

NEXT GENERATION OF UHPC DOUBLE WYTHE INSULATED PRECAST CONCRETE WALL PANELS

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Abstract

A typical precast concrete insulated panel consists of two outer wythes and the inner layer of insulation. Commonly, the minimum thickness of these panels is governed by the concrete cover requirements for steel reinforcement in the wythes. A new panel design consisting of two outer wythes, each is 25 mm (1 in.) thick ultra-high performance concrete (UHPC) and an internal 150 mm (6 in.) layer of insulation was tested in flexure to determine the structural performance and failure mode. The use of the UHPC wythes allows for a significant reduction in overall panel weight. In this study, three full-scale panels 3.0 m (10 ft.) long by 0.6 m (2 ft.) wide were manufactured with varying parameters. These included the use of steel or polyvinyl alcohol (PVA) fibres in the UHPC mix and the addition of glass-fibre reinforced polymer (GFRP) reinforcing bars in the wythes.

All full-scale panels were tested in four point bending to simulate uniform wind loading. The panel equivalent uniform pressure capacities at ultimate were 8.2 kPa (1.2 psi) for steel fibres panel, 6.8 kPa (1.0 psi) for PVA fibres combined with GFRP bars panel, and 4.1 kPa (0.6 psi) for PVA fibres panel. Based on the results, it can be concluded that the new design compares well with commonly available architectural concrete double wythe insulated panels with the added advantage of being only one third the self weight of conventional panels. This study represents the first phase of a larger research program to develop the next generation of double wythe insulated precast panels in Canada, using UHPC.

Keywords: Precast concrete, Insulated Panel, double wythe, Ultra-High Performance Concrete, GFRP.

INTRODUCTION

A typical precast concrete double wythe insulated panel consists of a layer of insulation sandwiched between two layers of concrete, known as wythes. Double wythe insulated panels can be used for architectural purposes only or can be used also as structural load-bearing walls¹. Generally, precast double wythe insulated panels span vertically between foundations and the floors but can also span horizontally between columns². The type and thickness of insulation is mostly governed by the thermal performance requirements, whereas, the structural performance is governed by the continuity and the shear transfer between the concrete wythes³. Although separated with a layer of insulation, concrete wythes are connected to each other using wythe connectors. The main purpose of these wythe connectors is to keep the panel intact during handling and service conditions, therefore, transferring mostly tension or compression forces⁴. The material and the shape of these connectors can vary based on the application and the amount of load to be transferred from one wythe to the other. Common types of connectors are made of steel or FRP, such as straight pins, C-tie, Z-tie and welded wire trusses. In addition solid sections of concrete can also be used^{1,5}. When higher level of forces are to be transferred between wythes, the connectors have to be able to provide a full shear transfer mechanism within the panel. Based on the degree of shear transferred between the concrete wythes, double wythe insulated panels can be classified as: noncomposite, partially composite or fully composite^{6,4} (Figure 1). The double wythe insulated panel will behave as fully composite when the concrete wythes are connected in such a way that no relative slip occurs between both wythes forcing the panel to behave as one integral unit. This will result in a much better structural performance compared to a noncomposite panels of the same size. In this case, connectors between wythes will transfer all the shear forces with negligible shear deformation⁷. A noncomposite panel consists of two concrete wythes that resist the load independently based on their individual stiffness. In this case, the wythe connectors used to keep the panel intact will resist only normal forces during stripping or transportation and will not provide shear transfer between the wythes. In reality, most of the double wythe insulated panel systems behave as partially composite. The shear connectors in this case will transfer only a fraction of the shear forces as required for a fully composite behavior².

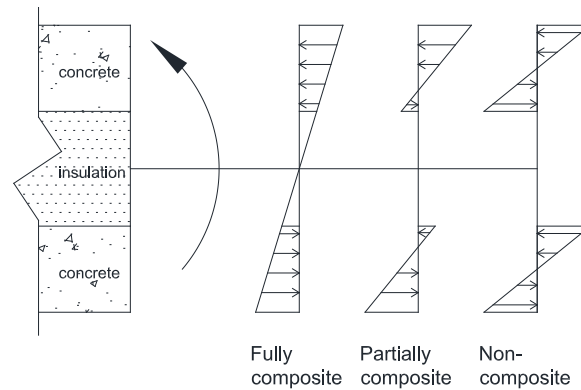


Fig. 1 Stress distribution in concrete double wythe insulated panels due to bending

Aside from the structural performance, the type of the shear transfer mechanism between concrete wythes directly affects the thermal efficiency of the sandwich panel. The use of concrete blocks or steel ties as shear connectors can cause thermal bridging, which reduces the thermal resistance of the panel. Research have shown that using steel connectors with as low as 0.08% reinforcement ratio of the concrete area, will reduce thermal resistance of the insulation layer by as much as 38%⁸. Over the last thirty years, connectors have been developed to connect the exterior layer through the insulation with a limited amount of thermal bridging. Stainless-steel wire, glass and carbon-fibre reinforced plastic provide a wide range of proven structural solutions with little impact on thermal performance⁹. Numerous studies have shown that using materials with lower thermal conductivity such as fibre-reinforced polymers (FRPs) will minimize thermal bridging while maximizing the composite action between concrete wythes⁴. Some of these shear connector designs are: bent-bars, glass fibre-reinforced polymer (GFRP) truss connectors^{10,11}, carbon fibre-reinforced polymer (CFRP) grids^{5,12}, and GFRP studs.³

Design guidelines are generally well established using normal strength concrete and FRP or steel connectors; however, very little information is available on the use of UHPC in insulated concrete panels. This study is focused on reducing the weight of double wythe insulated panels by using UHPC as a replacement for normal strength concrete. The main objective for this phase of the research is to investigate the flexural behavior of the double wythe insulated panels with only 25 mm (1") thick wythes and GFRP ties, intended to reduce thermal bowing.

EXPERIMENTAL PROGRAM

This phase of the study comprises 3 precast (NLW1, NLW2 and NLW3) UHPC double wythe insulated concrete wall panels designed and tested for flexure. All three panels were designed to have the same geometry, 3050 mm (10') long by 610 mm (2') wide and a total thickness of 200 mm (8"). The two concrete wythes, 25 mm (1") thick each, are separated by 150 mm (6") rigid expanded polystyrene (EPS) insulation. A thin layer of plastic sheet was placed at the interface of the concrete and the insulation to act as a bond breaker since the adhesion was not a parameter in this study. Two rows of 4.2 mm (0.16") diameter GFRP ties

spaced at 300 mm (1') were used as wythe connectors. These ties go through the insulation and with a 25 mm (1") embedment in each concrete wythe. The ties were machined with pointed ends in either side in order not to be visible in the concrete surface. Ties were used to transfer normal forces only from one wythe to the other, ensuring the panel remains intact and were not intended to transfer shear forces. The parameters for this phase are shown in Table 1, namely the types of fibres used in the concrete mix, and the effect of additional GFRP reinforcement bars in concrete wythes.

Table 1-Test Matrix

ID	Dimensions, mm (WxHxL)	GFRP Bars per Wythe	Insulation thickness, mm (in)	Fibres	Testing
NLW1	610x200x3050	0	150 (6")	Steel	Flexure
NLW2	610x200x3050	0	150 (6")	PVA	Flexure
NLW3	610x200x3050	7	150 (6")	PVA	Flexure

The first specimen NLW1 was made using steel fibres in the concrete mix. Polyvinyl alcohol (PVA) fibres were used for NLW2 instead of steel fibres, and the third specimen NLW3 was made using PVA fibres in the mix and additional reinforcement grid made out of seven 4.2 mm (.16") diameter GFRP bars as shown in figure 2, providing a GFRP reinforcement ratio of 0.6%.

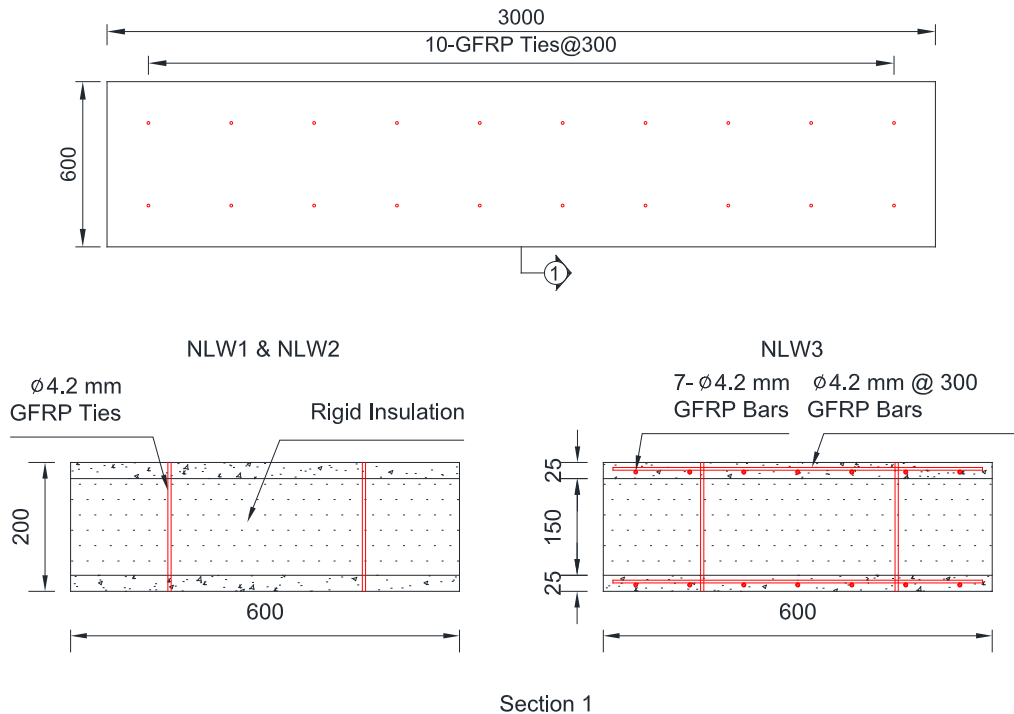


Fig. 2 General panel configuration. (Note: Dimensions in mm; 100 mm = 3.94 in.)

MATERIAL PROPERTIES

A commercially available product with pre-mixed ingredients was used for UHPC mixture. While all the dry ingredients for the mixture were premixed in bags, the fibres were added to the mix manually. Steel fibres with 2750 MPa (399 ksi) tensile strength and 13 mm (0.5") length at a dosage of 2% by volume were used in the concrete mixture for NLW1. PVA fibres that were used in the concrete mixture for the other two specimens were 12 mm (0.5") long and 800 MPa (116 ksi) tensile strength as reported from the supplier. A 3% dosage by volume was used for the PVA fibres. A total of 13 cylinders, 100x200 mm, with PVA fibres and 3 with steel fibres were cast. They were demolded after 4 days and were exposed to the same conditions as the full scale specimens (dry cure at +22 °C). Cylinders showed an average compressive strengths of 107 MPa (15.5 ksi) for PVA fibres and 125 MPa (18.1 ksi) for steel fibres after 3 months.

To determine the flexural strength of each mix, 10 prisms 50x100x400 mm (2"x4"x16") (WxHxL) were cast and exposed to the same conditions as the full scale panels. Prisms were tested in four point bending approximately 3 months after the cast. The average flexural strengths for the PVA and steel fibre mixes were 17.8 MPa (2.6 ksi) and 27.1 MPa (3.9ksi), respectively. GFRP bars with tensile strength of 1055 MPa (153 ksi) and modulus of 45.2 GPa (6555 ksi) as reported by the supplier were used for ties and the reinforcement grid. EPS foam with a density around 30 kg/m³ (1.87 lb/ft³) was used as insulation in between concrete wythes.

FABRICATION

Fabrication is shown in Figure 3. The formwork was made out of vinyl faced plywood sheets to ensure a smooth finish and was made for horizontal-flat casting. The bottom wythe was cast first and a wooden jig that slides over the top of the form was used to control the thickness and the uniformity. Concrete was placed gradually on a back and forth motion to ensure proper alignment of the fibres. The insulation boards wrapped in plastic sheet with all the GFRP ties assembled (Figure 3) were placed on top of the bottom wythe immediately after the cast. All the seams in between the insulation board and the formwork were sealed prior to casting the top wythe. This was to prevent any concrete leakage from top wythe to the bottom causing uplift of the insulation. Two 6.5 mm diameter (1/4") lifting cables were placed on the side at 1/3 from each end of the panel. Two 100x100 mm (4"x4") voids were cut out of the the foam boards from the top wythe to accommodate these cables (Figure 3). The top wythe was cast approximately 3 to 4 hours after the bottom wythe. This allowed the caulking around the foam board to cure. A straight steel edge was used to level off the surface. A plastic sheet was placed immediately after the cast to prevent any moisture loss.



Fig. 3 Fabrication of concrete double wythe insulated panels: a) inserting GFRP connectors into the foam; b) assembling the GFRP grid; c) voids for the lifting cables; d) casting concrete

TEST SETUP AND INSTRUMENTATION

All three specimens were tested in four-point bending as shown in figure 4 to simulate a uniform wind pressure. Each specimen was supported by a pin and a roller at 75 mm (3") from each end of the specimen. Once the specimen was in place, a hydraulic bottle jack with a long steel beam was used to push the panel up to a flat position, such that self-weight deflections were recovered. Prior to applying any additional load to the panel, the supporting jack was gradually released and the self-weight deflections were recorded. This was done because the self-weight of the panel will never act transversely in real life service condition. It was determined that an equivalent load of 2.2 kN (0.5 kips) represents the weight of the panel and the steel spreader beam. This load along with the corresponding self-weight deflections were added to the total load applied for the final test results. Three linear potentiometers (LPs) were used to measure the deflections, and two LPs at each end of the panel were used to measure the relative slip between concrete wythes. Two uniaxial electrical resistance concrete strain gauges were installed at mid-width, at the top and bottom surfaces of the panel at mid-span. In order to get the strain profile for each concrete wythe, two additional strain gauges were installed on the side of each concrete wythe at mid-span, at the inner surface of each wythe. The specimens were tested in a four point bending setup as shown in figure 4 using a 1 MN electro-mechanical testing machine. All the instrumentations were set to record data prior to releasing the hydraulic jack which was supporting the weight and leveling the panel. After the jack was released, the load was applied at a rate of 2

mm/min initially then was increased gradually to 5 mm/min due to the excessive deflections.

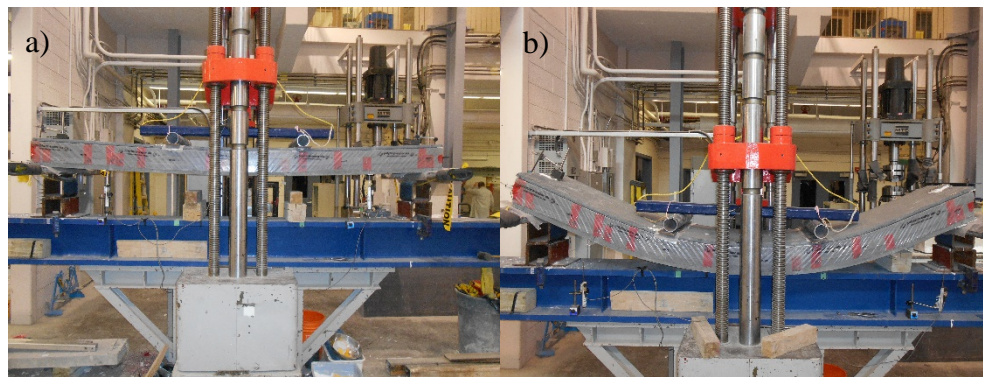
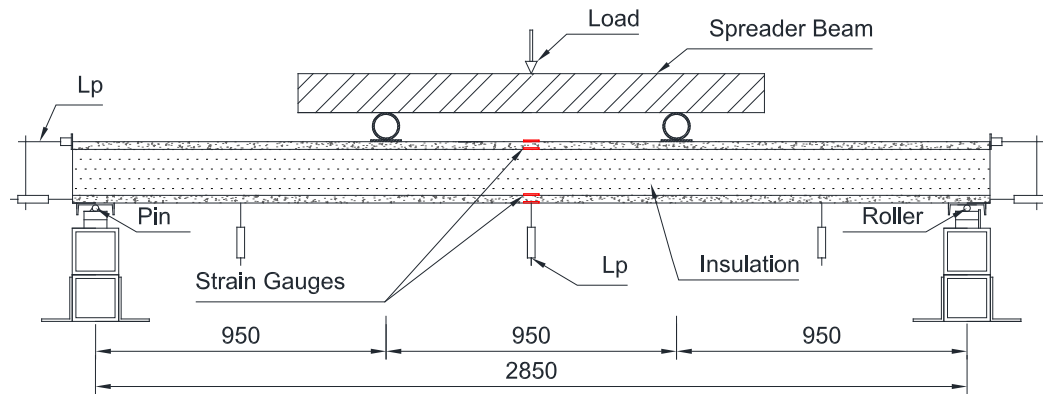


Fig. 4 Test setup and instrumentation; a) test specimen before the load was applied; b) test specimen after the ultimate load; (Note: Dimensions in mm; 100 mm = 3.94 in.)

EXPERIMENTAL RESULTS

All three specimens were tested to failure using the four point bending configuration. A summary of the results in terms of the load applied and the displacement recorded is provided in Table 2. The equivalent load of 2.2 kN (0.5 kips) due to the weight of the panel and the steel spreader beam has been added to the results.

Table 2-Summary of test results

ID	Fibres	GFRP Bars per Wythe	Deflection at release, mm	Deflection at peak load, mm (in)	Peak load, kN (kips)	Equivalent pressure, kN/m ² (psi)
NLW1	Steel	0	10 (0.4)	212 (8.3)	10.87 (2.4)	8.5 (1.2)
NLW2	PVA	0	17 (0.6)	149 (5.8)	5.21 (1.2)	4.1 (0.6)
NLW3	PVA	7	32 (1.25)	194 (7.6)	9.24 (2.1)	7.2 (1.0)

A general response for all three specimens was as follows: a various amount of deflections due to the self-weight, then a somewhat linear response initially, followed by cracking of

both wythes. As the foam was slipping between the two wythes, with the GFRP ties embedded within, the foam would occasionally lock itself resulting in sudden spikes or drops in the load. Theoretical analysis show that the cracking load for a single wythe with PVA fibres would be 2.33 kN (0.52 kips), whereas that of steel fibres is 3.54 kN (0.8 kips). Based on this, the theoretical cracking loads for fully composite panels would be 86.5 kN (19.4 kips) and 131.7 kN (29.6 kips) for PVA and steel fibres, respectively. Upon cracking of the wythes, the excessive foam slip between the concrete wythes continued to progress resulting in decrease of the overall stiffness of the system. Failure modes once the peak load was reached were: a major crack under one of the point loads of the top wythe for NLW1, followed by another crack on the bottom wythe. Significant cracking caused the bottom wythe of NLW2 to break into two pieces. The test was stopped for NLW3 after numerous cracks appeared on both wythes and loss of test setup clearance under the specimen. In all cases, the load has started dropping significantly already, past the peak, by the time the test was completed. Figure 4(b) shows the remarkable ductility of the UHPC panels.

EFFECT OF FIBRES

The effect of steel and PVA fibres in the concrete mixture can be seen when comparing specimens NLW1 and NLW2. The ultimate capacity was twice as high when steel fibres were used compared to the PVA fibres. As shown in the Figure 5, the specimen with steel fibres had the highest initial stiffness compared to the other two specimens.

EFFECT OF GFRP BARS

The additional reinforcement GFRP bars caused an increase of 77% of ultimate capacity. However, the presence of these bars decreased the initial stiffness which explains the higher initial deflections of the NLW3 compared to the NLW2.

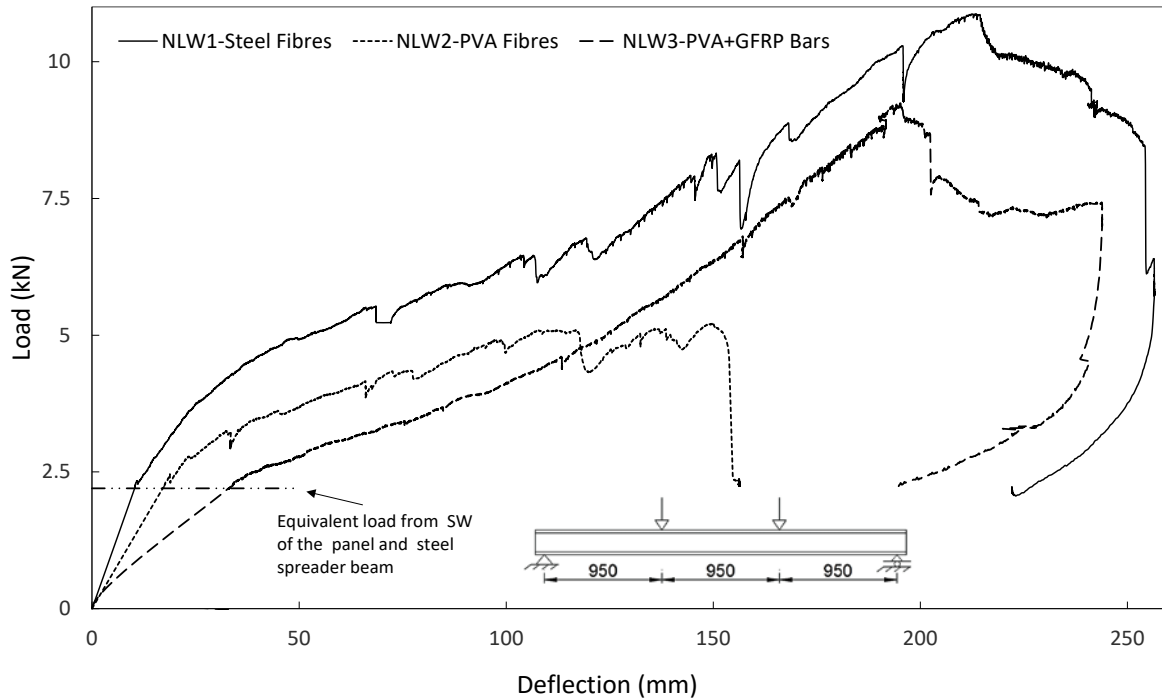


Fig. 5 Load-deflection curves of test specimens (Note: 100 mm = 3.94 in., 1 kN = 0.22 kips)

Strain profiles at mid-span for all three specimens from zero up to ultimate load are shown in Figure 6. It was noticed during the test that the strain readings were not consistent and uniform when the cracks occurred near the gauge area, especially for the specimens that had no bars to bridge the cracks and transfer the stresses more uniformly over the concrete surface.

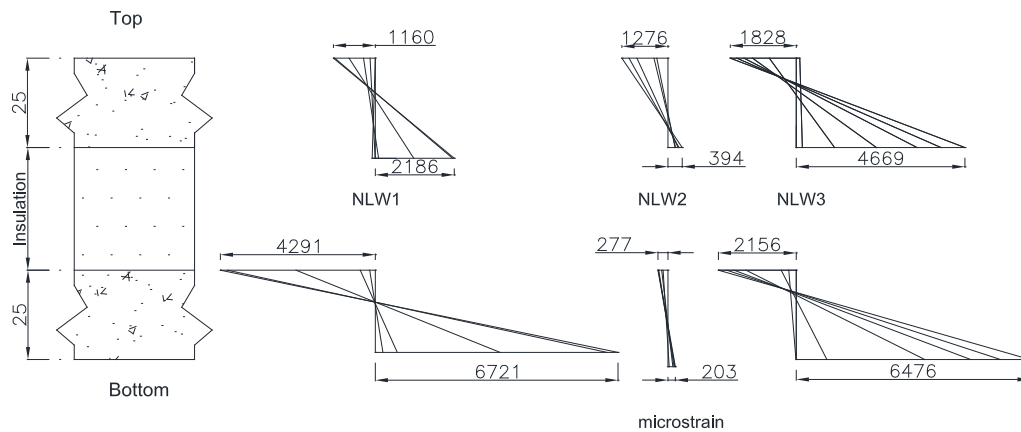


Fig. 6 Strain profiles of test specimens (Note: Dimensions in mm; 100 mm = 3.94 in.)

The effect of bars was also noticed in the crack distribution over the concrete surface. Figure 7 shows the crack patterns on the underneath (tension side) of the panel as tested. It can be seen that smaller cracks were developed in NLW1 and there were no major cracks going

across the entire width. NLW2, the second specimen with PVA fibres and no bars, had fewer cracks but all the cracks on the bottom wythe went across the entire width and there was a major crack at mid-span through the entire depth. NLW3 with 7 GFRP bars on each wythe had no major cracks going through the depth, instead they were more uniformly spread micro cracks across the length of the panel.

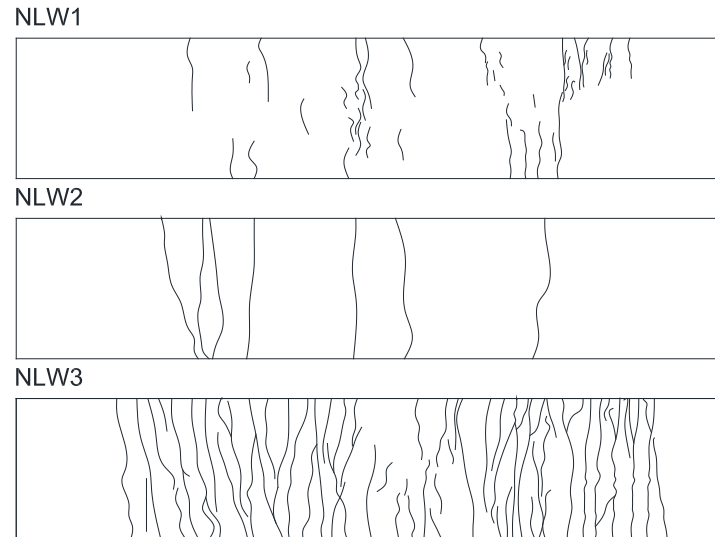


Fig. 7 Crack patterns of test specimens (Note: only bottom of the panel as tested is shown)

CONCLUSIONS

This experimental study examined the structural performance of UHPC double wythe insulated precast concrete panels. Based on the test results, following preliminary conclusions can be drawn:

- The use of PVA fibres in the UHPC mixture, when comparing to steel fibres, lowered the compressive and flexural strengths of the material by 14% and 34%, respectively.
- The panel with steel fibres reached the highest peak load, being 208% and 17%, respectively, higher than the panel with PVA fibres only and no bars and PVA fibres with additional GFRP bars.
- The presence of GFRP bars as longitudinal reinforcement increased the ultimate capacity by 77%, while prevented any major cracks to develop and allowed for more uniform micro cracks to occur.
- Regardless of the small embedment length of the GFRP ties connecting the two wythes through the insulation, there was no visual evidence that any of these connectors has pulled out of concrete or slipped during the test.

This study represents the first phase of a larger research program to develop the next generation of the double wythe insulated precast panels in Canada, using UHPC.

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