8th International Conference on Advanced Composite Materials in Bridges and Structures
8ème Conférence Internationale sur les matériaux composites d'avant-garde pour ponts et charpentes
Sherbrooke, Quebec, Canada, 18 – 20 August 2020 / 18 au 20 août 2020

EXPERIMENTAL BEHAVIOUR OF CONCRETE CONFINED WITH UNIDIRECTIONAL FLAX FIBER-REINFORCED BIO-BASED POLYMERS

Dillon Betts and Pedram Sadeghian
Department of Civil and Resource Engineering, Dalhousie University
1360 Barrington St, Halifax, NS, B3H 4R2, Canada
dillonbetts@dal.ca pedram.sadeghian@dal.ca

Amir Fam
Department of Civil Engineering, Queen's University
58 University Ave, Kingston, ON, K7L 3N6, Canada
amir.fam@queensu.ca

ABSTRACT: In this study, the effect of confining concrete with flax fiber-reinforced polymers (FFRPs) is examined. A total of six concrete specimens were tested under uniaxial compression. Each specimen had a diameter of 101.6 mm and a height of 203.2 mm. The main parameter of the tests was effect of FFRP thickness on specimen behavior. Two specimens were used as control specimens and tested without an FFRP wrap. The second and third set of specimens were wrapped with an FFRP such that the ratio of confinement pressure (f_l) to concrete compressive strength (f'_c) was 0.08 and 0.16 respectively. Each specimen was fitted with a yoke fixture to measure the lateral and longitudinal deflection using four linear potentiometer displacement gauges. Each test was performed at a displacement rate 0.6 mm/min and the data was sampled at a rate of 10 Hz. The strength of concrete confined with six layers of FFRP wrap was found to be approximately double that of the plain concrete specimens. The results indicate that FFRPs can effectively confine concrete and have potential for use in the rehabilitation of existing structures.

1. Introduction

The use of fiber-reinforced polymers in structural applications has increased in the recent past and has been studied at length (Bakis et al. 2002; Teng et al. 2003). FRPs can be used in new structures as well as in the rehabilitation of existing structures, such as the strengthening of concrete columns. The strength of existing concrete columns can be increased through confinement. FRPs are ideal for this application due to the ease of installation and their high relative strength. For this reason, there have been numerous studies on the use of FRPs for concrete confinement, specifically using synthetic FRPs, such as carbon FRPs (CFRPs) (Berthet et al. 2005; Xiao, Y. and Wu 2000) and glass FRPs (GFRPs) (Lam and Teng 2004; Nanni and Bradford 1995) and more recently basalt FRPs (BFRPs) (Campione et al. 2015; Sadeghian and Fillmore 2018).

As society becomes more environmentally conscious, it is important to determine ways to increase the sustainability of new structures and rehabilitation methods. One method of rehabilitating existing structures more sustainably is the use of natural materials, such as plant based FRPs. Some examples of plant FRPs are flax FRPs (FFRPs) or hemp FRPs (HFRPs). These FRPs can be fabricated using bio-based thermoset epoxy resins to further increase the sustainability of the composite. Flax fabrics are commercially available and have been shown to have a lower embodied energy than traditional fabrics, such as glass or carbon (Cicala et al. 2010). The structural uses of FFRPs for sandwich panel applications has been studied in the recent past (Betts et al. 2018). There have also been studies on the use of FFRP tubes and woven (bidirectional) FFRP wraps for the confinement of concrete (Yan et al. 2014; Yan and Chouw 2013), but the field of data remains extremely limited. Therefore, the aim of this paper is to provide more data to the limited field of knowledge by testing concrete specimens wrapped with unidirectional FFRPs.

2. Experimental Program

2.1. Test Matrix

A total of six concrete specimens were fabricated and tested under uniaxial compression. Each specimen started as a plain concrete cylinder with a diameter of 101.6 mm and a height of 203.2 mm. Two specimens were used as control specimens and the remaining four were wrapped with FFRPs: two with three layers and two with six layers. To distinguish the specimens, the following naming convention was used: FCC-XL-Y, where FCC means FFRP Confined Concrete, X is the number of layers of FFRP and Y is a sequential number (1 or 2) to distinguish identical specimens. For example, the first specimen wrapped with three layers of FFRP would be identified as FCC-3L-1. The test matrix is presented in Table 1.

Table 1 – Test Matrix

ID	Number of Specimens	Concrete Type	Layers of FFRP
FCC-0L	2	Plain	0
FCC-3L	2	Plain	3
FCC-6L	2	Plain	6

The number of FFRP layers was chosen such that the minimum required confinement pressure prescribed by ACI 440.2R-17 (American Concrete Institute 2017) was satisfied. A minimum required number of layers was determined to be three using Eq. 1, which is a combination of several equations from ACI 440.R2-17 (American Concrete Institute 2017). The second pair of wrapped specimens were each wrapped with six layers of FFRP.

$$n = \frac{0.08 f_c' D}{2 E_f t_f \kappa_e \epsilon_{fu}} \quad (1)$$

where n is the number of layers, f'_c is the compressive strength of the concrete, D is the cylinder diameter, E_f is the FFRP modulus of elasticity, t_f is the thickness of one layer of FFRP, κ_e is the strain efficiency factor of 0.55 as proposed by ACI 440.2R-17 (American Concrete Institute 2017), and ϵ_{fu} is the ultimate strain of the FFRP.

2.2. Material Properties

To determine the compressive strength of concrete, a simple compression test was performed on a cylinder cast from the same batch of concrete. The properties of the FFRPs were determined through uniaxial tension tests performed in a previous study (Betts et al. 2017). The tension tests were completed as per the specifications of ASTM 3039 (ASTM 2014). The tensile modulus, strength and ultimate strain were found to be 8.68 GPa, 100.8 MPa and 0.0153 mm/mm, respectively.

2.3. Specimen Fabrication

The concrete specimens were cast previously as a part of a larger study. The preparation and application of the FFRP wrap is presented in Figure 1. The fabric used was a unidirectional flax fabric with a reported areal mass of 275 g/m^2 which was supplied in a 300 mm wide roll. The fabric was first cut to a length such that it would wrap around the concrete cylinder for the desired number of FFRP layers. The strip of fabric was then cut to a width of 203.2 mm to match the height of the concrete cylinders. The resin used was a bio-based epoxy with an approximate bio-content of 30%.

The epoxy was first prepared by mixing the base epoxy and hardener. After mixing, the epoxy was applied in an even layer around the circumference of the concrete cylinder. The flax fabric was then placed carefully on the specimen and wetted with epoxy. The fabric was held in place while the epoxy was applied to the surface, such that the fibers remained in the hoop direction. After the wrapping was completed, a layer of parchment paper was applied to the outside and excess resin was removed using a plastic scraper. The FFRP-wrapped specimens were then allowed to cure for seven days.

Figure 1 – Specimen Preparation: (a) Cut Flax Fabric to Length; (b) Measure and Cut Flax Fabric to Correct Width; (c) Apply Coat of Epoxy to Concrete Cylinder; (d) Apply Flax Fabric to Wetted Cylinder; (e) Apply Epoxy to Surface of Flax Fabric; (f) Finished Wrapped Specimen

After curing, any excess FFRP at each end was removed using a grinder and a sulfurous capping compound was applied to each end of the specimen to provide a flat testing surface. After capping, each end of the specimen was wrapped with a 20 mm wide, two-ply basalt FRP (BFRP). The BFRP was applied to mitigate the possibility of premature local failure at the ends of the FFRP wraps. A finished specimen is shown in Figure 1f.

2.4. Test Set-up

Each specimen was tested under uniaxial compression at a rate of 0.5 mm/min on a 2 MN Instron Universal Test Machine. The test set-up is shown in Figure 2. The concrete specimens were placed on a steel platen and a spherical platen was placed at the top of the specimen to mitigate any alignment issues. As shown, four linear potentiometers (LPs) were used to measure displacement: two in the lateral direction and two in the axial direction. Two strain gauges were also applied at mid-height on the wrapped specimens on the side opposite the overlap: one in the hoop direction and one in the axial direction. Load and stroke displacement were also measured by the test machine. All data was sampled by the data acquisition unit at a rate of 10 Hz.

3. Experimental Results and Discussions

The results of the tests are presented in Figure 3 and Table 2. It should be noted that, as shown in Figure 3, the tests of the unconfined concrete specimens (FCC-0L) were terminated when after the load capacity reduced by 40% from the observed peak load, whereas the tests of the wrapped specimens (FCC-3L and FCC-6L) were terminated after specimen failure. Based on Figure 3, it is evident that FFRP wraps with both three and six layers were able to effectively confine the concrete and in turn increase the strength of the cylinder. Also, the specimens exhibited an approximately linear behavior after a strain of approximately ϵ'_c, the strain corresponding to the ultimate unconfined concrete stress. Both the cylinder strength and deformability increased with an increase of FFRP layers. Wrapping the concrete with three layers of FFRP increased the strength of the cylinder from 37.8 MPa to 58.3 MPa, an increase of 54%. Likewise, the compressive strength of concrete cylinders wrapped with six layers of FFRP improved by 108% to 79.7 MPa.

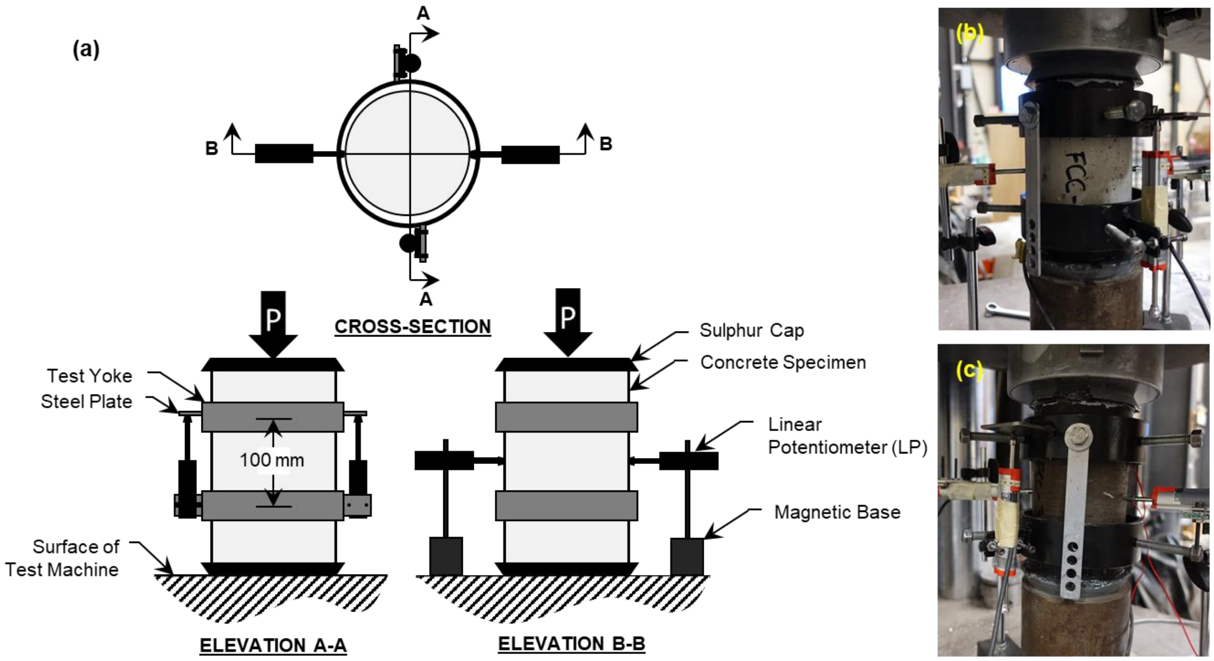

Figure 2 – Test Set-up (a) Schematic; (b) FCC-0L Specimen Test; (b) FCC-3L Specimen Test

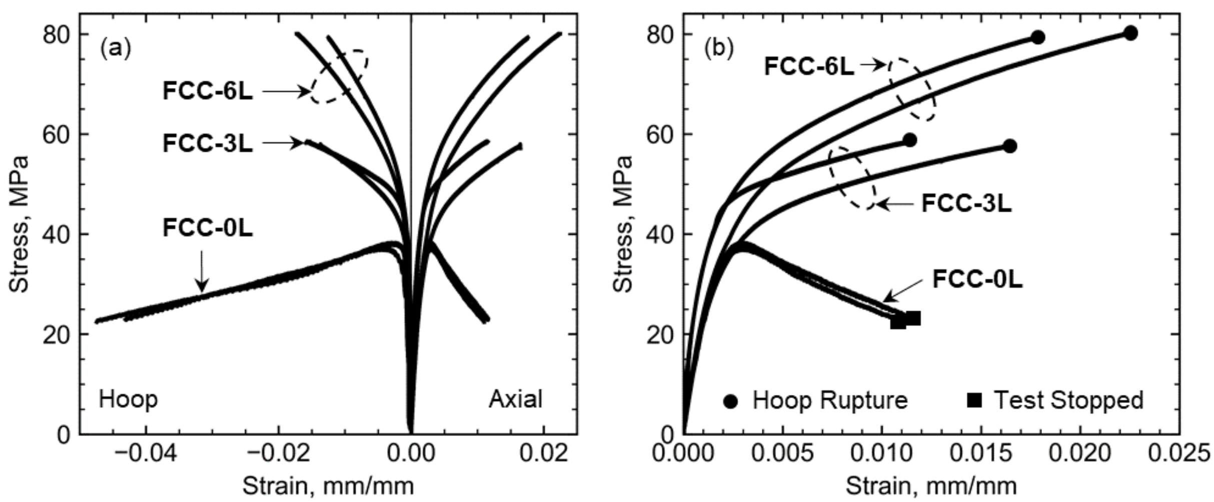

Figure 3 – Test Data (a) Stress vs. Hoop and Axial Strains; (b) Detailed View of Stress vs. Axial Strain

The strain corresponding to the maximum compressive strength (ϵ'_c for unconfined concrete and ϵ'_{cc} for confined concrete) also increased with the number of FFRP layers. When wrapped with six layers of FFRP, ϵ'_{cc} increased to 0.0200 mm/mm from the ϵ'_c of 0.0030 mm/mm of the unconfined concrete specimens, an increase of 567% (or a factor of 6.7).

Table 2 – Test Results

ID	f'_{cc}, MPa	ϵ'_{cc}, mm/mm	ϵ_{hr}, mm/mm
FCC-0L-1	38.3	0.0030	-
FCC-0L-2	37.2	0.0030	-
AVE	37.8	0.0030	-
SD	0.76	0.0000	-
FCC-3L-1	58.6	0.0114	0.0157
FCC-3L-2	58.0	0.0165	0.0137
AVE	58.3	0.0139	0.0147
SD	0.42	0.00356	0.00142
FCC-6L-1	79.4	0.0177	0.0125
FCC-6L-2	80.1	0.0222	0.0170
AVE	79.7	0.0200	0.0148
SD	0.51	0.00314	0.00320

Figure 4 – Tested Specimens (from left to right: FCC-0L-1, FCC-0L-2, FCC-3L-1, FCC-3L-2, FCC-6L-1, FCC-6L-2)

As can be seen in Figure 4, the unconfined concrete specimens both failed by shear cone failure and the wrapped specimens failed by hoop rupture. Table 2 shows that the average ultimate hoop rupture strain observed in the wrapped specimens was 0.0147 mm/mm. As mentioned previously, the ultimate strain of the FFRP observed during tensile coupon tests was 0.0153 mm/mm, which means that the hoop rupture strain during the tests reached 96% of the ultimate tensile strain of the FFRP. This is significantly higher than the strain efficiency factor 55% prescribed by ACI (American Concrete Institute 2017).

4. Conclusions

As a part of this study, six concrete specimens were tested under uniaxial compression. The main parameter of the tests was the effect of the thickness of unidirectional FFRP wraps on the compressive behavior and strength of concrete. It was determined that FFRPs can effectively confine concrete and that the confinement effect increases with FFRP thickness. It was also noted that after a concrete strain of ϵ'_c the confined concrete exhibited an approximately linear behavior. Based on the tests the following conclusions were made:

- three layers of FFRP wrap increased the strength of the concrete cylinders by 54% and six layers of FFRP increased the strength of the concrete cylinders by 108% and;

- wrapping the concrete with six layers of FFRP increased the ultimate strain of the cylinders by an average of 567%

As the test data in this study is limited, further research is required. Future research in this study should include testing of more samples, testing of larger concrete cylinders and testing the samples with more FFRP thicknesses on concrete strength. Additional research in this study will include the development of an analytical model to predict the behaviour of FFRP-confined concrete.

5. References

American Concrete Institute. (2017). “ACI 440.2R-17 - Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures.” American Concrete Institute, Farmington, MI, USA.

ASTM. (2014). “ASTM D3039/D3039M - Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials.” *Annual Book of ASTM Standards*, ASTM, West Conshohocken, Pennsylvania, US.

Bakis, C. E., Bank, L. C., Brown, V. L., Cosenza, E., Davalos, J. F., Lesko, J. J., Machida, A., Rizkalla, S. H., and Triantafillou, T. C. (2002). “Fiber-Reinforced Polymer Composites for Construction - State-of-the-Art Review.” *Journal of Composites for Construction*, (May).

Berthet, J. F., Ferrier, E., and Hamelin, P. (2005). “Compressive behavior of concrete externally confined by composite jackets: Part A: experimental study.” *Construction and Building Materials*, 19, 223–232.

Betts, D., Sadeghian, P., and Fam, A. (2017). “Tensile properties of flax frp composites.” *Asia Pacific Conference on FRP in Structures*, APFIS 2017, Signapore.

Betts, D., Sadeghian, P., and Fam, A. (2018). “Experimental Behavior and Design-Oriented Analysis of Sandwich Beams with Bio-Based Composite Facings and Foam Cores.” *Journal of Composites for Construction*, 22(4), 1–12.

Campione, G., La Mendola, L., Monaco, A., Valenza, A., and Fiore, V. (2015). “Behavior in compression of concrete cylinders externally wrapped with basalt fibers.” *Composites Part B: Engineering*, Elsevier Ltd, 69, 507–586.

Cicala, G., Cristaldi, G., Recca, G., and Latteri, A. (2010). “Composites Based on Natural Fibre Fabrics.” *Woven Fabric Engineering*, 317–342.

Lam, L., and Teng, J. G. (2004). “Ultimate Condition of Fiber Reinforced Polymer-Confined Concrete.” *Journal of Composites for Construction*, 8(6), 539–548.

Nanni, A., and Bradford, N. M. (1995). “FRP jacketed concrete under uniaxial compression.” *Construction and Building Materials*, 9(2), 115–124.

Sadeghian, P., and Fillmore, B. (2018). “Strain distribution of basalt FRP-wrapped concrete cylinders.” *Case Studies in Construction Materials*, Elsevier Ltd., 9, e00171.

Teng, J. G., Chen, J. F., Smith, S. T., and Lam, L. (2003). “Behaviour and strength of FRP-strengthened RC structures: a state-of-the-art review.” *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, 156(1), 51–62.

Xiao, Y. and Wu, H. (2000). “Compressive Behavior of Concrete Confined by Carbon Fiber Composite Jackets.” *Journal of Materials*, 12(2), 139–146.

Yan, L., and Chouw, N. (2013). “Behavior and analytical modeling of natural flax fibre-reinforced polymer tube confined plain concrete and coir fibre-reinforced concrete.” *Journal of Composite Materials*, 47(17), 2133–2148.

Yan, L., Chouw, N., and Jayaraman, K. (2014). “Effect of column parameters on flax FRP confined coir fibre reinforced concrete.” *Construction and Building Materials*, Elsevier Ltd, 55, 299–312.