Performance of CFRP wrapped UHPC Columns under Axial Compression

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***Abstract*—** A new class of concrete that exhibits highly improved strength and ductility properties has lately been developed. Ultra-High Performance Concrete (UHPC) is a relatively new material with several considerable advantages. Due to its low water-cement ratio and the presence of steel fibers, UHPC has higher compressive and tensile strengths than conventional concrete. The current research study addresses results of an experimental investigation on the behavior of axially loaded Carbon-fiber reinforced polymer (CFRP) wrapped UHPC columns. 6 plain UHPC columns and 12 CFRP-wrapped UHPC columns were tested under monotonic axial compression. The test results showed that CFRP wrap significantly increases the ultimate strength and strain of the UHPC columns. This increase is much more pronounced for the UHPC columns with greater number of FRP sheets.

***Keywords*—** Carbon-fiber reinforced polymer, steel fibers, ultra high performance concrete, ultimate strength.

I. Introduction

LATELY, the use of externally employed fiber-reinforced polymer (FRP) has been gained substantial popularity for strengthening of concrete structures. The FRP composites have been used successfully for rehabilitation and upgrading of deficient reinforced-concrete (RC) structures such as buildings, bridges, parking garages, chimneys, etc. One important application of this composite retrofitting technology is the use of FRP jackets to provide external confinement to RC columns where reinforcement is inadequate [1].

Lots of study were performed in order to study the behavior of low and normal strength concrete columns wrapped with FRP sheets by many researchers (Mirmiran and Shahawy [2], Samaan et al. [3], Toutanji [4], Ilki and Kumbasar [5], Lam and Teng [6], Harajli [7], Kumutha and Palanichamy [8]). Although there are lots of studies on low and normal strength concrete columns wrapped with FRP sheets, there is little information on the behavior of FRP-wrapped UHPC columns. This study aims to investigate the compressive behavior of UHPC columns wrapped with CFRP sheets. Compared with the unconfined counterparts, the gain in axial strength and axial strain, and failure modes of the CFRP wrapped UHPC columns were obtained and evaluated.

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II. Experimental Program

A. Specimen Layout

A total of 12 CFRP-wrapped and 6 unconfined control UHPC cylinders with a diameter of 100 mm and a height of 200 mm were prepared and tested under monotonic axial compression. CFRP sheets were bidirectional and wrapped only in the hoop direction. The concrete cylinder specimens were wrapped with two, three, four and five (2, 3, 4, and 5 layers) CFRP layers. Three specimens were prepared and tested for each thickness of CFRP sheets. The test program and specimen properties are given in Table 1. Mechanical and geometrical properties of the CFRP sheets and epoxy resin reported by the manufacturer are given in Table 2.

B. Concrete

The UHPC was produced by using very fine sand, cement, silica fume, super plasticizers and steel fibers. Six plain concrete cylinders (100 mm x 200 mm) were tested under axial loading to determine the average maximum strength of the concrete f_{co}, and its corresponding strain ε_{co}, at 28 days. The 28-day average compressive strength of the concrete cylinders was 159 MPa. The regular CEM I PÇ 42.5R was used as cement material in the mix. Water-binder (cement + silica fume) ratio was kept constant at 0.18. The typical mix

TABLE I
TEST PROGRAM AND SPECIMEN PROPERTIES

Specimen Group	Number of Specimens	Number of FRP layers	Thickness of FRP (mm)
P	6	N/A	N/A
C2	3	2	0.7
C3	3	3	1.05
C4	3	4	1.4
C5	3	5	1.75

TABLE II
MECHANICAL PROPERTIES OF FRP SHEETS

Specimen Group	Number of Specimens	Number of FRP layers	Thickness of FRP (mm)
P	6	N/A	N/A
C2	3	2	0.7
C3	3	3	1.05
C4	3	4	1.4
C5	3	5	1.75

composition of the UHPC used in this study is given in Table 3.

C. Specimen Preparation

The plastic pipes with length of 200 mm and diameter of 100 mm were cut and prepared for the casting of concrete. The UHPC was produced and cast into the plastic pipes. The specimens were kept in the mold for 24 h at room temperature of 20 °C. After demolding, the specimens were exposed to steam curing at 90 °C for 4 days. Heating rate of steam cure treatment was 11°C/h. After completion of their curing periods, were kept in laboratory atmosphere for cooling, and then cleaned and prepared for the wrapping. The resin system L285 produced by Hexion Corporation that was used for bonding the FRP jackets on the concrete columns was the epoxy resin made of two-parts, resin and hardener. The specimens were wrapped by CFRP jackets (2, 3, 4, and 5 plies) in transverse direction with 0-degree orientation. The last CFRP layer was wrapped around the cylinder with an overlap of the diameter of the column to prevent sliding or debonding of the FRP sheets during tests. CFRP sheets were cut and impregnated with epoxy resin by the hand lay-up technique. The top and bottom surfaces of the all columns were grinded smooth for the compression tests. Then, the wrapped concrete columns were left at room temperature for one week for the epoxy to harden sufficiently before testing.

TABLE III
UHPC MIX PROPORTIONS

	Mix Proportions (kg) for 1m^3 concrete
Cement	1000
Siliceous Sand(0.5-1.5 mm)	251
Siliceous Sand(0-0.5 mm)	377
Silica Fume	250
Super Plasticizer	31.75
Water	230
Steel Fiber	500
TOTAL	2640

D. Test Setup

Monotonic axial compression was applied on the specimens by using Instron testing machine with the capacity of 5000 kN. All specimens were loaded at a constant rate of 0.01 mm/s under displacement control. Axial load and strains were monitored for every 50 kN increment of load. Linear variable differential transducer (LVDTs) with a gauge length of 25 mm was used in axial direction to measure the axial deformation. For each specimen, two axial strain gauges and one hoop strain gauges, axial strains with a gauge length of 30 mm (PL-30-11) and lateral strains with a gauge length of 60 mm (PL-60-11), were installed at the mid-height of the specimens. The test setup is shown in Fig. 1.

Fig. 1 Test setup

III. Experimental results and discussions

All specimens were loaded in monotonic axial compression until failure. Failure of the unconfined UHPC specimens was brittle with a rapid load decrease after the peak load was reached. However, the steel fibers used in the mix significantly increase the post-cracking strain capacity or ductility of the UHPC material. The failure of the CFRP-wrapped UHPC columns was gradual, ending with a sudden and explosive noise. The typical failure of the unconfined UHPC columns and CFRP wrapped UHPC columns are shown in Fig. 2. and Fig. 3, respectively.

Fig. 2 Typical failure mode of unconfined UHPC

Fig. 3 Typical failure mode of CFRP confined UHPC

Axial stress-axial and hoop strains relationships for CFRP-wrapped UHPC columns with 2, 3, 4, and 5 layers and unconfined concrete specimens are shown in Fig. 4.

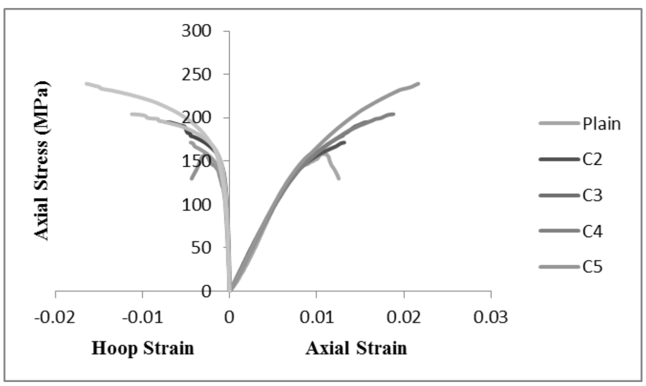

Fig. 4 Average stress-strain curves for CFRP-wrapped UHPC columns

The stress-strain curves of CFRP-wrapped all UHPC columns showed a typical bilinear trend with strain hardening.

From the results, it can be clearly seen that the confinement of the UHPC columns with CFRP materials increase the axial strength and axial and lateral strain capacity of the unconfined UHPC columns. In addition, the greater the number of CFRP layers, the greater the gain in axial strength and axial strain capacity with respect to unconfined UHPC columns. The gain in average ultimate strength is 6.2, 16.7, 25.5, and 48% for the specimens C2, C3, C4, and C5, respectively. Similarly, the gain in average axial strain is 18.6, 33.7, 62.8, and 88.9% for the specimens C2, C3, C4, and C5, respectively. The gain in axial strength and axial strain for the CFRP-wrapped UHPC columns with regard to number of layers is shown in Fig. 5 and Fig. 6, respectively.

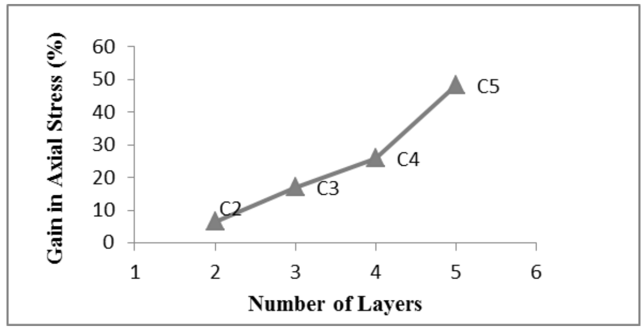

Fig. 5 Gain in axial stress vs. number of layers

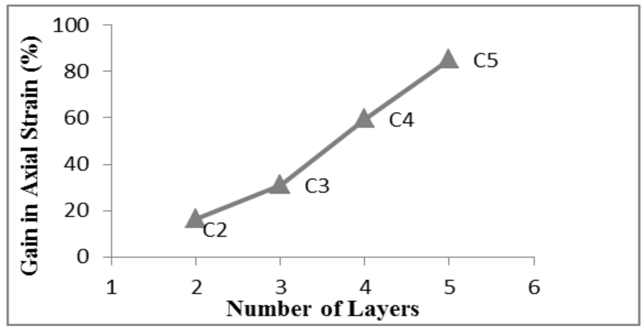

Fig. 6 Gain in axial strain vs. number of layers

IV. Conclusion

This study investigated the axial behavior of CFRP-wrapped UHPC columns. Based on the test results, the following results are highlighted:

The obtained results showed that the enhancement in axial strength and strain is significant for the CFRP wrapped UHPC columns. However, the gain in ultimate strength and ultimate strain was seen especially for the FRP-wrapped UHPC columns with higher confinement ratios. The greatest increase in axial strength and axial strain is 48% and 128%, respectively, compared with the unconfined counterparts.

The failure of the CFRP sheets initiated away from the overlap region at mid-height of the specimen and propagated to the top and bottom surfaces of the specimen. The failure of the CFRP-wrapped UHPC columns was gradual, ending with a sudden and explosive noise.

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