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Keywords

tube, filled, concrete, circular, reinforced, bar, frp, unreinforced, behavior, columns, flexural, axial

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Axial and Flexural Behavior of Unreinforced and FRP Bar Reinforced Circular Concrete Filled FRP Tube Columns

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Keywords: FRP tube, FRP bar, CFFT, Axial load, Flexural load, Ductility, $P - M$

Highlights

- 16 CFFT and 4 steel RC specimens are tested under concentric and eccentric axial loads and flexural load.
- Failure modes and load deformation behavior of tested specimens are reported.
- Effect of eccentricity on the axial load and ductility of CFFT specimens is investigated.
- Effect of four point loads on the flexural load and ductility of CFFT is investigated.
- Experimental axial load bending moment interaction curves are presented.

1. Introduction

The strength and ductility of steel bar Reinforced Concrete (RC) members in harsh and corrosive environments may decrease due to the corrosion of steel reinforcement. Fiber Reinforced Polymer (FRP) composites are considered as practicable alternative of steel reinforcement due to higher ultimate tensile strength to weight ratio, higher corrosion and chemical resistance, and higher electromagnetic neutrality of FRP composites [1]. Although the initial construction cost of FRP reinforcement (tubes and bars) is higher than steel reinforcement, structural members reinforced with FRP tubes and bars require less maintenance due to high corrosion resistance of FRP. Hence, the overall life cycle cost is expected to be less for structural members reinforced with FRP tubes and bars under severe environmental conditions [2].

The Concrete Filled FRP Tube (CFFT) technique for new column construction was investigated in the literature as a practicable alternative of steel RC column. In CFFT columns, FRP tube acts as longitudinal and transverse reinforcement (depending on the orientation of fibers), serves as a structural formwork and a barrier to corrosion accelerating agents. FRP tube also increases the shear strength of concrete and increases the strength and ductility of columns [3, 4]. A number of experimental studies were conducted to investigate the axial compressive behavior of CFFT over the last two decades. It is now well understood that CFFT enhances the axial compressive strength and ductility of confined concrete due to the lateral confinement provided by the surrounding FRP tube [3, 5-12].

The flexural behavior of CFFT was also investigated as FRP tube confines the concrete in the compression side and increases the structural stiffness in both axial and circumferential directions. In addition, failure of CFFT was ductile with significant warning before the rupture of FRP tube [13-15]. The flexural behavior of CFFT depends on the

stiffness and diameter to thickness ratio of FRP tube [16]. The CFFT exhibits higher flexural strength than steel RC beam. Moreover, fibers in the FRP tube oriented perpendicular to flexural load serve as longitudinal reinforcement and are effective in resisting load and hence increases the flexural strength [17].

In recent years, the use of FRP bar was investigated as a viable alternative of steel bar in RC members in axial compression. Numerous experimental studies were conducted to investigate the axial load-deformation behavior of FRP bar reinforced concrete columns for the effective application of FRP reinforcement in the construction industry. FRP reinforcement exhibits significantly higher corrosion resistance than steel reinforcement in RC columns. However, the axial load carrying capacity of FRP reinforced concrete columns was reported to be 5 – 13% smaller than the axial load capacity of steel reinforced concrete columns [1, 18-23]. Moreover, CSA-S806-12 [24] neglects the contribution of FRP bars in the compressive zone in both beams and columns, while ACI 440.1R-15 [25] does not include any recommendation for the use of longitudinal FRP bars in columns.

A number of studies reported the flexural behavior of FRP (GFRP) bar RC beams (e.g., [26-28]). The studies reported that sand coated GFPR bar RC beams exhibited higher ultimate flexural loads than steel RC beams. However, wider and deeper cracks in GFRP RC beams were observed than in steel RC beams. This was attributable to the lower modulus of elasticity of GFRP bar compared to steel bar.

A limited number of experimental studies were conducted on the behavior of bar reinforced CFFT under axial and flexure loads. Mohamed and Masmoudi [29] and Park *et al.* [8] tested steel bar reinforced GFRP-CFFT under concentric axial load. Axial load capacity of GFRP-CFFT was reported to be significantly increased with the addition of steel bars. Cole and Fam [30] and Mohamed and Masmoudi [31] tested GFRP bar reinforced GFRP-

CFFT in flexure. The GFRP-CFFT exhibited lower midspan deflections, lower ductility and higher flexural loads than steel RC beams. The flexural strength of FRP bar reinforced CFFT was reported to be influenced by the modulus of elasticity and ultimate tensile strength of bar.

The majority of the research studies conducted on unreinforced and bar reinforced CFFT was focused on the behavior of columns tested under concentric axial load. However, most of the columns in actual construction are subjected to combined axial and bending moments due to load eccentricities, construction errors and lateral loads [32-34]. The experimental research studies conducted on CFFT under eccentric axial load are very limited. To the knowledge of the authors, only Lillistone and Jolly [35] tested GFRP bar reinforced CFFT under axial load at a fixed eccentricity (5% of diameter of tube). GFRP bar reinforced CFFT columns exhibited 51% reduction in axial load carrying capacity under the eccentric axial load.

To bridge the gap in understanding the behavior of unreinforced and FRP bar reinforced CFFT columns under eccentric axial loads, experimental studies on FRP bar reinforced CFFT columns under different eccentric axial loads need to be carried out. A comprehensive research program including experimental and analytical investigations on the use of FRP reinforcement in structural members is on-going at the University of Wollongong, Australia [23, 36]. This paper presents results of an experimental investigation on the axial and flexural behavior of concrete filled Carbon FRP (CFRP) tube columns with and without CFRP bar and concrete filled Glass FRP (GFRP) tube columns with and without GFRP bar. Analytical investigation using non-linear finite element modelling of CFFT columns is considered beyond the scope of the paper.

2. Experimental Program

2.1. Description of the Experimental Program

Four steel Reinforced Concrete (RC) specimens, eight unreinforced Concrete Filled FRP Tube (CFFT) specimens and eight FRP bar reinforced CFFT specimens were cast and tested at the High Bay Laboratories, School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia. The specimens were divided in five groups with four specimens in each group. The first group, REF consisted of steel RC specimens. The second group, CT consisted of CFRP CFFT specimens without FRP bars. The third group, GT consisted of GFRP CFFT specimens without FRP bars. The fourth group, CTCR consisted of CFRP bar reinforced CFRP CFFT specimens. The fifth group, GTGR consisted of GFRP bar reinforced GFRP CFFT specimens. From each group, the first specimen was tested as a column under concentric axial load. The second specimen was tested as a column under 25 mm eccentric axial load. The third specimen was tested as a column under 50 mm eccentric axial load. The fourth specimen was tested as a beam under four point loading. Table 1 presents details of the specimens. The dimensions of the specimens were selected to be suitable to the capacity of the testing facilities in the laboratory. The specimens were labelled (First Column of Table 1) in two parts. The first part represents the type of FRP tube and the type of FRP bar. The second part represents load conditions (concentric and eccentric axial loads and four point loads). For example, Specimen CTCR-50 represents CFRP bar reinforced CFRP CFFT specimen tested under 50 mm eccentric axial load.

The REF specimens were reinforced longitudinally with six N12 (12 mm diameter deformed bars with 500 MPa nominal tensile strength) steel bars (reinforcement ratio = 2.2%) and helically with R10 (10 mm diameter plain bars with 250 MPa nominal tensile strength) steel helix of 150 mm inner diameter with a pitch of 60 mm. In REF specimens, a

concrete cover of 15 mm at the top and bottom ends and a concrete clear side cover of 20 mm were provided.

FRP tube properties such as thickness, ultimate tensile strength and orientation of fibers in FRP tube were selected to ensure that all tested CFFT specimens have strain hardening behavior so that FRP tubes were effective in confining the concrete. Also, the confining capacity of both types of FRP tubes is similar. CFRP and GFRP tubes of 0.5 mm and 1.5 mm thickness, respectively, were selected based on the review of literature. The modulus of elasticity of CFRP fibers was three times larger than the modulus of elasticity of GFRP fibers in the circumferential direction. FRP tubes were designed with two layers of fibers. The outer layer of fibers was orientated along the skew direction ($\pm 60^\circ$ with the longitudinal direction) and inner layer of fibers orientated along the circumferential direction (90° with the longitudinal direction). In CFRP tubes, 34% of the fibers were orientated along the circumferential direction and 66% of the fibers along skew direction. In GFRP tubes, 38% of the fibers were orientated along the circumferential direction and 62% of the fibers along the skew direction. CFRP tubes consisted of 63% fibers and 37% resin by volume whereas GFRP tubes consisted of 60% fibers and 40% resin by volume [37]. The mechanical properties of FRP tubes are provided in Table 2.

The CTCR specimens were longitudinally reinforced with six 15 mm nominal diameter CFRP bars (reinforcement ratio = 3.3%). The GTGR specimens were longitudinally reinforced with six 15.9 mm nominal diameter GFRP bars (reinforcement ratio = 3.7%). CFRP and GFRP bars were pultruded bars with all the fibers orientated along the longitudinal direction. The difference in longitudinal reinforcement ratios of Specimens REF, CTCR and GTGR was to incorporate the differences in modulus of elasticity and surface conditions of bars. CFRP bars consisted of 55 – 60% fibers and 40 – 45% resin by volume [37]. GFRP bars

consisted of 73% fibers and 27% resin by volume [38]. GFRP bars were sand coated whereas CFRP bars were smooth without any coating. In CTCR and GTGR specimens, a concrete cover of 15 mm at the top and bottom ends was provided.

2.2. Specimen Preparation

PVC pipes and FRP tubes were used as formworks for the test specimens. For REF specimens, PVC pipes of 205 mm inner diameter and 800 mm height were cleaned and placed in a wooden frame. Sixteen FRP tubes of 203 mm inner diameter and 812 mm height were cleaned and placed in a separate wooden frame. The wooden frames were made of plywood and consisted of circular holes of 207 mm inner diameter. In REF specimens, steel reinforcement cage was placed in PVC formworks on top of plastic chairs to provide the required concrete cover at the ends of the specimen. In CTCR and GTGR specimens, FRP bars were glued on the inner side of the tube along the circumference (60 degrees apart).

The specimens were cast with a batch of ready mix concrete obtained from a local supplier. The measured slump of the concrete batch was 120 mm. The maximum aggregate size of the ready mix concrete was 10 mm. The concrete was poured into the formworks in three stages. In every stage concrete was compacted using an electrical vibrator to remove air pockets within the concrete. After casting, all the specimens were cured by covering them with wet hessian rugs and plastic sheets to retain moisture for 28 days. The REF specimens were removed from the PVC pipes after 7 days. After curing, the top and bottom ends of the specimens to be tested under eccentric axial loads were vertically wrapped with 0.5 mm thick CFRP sheet up to 100 mm. Afterwards, the top and bottom ends of all the specimens were wrapped with two layers of 0.5 mm thick and 35 mm wide CFRP sheet in the circumferential direction. The FRP wrapping at the specimen ends was done to prevent premature failure during testing.

2.3. Preliminary Material Testing

Preliminary material testing included testing concrete cylinders, steel bars and FRP bars. The concrete cylinders of 100 mm diameter and 200 mm height were cast as recommended in AS1012.9-1999 [39] and cured in a water tank. The concrete cylinders were tested at 7 and 28 days. The average compressive cylinder strengths at 7 and 28 days were 30.9 MPa and 37 MPa, respectively. Five specimens each of 400 mm in length from each of N12 and R10 steel bars were tested in tension using the 500 kN Instron testing machine according to AS1391-2007 [40]. The average tensile strengths of N12 and R10 bars were 600 MPa and 400 MPa, respectively. The cross-sectional area of CFRP and GFRP bars were measured by immersion test as recommended in ISO 104061-1 [41]. The average cross-sectional area and diameter of CFRP bar were 177 mm² and 15 mm, respectively, which were identical to nominal cross-sectional area and diameter provided by the manufacturer [37]. The average cross-sectional area and diameter of GFRP bar were 292 mm² and 19.3 mm, respectively. The nominal cross-sectional area and diameter of GFRP bar provided by the manufacturer were 198 mm² and 15.9 mm, respectively [38]. The difference in the nominal and measured cross-sectional area and diameter of GFRP bar might be due to sand coat. Although, sand coat improves the bond between bar and concrete, its effect on the strength of bar is negligible. Hence the nominal cross-sectional area and diameter of CFRP and GFRP bars were used in calculating the ultimate strength and modulus of elasticity. Three specimens of 1555 mm in length from each of the 15 mm diameter CFRP bars and 15.9 mm diameter GFRP bars were tested in tension using the 500 kN Instron testing machine according to ASTM D7205/D7205M-11 [42]. The average tensile strengths of CFRP and GFRP bars were 1157 MPa and 1395 MPa, respectively. The average tensile modulus of elasticity of CFRP and GFRP bars was 89.4 GPa and 56 GPa, respectively. Five specimens from each of 15 mm diameter CFRP bars (60 mm in length) and 15.9 mm diameter GFRP

bars (80 mm in length) were tested in compression using the 100 kN Instron testing machine according to ASTM D695-10 [43]. The average compressive strength of CFRP and GFRP bars was 596 MPa and 846 MPa, respectively. The average compressive modulus of elasticity of CFRP and GFRP bars was 49 GPa and 42 GPa, respectively.

3. Test Procedures and Instrumentation

3.1. Specimens under concentric and eccentric axial loads

The top end of the column specimens to be tested under concentric axial load were capped with high strength plaster within a circular loading head of 235 mm inner diameter and 100 mm height made from high strength steel (Fig. 1a). The loading head was centered over the top end of the specimens to remove minor eccentricities. The top and bottom ends of the specimens to be tested under eccentric axial loads were capped with high strength plaster within the circle inscribed in square loading heads. The loading heads consisted of a 235 mm square cross section adaptor plate of 50 mm thickness (Fig. 1b) and ball joint plate of 50 mm thickness (Fig. 1c). The adaptor plate has two sockets along the length of the plate for the application of 25 mm and 50 mm eccentric axial loads. The loading heads were first centered over the capped top and bottom ends of the specimens and then the ball joint plates were firmly placed in the required sockets. To measure the axial deformation of the test specimens, two vertical LVDTs were fixed along the two opposite corners of the 5000 kN Denison Universal Testing Machine (UTM) in the test region. For the specimens tested under eccentric axial load, a laser triangulation was placed at the mid-height of the specimens to measure the lateral deformations (δ) of the specimens. The specimens were tested in the UTM as shown in Fig. 2(a) and 2(b). The specimens were preloaded to 100 kN under a force controlled load application at the rate of 50 kN/min to adjust minor misalignments between the specimen and the UTM loading heads then unloaded to 20 kN. Afterwards, the testing

was resumed under a displacement controlled load application at the rate of 0.3 mm/min until the rupture of FRP tube or the resistance of the specimens dropped to 25% of the peak load.

3.2. Testing of specimens under four point loads

The beam specimens were tested under four point loading using two platen rigs (top and bottom) placed diagonally in the UTM (Fig. 1d). To test the specimens, the bottom platen rig of clear span of 705 mm was placed diagonally across the centerline on the bottom loading head of the UTM. A laser triangulation was attached to the bottom platen rig to measure midspan deflections. Specimens were centered over the bottom platen rig with 53.5 mm overhang at the ends. The clear span of the bottom platen rig was marked on the specimen and divided in three equal segments of 235 mm lengths (Fig. 2c). The top platen rig was centered over the top of the middle segment of the specimen. To measure midspan deflection, two vertical LVDTs were fixed on the two opposite corners of the UTM in the test region. The specimens were preloaded to 100 kN under a force controlled load application at the rate of 50 kN/min then unloaded to 20 kN. Afterwards, the test was resumed under a displacement controlled load application at the rate of 0.3 mm/min until the resistance of the specimens dropped to 25% of the peak load or midspan deflection reached to 45 mm.

4. Experimental Results and Discussions

The ductility (μ) of the tested specimens was calculated using the energy method in which ductility is considered as the ratio of areas under the axial load-axial deformation curve [44]. The ductility of the tested specimens was calculated according to Equation 1.

$$\mu = \frac{A_2}{A_1} \quad (1)$$

where A_1 and A_2 = area under load deformation curve up to δ_y and δ_u , respectively [34, 45 - 47] [45-47]. To compute δ_y , a best fit regression line to the initial linear elastic part of the load deformation curve and a horizontal line corresponding to the peak load of the specimen were drawn. The deformation corresponding to intersection of the extrapolated best fit regression line and the horizontal line represent the yield deformation δ_y . The deformation corresponding to 85% of the peak load in the descending part of the load-deformation curve represents δ_u (Fig. 3).

All specimens were tested to the rupture of CFFT. The failure of specimens tested under concentric axial load was marked by rupturing of fibers at the mid-height of the specimen and crushing of concrete. Unreinforced CFFT specimens tested under eccentric axial load were split in two halves at the mid-height of the specimen with crushing of concrete. FRP bar reinforced CFFT specimens tested under eccentric axial load failed by rupturing of fibers close to the mid-height of the specimen with outward buckling of FRP bars and crushing of concrete. Unreinforced CFFT specimens tested under four point loads failed by rupturing of fibers and splitting of concrete in two halves in the middle third segment whereas FRP bar reinforced CFFT specimens failed by rupturing of fibers with bending of bars and crushing of concrete.

4.1. Concrete filled FRP tube specimens under concentric axial load

Specimens CT-0 and GT-0 failed in a brittle manner with loud snapping sounds from rupturing of fibers followed by crushing of concrete. Specimen CTCR-0 failed with very loud snapping sounds from rupturing of fibers along the entire height of the specimen and crushing of concrete. In Specimen CTCR-0, outward buckling of CFRP bars was observed which indicated that CFRP bars were effective in carrying axial load. Specimen GTGR-0 failed in

the top one-third segment of the specimen with rupturing of the top end of the GFRP bars. At failure, the peak axial load in Specimen GTGR-0 did not drop to zero unlike Specimen CTCR-0. The axial load in Specimen GTGR-0 dropped to 25% of the peak axial load without further reduction in axial load with increasing axial deformation until the test was stopped. The failure of Specimen REF-0 was characterized by spalling of the concrete cover, crushing of concrete and buckling of steel bars without rupturing of steel helix (Fig. 4).

The axial load-deformation behaviors of the tested column specimens under concentric axial load are presented in Fig. 5. Specimens CT-0, GT-0, CTCR-0 and GTGR-0 carried 15.8%, 23.2%, 43.7% and 83.9% higher peak axial loads, respectively, than the axial load carried by Specimen REF-0. Specimens CT-0, GT-0, CTCR-0 and GTGR-0 showed 73.1%, 117.9%, 52.2% and 88.1% higher ductility, respectively, than Specimen REF-0. The higher peak axial loads and ductility in Specimens CT-0 and GT-0 than the peak axial load and ductility in Specimen REF-0 indicate the greater effectiveness of FRP tube in confining the concrete than steel helix. The effect of FRP tube confinement was more pronounced in increasing the ductility than peak axial loads. This is because FRP tubes have two-thirds of the fibers orientated along the circumferential direction which were effective in confining concrete. Specimens CTCR-0 carried 24.1% higher peak axial load than Specimen CT-0. Similarly, Specimen GTGR-0 carried 49.3% higher peak axial load than Specimen GT-0. This showed that FRP bars were also effective in resisting axial compression along with concrete (Table 3).

4.2. Concrete filled FRP tube specimens under eccentric axial load

Specimens CT-25 and GT-25 failed by splitting in two halves at the mid-height accompanied by the rupture of fibers and crushing of concrete. The failure in Specimens CTCR-25 and GTGR-25 was characterized by rupture of fibers, outward buckling of FRP

bars and crushing of concrete. Unlike Specimens CT-25 and GT-25, Specimens CTCR-25 and GTGR-25 did not split into two halves at the mid-height of the specimens because of the presence of FRP bars. In Specimen CTCR-25, most of the fibers ruptured near the mid-height whereas in Specimen GTGR-25, most of the fibers ruptured near the top one-third segment of the specimen. The failure of Specimen REF-25 was due to the crushing of concrete without buckling of steel bars and fracture of steel helix (Fig. 6).

The axial load-axial deformation behaviors of tested column specimens under 25 mm eccentric axial load are shown in Fig. 7. Specimens CT-25 and GT-25 carried 15.0% and 3.2% smaller peak axial loads, respectively, than Specimen REF-25. This might be due to the reduction in the confinement effectiveness of FRP tubes under eccentric axial load as tubes were subjected to both axial compression and bending moment. Also, Specimens CT-25 and GT-25 were not reinforced with FRP bars. Specimens CTCR-25 and GTGR-25 carried 33.1% and 67.5% higher peak axial loads, respectively, than Specimen REF-25 which shows the effectiveness of FRP bars in resisting axial loads. Specimen GTGR-25 resisted higher peak axial loads than Specimen CTCR-25 as GFRP bars have higher ultimate tensile strength than the CFRP bars. Also, GFRP bar has larger nominal diameter than CFRP bar. Specimens CT-25, GT-25, CTCR-25 and GTGR-25 showed 51.3%, 58.1%, 54.1% and 73.3% higher ductility, respectively, than Specimen REF-25 (Table 3).

The failure of Specimens CT-50 and GT-50 was characterized by splitting of the specimens in two halves at the mid-height with crushing of concrete and rupture of fibers. Specimen CTCR-50 failed due to rupture of fibers at the mid-height with significant lateral deformation but without splitting of the specimen. Specimen GTGR-50 failed due to rupture of fibers mainly in the top one-third segment of the specimen along with crushing of concrete but without splitting of specimen in two halves. Specimen REF-50 failed due to crushing of

concrete primarily in the top half of the specimens without buckling of steel bars or rupturing of steel helix (Fig. 8).

The axial load-deformation behaviors of the tested column specimens under 50 mm eccentric axial load are presented in Fig. 9. Specimens CT-50 and GT-50 carried 17.7% and 11.2% smaller peak axial loads, respectively, than Specimen REF-50. Specimen CTCR-50 and GTGR-50 carried 12.1% and 53.2% larger peak axial load than Specimen REF-50. Specimen CT-50 exhibited 1.9% smaller ductility than Specimen REF-50 whereas Specimen GT-50 exhibited 15.4% larger ductility than Specimen REF-50. This shows that the confinement effectiveness of FRP tube was reduced under 50 mm eccentric axial load. However, Specimens CTCR-50 and GTGR-50 exhibited 72.7% and 107.8% larger ductility, respectively, than Specimen REF-50 (Table 3).

4.3. Effect of Eccentricity

The effect of eccentricity on peak axial loads and ductility of the 15 specimens tested as columns is presented in Fig. 10. Increase in eccentricity resulted in larger reduction in peak axial loads in CFFT specimens (CT, GT, CT-CR and GT-GR) than in steel RC specimens (REF). This may be because the modulus of elasticity of FRPs is smaller than the modulus of elasticity of steel. Moreover, FRPs have smaller compressive strength than tensile strength. In general, increased eccentricity resulted in larger reduction in peak axial load in unreinforced CFFT (CT and GT) specimens than in FRP bar reinforced CFFT (CTCR and GTGR) specimens. Increase in eccentricity resulted in decrease in ductility of tested specimens. The CT and GT specimens exhibited significantly larger reduction in ductility than CTCR and GTGR specimens. The smaller reduction in ductility of CTCR and GTGR specimens is due to the addition of FRP bars which were effective in carrying axial compressive loads. The reduction in ductility in REF specimens was smaller than the reduction in ductility in CT and

GT specimens, although FRP tubes have two-thirds of the fibers orientated along the circumferential direction but FRPs are significantly weaker in compression than in tension. Increase in eccentricity resulted in larger reduction in ductility in GFRP-CFFT specimens than in CFRP-CFFT specimens as modulus of elasticity of GFRP tube was one-third of modulus of elasticity of CFRP tube.

4.4. Concrete filled FRP tube specimens under four point loads

Specimen CT-B failed due to rupture of inner circumferential fibers and outer skew fibers and also split in two halves in the middle segment of the specimen. The failure in Specimen GT-B was due to the rupture of inner circumferential fibers. However, the outer skew fibers were stretched but did not rupture. The specimen was split in two halves in the middle-third segment. Moreover, no slippage between FRP tube and concrete was observed. The observed failure in Specimens CTCR-B and GTGR-B was characterized by rupturing of fibers and bending of bars without splitting of the specimen. Specimens CTCR-B and GTGR-B failed due to rupture of fibers on the bottom (tension) and top (compression) sides with bending of bars and crushing of concrete. Slippage of CFRP bars in Specimen CTCR-B was observed whereas slippage of GFRP bars in Specimen GTGR-B was very small. CFRP bars were slipped as CFRP bars were smooth uncoated bars. Specimen REF-B failed with wide and long flexural cracks in the tension region followed by crushing of concrete in the compression region within the middle segment of the tested specimen (Fig. 11).

Flexural load versus midspan deflections of beam specimens tested under four point loads is shown in Fig. 12. Specimens CT-B and GT-B carried 73.2% and 66.6% smaller peak flexural loads, respectively, and 28.4% and 27.4% smaller midspan deflections at peak flexural load, respectively, than Specimen REF-B. This may be due to the fact that most of the fibers in both CFRP and GFRP tubes were orientated along the circumferential direction

and were not very effective in resisting flexural load under bending. Specimen CTCR-B carried 35.7% smaller flexural load and 24.4% smaller midspan deflection at peak flexural load than Specimen REF-B, as smooth CFRP bars slipped under the applied four point loads due to smaller friction between the bars and the concrete. Specimen GTGR-B carried 29.3% larger flexural load and 22.0% smaller midspan deflection at peak flexural load than Specimen REF-B, although GFRP bars were sand coated and exhibited higher frictional resistance between the bars and the concrete but small slippage was still observed. The measured results of Specimen GTGR-B obtained in this study were close to the test results reported by Cole and Fam [30] and Masmoudi and Mohamed [31]. Specimens CTCR-B and GTGR-B exhibited larger midspan deflections at ultimate flexural load than Specimen REF-B. Specimens CT-B, GT-B, CTCR-B and GTGR-B exhibited 63.7%, 50.4%, 12.0% and 1.0%, respectively, smaller ductility than REF-B (Table 4).

5. Experimental Axial Load Bending Moment Interaction Diagrams

The experimental axial load-bending moment interaction diagrams for CT, GT, CTCR, GTGR and REF specimens were drawn using pure axial load ($e = 0$ mm), combined axial and bending ($e = 25$ mm and $e = 50$ mm) and bending (four point load) to investigate the axial load bending moment capacity of the tested specimens. The bending moment capacity (M) of the column specimens was calculated considering both the primary and secondary moments. The primary moment (M_I) was due to applied load eccentricity (e) while the secondary moment (M_{II}) was due to lateral deformations (δ) corresponding to the peak applied load. The bending moment capacity (M) of the specimens tested as columns was calculated using Equation (1):

$$M = M_I + M_{II} = Pe + P\delta \quad (1)$$

where P is the applied axial load. The bending moment capacity (M) of specimens tested as beams under four point loads was calculated using Equation (2):

$$M = \frac{PL}{6} \quad (2)$$

where P is the applied flexural load under four point loads arrangement and L is the span length of test specimen. In this study the span length was 705 mm (Table 5).

In constructing the axial load-bending moment interaction ($P - M$) curves for CT, GT, CTCR and GTGR specimens, peak loads and lateral deformations at peak loads were selected under different load conditions. This approach of constructing axial load-bending moment interaction diagram for FRPs is similar to the axial load-bending moment interaction diagram approach adopted by Yazici and Hadi [48], Hadi and Zhao [49], Hadi and Widiarsa [45] and Hadi *et al.* [46] for different types of FRP confinements for RC members. The peak load corresponds to the maximum value of load resisted by the specimen before the rupture of FRP tube. The peak load in REF specimens was assumed to be the load at the first peak of axial load-axial deformation curve (cover spalling) of steel RC specimens.

The plotted axial load-bending moment interaction ($P - M$) curves showed that FRP bar reinforced CFFT specimens (CTCR and GTGR) exhibited higher peak loads and bending moments than unreinforced CFFT specimens (CT and GT) (Fig. 13) which could be attributed to the increase in load carrying capacity of specimens due to the addition of FRP bars. The GT and GTGR specimens exhibited higher peak loads and bending moments than the CT and CTCR specimens. The peak loads and bending moments of GTGR specimens were higher than those of CTCR specimens. This was due to the fact that GFRP bars have higher compressive and tensile strengths than CFRP bars. Moreover, sand coated GFRP bars have higher frictional resistance and better compatibility with concrete than the frictional resistance and compatibility between smooth CFRP bars. The axial load-bending moment

interaction curve for REF specimens was similar to the axial load-bending moment interaction curves for CT and GT specimens. This shows that unreinforced CFFTs were both effective in resisting load and confining the concrete under different load conditions. The axial load-bending moment interaction curves for CTCR and GTGR specimens were significantly larger than the axial load-bending moment interaction curve for REF specimens exhibiting the effectiveness of FRP bars in resisting loads in addition to CFFT.

6. Conclusions

In this experimental study, 16 concrete filled FRP tube (CFFT) specimens (CT, GT, CTCR and GTGR) were tested to investigate the influence of FRP tube confinement and FRP bars on the load-deformation behavior under different load conditions. Four conventional steel Reinforced Concrete (RC) specimens (REF) were also tested for comparison purposes. Based on the experimental results of this study, the following conclusions are drawn:

1. Unreinforced CFFT (CT and GT) specimens resisted higher axial loads and axial deformation at peak loads than REF specimens under concentric axial loads. CT and GT specimens resisted smaller axial loads than REF specimens under axial eccentric loads. The average axial and lateral deformations at peak loads in CT and GT specimens were higher than those in REF specimens under eccentric axial loads. Unreinforced CFFT (CT-B and GT-B) specimens resisted smaller flexural loads and midspan deflections than Specimen REF-B.
2. The CFFT specimens exhibited larger decrease in peak axial load than REF specimens with an increase in the applied load eccentricity from 0 mm to 50 mm. The CFFT specimens exhibited higher average ductility than REF specimens under applied load eccentricity of 0 mm, 25 mm and 50 mm. Reduction in ductility in REF specimens was smaller than the reduction in ductility of CT and GT specimens,

however, reduction in ductility of REF specimens was larger than the reduction in ductility in CTCR and GTGR specimens as the applied load eccentricity was increased from 0 to 50 mm.

3. FRP bar reinforced CFFT (CTCR and GTGR) specimens exhibited higher average axial loads and higher axial and lateral deformations at peak loads than REF specimens tested under concentric and eccentric axial loads.

4. FRP bar reinforced CFFT (CTCR-B and GTGR-B) specimens exhibited higher ultimate midspan deflections than Specimen REF-B. Specimen GTGR-B resisted higher flexural load than Specimen REF-B. Specimen CTCR-B resisted smaller flexural load than Specimen REF-B due to slippage of CFRP bars.

5. The axial load-bending moment capacity of GTGR and CTCR specimens were larger than the axial load-bending moment capacity of CT, GT, and REF specimens. The axial load-bending moment capacity of GT and CT specimens was similar to the axial load-bending moment capacity of REF specimens.

The use of FRP tube confined concrete can be recommended in combination with FRP bars to enhance the peak axial load and ductility of columns under eccentric axial compression as an alternative of steel RC columns in areas where corrosion of steel bar is a major concern.

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Table 1

Test Matrix

Test specimen	Internal diameter (mm)	Height (mm)	Internal longitudinal reinforcement	Lateral confinement	Test eccentricity
REF-0	205	800	Steel	Steel	0
REF-25					25
REF-50					50
REF-B					Four point load
CT-0	203	812	-	CFRP Tube	0
CT-25					25
CT-50					50
CT-B					Four point load
GT-0	203	812	-	GFRP Tube	0
GT-25					25
GT-50					50
GT-B					Four point load
CTCR-0	203	812	CFRP	CFRP Tube	0
CTCR-25					25
CTCR-50					50
CTCR-B					Four point load
GTGR-0	203	812	GFRP	GFRP Tube	0
GTGR-25					25
GTGR-50					50
GTGR-B					Four point load

Table 2

Mechanical properties of FRP tubes

Tube type	Modulus of elasticity in circumferential direction E_c (GPa)	Ultimate tensile strength in circumferential direction $f_{tu,c}$ (MPa)	Modulus of elasticity in longitudinal direction E_l (GPa)	Ultimate tensile strength in longitudinal direction $f_{tu,l}$ (MPa)
CT	54	1188	16.2	142.6
GT	18	810	5.4	92.2

Table 3

Test results of specimens tested under concentric, 25 and 50 mm eccentric axial loads

Test specimen	Peak axial load (kN)	Axial deformation at peak axial load (mm)	Lateral deformation at peak axial load (mm)	Ductility (μ)
REF-0	1529	2.4	-	6.7
REF-25	888	4.2	3.3	5.3
REF-50	594	3.2	3.2	3.7
CT-0	1770	18.1	-	11.6
CT-25	755	3.5	4.7	8.1
CT-50	489	2.8	3.9	3.6
GT-0	1884	21.3	-	14.6
GT-25	860	4.2	5.8	8.4
GT-50	523	4.1	4.0	4.3
CTCR-0	2197	20.9	-	10.2
CTCR-25	1182	6.5	12.3	8.2
CTCR-50	666	4.3	19.2	6.4
GTGR-0	2812	23.1	-	12.6
GTGR-25	1487	13.5	13.4	9.2
GTGR-50	910	11.6	21.0	7.7

Table 4

Test results of specimens tested under four point loads

Test specimen	Peak flexural load (kN)	Midspan deflection at peak flexural load (mm)	Ductility (μ)
REF-B	347	37.3	9.9
CT-B	93	26.7	3.6
GT-B	116	27.1	4.9
CTCR-B	223	28.2	8.7
GTGR-B	448	29.1	9.8

Table 5

Experimental peak axial load and bending moment capacities of tested specimens

Test specimen	Peak axial load (kN)	Lateral deformation at peak axial load (mm)	Moment capacity (kN.m)
REF-0	1529	-	0.0
REF-25	888	3.3	25.1
REF-50	594	3.2	31.6
REF-B	347	37.3	27.0
CT-0	1770	-	0.0
CT-25	755	4.7	22.4
CT-50	489	3.9	26.3
CT-B	93	26.7	11.0
GT-0	1884	-	0.0
GT-25	860	5.8	26.5
GT-50	523	2.3	27.4
GT-B	116	27.1	13.8
CTCR-0	2197	-	0.0
CTCR-25	1182	12.3	44.1
CTCR-50	666	19.2	46.1
CTCR-B	223	28.2	26.3
GTGR-0	2812	-	0.0
GTGR-25	1487	13.4	57.1
GTGR-50	910	19.8	63.5
GTGR-B	448	29.1	52.6

(a)

(b)

(c)

(d)

Fig. 1. Test apparatus (a) Concentric loading Heads, (b) Eccentric Adaptor Plates, (c) Eccentric Ball Joint Plates and (d) Rigs for four point load

(a) Concentric

(b) Eccentric

(c) Four point loads

Fig. 2. Testing arrangements for specimens tested under (a) Concentric loads, (b) Eccentric loads and (c) Four point loads

Fig. 3. Calculation of ductility of tested specimens

Fig. 4. Specimens tested under concentric axial load

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Fig. 5. Axial load-axial deformation behavior of specimens tested under concentric axial load

Fig. 6. Specimens tested under 25 mm eccentric axial load

Fig. 7. Axial load-axial deformation and axial load-lateral deformation behavior of specimens tested under 25 mm eccentric axial load

Fig. 8. Specimens tested under 50 mm eccentric axial load

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Fig. 9. Axial load-axial deformation and axial load-lateral deformation behavior of specimens tested under 50 mm eccentric axial load

(a) Peak axial load

(b) Ductility

Fig. 10. Effect of eccentricity (a) Peak axial load and (b) Ductility

Fig. 11. Specimens tested under four point loads

Fig. 12. Flexural load-midspan deflection behavior of specimens tested under four point loads

Fig. 13. Peak axial load bending moment interaction diagram of REF, CT, GT, CTCR and GTGR specimens