Performance of square concrete-filled FRP tubes versus steel reinforced concrete columns

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ABSTRACT: Concrete-filled fiber reinforced polymer (FRP) tubes (CFFTs) have become more popular than conventional steel reinforced concrete (RC) columns especially in corrosive environments. Many researches concentrated on circular columns more than square and rectangular ones; however these shapes are commonly used in the majority of buildings. In this research, square CFFT columns had two different thicknesses of filament-wound FRP tubes were compared with RC columns which had two percentages of steel ties to investigate their performance under concentric axial load. Moreover, unreinforced plain concrete (PC) column was tested to represent the confinement effect on the strength and ductility of concrete.

1   INTRODUCTION

In recent years, concrete-filled FRP tubes (CFFTs) have been introduced as alternative structural members in new construction instead of the conventional steel reinforced concrete (RC) columns. The outer FRP tube provides corrosion resistant element, lateral and longitudinal reinforcement, lightweight permanent formwork, in addition to confining the inner concrete core which supports the tube against local buckling and resist compressive loads. In CFFTs, both the strength and ductility are greatly enhanced because of FRP confinement [Fam & Rizkalla (2003)].

Most of the available studies on the behavior of CFFT columns have concentrated on circular columns [Mirmiran et al. (2000), Fam & Rizkalla (2001), Mohamed et al. (2010), and others], while relatively few studies have addressed square and rectangular columns [Fam et al. (2005), Diego et al. (2007), Togay et al. (2008)]. Concepts and results achieved for circular sections cannot be simply adjusted to deal with rectangular sections, because their mechanical behavior is completely different. Moreover, the confinement of square or rectangular sections is less efficient because many areas of the concrete may not be confined in addition to stress concentration at the corners. Further research through experimental and numerical studies is required to increase engineering knowledge on the behavior of the square and rectangular columns confined by FRP tubes.

2   EXPERIMENTAL WORK

Three groups of short square columns were tested under concentric axial load in this research. The first group consisted of two unreinforced CFFTs differed in the thickness of the FRP tube.

The second group consisted of two conventional RC columns having the same longitudinal steel reinforcement but differed in the amount of steel ties reinforcement. The previous two groups were tested and studied to compare the performance of FRP tube versus conventional steel ties. Finally, a PC column was tested as a reference to study the effect of confinement on the strength and ductility of plain concrete. The details of FRP tubes used to form the CFFTs, the configuration of column specimens, formworks and casting process, and test setup are illustrated below.

2.1   FRP tubes

Fiber E-glass and vinyl ester Resin were used to manufacture square tubes by filament winding process. Two orientation angles of the fiber were used in all the tubes, 90° and $\pm65^o$. These orientations of fiber strengthened the lateral direction of the compressed column to be effective in the confinement process. Two tubes were manufactured, Tube (A) and (B). After curing, the mechanical and physical properties of the tubes were measured according to ASTM standards [ASTM D 638 (2001), ASTM D 3176 (2004), ASTM D 3418 (2008)]. Table 1 lists the properties of the manufactured filament-wound GFRP tubes.

Table 1. Properties of manufactured filament-wound GFRP tubes

Tube	Cross section (mm)	Stacking sequence	*No. of layers*	t_f (mm)	Fiber (%)	Axial direction			Lateral direction		
						E_x (GPa)	F_x (MPa)	ε_x (%)	E_y (GPa)	F_y (MPa)	ε_y (%)
A	254×254 corner radius 25.4	90°, $\pm65^o$, 90°	4	4.37	62	3.6	22.7	0.6	22.7	334.5	1.47
B	254×254 corner radius 25.4	90°, $\pm65^o$, $\pm65^o$, 90°	6	7.49	49	3.8	22.3	0.6	15.1	163.9	1.08

2.2   Column specimens details

The experimental work contained five column types, and each column type contained two identical specimens. The five columns types were divided into three groups. The first group consisted of two square CFFT columns (CFFT4, CFFT6) which had no steel reinforcement. CFFT4 had tube A with four layers of fibers, while CFFT6 had tube B with six layers of fibers. The second group consisted of two conventional RC columns (RC6, RC12) which had the same longitudinal steel reinforcement 4Φ10. RC6 had steel ties Φ10/100mm, while RC12 had steel ties Φ10/50mm. The yield strength of the used steel reinforcement was 416 MPa. The reinforcement arrangement is shown in Figure 1. The third group contained only a PC column without any reinforcement. All specimens had the same cross section (254*254 mm) and the same height (600 mm) and were casted with the same patch of concrete. Table 2 lists the details of column specimens.

2.3   Formwork and concrete

It was simple and fast to build the formwork for the CFFTs, because the tubes themselves acted as a permanent formwork. The tubes were arranged together and fixed to steady wooden floor as shown in Figure 2(a). While the RC and PC columns needed a wooden box formwork containing six rooms to be made. The rooms had the same dimensions of tubes cross section and height as shown in Figure 2(b). The formworks were filled with the same patch of normal weight concrete. The specimens were cured under a plastic foil during the first 7 days and under laboratory environment afterwards. The average standard concrete cylinder compressive strength at 28 days was 40.4 MPa.
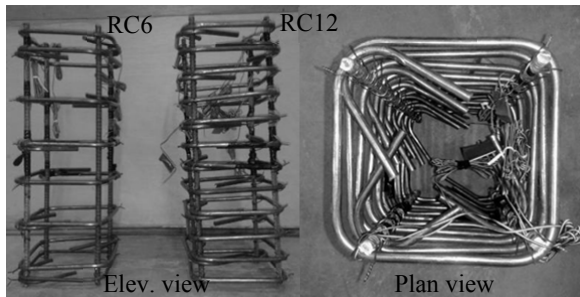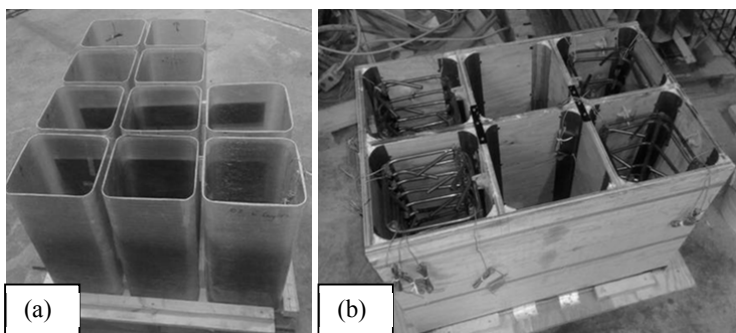
Figure 1. Reinforcement of RC6, RC12

Figure 2. (a) Tubes as a formwork, (b) Wooden formwork for conventional columns

Table 2. Details of column specimens

Specimen	Cross section (mm)	Height (mm)	Tube	Reinforcement	f_c' (MPa)
PC			---	---	
RC6			---	Long. rft 4Φ10, ties Φ10/100mm	
RC12	254×254 corner radius 25.4	600	---	Long. rft 4Φ10, ties Φ10/50mm	40.4
CFFT4			A	---	
CFFT6			B	---	

2.4   Test Setup and Instrumentations

The column specimens were tested under concentric axial load using FORNEY machine with 6000 KN capacity as shown in Figure 3. The loading rate range was 2.5±0.2 KN/sec. It was controlled manually during the test by controlling the loading rate of the hydraulic pump. Capping with thin layers of high performance cement grout was made for all columns top and bottom faces before testing. Two steel tie raps of 6.0 mm thickness and 60.0 mm width were used to confine the top and bottom ends of specimens to avoid the local failure at these positions. Two LVDTs were fixed on opposite sides of specimen to measure the axial displacement. For each column specimen, two pairs of strain gages on two adjacent faces were mounted on the mid-height of external surface of the column. Each pair contained one axial strain gage and another lateral strain gage. Additional strain gages were mounted, before casting concrete, on ties branches and longitudinal reinforcement at the mid height of the RC columns. The axial load, displacements, and gages strains were recorded automatically during the test using a data acquisition system.

Figure 3. Test setup

3 RESULTS AND ANALYSIS

3.1 Pattern of Failure

The failure of the PC column started with vertical cracks at the center of the column face and propagated along the whole length of the column in all faces. The cracks width increased with increasing loading. Finally aggressive wide cracks along the length of the column were occurred at failure causing splitting of the column as shown in Figure 4. This aggressive pattern of failure was happened because there was not any reinforcement, longitudinal or lateral reinforcement.

The RC columns behaved stable and more ductile than the PC column. In general the size of cracks was smaller than that of PC column and the failure is limited at the mid-height of column. The failure started with vertical cracks followed by crushing of concrete cover outwards. RC12 was stiffer than RC6. The increase in ties percentage reduced the cracks widths and confined the inner crushed concrete core slightly better.

The failure patterns of CFFT4 and CFFT6 were similar. It started with brighten zones on the FRP surface. Then aggressive fracture at the corners of the tube was happened suddenly. This fracture ran fast along the length of the specimen mainly at the middle third of the column height. At ultimate load, when confinement action was no longer provided due to FRP fracture, it was noted that the crushed concrete fell down between the fractured FRP. Hence, this indicates that the concrete core was significantly damaged even before reaching ultimate load.
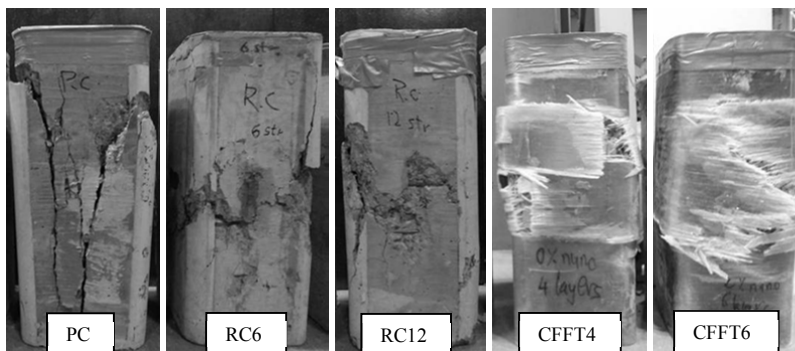

Figure 4. Failure Pattern of Specimens

3.2 Load-displacement and stress-strain relationships

3.2.1 General

The relationships between the axial compressive load and the axial displacements of the columns are plotted in Figure 5. Figure 6 represents the relationships between the compressive stress and the axial strains on the left side, and the relationships with the lateral strains on the right side. Table 3 lists summary of test results and comparisons with the PC column as a reference in addition to failure mode.

The PC column is considered as a reference to be compared with the CFFTs and RC columns to study the confinement effect. CFFT4 and CFFT6 columns are compared together to investigate the effect of tube thickness. RC6 and RC12 columns are compared together to investigate the effect of the steel ties percentage on the performance of conventional RC columns. CFFTs and RC columns are compared together to investigate the performance of the two types of columns.

The ultimate compressive strength of the unconfined square PC column is smaller than the unconfined cylinder compressive strength of concrete (f_c') by 30%. This indicates the effect of aspect ratio and cross section shape on the compressive strength of concrete, in addition to the absence of reinforcement.

For CFFT columns the axial strain gages were cut or disturbed before reaching the end of the test due to the axial sliding of the tube wall layers at high load value. This is a result of the main orientation of fibers in the lateral direction unlike the axial direction. The lateral strain was obtained from the readings of the lateral strain gages which were steady till failure for all columns except the strain gages of PC column were cut due to the vertical splitting cracks at the mid-faces of PC column. In general the values of the lateral strains were smaller than the axial ones. CFFTs reached high lateral strain values compared to the conventional RC columns.

At initial stage of loading, the initial stiffness of all columns were similar depending mainly on the compressive strength and stiffness of the concrete core regardless of the FRP tube thickness in CFFTs or steel ties percentages in RC columns. Moreover, the lateral strain values were neglected at the beginning of loading where the lateral expansion of the concrete core is still very small; therefore the effect of the confinement is still imperceptible.

Table 3. Summary of test results

Specimen	P_u (kN)	f_c^*	f_{cc}	f_{cc}/f_c^*	f_{cc}/f_c'	Δ_u (mm)	Δ_{ui}/Δ_{uPC}	Failure mode
PC	1795.2	28.07	---	1.0	0.70	2.12	1.0	S
RC6	2496.5	28.07	39.03	1.39	0.97	3.11	1.47	C
RC12	2582.2	28.07	40.37	1.44	1.00	3.01	1.42	C
CFFT4	2505.9	28.07	39.18	1.40	0.97	14.82	6.99	C-R
CFFT6	2936.8	28.07	45.91	1.64	1.14	20.01	9.44	C-R

f_c^*: unconfined strength of PC column as a reference,
f_c': unconfined cylinder compressive strength (=40.4MPa),
f_{cc}: confined compressive strength of specimen,
Δ_u: the axial displacement at maximum compressive load.
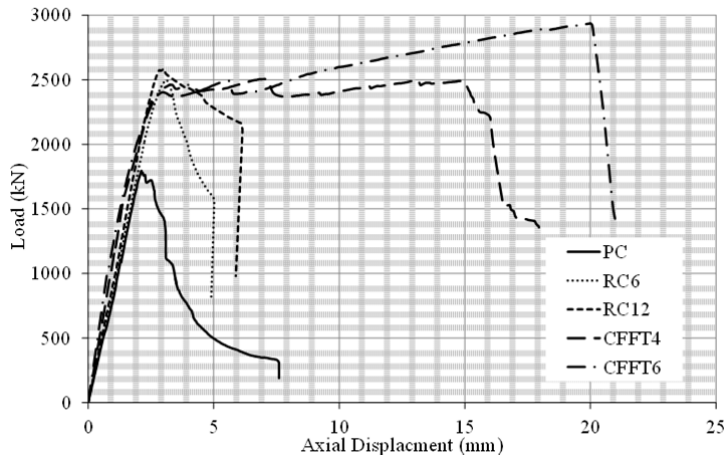S: vertical splitting, C: crushing of concrete, R: rupture of FRP tube

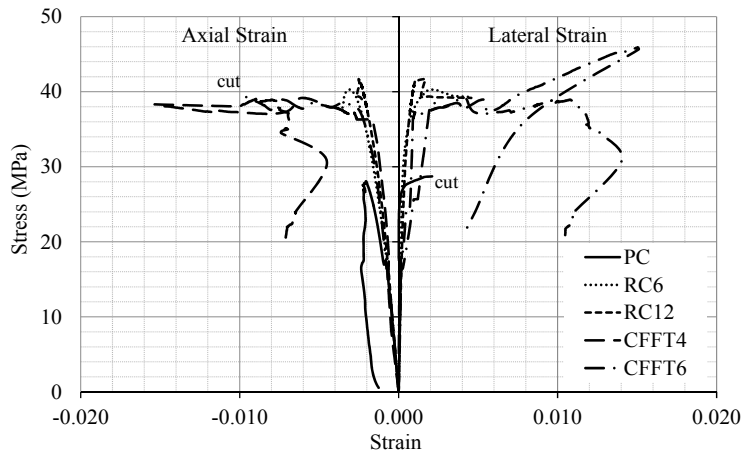Figure 5. Load-axial displacement relationship

Figure 6. stress-strain relationship

3.2.2   Behavior of CFFTs; effect of tube thickness

The load-axial displacement curves and stress-axial strain curves of CFFTs typically consisted of two main stages and could be considered as bilinear. The first stage began with linear behavior till reaching about 57% of the PC column capacity. Before reaching the PC column ultimate capacity, the cracking of the concrete makes its expansion to begin to be significant and the confinement opposes this expansion by tensioning the fibers. This action can be observed on the lateral strain curves where there is a jump in lateral strain value at 80-85% of the unconfined PC column strength. After that, the axial stiffness was slightly reduced till reaching the unconfined cylinder compressive strength (f_c') of concrete core. Afterwards, the second stage was occurred with the initiation of concrete crushing as the confining pressure of the FRP tubes started to be more activated. The axial stiffness of the CFFTs was suddenly reduced and the curve exhibits a hardening region until the failure point. In this stage, the confinement of the GFRP jacket affects significantly the behavior of the specimens and the slope of the last linear line of the curve depends mainly on the jacket stiffness and thickness. The thicker FRP tube (Tube B, 7.49mm thickness at CFFT6 column) demonstrated a significant enhancement in the ultimate load carrying capacity and ductility.

The load-axial displacement curves clearly show that confinement with FRP tubes enhanced the performance of concrete, both its strength and ductility, under axial load. Enhancement in ductility is more pronounced than the gain in ultimate load for CFFTs, as compared to that of control PC column. The gain in capacity due to confinement was 64% and 40% for CFFT6 and CFFT4 respectively. In this research, the percentage $\Delta_{ui} / \Delta_{uPC}$ is used to represent the ductility. CFFT6 and CFFT4 ultimate displacement Δ_{ui} reached 9.4 and 7.0 times, respectively, the ultimate displacement of the reference PC column Δ_{uPC}. The thicker CFFT6 (t_f=7.49mm) behaved stronger and more ductile than CFFT4 (t_f =4.37mm) where the strength and ductility were increased by 14% and 135%, respectively. This indicates that increasing the thickness of the FRP tubes increased the performance of the CFFT column.

3.2.3   Behavior of RC columns; effect of steel ties percentage

The RC columns had more strength and ductility than the PC column. However, they are still less ductile than the CFFTs. The two RC columns, RC6 and RC12, had the same axial stiffness. Unlike the square PC column, they reached the unconfined cylinder compressive strength of concrete f_c'. It is a result of the existing of the longitudinal and lateral steel reinforcement. The lateral reinforcement prevented the vertical splitting of column that happened in the PC column. That is why there is a minimum reinforcement ratio for both longitudinal and lateral reinforcement in RC column should be respected in design.

RC6 column reached strength 39% more than the PC column strength, while RC12 column reached strength 44% more than the PC column strength. Although the steel ties percentage was increased in RC12 two times more than that of RC6, the gain in strength was 5%. This small value in strength gain does not deserve increasing steel ties percentage and reducing ties spacing more than standards requirements. This indicates that increasing the percentage of steel ties in conventional RC columns is not significant to increase the strength of RC columns.

The only difference between the two RC columns appeared after reaching failure load where RC12 column kept residual strength more than RC6 column. It is shown in the descending branch of curves after ultimate load point. The spacing between steel ties in RC12 column was 50mm while in RC6 column it was 100mm. The smaller spacing kept the inner crushed concrete core in its place and prevented the crushed concrete to go out. This means, there was a partially confinement effect on RC12 more than that on RC6.

3.2.4   Confinement performance of CFFTs and RC columns

A comparison among CFFTs columns and RC column was done to investigate the confinement performance of these types of columns. In general, the confinement performance of square CFFTs was better than that of RC column confined by conventional steel ties. Increasing the steel ties in RC columns did not show any significant enhancement in strength and ductility of RC column. While, increasing the thickness of FRP tube increased both the strength and ductility of CFFTs.

Although CFFT4 had only 4.37 mm thickness of FRP tube, it reached the same strength of RC12 column which was laterally over reinforced. Moreover, the gained ductility for CFFT4 column was 500% that of RC12 column. CFFT6 column, which had a tube thickness 7.49 mm, had a gain in strength and ductility equal to 14% and 620% of that of RC12 column respectively. These results indicate the better performance of square filament-wound CFFT comparing with the conventional RC columns, in addition to its simplicity. So, further research is required to increase engineering knowledge on the behavior of this modern and effective structure to be introduced to design standards codes.

4   CONCLUSIONS

The main concluded points of this research could be summarized as following:

[1] A lot of time is needed to prepare the reinforcement and make a formwork to conventional RC column comparing with CFFTs where the tubes themselves acted as a permanent formwork and reinforcement.

[2] An enhancement in both ductility and strength was obtained due to confining the square PC column by conventional steel ties or FRP tube.

[3] The thicker FRP tube demonstrated a significant enhancement in the ultimate load carrying capacity and ductility.

[4] The load-axial displacement curves and stress-axial strain curves of CFFT columns could be considered as bilinear.

[5] Increasing the steel ties in RC columns did not show any significant enhancement in strength and ductility of RC column.

[6] The confinement performance of square CFFTs was better than that of RC column confined by conventional steel ties especially in ductility. Unreinforced CFFT with 4.37 mm thickness of GFRP tube reached the same strength of RC column which was laterally over reinforced. Moreover, the gained ductility for CFFT column was 500% that of RC column.

[7] Further research is required to increase engineering knowledge on the behavior of square filament-wound CFFTs to introduce it in design standards codes.

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