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Carbon Fiber Reinforced Polymer (CFRP) Composite Spirals as Confinement Reinforcement for Concrete under Axial Compression

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Abstract The use of fiber composites in structural strengthening applications has been implemented for many years. Among others, this type of material has been employed as means to confine concrete and achieve superior material behavior. Confinement can be achieved either by wrapping the concrete with FRP fabrics or by embedding FRP stirrups or spiral (helical) reinforcement in concrete. Although FRP spirals have been used as reinforcement in concrete members, this was primarily in the form of FRP bars used as shear reinforcement in RC members under flexure. Some studies have been conducted using FRP spiral strips that were bonded on the outside face of cylindrical specimens and their confinement effect on concrete under axial compression was evaluated. This study deals with the experimental testing of concrete cylindrical specimens that utilize embedded carbon FRP (CFRP) composite spiral reinforcement, a unique application with limited investigation as to its effect on concrete confinement. Standard (300 mm x 150 mm) concrete cylinders were cast both with and without the embedded CFRP spiral. The cylinders were tested in axial compression to determine the effect of the CFRP spiral on their strength and ultimate deformation. This study contributes to the field of concrete confinement and in an area that is not well investigated especially when the FRP spiral is embedded into concrete. Experimental results indicate very significant improvements in ultimate strength and strain with more the enhancement reaching 116% for the strength and 147% for the strain. Comparing energy absorption capacity of the CFRP spirally confined concrete with the unconfined concrete, the improvement is even higher and reaches 320%. Therefore, the use of embedded CFRP spiral to confine concrete is effective and provides significant confinement and enhances concrete properties.

Keywords Concrete Confinement, CFRP Spiral, FRP Composites, Ductility, Concrete Strength, Experimental Testing

1. Introduction

Typically, concrete tends to behave in a rather brittle manner. Even though concrete does not crush when it reaches its maximum resistance, but rather undergoes additional deformation prior to reaching crushing strains, the deformability capacity of the material is limited. The additional deformation taking place after maximum resistance is reached is also known pseudo-ductility. The ability to undergo additional deformation after the maximum resistance tends to reduce as the strength of the concrete is increased. That is why typically concrete with higher strength shows a more brittle behavior compared to lower strength concrete.

The way concrete behaves can be changed and it can be made to show an improvement in its ductility if confinement is provided to the material. Confinement has been utilized for many years using steel stirrups and spirals. The use of FRP composite materials provided an alternative for such applications with excellent results. When concrete is confined degradation and concrete crushing is delayed and the ultimate deformation of the material is increased. This implies that the material behavior is more ductile. The improvement depends on the amount and type of material used in each confinement application.

Initially, researchers began to investigate confinement of concrete with the used of wraps made with FRP sheets applied to concrete. Numerous researchers tested samples wrapped with FRP composites [1-5]. Experimental results from such studies indicate that the properties of FRP wrapped concrete are enhanced. For example, the maximum resistance of concrete using FRP wraps for confinement was found to be as much as 420% higher with respect to the initial resistance of the reference concrete samples. The type of FRP composite material as well as the amount of material used for the wraps dictates the improvement.

Carbon composite grids have been investigated to determine whether they can be a viable option for concrete confinement. Concrete cylinders with carbon grid were tested in compression and the properties of the material were evaluated [6, 7]. In other instances, the carbon grids were used in short piles under compression [8] or as confinement reinforcement in compression-controlled RC members [9, 10]. There is an agreement among researchers since all concluded that the carbon grid improved both the material capacity as well as the maximum deformation capacity of concrete. In a study by Michael and Hamilton [9] in which compression-controlled spun cast piles that were reinforced with CFRP composite rebars and CFRP composite grid the constructed piles were tested in flexure. The study showed that a more ductile behavior can be achieved by such members due to the use of the embedded CFRP composite grid as confinement reinforcement. In another study Michael and Hamilton [10] tested concrete beams that were designed as compression-controlled. These beams employed CFRP grid tubes placed in the compression zone of the members in order to confine concrete. Based on the experimental ductility indices it was found that there was an enhancement of 25%. The improvement was higher when the capacity of the members to absorb energy was evaluated with the grid members having 35% higher capacity than the reference samples. Seliem et al. [11] studied the use of a CFRP grid in concrete piles that were also prestressed. The CFRP grid was used as replacement of the steel spirals that typically are used in these members. The carbon grid was found to be able to produce similar confinements as the steel square spirals spaced at 7.5 cm.

The use of FRP spiral strips is a good alternative to the use of FRP bars to produce spiral reinforcement which has been the subject of study in a number of investigations. The FRP spiral bars did not performed at the same level as straight bars and that was attributed to the fact that in order to produce the spiral the bars were bent and that caused the fibers to squeeze in the inside face reducing their effectiveness [12, 13]. Although there are studies based what is called FRP hoop strip wrapping method [14–24], investigations on FRP spiral wrappings are limited. Externally applied FRP spiral strips have been used to confined concrete [25–27], however, the behavior of embedded internal FRP spiral strips for concrete confinement has not been studied at least with respect to evaluating the level of confinement provided by embedded spirals and the possible effect on the properties of concrete when loaded in uniaxial compression.

Partial FRP wraps have proved to be an effective technique for improving the maximum deformation of concrete. This implies that partial FRP wraps can present an alternative for strengthening against earthquakes in applications involving concrete columns [25–27]. Ismail et al. [26], as part of their investigation, tested 3 different externally applied FRP schemes (full wraps, horizontal partial wraps and spiral wraps) in axial compression. The results from the spiral strips manufactured with 2 layers of carbon FRP material showed an increase in concrete strength which was 1.16 to 1.44 times higher. When the maximum strains were evaluated the enhancement was higher and between 1.54 and 2.58 times higher compared to the reference samples.

In the present study a series of cylindrical specimens with and without a premanufactured spiral made from CFRP strips were constructed and tested in axial compression to evaluate the confining effect of the CFRP spiral strip reinforcement for concrete. The custom made premanufactured CFRP spiral was embedded into a number of specimens and then concrete was cast. This type of application can be used for reinforcing new concrete members as an alternative to the use of steel spiral reinforcement especially in applications in highly corrosive environments. Since this unique application has not been investigated the results of this study will enrich the data pool in the area of confined concrete properties when an embedded FRP spiral is used to confine concrete.

2. Experimental Program

2.1. Materials

The concrete used in this study was of Grade C16/20 based on Eurocode 2 [28]. Locally available materials were used. Both coarse and fine aggregates produced by crushing local diabase rock were used in the mixture. The maximum aggregate size used was 10 mm. This was decided so that in the filling of the small spaces between the CFRP spiral and the cylinder mold is easier. The concrete mixture proportions can be found in table 1. The mixture had a water to cement ratio of 0.5.

Table 1. Design Mixture Amounts

Constituent Material	Amount (kg/m^3)
Portland Cement	300
Water	150
Coarse Aggregate (4/10)	1072
Fine Aggregate (0/4)	838

The CFRP composite spiral reinforcement was manufactured by cutting strips of carbon FRP unidirectional fabric (SikaWrap® – 300 C) and embedding them in a two-component epoxy matrix (Sikadur®-330). The material properties of the fibers and the epoxy matrix can be found in table 2 (carbon fabric) and table 3 (epoxy). The properties in the two tables are manufacturer reported properties [29, 30].

Table 2. Fiber Properties [28]

Property	Value
Density	1.82 g/cm^3
Fabric thickness	0.167 mm
Area density	304±10 g/m^2
Tensile strength	4000 MPa
Tensile modulus of elasticity	230 GPa
Elongation at fracture	1.7%

Table 3. Epoxy Properties [29]

Property	Value (7-days ~23°C)
Modulus of elasticity in flexure	~3 800 MPa
Tensile modulus of elasticity	~4 500 MPa
Strength in tension	~30 MPa
Tensile strain at break	~0.9%
Tensile adhesion strength	> 4 MPa (sand blasted surface)

2.2. Specimen Test Matrix

Eight standard size cylindrical specimens were manufactured with a radius equal to 75 mm and a height of 300 mm. Three of the specimens were not reinforced and therefore served as reference specimens while the other five specimens were reinforced with the embedded premanufactured CFRP composite spiral. The composite spiral was manufactured by using four 20 mm wide strips with each strip layer impregnated with the epoxy resin. The width w_{sp} of the spiral was 20 mm and the thickness t_{sp} 2.5 mm. A steel roller was used to ensure full penetration and fiber impregnation by the epoxy as well as to ensure removal of any air pockets from the composite material. In order to form the spiral a PVC pipe was used as a mold. The pipe diameter was 125 mm. In order to ensure that the appropriated spiral spacing was maintained the spiral shape was traced on the PVC pipe using a paper tape which allowed for an accurate and fast placing of the impregnated CFRP fabric strips on the mold (Figure 1). A schematic of the spiral is shown in Figure 2. The diameter of the core (out to out of the spiral) D_c was 130 mm, the spiral pitch (center to center of strip) s_{sp} was 50 mm and the clear space s from spiral strip to spiral strips was 30 mm. A premanufactured CFRP strip spiral is depicted in Figure 3.

Figure 1. Traced Spiral Arrangement on PVC Pipe Mold

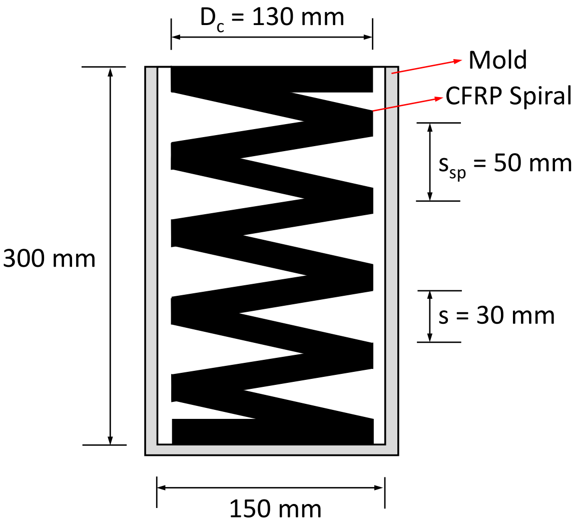

Figure 2. Schematic of CFRP Spiral Reinforcement Arrangement in the Mold

Figure 3. Finished Spiral on PVC Pipe Mold

All cylinders were cast on the same day from the same patch. The details for all the manufactured samples can be found in table 4. The concrete was placed in layers and the required compaction was applied to each concrete layer according to EN-12390-2 [31]. The finished specimens were air cured for 28 days prior to testing.

2.3. Test Set-Up and Instruments

All concrete cylindrical specimens were loaded to failure on day 28 from casting. Specimen loading was conducted in a 2000 KN compression frame. For the measurement of length changes during the testing two linear variable displacement transducers (LVDTs) were installed.

Neoprene pads were used to accommodate any specimen irregularities at the 2 ends. A data acquisition system was employed and applied load and associated length changes were recorded of each specimen. The test was conducted in load-controlled mode. The load was applied at a constant rate of approximately 0.3 MPa/s, a loading rate that conforms to the requirements of the European specification for testing hardened concrete (EN-12390-3 [32]). Data was collected at a rate of 5 Hz. The failure mode for each specimen was also recorded at the end of each test.

Table 4. Cylindrical Specimen Details

Confinement Scheme	Cylinder Code	Unconfined /Confined Core Diameter D_c (mm)	Spiral Strip Width w_{sp} (mm)	Spiral Pitch s_{sp} (mm)	No. of CFRP Layers	Thickness of CFRP Spiral (mm)
No Confinement	C-1	150	-	-	-	-
No Confinement	C-2	150	-	-	-	-
No Confinement	C-3	150	-	-	-	-
CFRP Spiral	CFRP-SP-1	130	20	50	4	2.5
CFRP Spiral	CFRP-SP-2	130	20	50	4	2.5
CFRP Spiral	CFRP-SP-3	130	20	50	4	2.5
CFRP Spiral	CFRP-SP-4	130	20	50	4	2.5
CFRP Spiral	CFRP-SP-5	130	20	50	4	2.5

C = Control specimen, CFRP-SP = Carbon FRP Spiral

3. Results and Discussion

Figure 4. Control Specimen Splitting Failure Mode

Figure 5. CFRP Spiral Specimen Failure Raptured CFRP Spiral Strip

Reference control specimens failed with a splitting failure mode while CFRP spiral specimens failed when one of the CFRP spiral strips raptured. The splitting failure mode of the control specimens is not a desirable mode of failure. However, the fact that all specimens were made from the same concrete allows us to conclude that the concrete used in the CFRP spiral specimens behaved the same and therefore the results obtained are comparable. Failed control specimens are shown in Figure 4 while a failed CFRP spiral specimen is shown in Figure 5.

Results from all specimens are listed in Table 5. The average resistance of the reference specimens was 14.9 MPa while the CFRP spiral confined concrete strength was approximately 2.2 times higher and equals to 32.2 MPa. Similar values were obtained when comparing the maximum strains calculated from the maximum recorded axial deformations. The average maximum strain for the CFRP spiral specimens was 2.5 times larger compared to the average maximum strain for the unconfined specimens. These values represent very significant improvement in resistance and maximum deformation (strain) for concrete confined using the CFRP spiral. The strength has increased by 220% while the ultimate strain by 240% for the confined concrete compared to the unconfined concrete. It was noticed that the average ultimate strain of the unconfined concrete is relatively low with a value of approximately 0.0026. This was attributed to the undesirable mode of failure exhibited by the reference specimens and it is hypothesized that such a failure mode was possibly associated with a premature failure of the material and hence the lower values of the crushing strain. As noted earlier this does not significantly influence the comparison between the two specimen groups since all specimens were manufactured from the same concrete patch and therefore the same behavior is expected from the concrete material used in both groups.

Using the recorded data, stress and strain were calculated and the associated curves were developed and plotted. The stress vs. strain curves for the reference unconfined specimens are shown in Figure 6. The curves for the spirally confined samples are depicted in Figure 7.

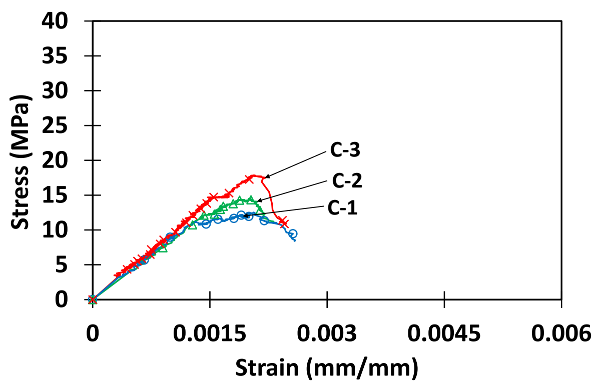

Figure 6. Stress- Strain Curves for Unconfined Specimens

In Figure 6 it is evident that control specimen C-2 is the specimen that very closely follows the average behavior of the control specimen group. On the other hand, looking at Figure 7 of the spiral reinforced specimens CFRP-SP-1 and CFRP-SP-5 represent the 2 extremes (worst and best performance) in the group. However, the average of CFRP-SP-1 and CFRP-SP5 is very close to the overall average in the CFRP-SP specimen group. Specimens CFRP-SP-2, CFRP-SP-3 and CFRP-SP-4 had very similar behavior and are very close to the average behavior of the group with specimen CFRP-SP-3 almost matching the average behavior of the spirally reinforced group of specimens. In order to better visualize the differences between the two groups the curves for samples C-2 and CFRP-SP3 are plotted in Figure 8 each representing the average curve in their group. The graphical comparison between the two as seen in Figure 8 agrees with the numerical values in Table 5.

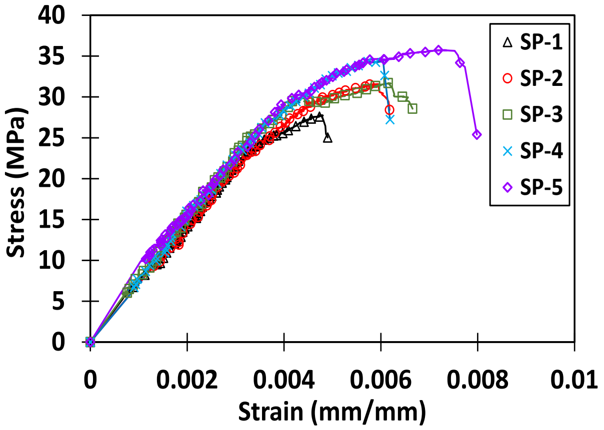

Figure 7. Stress- Strain Curves for CFRP Spiral Confined Specimens

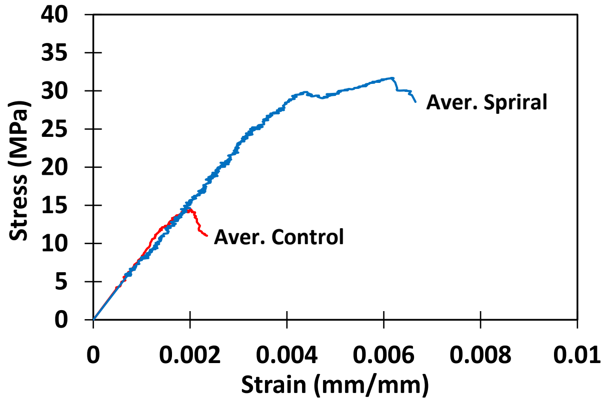

Figure 8. Average Axial Stress- Strain Curves for Control and for CFRP Spirally Confined Specimens

The stress-stain curve shape of the control specimens follows a typical shape of such a curve for an unconfined concrete tested in uniaxial compression. The curves of the CFRP spiral specimens have an initial part which is relatively linear (up to a stress value of 23 MPa) which is probably the point at which spalling of the concrete covering the CFRP spiral takes place. After that the curves become non-linear and their slope reduces as the stress increases. Once the maximum stress is reached there is a sudden drop in the stress which is associated with the rapture of the spiral and the loss of confinement that leads to failure of the material.

The use of the CFRP spiral as confinement reinforcement in concrete has significantly improved both the strength and deformability of concrete and in fact has more than double those characteristics. The results support the statement that the embedded CFRP spiral is providing an effective confinement for concrete which improves its properties significantly.

Table 5. Experimental Results

Cylinder Code	Unconfined/Confined Core Diameter D (mm)	Peak Load (kN)	Ultimate Displacement δ (mm)	Peak Stress (N/mm^2)	Ultimate Strain (mm/mm)	Average Peak Stress (N/mm^2)	Average Ultimate Strain (mm/mm)
C-1	150	156.0	0.774	12.5	0.00258		
C-2	150	255.6	0.767	14.5	0.00256	14.9	0.00258
C-3	150	315.1	0.777	17.8	0.00259		
CFRP-SP-1	130	368.3	1.471	27.8	0.00490		
CFRP-SP-2	130	419.0	1.854	31.6	0.00618		
CFRP-SP-3	130	420.6	1.996	31.7	0.00665	32.2	0.00638
CFRP-SP-4	130	456.6	1.857	34.4	0.00619		
CFRP-SP-5	130	474.2	2.394	35.7	0.00798		

Another way to evaluate the improvement achieved by the CFRP spiral reinforcement and evaluate its confining effect on concrete is to calculate and compare the amount of energy each sample absorbs prior to its failure. This is called energy absorption capacity (W). The capacity relating to the energy absorption is equal to the area under the graph of the load and deformation. The areas under the associated curves for each sample were calculated. The calculated energy absorption capacities for all specimens as well as the average values in each group are listed in Table 6.

Table 6. Energy Absorption Capacities

Specimen	W (KN mm)	Aver. W (KN mm)
C-1	126.5	130.8
C-2	119.6	
C-3	146.4	
CFRP-SP-1	343.9	550.7
CFRP-SP-2	458.6	
CFRP-SP-3	580.3	
CFRP-SP-4	549.7	
CFRP-SP-5	821.0	

Based on the average energy absorption capacity for the control and CFRP spiral specimen groups the improvement in the energy absorption capacity is even larger than the improvement in strength and deformability. The capacity for energy absorption of the CFRP spiral samples is on average 4.2 times higher compared to the controlled specimens. This indicates that the CFRP spirally confined concrete has a significantly higher ability to absorb energy prior to failure compared to reference concrete samples. The amount of energy absorbed by the spirally confined concrete is significantly higher.

4. Conclusions

In this paper experimental results from a study investigating the use of an embedded CFRP spiral used as confinement reinforcement for concrete were presented. These results support and help in the derivation of a number of conclusions listed below:

1) The use of CFRP spirals to confine concrete has proven to be an effective way to not only confine the material but also to significantly enhance its properties.
2) The ultimate resistance of the CFRP spirally reinforced concrete was improved by approximately 116% in comparison to the reference unconfined resistance. The deformability capacity of the confined concrete was also greatly enhanced with the ultimate strain for the confined specimens reaching values up to 147% higher compared to the values of the unconfined specimens.
3) The capacity for energy absorption of the concrete reinforced with the CFRP spiral was higher by 320% with respect to the unconfined reference concrete.
4) Due to the limited availability of data for this type of application further investigations are necessary. This is a unique type of application with a limited pool of data. The parameters that affect the properties and behavior of concrete confined by CFRP spiral reinforcement need to be understood to a greater degree and through a larger number of experimental studies validated.

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