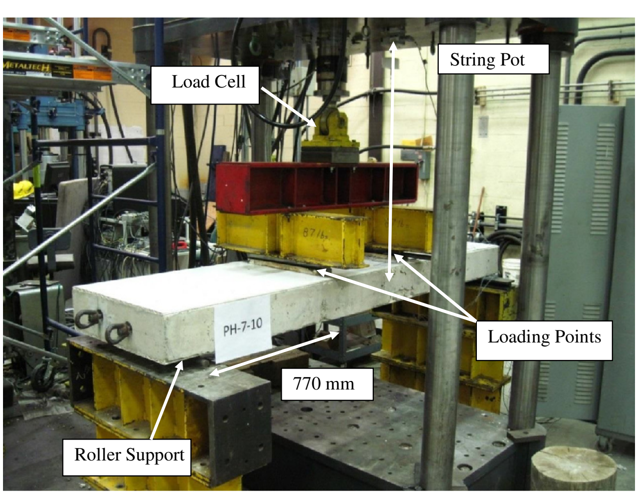


Fig. 2. Test set-up.

Table 2
Control results.

Specimen	$P_{cracking}$ (kN)	P_{yield} (kN)	P_{peak} (kN)	$\Delta_{cracking}$* (mm)	Δ_{yield} (mm)	Δ_{ult} (mm)	Ductility index	Toughness (kN mm)
Thickness = 152 mm (6 in)								
C-6-10	14.6	32	41	1.9	14.4	226	15.7	8505
C-6-15	17	69	77.2	1.3	19.6	90	4.6	5820
Thickness = 178 mm (7 in)								
C-7-10	17.5	44.5	55.5	1.6	11.4	139	12.2	7090
C-7-15	20	84	91	2.1	17.4	99.9	5.7	8058
Thickness = 203 mm (8 in)								
C-8-10	22	53	66	1.2	10.1	136	13.5	8316
C-8-15	21	102	114	1	13.2	158	12.0	16,775

* Δ stands for deflection.

Table 3
Flat panel and hollow panel encased results.

Specimen	P_{crack} (kN)	P_{yield} (kN)	P_{peak} (kN)	$\Delta_{cracking}$ (mm)	Δ_{yield} (mm)	Δ_{ult} (mm)	Ductility index	Toughness (kN mm)
Thickness: 152 mm (6″)								
PF-6-10	20 (37%)[a]	43 (34%)	55 (34%)	1.4	15.4	300 (33%)	19.5 (24%)	15,318 (80%)
PH-6-10	18 (23%)	38 (19%)	57 (39%)	2.6	17.6	311 (38%)	17.7 (13%)	17,719 (108%)
PF-6-15	27.5 (62%)	82.5 (20%)	93 (20%)	1.4	15.1	185 (106%)	12.3 (167%)	14,862 (155%)
PH-6-15	22 (29%)	76 (10%)	89 (15%)	3.1	20.4	135 (50%)	6.6 (44%)	11,362 (95%)
Thickness: 178 mm (7″)								
PF-7-10	30 (71%)	54 (21%)	72 (30%)	1.3	9.8	255 (83%)	26.0 (113%)	18,429 (160%)
PH-7-10	25 (42%)	46 (3%)	75 (35%)	2.2	14.6	143 (3%)	9.8 (−20%)	9683 (37%)
PF-7-15	31 (55%)	96 (14%)	111 (22%)	1	14.1	178 (78%)	12.6 (120%)	16,824 (109%)
PH-7-15	24 (20%)	85 (1%)	104 (14%)	1	17.1	124 (24%)	7.3 (26%)	12,389 (54%)
Thickness: 203 mm (8″)								
PF-8-10	33 (50%)	64 (21%)	89 (35%)	0.9	8.2	262 (93%)	32.0 (137%)	22,515 (170%)
PH-8-10	31 (41%)	60 (13%)	95 (44%)	1.1	9.6	216 (59%)	22.5 (67%)	18,228 (119%)
PF-8-15	41 (95%)	120 (18%)	138 (21%)	0.9	10.9	209 (32%)	19.2 (60%)	26,190 (57%)
PH-8-15	35 (67%)	103 (1%)	135 (18%)	1.3	12.3	154 (−3%)	12.5 (5%)	18,297 (10%)

[a] Values in brackets represent the enhancement compared to the control walls.

specimens with 15 M rebars, the PVC panel in compression (top) buckled and partially lift off the concrete surface (Fig. 4(a)).

Failure of hollow panel encased walls began with "bubbling" on the compression side of the wall (Fig. 4(c)). The bubbled surface propagated from the right loading point to left, and became more pronounced as the load increased. Eventually, the crushed concrete tried to push up on the PVC hollow panel, which in turn buckled excessively and folded over, producing final failure (Fig. 4(d)). This PVC buckling occurred at midspan or just underneath the right loading point.

In addition to the panel bubbling and buckling, a new phenomenon was observed during the testing of these specimens, which was the slip of the panels resisting the tensile forces, otherwise known as differential elongation. As the load increased after yielding, the PVC panels on the tension side of the beams continued to elongate. However, the applied load did not provide enough clamping or frictional forces at the supports to keep the elongated panels in place. Unlike the flat panels, the hollow panels did not have nubs to interlock with the concrete wall, but a smooth surface against the case concrete. Therefore, the tension panels experienced differential elongation under loading. This was most pronounced in the 152 mm (6″) thick specimens. As the walls increased in thickness, so did the applied load and the resultant friction between the PVC and concrete, reducing the extent of the slips.

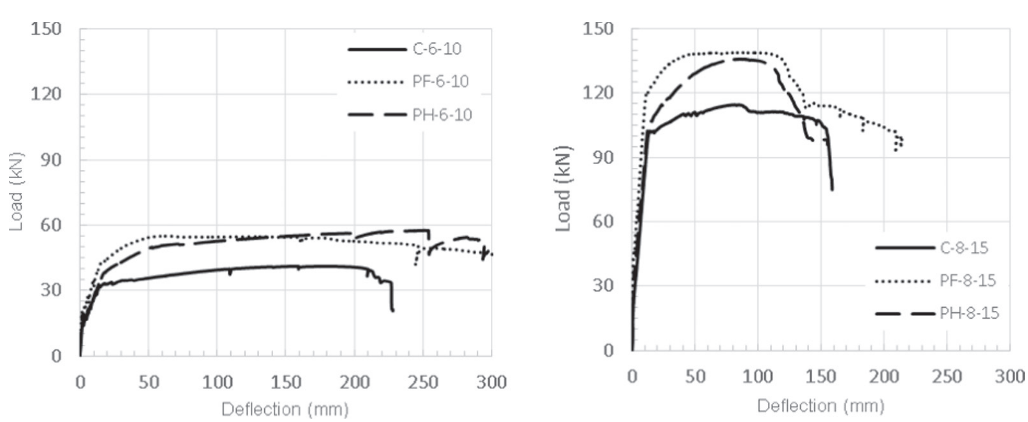
3.2. Load-deflection behavior

All of the specimens had similar load deflection behavior (Fig. 3). Initially, the load increased with minimal deflection (<2 mm) until the specimen cracked at midspan. After cracking, the load continued to increase as the deflection increased until the steel yielded. After yielding, the slope of the curve was shallower than the post cracking slope. Past the yielding point, the load versus deflection curves differed depending on the reinforcing ratio and panel type.

For the specimens with flat panels reinforced with 10 M rebars ($\rho =$ 0.0031–0.0057%), the load increased with deflection until the curve plateaued with increasing deflection and a constant load. The ultimate deflection ranged between 250 and 350 mm, with thinner walls resulting in the highest deflections. For the specimens with flat panels reinforced with 15 M rebars ($\rho =$ 0.0062–0.0117%), the load increased with deflection until reaching a peak. However, the peak load plateau was narrower than the 10 M reinforced walls, with failure occurring around 150 mm of deflection. For walls with hollow panels reinforced with 3–10 M rebars, the peak load was achieved through a gradual plateau whereas specimens reinforced with 3–15 M rebars reached their peak load more quickly and deflected much less. Sudden drops in the load were observed in both curves. These drops were attributed to the PVC panels slipping on the tension side of the wall.

3.2.1. Cracking load

As seen in Table 3, the flat panel PVC encasement increased the cracking load of the walls by an average of 52% and 71% for 10 M and 15 M reinforcement levels respectively. The hollow panel PVC encasement increased the cracking load of the walls by an average of 35% and 39% for the 10 M and 15 M reinforcement respectively. The cracking



152mm thick walls with -310M Bars   203mm thick walls -315M Bars

Fig. 3. Typical load versus displacement data.

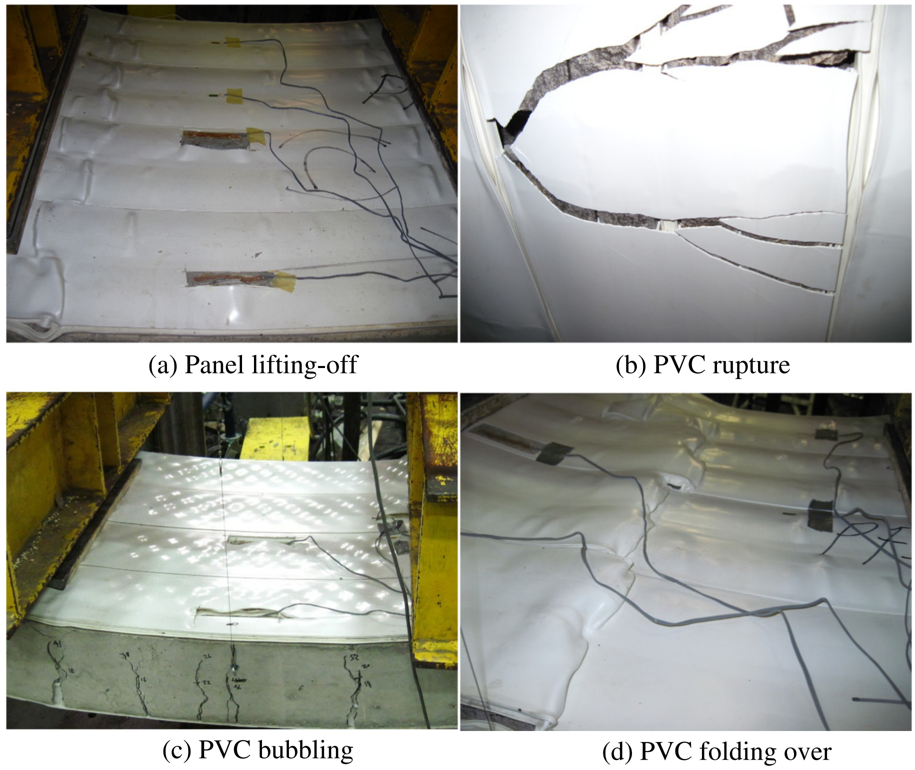


Fig. 4. Failure modes for flat panel and hollow panel encased walls.

deflection ranged from 0.9 to 3.1 mm, in comparison with 1 to 2 mm for the control walls.

3.2.2. Yield load

PVC encased walls showed a higher yield load than the equivalent control specimens. The enhancement was influenced by the quantity of reinforcing steel, with specimens reinforced with 3–10 M rebars showing greater improvement than specimens with 3–15 M rebars (Table 3).

The observed improvement in the yield load can be attributed to the PVC panel on the tension side of the wall providing a supplementary tensile force within the cross-section. The improvement in yield load was most significant for the 10 M reinforced walls as the tensile force in the PVC was more significant relative to the force in the yielding steel bars. For the walls with hollow panels, the improvements were less due to the steel reinforcement being placed at a shallower depth as a result of hollow panel's thickness, negating some of the benefit from the additional material in the hollow panels. In addition, the strain levels observed in the PVC in the hollow panels at yielding resulted in a material stress significantly lower than the potential peak stress. The PVC was not fully utilized and therefore provided a mild enhancement to the cross-sectional resistance. The yield deflection for the encased walls and the control walls was similar. Hence, the presence of the PVC panels did not have a significant influence on the yield deflection.

3.2.3. Peak load

Specimens reinforced with 3–10 M rebars showed a greater improvement at peak load than specimens reinforced with 3–15 M rebars. The increase in peak load for the walls reinforced with 3–10 M rebars varied between 30% and 39% but varied between 14% and 22% for the walls reinforced with 15 M bars.

For both types of PVC encasement, the improvement to load resistance was higher at the peak load than at yield load. The PVC was able to contribute a more significant portion of the tensile force within the cross-sections reinforced with 10 M bars. The observed improvement for the walls encased with hollow panels and reinforced with 10 M rebars was higher than the respective flat panel walls. When comparing the peak loads of the walls with hollow panels with the flat panels, the findings were consistent for a given reinforcement. For walls reinforced with 3–10 M rebars, the specimens with hollow panels showed equivalent or slightly higher peak load values (increase of 3% to 10%) than the specimens with flat panels. However, for specimens reinforced with 3–15 M rebars, the specimen with flat panels achieved slightly higher load capacity (increase of 2% to 6%) than the equivalent specimen with hollow panels. Therefore, it could be safely assumed that the specimens with hollow panels showed almost the same peak load as the specimens with flat panels, in spite of the reduced depth of the reinforcing steel and the reduced cross-sectional area of concrete. This behavior can be attributed to the relative influence of the panel type. As the hollow panels have twice the area of PVC, there is an increased contribution of the panel in ultimate flexural resistance.

The increase in ultimate deflection varied between 3% and 106% as shown in Table 3. In addition, the presence of the PVC panels increased the ductility index by a minimum of 5% and a maximum of 167%. This increased ductility was also reflected in the toughness of the flat panel encased walls. Toughness was calculated as the total area under the load versus deflection curve. Improvement in toughness varied from 10% to 170%. Overall, the presence of the PVC panels significantly improved the energy absorption of the walls. This was due to the PVC containing the crushed concrete surfaces on the compression side of the walls, prolonging the ultimate failure and disintegration of the compression zone.

The walls with hollow panels showed a reduced ductility compared with the equivalent walls with flat panels due to the tension panel slip. As the slip occurred, resulting in differential elongation between the panels and the tension side of the concrete face, the PVC and concrete ceased to act as a pure composite. The reinforced concrete core predictably ailed as expected (steel yielding followed by concrete crushing), but without an effective bond to the encasing panels, the concrete failure promoted the wall failure sooner than an equivalent flat panel encased specimen, where the bond between PVC and concrete was maintained for a longer duration. It can be concluded that specimens encased in flat panels showed an overall superior behavior than the ones encased in hollow panels.

3.3. Load-tensile strain behavior

Tension forces within the wall specimens were resisted by the steel rebar, PVC panels, and portions of the PVC connector that were continuous in the longitudinal direction through the wall. Fig. 5(a) shows a typical load versus tensile strain behavior of the steel and PVC panel (PF-7-10). The vertical axis represents the load (kN) and the horizontal axis represents the strain gauge readings (με). The strains in the PVC and steel were small until the cracking load was reached (30 kN). After the concrete cracked, the strains in the steel and PVC panels increased linearly with the load until the steel yielded at 56 kN. Past yielding, the steel strain gauge failed while the PVC gauge continued to steadily increase in strain while the load plateaued and then decreased gradually until failure occurred.

3.4. Load-compressive strain behavior

The compressive forces in the wall were resisted by the concrete, the PVC panels on the compression side of the specimen, and the continuous portions of the PVC connectors that were above the neutral axis of the specimen. Fig. 5(b) provides a typical load versus compressive strain behavior for the concrete and the PVC panels for the walls encased with flat panels. The vertical axis represents the load (kN) and the horizontal axis represents the compressive strain (με). Strains in both materials were low and increased linearly until the cracking load was reached (30 kN). The strains in the concrete and the PVC panels were similar until the steel yielded. Beyond the yield load (56 kN), the strain gauge readings of the concrete and PVC panels increased more rapidly. The concrete crushed at a strain gauge reading of −3000 με, while the PVC continued to experience compressive strains up to −8300 με.

It is worth noting that the specimen presented (PF-7-10) failed primarily due to two of four PVC panels rupturing on the tension face. Prior to rupture of the panels, the panels were buckled on the compression face but the specimen continued to resist the applied load until complete failure. The PVC strains at failure ranged from −3000 με to −15,000 με, depending on the proximity of the gauge to the failure location. The average PVC compressive strain at failure was −10,000 με.

Fig. 6 provides a typical load versus compressive strain behavior for the concrete and PVC panels for the walls encased with hollow panels. The overall behavior was very similar to the behavior of the walls encased with flat panels. However, when comparing the behavior of the inner and the outer PVC panel at the cracking load, the strains in the concrete and inner panel of PVC remained similar but the strain in the outer PVC panel rose, as it was located further away from the neutral axis. This difference in strains remained through the specimen yielding (76 kN) and eventual failure. Concrete crushed at −3000 με, while the PVC continued to experience compressive strains beyond −8000 με.

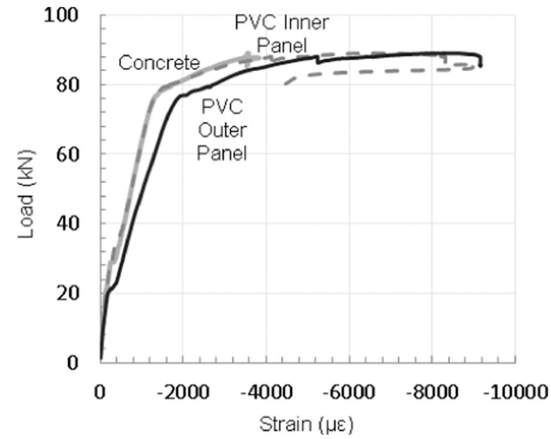


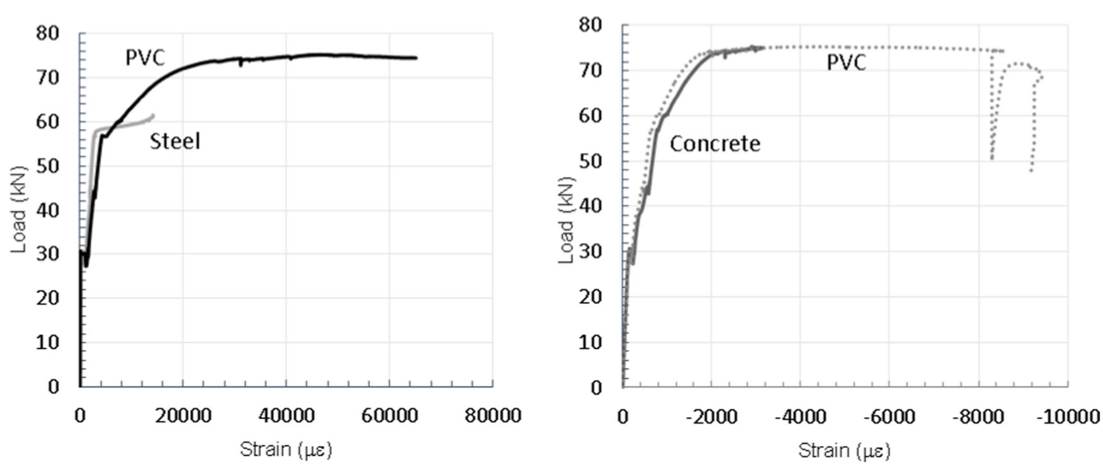
Fig. 6. Typical load-strain data for hollow panel encased walls.

It is worth noting that the specimen presented experienced panel slip on the tension face but the compressive strains were maintained despite these slips. The recorded strains in the PVC panels at failure ranged from −6000 με to −14,000 με, depending on the failure location. The average strain at failure for both the outside and inside PVC panels was −10,000 με, which was the same average compressive strain for specimens with flat panels.

3.5. Discussion of results

3.5.1. Reduction of wall thickness

Fig. 7 compares load deflection behavior of a 152 mm wall encased with flat panels to a control wall with a core thickness of 178 mm. Both walls were reinforced with 3–15 M rebars. Since the PVC encased walls with flat panels showed a superior behavior compared with the hollow panel encased walls (Table 3), hollow panel walls were eliminated from this comparison. The solid line represents the PVC encased specimen and the dashed line represents the control specimen.



(a) Tensile strain (b) Compressive strain

Fig. 5. Typical load-strain data for flat panel encased walls.

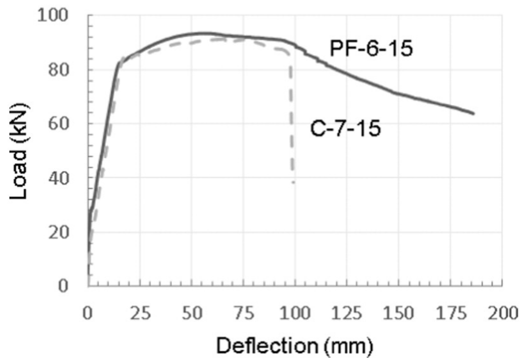


Fig. 7. Load deflection for C-7-15 and PF-6-15.

The 152 mm thick PVC encased wall behaved very similarly to the 178 mm thick concrete wall, with the PVC specimen having yield and ultimate loads nearly identical to the thicker control wall. Three other sets of results were summarized, comparing flat panel encased walls with a control wall with the same quantity of steel reinforcement whose core thickness was increased by 25 mm. These results are presented in Table 4. It is clear that PVC encased specimens with a reduced 25 mm core thickness provided comparable yield and ultimate loads to the corresponding control walls. In addition, the ultimate deflection was significantly improved.

3.5.2. Damage investigation of PVC encased walls

After the completion of a flexure test, portions of the panels from each PVC encased wall were removed to expose the concrete surface. The exposed surfaces were examined to gain insight into how the previously discussed failure modes occurred, and to further understand the interaction between the PVC and concrete.

Fig. 4(c) presents the compression face of a wall encased in flat panels during testing. Bumps or bubbles in the PVC panel can be seen across the width of the wall. At location where the panels are linked to PVC connectors, these bumps are either less pronounced or not present. When the PVC panels were removed at the “bump” locations, crushed concrete was observed. As the concrete was contained by the panels and connectors throughout testing, the exposed concrete was effectively pulverized. In areas outside of the failure locations, removal of the panels revealed a smooth, clean concrete surface.

The flat panel encased walls did not experience panel slip during testing. As the panels were removed, portions of the PVC were more difficult to take off than the hollow panels. The underside of each flat panel had two nubs. These nubs had concrete paste attached to them as the panels were removed, implying that some mechanical bond was present in connecting the concrete to the panel. In contrast, the hollow panels had a completely smooth surface, giving further indication that there was only frictional bond present in the hollow panel encased specimens.

Table 4
Comparison of PVC encased walls with 25 mm thicker control walls.

Specimen	Yield load (kN)	Percentage of control	Peak load (kN)	Percentage of control	Δ_{ult} (mm)	Percentage of control
C-7-10	44.5		55.5		139	
PF-6-10	43	97%	55	99%	300	216%
C-7-15	84		91		99.9	
PF-6-15	82.5	98%	93	102%	185	185%
C-8-10	53		66		136	
PF-7-10	54	102%	75	114%	255	188%
C-8-15	102		114		158	
PF-7-15	96	94%	111	97%	178	113%

Table 5
Cores drilled from tested specimens.

Type		Number of specimens	Average compressive strength (MPa)
Control cores	C-8-10	4	27.5 ± 1.3
PVC encased cores	PH-8-10	2	28.2 ± 1.3
	PH-8-15	2	
Cylinders	Cylinders	8	26.7 ± 0.7

3.5.3. Effect of PVC encasement on concrete strength

With a permanent formwork layer against the concrete, mix water would be restricted from exiting the walls, prolonging the curing process. Hence, the SIP system may provide an increase in concrete compressive strength over the conventionally formed walls. After the flexural tests were completed, three wall specimens were selected for core sampling. Table 5 shows the walls selected and the number of cores taken from each wall. The cores were tested to determine the actual compressive strength of the control and PVC encased walls. The core strengths were compared with the remaining cylinders from the concrete cast.

The compressive test results and confidence intervals are presented in Table 5. The concrete cores taken from the PVC encased walls showed a minimal improvement over the control specimen and cylinders. However, due to the small sample size and confidence interval presented, it can be concluded that the PVC encasing does not appear to provide any significant benefit to concrete strengths.

4. Conclusions

The following conclusions can be made from the experimental results:

1. All PVC encased specimens failed by steel yielding on the tension side and concrete crushing and PVC buckling on the compression side. Differences in failure mode were a result of the PVC panel tension rupturing (flat panel) or experiencing differential elongation (hollow panel).
2. PVC encasement improved the load capacity of the reinforced concrete walls. For flat panel encased walls, the average improvement at yield and ultimate loads was 21% and 27% respectively. Hollow panel encased walls recorded average yield and ultimate load improvements of 8% and 27% respectively. The effect of the PVC encasement lessened as the reinforcing ratio or wall thickness increased. Lightly reinforced, thin walls had the highest improvement.
3. A comparison was made between walls with the SIP PVC system and walls that were conventionally constructed and 25 mm (1″) thicker. The yield and peak loads were very similar in this comparison, suggesting the potential for using the SIP system as a means to reduce the wall thickness and achieve the same structural performance.
4. PVC encasement improved the ductility at ultimate load level and the toughness of the reinforced concrete walls by an average of 50% and 96%, respectively.
5. There was no statistically significant difference observed in the concrete strength of PVC encased walls and traditionally formed concrete.

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