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Strength and ductility behavior of circular concrete columns reinforced with GFRP bars and helices

Abstract

Long-term durability is a concern for Reinforced Concrete (RC) structures. Instances of premature deterioration of concrete structures due to corrosion of steel reinforcement are increasing. The use of Glass Fiber Reinforced Polymer (GFRP) bars as an alternative to traditional steel reinforcement in RC structures may resist premature deterioration. Although RC building and bridge columns in coastal areas are susceptible to significant deterioration, studies on concrete columns reinforced with GFRP bars and helices are limited. Also, design codes do not recommend the use of GFRP bars in compression members. This study investigates the use of GFRP bars and helices as longitudinal and lateral reinforcement, respectively, in concrete columns. Five circular normal strength RC columns with 205 mm in diameter and 800 mm in height were cast and tested under concentric loads. The influence of the longitudinal GFRP reinforcement and the spacing of the GFRP helices on the strength and ductility capacity of the columns were investigated. The experimental results showed that the contribution of the longitudinal GFRP bars was lower than the contribution of longitudinal steel bars to the load carrying capacity of the columns. Also, the load carrying capacity of the GFRP-RC columns was smaller than that of steel-RC columns. However, the ductility capacity of the columns was not affected by the use of GFRP helix instead of steel helix.

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STRENGTH AND DUCTILITY BEHAVIOR OF CIRCULAR CONCRETE COLUMNS REINFORCED WITH GFRP BARS AND HELICES

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Long-term durability is a concern for Reinforced Concrete (RC) structures. Instances of premature deterioration of concrete structures due to corrosion of steel reinforcement are increasing. The use of Glass Fiber Reinforced Polymer (GFRP) bars as an alternative to traditional steel reinforcement in RC structures may resist premature deterioration. Although RC building and bridge columns in coastal areas are susceptible to significant deterioration, studies on concrete columns reinforced with GFRP bars and helices are limited. Also, design codes do not recommend the use of GFRP bars in compression members. This study investigates the use of GFRP bars and helices as longitudinal and lateral reinforcement, respectively, in concrete columns. Five circular normal strength RC columns with 205 mm in diameter and 800 mm in height were cast and tested under concentric loads. The influence of the longitudinal GFRP reinforcement and the spacing of the GFRP helices on the strength and ductility capacity of the columns were investigated. The experimental results showed that the contribution of the longitudinal GFRP bars was lower than the contribution of longitudinal steel bars to the load carrying capacity of the columns. Also, the load carrying capacity of the GFRP-RC columns was smaller than that of steel-RC columns. However, the ductility capacity of the columns was not affected by the use of GFRP helix instead of steel helix.

Keywords: GFRP bar, GFRF helix, Reinforced concrete, Column

1 Introduction

Fibre Reinforced Polymer (FRP) bars are considered as a viable alternate of steel reinforcement in Reinforced Concrete (RC) members particularly in harsh corrosive coastal environments [1]. This is because steel bars may corrode in such environments and cause the deterioration of the RC columns [2]. However, the FRP bars are noncorrosive, nonmagnetic and nonconductive materials and they possess high tensile strength to weight ratio. In addition, the cost of repair and rehabilitation of deteriorated structures may be significant [3]. For instance, in the United States, the annual repair and replacement cost for bridge substructures (bridge piers and columns) is about two billion dollars and for marine piling is about one billion dollars [4].

Although FRP bars have favourable tensile strength, their compressive strength and modulus of elasticity are the major concerns in reinforcing concrete columns. The compressive strength of FRP bars depends on the type of fiber, the fiber-volume fraction, and the type of resin. Higher compressive strength

is expected for bars with higher tensile strength. The compressive strength of the GFRP bars is about 40 to 80% of their tensile strength. Also, the compressive modulus of elasticity of the GFRP bars is about 75 to 100% of their tensile modulus of elasticity [5-9]. Therefore, steel bars cannot simply be replaced with GFRP bars due to differences in the mechanical properties of the two materials [10]. Also, because of the lack in the experimental studies, the Japan Society of Civil Engineers [11] and CSA S806-12 [12] ignore the contribution of GFRP bars in the axial load carrying capacity of RC columns. Also, the ACI 440.1R-06 [13] does not recommend the use of GFRP bars in compression members. Therefore, in this study the behavior of columns reinforced with GFRP bars and helices and with only GFRP helices are investigated.

2 Experimental Program

2.1 Specimen Design and Preparation

In this study, five circular concrete columns were cast and tested under axial compressive loads. All columns were 205 mm in diameter and 800 mm in height. The first column (reference column) was reinforced longitudinally with six steel bars and transversally with steel helices. The second and third columns were reinforced longitudinally with six GFRP bars and transversally with GFRP helices at 60 mm and 30 mm centers, respectively. The fourth and fifth columns were reinforced only transversally with GFRP helices at 60 mm and 30 mm centers without any longitudinal reinforcement. Table 1 provides reinforcement details of the columns. The columns are identified by the longitudinal reinforcement material and its number and the transverse reinforcement material and its spacing. For example, Column G6-G60 is reinforced longitudinally with six GFRP bars and transversally with GFRP helix at 60 mm pitch. Column 00-G30 has no longitudinal reinforcement but transversally reinforced with GFRP helix at 30 mm pitch.

Table 1 Test Matrix

Columns	Longitudinal reinforcement				Transversal reinforcement			
	Material	Number of bars	Diameter of bars (mm)	Reinf. ratio %	Material	Diameter of bar (mm)	Pitch (mm)	Reinf. ratio %
S6-S60	Steel	6	12	2.06	Steel	10	60	3.27
G6-G60	GFRP	6	12.7	2.30	GFRP	9.5	60	2.97
G6-G30	GFRP	6	12.7	2.30	GFRP	9.5	30	5.94
00-G60	-	-	-	-	GFRP	9.5	60	2.97
00-G30	-	-	-	-	GFRP	9.5	30	5.94

2.2 Materials

All the columns were cast on the same day with ready mix concrete with an average 28-day compressive strength of 37 MPa. Two different diameter steel bars were used to reinforce the steel-RC columns. Deformed steel N12 (500 MPa nominal tensile strength) and plain mild steel R10 (250 MPa nominal tensile strength) bars were used as longitudinal and transversal reinforcement, respectively. The tensile strength and modulus of elasticity of the reinforcing steel bars were found according to AS 1391-2007 [14] and the results are reported in Table 2. Sand coated #4 (12.7 mm) GFRP bars were used for longitudinal reinforcement and sand coated #3 (9.5 mm) helices were used for transverse reinforcement. Five pieces of each diameter with a test length of 40 times the diameter of the bars plus the required gripping length at both ends as recommended by ASTM D7205-06 [15] were tested to determine the tensile strength and modulus of elasticity of the GFRP bars. The results are reported in Table 2. The GFRP

bars and helices had a sand-coated surface to enhance the bond strength between the bars and surrounding concrete. The GFRP bars and helices were provided by V-Rod Australia [16].

Table 2 Mechanical properties of steel and GFRP bars

Bar size	Diameter (mm)	Area (mm ²)	Tensile strength (MPa)	Elastic tensile modulus (GPa)	Tensile strain (mm/mm)
N12	12	113	600*	200	0.0030*
R10	10	78.5	400*	190	0.0021*
#4	12.7	126.7	1600 ⁺	66	0.0242 ⁺
#3	9.5	71.3	1700 ⁺	76	0.0224 ⁺

* Yield strength and strain.

⁺ Ultimate strength and strain.

2.3 Column Fabrication and Instrumentation

The formwork used for casting the columns was PVC pipe. The longitudinal steel and GFRP reinforcement were prepared and cut to 760 mm to have 20 mm clear cover at the top and bottom of the reinforcement cage. The transverse steel helix was prepared by forming a coil with 170 mm outer diameter and 60 mm pitch. The GFRP helices were manufactured in a coil shape with 170 mm outer diameter for this experiment by the manufacturer [16]. The clear covers to the face of the helices were 17.5 mm for all the columns. Then, the steel and GFRP reinforcement cages were assembled for the columns. The PVC moulds were fixed vertically in a wooden formwork and the cages were inserted into the PVC moulds. The concrete was placed into the formwork and vibrated using an electric vibrator to compact and to remove the air bubbles. Next, the columns were cured by covering with wet hessian and kept in the laboratory at an ambient temperature for 28 days before testing.

The axial deformation of the columns was recorded by two Linear Variable Differential Transducers (LVDT) attached vertically to the testing machine in the diagonally opposite direction. Before casting the concrete, two electrical strain gauges were attached at the mid-height to two opposite longitudinal bars in order to capture the axial strain at these bars. In addition, two electrical strain gauges were attached in the opposite directions at the mid-height of the helical reinforcement to measure the strain in the hoop direction.

2.4 Testing Procedure

All columns were tested at the laboratories of the School of Civil, Mining and Environmental Engineering at the University of Wollongong, Australia. The Denison 5000 kN compression testing machine was used to test the columns. The top and bottom of the columns were wrapped by a single layer of CFRP sheet to prevent the premature failure of the concrete during axial compression tests and the width of CFRP sheet was 75 mm. Also, both ends of the columns were capped by high strength plaster in order to distribute the load uniformly. The test started with a force-controlled pre-loading the columns at the rate of 2 kN/s to about 10% of their yield loads and then unloading the columns to 20 kN. Afterwards, the test resumed with the applied of displacement control loading (0.003 mm/s) until the resistance of the tested columns dropped to 30% of the yield load or until the axial displacement reached a value of 30 mm. The applied axial load and displacement of the columns were recorded through the internal load cell of the Denison machine. Also, the experimental test results were recorded through the LVDTs, the strain gauges and a sensor that is located on the bottom of the testing machine to capture the applied axial load and displacement of the columns. The LVDTs, strain gauges and the sensor were connected to a data-logger to record the reading every 2 seconds.

3 Experimental Results and Discussion

3.1 Failure Modes

Figure 1 shows the failure modes of the tested columns. It can be observed that the steel columns failed by buckling of the longitudinal bars and followed by the crushing of the concrete core. However, GFRP-RC columns with longitudinal bars failed by rupture of the GFRP helices that caused buckling and crushing of the longitudinal bars and followed by crushing of the concrete core. Also, the GFRP-RC columns without longitudinal bars failed rupture of the GFRP helices and followed by crushing of the concrete core.

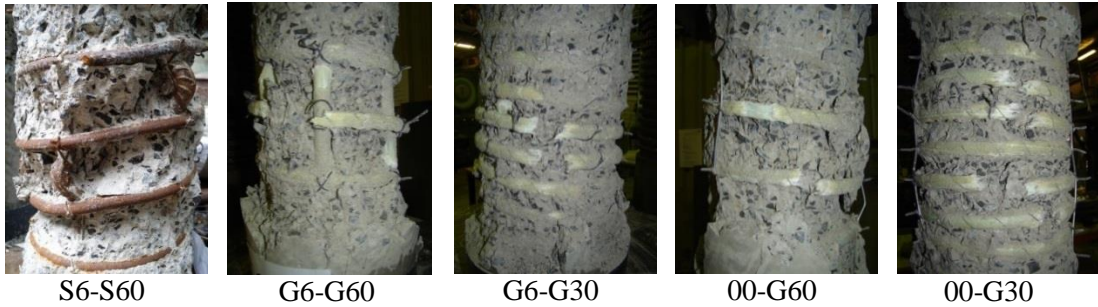


Figure 1. Failure of the columns

3.2 Axial Load and Axial Deformation Behavior

Generally, all the columns behaved similarly in the ascending part till the yield point and the ascending part was mainly dominated by the concrete stiffness. There were two main points in the load-deformation relationship, which were yield and ultimate point. The yield point shows the maximum load carried by the reinforced gross concrete section (concrete cover and core). At this point, the concrete covers have been cracked and after this point cover spalling started. The ultimate point expresses the maximum load carried by the confined concrete core. In some cases, the ultimate load was greater than the yield load depending on the confinement conditions and type and ratio of the longitudinal reinforcement. Figure 2 shows the load-deformation behavior of the tested columns.

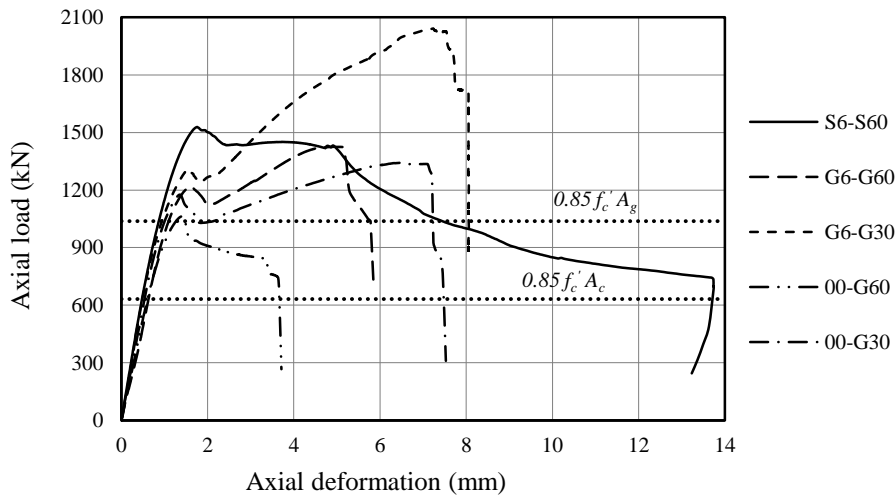


Figure 2. Axial load-axial deformation behavior of the columns

3.3 Summary of Test Results

Table 3 summarizes the test results of the tested columns. It can be observed that Column G6-G60 obtained about 20% lower yield load than the reference column because of the smaller modulus of elasticity of the GFRP bars. Reducing the spacing of the GFRP helices led to increase of the yield load of the columns by 7.3 and 10% for the columns with and without longitudinal reinforcement, respectively. Columns 00-G60 and 00-G30 gained about 13 and 10.6% lower yield load than Columns G6-G60 and G6-G30, respectively. It can also be observed that Column G6-G60 obtained about similar ductility capacity with the reference column. The ductility capacity was defined as the ratio of ultimate to yield axial deformation [17]. Reducing the spacing of the GFRP helices could also increase the ductility capacity by about 1.5 and 2.2 times for the columns with and without longitudinal bars, respectively. Also, longitudinal GFRP bars could improve the ductility capacity of the columns in comparison to the columns without longitudinal bars because of reducing the unconfined concrete core area.

The nominal load carrying capacity (P_o) of the steel and GFRP-RC columns was calculated by Equation 1 and 2, respectively. It is assumed that the strain in the GFRP bars is approximately equal to the concrete ultimate strain, which is equal to 0.003 as defined by ACI 318-11 [18]. The ratio of experimental to calculated load carrying capacity of the columns is reported in Table 3. It can be seen that there is a reasonable and close agreement between the experimental and calculated results.

$$P_o = 0.85 f'_c (A_g - A_s) + f_y A_s \quad (1)$$

$$P_o = 0.85 f'_c (A_g - A_f) + 0.003 E_f A_f \quad (2)$$

where, P_o is the nominal load carrying capacity of the columns, f'_c is the cylinder concrete compressive strength, A_g is the gross concrete cross-section area, A_s is the area of the steel bars, f_y is the yield strength of the steel bars, A_f is the area of the GFRP bars, and E_f is the modulus of elasticity of the GFRP bars.

Table 3 Experimental results

Columns	Yield point		Ultimate point		P_o (kN)	P_y/P_o	Ductility (Δ_u / Δ_y)
	Load (P_y) (kN)	Deformation (Δ_y) (mm)	Load (P_u) (kN)	Deformation (Δ_u) (mm)			
S6-S60	1528	1.757	1451	5.879*	1424	1.07	3.3
G6-G60	1220	1.611	1425	5.146	1165	1.05	3.2
G6-G30	1309	1.563	2041	7.549	1165	1.12	4.8
00-G60	1063	1.404	940	3.110*	1038	1.02	2.2
00-G30	1170	1.353	1343	6.525	1038	1.13	4.8

* Taken when the load descended to 80% of P_y .

4 Conclusions

Based on the experimental investigations of this study, the following conclusions can be drawn:

1. The GFRP-RC columns obtained about 20% lower yield load and same ductility capacity in comparison with the conventional steel-RC columns.
2. Reducing the spacing of the GFRP helices can improve the performance of the columns in terms of the load carrying and ductility capacity.
3. Longitudinal GFRP bars can improve the load carrying and ductility capacity of the columns.
4. Ignoring the contribution of the GFRP bars in compression is not recommended because it results to a large discrepancy between the experimental and calculated results.

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