Compressive behavior of filament winded GFRP tube-encased concrete columns

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ABSTRACT: The application of glass fibre-reinforced polymers (GFRP) tubes for the confinement and reinforcing the axial structure members (columns, piles, and pier bridges) is relatively recent. A research program is currently being carried out at the laboratories of the Department of Civil Engineering, University of Sherbrooke. The objective of that program is to investigate and evaluates the compressive behaviour of the GFRP tube-encased concrete columns. The FRP tubes benefits are in confinement, protective jackets, providing shear or/and flexural reinforcement and permanent formwork. This paper presents the experimental results for ten unconfined cylinders, six confined cylinders, four CFFT columns and two control specimens. The parameters were used in the investigation include confinement by GFRP tubes, the effect of laminate thickness of the GFRP tubes, and presence of longitudinal steel bars. The results compared to steel spiral reinforcement which have the same confinement pressure of the GFRP tubes. The diameter of the GFRP tubes which used in this investigation was 152 mm, the tubes have three different thicknesses 2.65, 2.70 and 6.40 mm, the fibre orientation mainly in the hoop direction with different angles combination of ±45, ±60, and ±65 degree. The composite GFRP tubes are fabricated using the filament winding technique; E-glass fiber and Epoxy resin are utilized for manufacturing these tubes. The results indicated that the behavior of the reinforced concrete filled GFRP tubes (CFFT) affected by presence of the longitudinal steel bars, laminate thickness. Test results of the stress-strain, steel strain, load-deformation, dilation and the final failure modes behaviors were presented for all specimens.

1 INTRODUCTION

In general, fibre reinforced polymer (FRP) composite materials have recently been used as internal or external reinforcement in the field of civil engineering constructions. It is used as internal reinforcement for beams, slabs and pavements (Masmoudi et al, 1998; Benmokrane et al, 2006). Also it is used as external reinforcement for rehabilitation and strengthening different structures (Spadea et al, 2000; Almusallam & Al-Salloum 2001; Teng et al, 2002). However, in recent year, the application of concrete filled FRP composites tubes (CFFT) for different structural applications piles, column, girder, bridge piers have been studied and investigated (Karbhari et al. 2000; Fam et al 2003; Karbhari 2004). The benefits of CFFT columns include protective jacket, flexural and shear reinforcements, confinements, durability, formwork and corrosion resistance. The general process used to manufacture FRP tubes is one of placing and retaining fiber reinforcements in the direction needed to provide the hoop and axial strength. It can be done by pultrusion, filament winding, centrifugal casting or resin infusion. In the filament winding process, the placement of the primary fibre-glass reinforcement is tightly controlled and can be oriented in either a hoop or axial direction or any where in between as needed to develop the necessary strength properties in the hoop or axial direction. Confinements of the
concrete are produced by the reaction of FRP tubes normal to the hoop direction for structure members under uniaxial loads. So that the fibre layers in the hoop direction activated to provide the confinement of the concrete. The axial layer is not economic in case of CFFT columns. However the earlier local buckling of the axial layer is more expected under compression load on the CFFT columns. Kaynak et al. 2005 conducted a split-disk tests for specimens produced with five different winding angle to investigate processing parameters of continues FRP tubes produced by filament winding technique. The results indicate that both hoop tensile strength and hoop tensile modulus of elasticity depended strongly on the fibre direction of specimens. Specimens having 90° and ±65° had much higher values compared to the ones having ±45°, ±25° and 0°.

This paper presents the experimental results for ten unconfined cylinders, six confined cylinders, four CFFT columns and two control specimens. The parameters were used in the investigation include the effect of laminate thickness, confinement and presence of longitudinal steel bars. The results compared to steel spiral reinforcement which have the same confinement pressure of the GFRP tubes. Test results of the stress-strain, steel strain, load-deformation, dilation and the final failure modes behavior were presented for all specimens.

2 EXPERIMENTAL PROGRAM

2.1 Materials

Three types of glass-fiber reinforced polymer GFRP tubes were used. The GFRP tubes are fabricated using filament winding technique; E-glass fibre and Epoxy resin are utilized for manufacturing these tubes. The internal diameter for all tubes is constant equal 152 mm. Table 1 presents the details for the three types A, B and C of the GFRP tubes, where $E_x$ and $E_y$ are the Young’s modulus in the longitudinal and hoop direction. The laminate theory is used to calculate the Young’s modulus in the axial and transverse directions based on the mechanical properties of the fibre and resin which was supplied by the manufacture.

All specimens were constructed from the same batch of concrete using a ready mix concrete, the concrete mixture was intended to provide 30 MPa. The maximum size of the coarse aggregates was about 20 mm. Water reducing admixture with super plasticizer was used to increase the workability of the concrete mix; the slump test was done before casting the specimens for the two batches (110 to 120 mm). Ten plain concrete cylinders (152 x 305 mm) were tested at 28-days under axial load; the average concrete strength for ten cylinders was found 30 MPa. Deformed and mild steel bars No. 10 M and 3.2 mm diameter, respectively, were used to reinforce the CFFT columns and control specimens. Tensile test for five specimens conducted for each type of the steel bars. The results indicated that the yield tensile strength were 462 and 675 MPa, also the ultimate tensile strength were 577 and 820 MPa for 10 M and 3.2 mm bars, respectively.

2.2 Test matrix

The experimental program for this paper includes six confined CFFT cylinders (152 x 305 mm), four confined CFFT columns (152 x 912 mm) and two control spiral steel columns. All specimens were tested under a concentric uniaxial load. The specimens are identified as shown in Table 2. The first letter indicates the tube type used from Table 1, the first number shows the height of the column and the second letter indicate the CFFT columns with longitudinal steel bars or without, letter (S) and (W) indicate with and without, respectively. The parameters considered in this paper are thickness of the GFRP tubes, presence of internal steel reinforcement and using GFRP tubes instead of spiral steel. Two cylinders where cut from GFRP tube type A, B and C which different thicknesses. These CFFT cylinders were tested under compression load to obtain the stress-strain behavior of the confined concrete and to study the effect of tube thickness on the confinement of the concrete strength. Also, it is aimed to compare the ultimate strength values for the GFRP concrete cylinders with the following medium height columns constructed from the same type of concrete and GFRP tubes.
Also to study the effect of laminate thickness and confinement using GFRP tubes, a total of three medium height 912 mm CFFT columns were constructed, the three GFRP tube A, B and C were used for these columns (A-90-S, B-90-S and C-90-S). The three CFFT columns were internally reinforced with six deformed steel longitudinal bars 10 M with constant reinforcement ratio equal to 2.99 %. The bars were distributed uniformly inside the cross section of the GFRP tube. To study the effect of presence of the steel bars for CFFT columns, specimen B-90-W was casted without internal longitudinal steel bars and was considered to be reference for specimen B-90-S.

Finally, the last two specimens were a spirally steel reinforced concrete column with the same height. The specimens were reinforced with 6 longitudinal deformed steel bars No. 10 M. Also; mild steel bar of diameter 3.2 mm was used for the spiral reinforcement. The pitch equals to 50.6 mm of the spiral was designed to give approximately the same stiffness of the confinement for GFRP tube type A. The pitches of the spiral were reduced to 25 mm along a distance of 125 mm of the two ends of the column. This was to avoid the local failure at the end regions of loading. All specimens were cast with concrete in a vertical position. This was performed by fixing the GFRP tubes specimens in a vertical position inside the wooden box formwork. Two holes were drilled at the top and bottom of the wooden box to fix each specimen vertically. Also the bottom surface area of the wooden box was attached with a horizontal wood plate to prevent the leakage of the concrete.

2.3 Instrumentation and test setup

There are two types of the instrumentation in this study to capture the local strain distributions, internal instrumentation for the steel bars and external instrumentation on the surface of GFRP tube. Before casting, two of the longitudinal steel rebar, were instrumented by strain gages at mid height. The spiral steel reinforcements were also prepared for the installation of the strain gages, two at the middle height and two below the loading end. Before testing, two axial and two transverse electrical resistance strain gages were mounted 180 degree apart along the hoop direction for each specimen on the external surface of the GFRP tubes.

The axial and horizontal displacement for each column was measured by linear variable displacement transducers (LVDTs). The LVDTs used have a maximum range of (100 mm) and with accuracy of (0.01mm). The specimens were tested using a 6,000 kN capacity FORNEY machine, the loading rate range was 2.0 to 2.50 kN/s during the test by manually controlling the loading rate of the hydraulic pump. Figure 1 shows a typical setup for CFFT under axial compression load.

<table>
<thead>
<tr>
<th>Tube type</th>
<th>Internal diameter (mm)</th>
<th>Thickness (mm)</th>
<th>Number of layers</th>
<th>Stacking sequence</th>
<th>$E_X$ (MPa)</th>
<th>$E_Y$ (MPa)</th>
<th>Hoop tensile strength (MPa)</th>
<th>Axial tensile strength (MPa)</th>
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<tr>
<td>A</td>
<td>152</td>
<td>2.65</td>
<td>6</td>
<td>[±60°],3</td>
<td>8785</td>
<td>20690</td>
<td>640</td>
<td>57</td>
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<tr>
<td>B</td>
<td>152</td>
<td>2.70</td>
<td>8</td>
<td>[±60°],4</td>
<td>8785</td>
<td>20860</td>
<td>640</td>
<td>60</td>
</tr>
<tr>
<td>C</td>
<td>152</td>
<td>6.40</td>
<td>14</td>
<td>[±65°]3,±45°,±65°</td>
<td>9270</td>
<td>23630</td>
<td>1063</td>
<td>62</td>
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</table>

<table>
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<tr>
<th>Specimen ID</th>
<th>Tube type</th>
<th>GFRP Reinforcement</th>
<th>Steel bars</th>
<th>No. of specimen</th>
<th>$P_{Max}$ (kN)</th>
<th>$(f'_{cc}/f'_c)$</th>
<th>$(\varepsilon_{cc}/\varepsilon_c)$</th>
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</thead>
<tbody>
<tr>
<td>Cylinder-A</td>
<td>A</td>
<td>6.97</td>
<td>-----</td>
<td>2</td>
<td>1350</td>
<td>2.48</td>
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<tr>
<td>Cylinder-B</td>
<td>B</td>
<td>7.50</td>
<td>-----</td>
<td>2</td>
<td>1490</td>
<td>2.73</td>
<td>16.95</td>
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<tr>
<td>Cylinder-C</td>
<td>C</td>
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<td>-----</td>
<td>2</td>
<td>2160</td>
<td>4.00</td>
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<td>A-90-S</td>
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<td>6.97</td>
<td>6 No. 10</td>
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<td>2.67</td>
<td>13.00</td>
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<tr>
<td>B-90-S</td>
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<td>2.93</td>
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<td>C-90-S</td>
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<td>13.157</td>
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<td>1</td>
<td>2323</td>
<td>4.30</td>
<td>18.00</td>
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<tr>
<td>B-90-W</td>
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<td>7.50</td>
<td>6 No. 10</td>
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<td>1182</td>
<td>2.16</td>
<td>20.00</td>
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<tr>
<td>Control</td>
<td>Steel spiral</td>
<td>6 No. 10</td>
<td>2</td>
<td>822</td>
<td>---</td>
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</table>
3 TEST RESULTS AND DISCUSSION

Table 2 presents a summary of test results for all specimens. $P_{\text{Max}}$ is the maximum axial load, $(f'_{cc}/f'_{c})$ the average ratios of confined concrete compressive strength to unconfined concrete cylinder strength. Also $\varepsilon_{cc}/\varepsilon_{c}$ is average ratios of the ultimate axial confined CFFT specimens to the ultimate axial strain of the unconfined concrete. The stress–strain curve for the confined and unconfined concrete cylinders for the different GFRP confinement cylinders are shown in Figure 3. The stress-strain curve of the CFFT cylinders is bilinear shape; the stress-strain curves at the first stages of the loading for the confinement specimens were similar to the unconfined concrete up to the unconfined concrete strength. After that softening started for the curve followed by the second linear curve which presents the GFRP confinement effect due to concrete cracking and the lateral expansion of the concrete. Figure 2 shows the failure mode for the three types of the confined cylinders by GFRP tubes. All specimens failed due to the rupture of the fibre in the hoop direction with sudden failure at the ultimate hoop stress resulting from the dilation of the concrete. The fracture of the GFRP tubes occurred along the total height of the cylinders started from top or bottom and extending to the opposite direction. The failure of the 912 mm CFFT columns occurred due to buckling immediately followed by the rupture of the GFRP tube. For CFFT columns, typical failure was generally recorded by rupture of the GFRP tubes at the mid height. Most specimens failed in single curvature buckling mode. Shear failure occurred as the primary mode of failure for the specimen B-90-W. The ultimate load of specimen B-90-W (without steel bars) was lower than the failure load of specimen B-90-S with steel bars. This was the result of the dowel action of the steel bars which gives ductility to the concrete and resists the sliding of the concrete cone inside the tube at 45 degree. However, for all 912 mm CFFT columns height, the buckling occurred with excessive horizontal displacement immediately before the rupture of GFRP tubes approximately after 90 % of the peak strength. The failure of the 912 mm control specimen started by vertical cracking in the bottom region of the column distributed uniformly around the hoop direction and without buckling. Also the ultimate load was lower than of the CFFT columns.

The axial stress versus axial and lateral strains for control and CFFT columns are shown in Figures 4 and 5, respectively. The concrete begins to expand with increasing the axial load. The stress-strain responses start to exhibit a softening area at 70 to 75 % of the ultimate confined concrete strength or at 140 to 150% of the unconfined concrete strength. After softening higher strain values obtained as compared to the control specimen, which yields to the enhancement of the ductility of the CFFT. It is significantly clear that the enhancement in the ductility of the CFFT columns increased due to the confinement action. As the maximum strains for the control and CFFT column are approximately 0.002 and 0.04 respectively. The load-strain curve of the steel bars in the CFFT columns exhibited a linear response until earlier yielding of the steel bars, approximately at 65-75 % of the ultimate load capacity for CFFT specimens. Also the earlier yielding occurred at strain equal to 0.0026 approximately; however this value present the ultimate stain of the unconfined concrete. At the earlier yielding of the load-strain curve presented reverse action due to the expected local buckling of the steel bars. After that, the strain was continued aggressively in the horizontal direction at 65-75 % of the ultimate load capacity for each specimen, see Figure 6.
To study the effect of the tube thickness, the presence of the steel bars and the confinement on the ultimate load capacity of the CFFT columns, Load-axial deformation relationships for each column plotted as shown in Figure 7. The initial tangent modulus for all specimens showed the similar behaviour until yielding or softening stages as a linear response. Specimen C-90-S showed the maximum ultimate load value with a higher improvement in the ductility relative to the control and the rest of CFFT specimens. Also, it was evident that, reinforcing the CFFT intensified the ultimate capacity of specimen B-90-S by 35 % and improved the ductility of the column by increasing the maximum deformation up to 15 % of the deformation of B-90-W.

Figure 8 shows the axial strain against dilation relationships for the CFFT cylinders. Dilation is defined as the ratio of transverse strain to axial strain. The initial dilation rate remains relatively constant, having a value approximately equals to Poisson’s ratio for the unconfined concrete, through an axial strain of approximately $0.6\varepsilon_c$. The peak dilation values were 0.86, 0.7 and 0.58 for CFFT tube A, B and C, respectively. As the thickness of the GFRP tube increases the dilation rate decreases at all load levels after the first stage. The peak dilation for the CFFT column without steel bars was higher than for CFFT column with steel bars. This presents the effect of the existence of longitudinal steel bars inside the CFFT columns.

![Figure 3. Stress-strain relationship for cylinders.](image)

![Figure 4. Stress-strain relationship for control column.](image)

![Figure 5. Stress-strain relationship for CFFT columns.](image)

![Figure 6. Load-steel strain relationship.](image)

![Figure 7. Load-deformation responses for CFFT.](image)

![Figure 8. Experimentally observed dilation behavior.](image)
4 CONCLUSION

The experimental results for ten unconfined cylinders, six confined cylinders, four CFFT columns and two control specimens as reference specimen were investigated. The behavior of the CFFT specimens is affected by the laminate thickness, presence of the longitudinal steel bars. The experimental stress-strain, load-axial deformation, load-steel strain, failure modes and dilation behaviors for all specimens were presented in this paper. The following conclusions can be drawn from the experimental results obtained in this study:

- Significant increase in strength and ductility of concrete columns can be achieved by using concrete filed GFRP tubes.
- The test results indicate that by increasing the thickness of the GFRP tubes a significant improvement is achieved in the confinement efficiency.
- The stress-strain curve of the CFFT tubes with and without longitudinal steel bars is bilinear with transition zone at 70 to 75 % of the ultimate confined concrete strength or at 140 to 150% of the unconfined concrete strength.
- The longitudinal steel bars provide significant dowel action, which delays the dilation of concrete core inside CFFT, thereby improving the ductility of CFFT columns.
- CFFT column without longitudinal steel bars suffer from the earlier failure induced by the sliding of the concrete core and a higher dilation ratio after full confinement activation of the GFRP tubes.
- The initial dilation ratios for all specimens appear to be the same having a value approximately equals to Poisson’s ratio for the unconfined concrete, the peak dilation values depend on the confinement level of the GFRP tubes. The peak dilation for the CFFT column without steel bars is higher than for CFFT column with steel bars.

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6 REFERENCES

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