Structures 5 (2016) 123–130

Contents lists available at ScienceDirect

Structures

journal homepage: http://www.elsevier.com/locate/structures

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

Benjamin Scott [a,1], Noran Wahab [b,2,*], Adil Al-Mayah [b], Khaled A. Soudki [b,3]

[a] Tacoma Engineers, Barrie, Ontario, Canada
[b] Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, ON, N2L 3G1, Canada

ARTICLE INFO

Article history:
Received 18 June 2015
Received in revised form 19 September 2015
Accepted 22 September 2015
Available online 9 October 2015

Keywords:
PVC encased
Reinforced concrete wall
Polymer
Flexure
Buckling
Slip

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

* Corresponding author.
E-mail addresses: nwahab@uwaterloo.ca (N. Wahab), aalmayah@uwaterloo.ca (A. Al-Mayah).
[1] Benjamin is an Engineer in training (EIT) and holds a MAsters degree (MASC).
[2] (On leave from Cairo University, Egypt).
[3] (deceased 17 September 2013).

http://dx.doi.org/10.1016/j.istruc.2015.09.005
2352-0124/

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.

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.

Table 1
Test matrix.

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

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 $\pm$ 0.7 MPa and 24.0 $\pm$ 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 $\pm$ 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.