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Behavior of Circular Concrete Columns Internally Reinforced with CFRP Bars and Spiral Stirrups

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Abstract: This paper presents an experimental investigation on circular reinforced concrete (RC) columns reinforced with carbon fiber-reinforced-polymers (CFRP) longitudinal bars and new developed CFRP-spirals. A total of 5 specimens were tested under pure axial compression load. The column specimens have constant dimensions, 300 mm in diameter and 1500 mm in height. The specimens were designed according to CAN/CSA S806-12 code requirements. Effect of two experimental variables; type of reinforcement and longitudinal CFRP-reinforcement ratio were investigated. Plain and steel-RC columns were introduced in the test matrix as control specimens. The test results showed that the CFRP-RC specimens provided similar strength capacity as compared with the steel RC-column. Also, increasing the longitudinal reinforcement ratio was able to maintain the peak load with a little enhancement in the ductility index.

1. INTRODUCTION

Reinforced concrete (RC) vertical members such as columns, piles, and bridge columns are transmitting compression loads from upper to lower levels in building, marine structures and bridges. These axial members are the most important elements in the structure, failure one of them in a critical location can cause a progressive collapse of whole structure. These members are conventionally reinforced with longitudinal steel bars and transvers stirrups. The steel bars have limited service life and high maintenance costs, especially when used in aggressive and/or harsh marine environments due to corrosion problem. The problem associated with the corrosion has been led to the deterioration of concrete, loss of serviceability and hence brittle failure of many structures. The high costs associated with the corrosion of steel reinforcement command a solution that will attack the problem from its root cause. The use of fiber-reinforced polymers (FRP) composite bars has increased during the last decade. Known to be corrosion resistant, FRP reinforcing bars provides an alternative to steel reinforcement. FRP materials in general offer many advantages over the conventional steel, including one quarter to one fifth the density of steel, no corrosion even in harsh chemical environments and greater tensile strength than steel.

In the last decade, considerable efforts have been made to apply FRP composites in the construction industry and structural applications as internal reinforcement for concrete structures. It has been used as internal reinforcement for beams, slabs and pavements [Rizkalla, et al. 2003; Benmokrane et al. 2006]. These efforts are greatly improving the knowledge of how concrete members reinforced with FRP bars should be analyzed and designed in flexure and shear. On other hand, the axial behavior of FRP reinforced concrete compression members has not defined yet. This is partly due to a lack of experimental data, which can describe the behavior of members reinforced with such materials. The lack of information relevant to this area is also addressed in the American Concrete Institute (ACI 440.1R-06) design guide and the Canadian Highway Bridge Design Code (CAN/CSA S6-06) design provisions as one of the areas remains to be researched to further develop strength design guidelines for such members. This leaves research gaps in need of valuable investigations to introduce appropriate provisions in guidelines and codes for the design issues of FRP-RC members under axial loads.

Testing of FRP bars in compression is typically complicated by the occurrence of fiber micro-buckling due to the anisotropic and non-homogeneous nature of the FRP material. Therefore, standard test method for FRP bars under axial compression loads is not introduced yet, ACI 440.1R-06. On the other hand, the ACI 440.1R-06 design guide (ACI Committee 440 2006) does not recommend the use of FRP bars as longitudinal reinforcement in columns or as compression reinforcement in flexural members. It is stated that the FRP reinforcement should not be relied on to resist compression. The ACI 440.1R-06 highlights that further research is needed in this area. Also, the Canadian codes CSA/CAN S6-06 and CSA/CAN S806-12 neglect the compression resistance contribution of FRP longitudinal reinforcements in the flexural and compression concrete members in the compression zone.

Previous research works indicate that the strength and modulus of FRP bars in compression are lower than that in tension. Kobayashi and Fujisaki (1995) investigated experimentally the behavior of concrete columns reinforced with GFRP bars and stirrups. The test results indicated that, the compressive strength of GFRP bars was 30-40 % of its tensile strength and the column axial capacity could be predicted from the following equation:

$$P_o = 0.85 f_c^{'} (A_g - A_{FRP}) + 0.35 F_{FRPu} A_{FRP} \tag{1}$$

Where, P_o is the nominal concentric axial load capacity with no eccentricity. A_g and A_{FRP} are gross sectional area of concrete and area of FRP reinforcements, respectively. f'_c and F_{FRPu} are the unconfined concrete compressive strength and ultimate FRP tensile strength, respectively.

Leung and Burgoyne (2001) studied the behavior of short concrete cylinders confined with aramid spiral stirrups. Four different spacing were used (10, 20, 35 and 50 mm). The test results indicated that decreasing the spiral pitch increased the peak load. In 2005, the compression behavior of square concrete columns reinforced with FRP bars has been reported [9]. Columns were 250 x 250 mm and 1250 mm high. Three different reinforcement ratios (0.723, 1.08 and 1.45%) were used by using 4, 6 and 8 No.12 mm GFRP bars, respectively. The study reported that increasing the reinforcement ratio increased the ductility and it had a significant effect on the initial cracking loads, ultimate strain, and ultimate loads that the columns resisted. Also, increasing the GFRP reinforcement ratio from 0.723 to 1.08% had a noticeable significant effect on all the behavior of tested columns more than increasing it from 1.08 to 1.45%.

The few studies carried out on CFRP-RC columns in the recent indicated that the behaviors of such columns have not yet been fully investigated. In addition, up to date no experimental data on the axial behavior of circular CFRP-RC columns have been introduced. Therefore, in this study five circular reinforced concrete columns were prepared and tested under axial compression load to provide a better understanding of the behavior of such columns. Specimens were reinforced with CFRP longitudinal bars and new developed CFRP-spiral stirrups. The following sections present the experimental program, test results and discussion.

2. EXPERIMENTAL PROGRAM

2.1 Materials

Normal weight concrete was employed in this study with average compressive strength 42.9 MPa. The actual compressive strength was determined based on the average test results of ten concrete cylinders at the day of testing the column specimens. Two steel bar diameters were used to reinforce the control specimens. Deformed steel bar No.5 (nominal diameter 16 mm and nominal cross sectional area 200 mm^2) was used as longitudinal reinforcement. While, steel bar No.3 (nominal diameter 9.5 mm and cross sectional area 71 mm^2) was employed as transverse spiral reinforcement.

New developed spiral stirrups and straight sand coating CFRP bars were used to reinforce the column specimens in the transverse and longitudinal direction. The bars were made of continuous carbon (fiber carbon content 73%) impregnated in a vinylester resin using the pultrusion process and manufactured by a Canadian company [Pultrall Inc.]. The carbon fibers give the bar mechanical strength, while the resin matrix (resin, additives and fillers) provides corrosion resistance in harsh environments. The CFRP bars had a sand-coated surface to enhance bond performance between bars and surrounding concrete. Grade II as classified in the CAN/CSA S807-10 according to the tensile young's modulus (110 GPa) was used in this study. Straight bars No.4 (nominal diameter 12.7 mm and nominal cross-sectional area 126.7 mm^2) were used as longitudinal reinforcement for all the CFRP-RC columns. However, bar diameter No.3 (nominal diameter 9.5 mm and nominal cross-sectional area 71.3 mm^2) were used as spiral reinforcement. Table 1 presents the mechanical properties of the CFRP bars.

Table 1: Mechanical Properties of CFRP Bars

Bar Size	Area (mm^2)	Elastic Tensile Modulus E_f (GPa)	Nominal Tensile Strength MPa	Tensile Elongation %
# 3	71.3	120	1596	1.33
# 4	126.7	140	1899	1.32

2.2 Test Matrix and Specimen Preparation

A total of five column specimens were tested in this study under pure axial compression load. The specimens had 300 mm diameter cross section and 1500 mm height. Steel-RC circular column was reinforced longitudinally with bars No.5 (16 mm nominal diameter). While circular CFRP-RC columns were contained longitudinal bars No. 4 (12.7 mm nominal diameter). On other hand, all specimens were reinforced transversely with No. 3 (9.5 mm nominal diameter) spiral reinforcement with constant pitch equal to 80 mm. The test matrix and reinforcements details of the test specimens are shown in Table 2. Each specimen is identified with two codes. The identifications S and C were used for specimens reinforced with steel and CFRP bars, respectively. Also, the letter V was used to refer to the vertical reinforcement. While the number in the specimen identification represents the number of longitudinal steel or CFRP bars. The specimens were divided in the test matrix to two groups. Group I includes two control specimens: plain concrete column (P) without reinforcement and steel specimen (S6V) reinforced with 6No.5 steel bars and No. 3 steel spiral with pitch equal to 80 mm these two specimens were used as reference for all the CFRP-RC columns in this study. Group II includes three specimens to study the effect of longitudinal reinforcement ratio. The three specimens were reinforced in the transverse direction with spiral CFRP stirrup No.3 with constant pitch value equal to 80 mm. The specimens have three different longitudinal reinforcement ratios ranging from 1.04 to 2.43% using CFRP bar No. 4.

Table 2: Test matrix, specimens' details and summary of test results.

Series No.	RFT. Type	Specimen ID	Vertical RFT.		Horizontal RFT.			P_{Peak} kN	P_{Peak}/P_o	$\varepsilon_{c\text{-}Peak}$ με	$\varepsilon_{bar\text{-}Peak}$ με	Ductility index
			ρ_{st} %	No. of bars	ρ_s %	Bar size	pitch (mm)					
I	---	Plain (P)	---	---	---	---	---	2468	---	1672	---	1.00
	Steel	S-6V	1.65	6 No.5	1.48	3	80	3142	1.03	2178	1800	1.80
II	CFRP	C-10V	1.73	10 No.4	1.48	3	80	3013	0.93	1926	1843	1.25
		C-6V	1.04	6 No.4	1.48	3	80	2906	1.01	1756	1648	1.22
		C-14V	2.43	14 No.4	1.48	3	80	3108	0.87	1996	2068	1.28

CFRP and steel cages were assembled for different columns configurations. Figure 1 shows the overview of the fabricated CFRP cage from the straight bars and spiral stirrup. Each coil of steel or CFRP spiral reinforcement consists of one complete helical spiral without any lapped splice. The pitch of spiral was reduced to 50 mm outside the test region at both ends of the columns (250 mm length) to avoid premature failure in the end regions of the columns. The circular columns were prepared for vertical casting using very stiff cardboard tubes. Wooden formworks were used to hold all the cardboard tubes in vertical position. After, the steel and CFRP cages were inserted in the formwork. Plastic spacers were used along the cages side to support the cages and to ensure the required concrete cover (30 mm). All columns were cast vertically to simulate typical construction practice of columns. The concrete was provided by a local ready-mix concrete company. Concrete was discharged in the columns directly from ready-mix concrete truck in approximately 3 lifts and an electric internal vibrator was used to consolidate the concrete and to remove air bubbles at each lift. Figure 2 illustrates the column specimens after casting.

Figure 1: CFRP-cage overview

Figure 2: Fabrication and preparation the column specimens

2.3 Instrumentation and Test Setup

Seven electrical resistance strain gauges with gauge length 10 mm were used to capture the local strain distributions in both transverse and longitudinal steel and CFRP reinforcements. At the mid height of each column, three longitudinal bars were instrumented with resistance electrical strain gauges to measure the strain in the steel and CFRP bars. Also four electrical resistance strain gauges were attached on spiral reinforcement; the instrumented spirals were located in the test region of the specimens. Four linear variable displacement transducers (LVDTs) were located at specimen mid height to measure the axial deformations of each specimen under applied load. LVDTs were placed vertically at 90 degrees apart along the hoop direction of the specimen over a gauge length of 400 mm. All specimens were prepared before the test by a thin layer of high strength cement grout capping on the top and bottom surfaces for leveling and ensuring uniform distribution of the applied load across the specimens' cross section. Steel collars of 254 mm width and 12.7 mm thickness were placed at the top and bottom of each specimen to provide additional confinement at the end regions and to avoid the local failure of the specimen's ends. The column specimens were tested under axial concentric loading using 11,400 kN capacity MTS testing machine. The test started with a loading rate of 2.5 kN/s up to a load level 2100 kN. Then, the test was continued using displacement control with a rate of 0.002 mm/s until the resistance of the given specimen dropped to 35% of the peak axial load. The internal load cell of the MTS testing machine was used to measure the axial load and head machine displacement that were applied to the column specimens. During the test load, axial displacement and the reinforcement strains (longitudinal and transverse reinforcements) were recorded by using automatic data acquisition system connected to the computer. Figure 3 shows typical test setup for the concentrically loaded columns.

Figure 3: Test setup

3. EXPERIMENTAL TEST RESULTS AND DISCUSSION

The experimental test results of the five circular RC columns tested in this research were summarized in Table 2 in terms of peak load (P_{Peak}), corresponding axial concrete strain ($\varepsilon_{c\text{-}Peak}$) and the measured average axial strain in the longitudinal bars ($\varepsilon_{bar\text{-}Peak}$). Also, the ratios of the experimental values to the predicted nominal capacities (P_{Peak} / P_o) are presented for each specimen. The predicted load (P_o) was calculated based on the concrete cylinder compressive strength at the day of the testing by using equation (1). Table 2 indicated that the average strain of CFRP longitudinal reinforcement varied from 12 to 16% of its ultimate tensile strain at the peak load level. In addition, it was found that the ratios of the experimental peak load to predict values (P_{Peak}/P_o) were ranged from 0.87 to 1.01. These values indicated that using Equation (1) provided overestimated predictions of the nominal capacity of CFRP-RC columns, considering the contribution of CFRP bars in compression equal to 40% of CFRP tensile strength. This results need to modify to be compatible with the research work and experimental test results conducted in this study. On the other side, the deformability of test columns was obtained to quantify the effect of test variables on the post peak behavior. In this study, the area under load-axial strain curve ductility ratio was used to quantify the deformability. Table 2 presents the estimated ductility index based on the ratio of the area under load versus strain curve up to a load of 0.85 times the peak load on the descending side to the area under the curve up to peak load.

Effect of Type of Reinforcement

The CFRP and steel RC columns (C10V and S6V) were designed to have the same reinforcement ratio ($A_{st} = A_F$), using 10 No. 4 longitudinal CFRP bars and 6 No. 5 longitudinal steel bars. Where, A_s and A_F are area of steel and CFRP longitudinal reinforcements, respectively. The CFRP RC specimen (C10V) with 80 mm spiral spacing exhibited the same axial load-strain behavior as the steel RC counterpart specimen (S6V), see Figure 4. Using CFRP and steel reinforcements increased the peak loads to 1.18 and 1.27 times that of the plain specimen, respectively. It was found that the confinement efficiency provided with using CFRP longitudinal bars and spiral stirrups in the CFRP RC specimen as measured by the strength enhancement of concrete core at the maximum stress was approximately similar to the counterpart steel RC specimen, (1.52 and 1.6, respectively). The axial capacity of CFRP RC column (C10V) was insignificantly affected, on average 7.5% less as compared with the counterpart steel RC column. CFRP RC column developed some limited ductility, initiated by the gradual crushing of concrete core. Though limited in numbers, the comparison of ductility index indicated that CFRP RC column was able to sustain approximately 95% of the ductility index observed in the counterpart steel RC column. Whereas, the steel RC column (S6V) showed lower rate of strength decay after the peak load than in the case of the counterpart CFRP specimen (C10V). For all the CFRP RC columns with 10 longitudinal CFRP bars, the load carried by the longitudinal CFRP reinforcements ranged between 11 and 14% of the peak load (P_{max}), whereas the average load carried by the vertical steel reinforcement was approximately 15% of the peak load. On the other hand, the results indicate that the average concrete strain and the measured strain on CFRP and steel bars show similar behavior up to peak load resistance, and there was no distress in the CFRP bars. The maximum measured compressive strain in CFRP bars of specimen (C10V) was 6,000 με, confirming that the bars were effective in resisting compression load. In conclusion, CFRP reinforcement used as column compression reinforcement maintained its integrity and load resistance until after surrounding concrete crushed and spalled off beyond the peak stress until after the crushing of concrete.

Longitudinal CFRP Reinforcement Ratio

Figure 5 show the load versus axial strain curves for the CFRP RC columns (C6V, C10V and C14V). These specimens were designed with three different longitudinal reinforcement ratios (1.0, 1.7, and 2.4%, respectively). Specimen with low reinforcement ratio (1%) failed in a brittle and explosive manner as compared with the behavior of specimens having higher reinforcement ratio (1.7 and 2.4%). Specimens C6V-3H80, C10V-3H80 and C14V-3H80 lost 27, 16 and 12% of its maximum capacities after reaching the peak load due to the sudden spalling of the concrete cover. The post peak curves of the lower reinforcement ratio columns are steeper indicating faster rate of strength decay. The increasing trend of strength enhancement and ductility values from lower to higher reinforcement ratio show that effectiveness of confinement increases as the reinforcement ratio increases. The ductility values ranged between 1.7 to 1.95 and confinement efficiency ratios ranged from 1.46 and 1.63. The higher ratios are obtained for specimens with higher reinforcement ratio. Also, with increasing the vertical reinforcement ratios from 1.0 to 2.4% reduced the transverse reinforcement strain (ε_{spiral}) at the peak load level by 66%. On the other hand, Table 2 shows enhancement in strength capacity 7%, and the CFRP bars used contributed from 11 to 17% of column capacity when the longitudinal reinforcement ratio was increased from 1.0 to 2.4%.

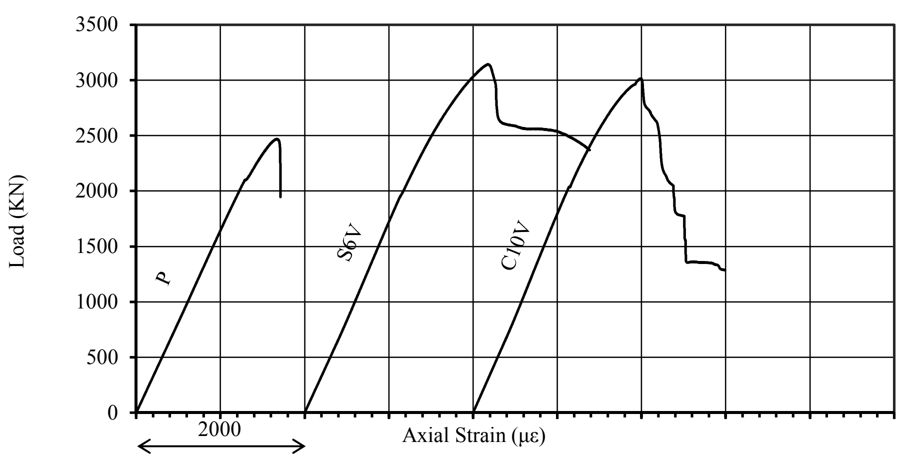

Figure 4: Effect of type of reinforcement on the load-strain curves of the tested specimens.

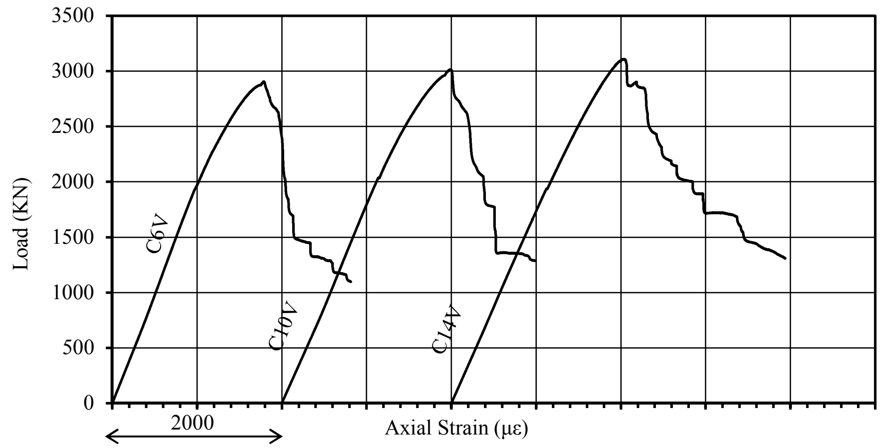

Figure 5: Effect of longitudinal reinforcement ratio on the load-strain curves of the tested specimens.

4. CONCLUSIONS

This study was conducted to investigate the behavior of circular RC columns reinforced with CFRP bars and spiral stirrups under pure axial compression load. New developed CFRP-spiral stirrups were used to reinforce the CFRP-RC tested specimens. The effects of two test parameters on column strength were investigated; type of reinforcement and vertical reinforcement ratio. Based on the experimental test results carried out in this study, the following conclusion can be drawn:

1. The general behavior of tested concrete columns reinforced with longitudinal CFRP bars and laterally with CFRP spiral stirrups is similar to that control specimen reinforced with steel bars and stirrups.
2. The load carrying capacity and ductility of tested CFRP-RC columns were not directly proportional to the difference in the vertical reinforcement ratio. Increasing the reinforcement ratio from 1.04 to 2.43% enhanced the peak load and ductility by 7 and 5 %, respectively.
3. Setting the CFRP compressive strength at 27.5% of the CFRP maximum tensile strength yielded a reasonable estimate of ultimate capacity compared to the experimental
4. Using Equation (1) provides conservative predictions of the nominal capacity of CFRP-RCcolumns, considering the compressive strength of CFRP bars as 27.5 percent of its tensile strength.

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REFERENCES

American Concrete Institute. 2011. ACI 318-11. Building Code Requirements for Structural Concrete and Commentary, Farmington Hills, MI.

American Concrete Institute. 2006. ACI 440.1R-06. Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bar, Farmington Hills, Mich.

American Concrete Institute. 2007. ACI 440R-07. Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures, Farmington Hills, Mich.

Benmokrane, B., El-Salakawy, E. F., El-Ragaby, A., and Lackey, T. 2006. Designing and Testing of Concrete Bridge Decks Reinforced with Glass FRP Bars. Journal Bridge Engineering, 11 (2): 217-229.

Canadian Standard Association. 2010. CSA/CAN S6-06 edition 2010, Canadian Highway Bridge Design Code, Mississauga, Ontario, Canada.

Canadian Standard Association. 2012. CSA/CAN S806-12. Design and Construction of Building Components with Fibre Reinforced Polymer, Mississauga, Ontario, Canada.

De Luca, A., Matta, F., and Nanni, A. 2010. Behavior of Full-Scale Glass Fiber-Reinforced Polymer Reinforced Concrete Columns under Axial Load. ACI Structural Journal, 107 (5): 589-596.

Kobayashi, K., and Fujisaki, T. 1995. Compressive Behavior of FRP Reinforcement in Non-Prestressed Concrete Members. Proceedings of the Second International RILEM Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures, Ghent, Belgium: 267-274.

Leung, H. Y., and Burgoyne, C. J. 2001. Compressive Behavior of Concrete Confined by Aramid Fibre Spirals. International Conference on Structural Engineering Mechanics and Computation, June, Cape Town, South Africa: 1357-1346.

Rizkalla, S., Hassan, T., and Hassan, N. 2003. Design Recommendations for the use of FRP for Reinforcement and Strengthening of Concrete Structures. Journal of Progress in Structural Engineering and Materials, 5 (1): 16-28.

Sharma, U. K., Bhargava, P., and Kaushik, S. K. 2005. Behavior of Reinforced Concrete Short Columns with Fiber Reinforced Polymers Bars. International Journal of Civil and Structural Engineering, 1 (3): 545-557.