BEHAVIOUR OF HOLLOW COLUMNS CONFINED WITH FRP

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***Abstract :** Confining columns with fiber reinforced polymer (FRP) composites have been investigated in the last few decades to answer problems in upgrading and retrofitting reinforced concrete (RC) columns; however, most studies concentrate on solid columns. This paper investigates the comparative behaviour of FRP confined hollow RC columns subjected to axial concentric loading. A total of twelve RC columns made from high strength concrete (HSC) were tested. Six of the columns had a circular cross section and five of them were hollow columns. The remainder columns had a square cross section, similarly five of them were hollow columns. Six columns from each configuration were left unconfined as control specimens, while the others were confined with FRP. It was found that FRP confinement increased hollow RC columns' axial load and ductility capacities; and hollow columns having circular holes had better performance compared to hollow columns having square holes.*

***Keywords :** concrete columns, fiber reinforced polymers, high strength concrete, hollow sections.*

Abstrak : Pelapisan kolom dengan komposit *fiber reinforced polymer (FRP)* telah diteliti selama beberapa tahun terakhir untuk menjawab masalah-masalah dalam peningkatan dan *retrofit* kolom-kolom beton bertulang; tetapi kebanyakan penelitian berkonsentrasi pada kolom-kolom solid. Tulisan ini mengungkapkan perbandingan perilaku dari FRP yang melapisi kolom beton bertulang berlubang yang dibebani oleh beban aksial terpusat. Sejumlah dua belas kolom terbuat dari beton mutu tinggi di uji. Enam kolom memiliki penampang bundar, dimana lima diantaranya adalah kolom berlubang. Kolom lainnya memiliki penampang persegi, dimana lima diantaranya adalah juga kolom berlubang. Enam kolom dari tiap konfigurasi tidak dilapisi oleh FRP berperan sebagai kolom control, sedangkan yang lainnya dilapisi dengan FRP. Dihasilkan bahwa pelapisan dengan FRP meningkatkan beban aksial dan kapasitas daktilitas kolom berlubang; kolom dengan lubang bundar memiliki perilaku yang lebih baik daripada kolom dengan lubang persegi.

Kata kunci : kolom beton, *fiber reinforced polymers*, beton mutu tinggi, penampang berlubang.

INTRODUCTION

An increase demand of constructing high rise concrete structures has led people to use high strength concrete in lieu of normal strength concrete, to get stronger concrete structures and to minimize the size and weight of concrete members in the structure. Fiber Reinforced Polymers (FRP) is a popular material to be used as external confinement of concrete members for both strengthening and retrofitting purposes. By applying FRP material in concrete members, no significant increase in weight of structure will occur, while FRP material significantly enhances the concrete structure's performance especially in terms of strength and ductility. Furthermore, increase ductility in concrete structures allows structure to display failure signs and warns inhabitants that the structure could fail in turn to save lives.

Due to the huge potential market of FRP applications, researchers have investigated the compressive strength and stress-strain behaviour of FRP confined composite members. However,research and circular column with circular hole (Pessiki et al. 2001; Lam and Teng 2002; Hadi 2006; Hadi 2007). Therefore, this paper is important to identify the base knowledge of FRP confinement on hollow reinforced concrete columns with different shapes of hole under axial concentric loading.

Regarding of this, twelve columns were tested under an axial concentric load. Measurements taken throughout the experiment were load, deflection, and ductility. Comparison between the theoretical calculations and the experimental results were also undertaken.

This paper confirms that the axial load, deflection and ductility capacity of columns can be greatly improved by external confinement of FRP; however, recent confinement modelling procedures are still quite inaccurate for more complex design purposes. Thus, approach confinement models are proposed. Further research of FRP external confinement is also recommended to achieve more efficient and safer designs.

CONFINEMENT MODELS

Richart et al. (1928) proposed the following formula for predicting the compressive strength of the confined RC column (f''_{cc}) of circular columns:

$$\frac{f'_{cc}}{f'_{co}} = 1 + k_1 \frac{f_l}{f'_{co}} \quad (1)$$

where f''_{co}= compressive strength of the unconfined RC column, k_1= effectiveness coefficient of confinement, and f_l = lateral confining pressure. Thus, for Eq. (1) Teng et al. (2001) proposed a value of k_1 = 2.

Teng et al. (2001) also modified Eq. (1), for predicting the f''_{cc} of square columns as following:

$$\frac{f'_{cc}}{f'_{co}} = 1 + k_1 k_s \frac{f_l}{f'_{co}} \quad (2)$$

$$k_s = \frac{b}{h}\frac{A_e}{Ac} \quad (3)$$

$$\frac{A_e}{Ac} = \frac{1-[(b/h)(h-2Rc)^2 + (h/b)(b-2Rc)^2]/(3Ag) - \rho_{sc}}{1-\rho_{sc}} \quad (4)$$

$$A_g = bh - (4-\pi)Rc^2 \quad (5)$$

where k_s= shape factor, b and h = width and height of rectangular or square cross section, $\frac{A_e}{Ac}$ = effective confinement area ratio, Rc= corner radius, ρ_{sc} = cross sectional area ratio of longitudinal steel, and A_g= gross sectional area of column. For Eq. (2) Teng et al. (2001) proposed a value of k_1 = 2.98.

Failure of FRP confinements when wrapping concrete columns will occur when its ultimate lateral confining pressure is reached. Teng et al. (2001) has proposed the following formula, for calculating the lateral confining pressure (f_l) of FRP confined solid circular RC columns (see Figure 1a):

$$f_l = \frac{2 f_{frp} t_{frp}}{d} = \frac{\rho_{frp} f_{frp}}{2} \quad (6)$$

$$\rho_{frp} = \frac{A_{frp}}{A_{column}} \quad (7)$$

where f_{frp}= tensile strength of FRP in the hoop direction, t_{frp}= thickness of the FRP confinement, d= diameter of the confined RC column, ρ_{frp}= FRP volumetric ratio, A_{frp}= cross sectional area of FRP, A_{column}= cross sectional

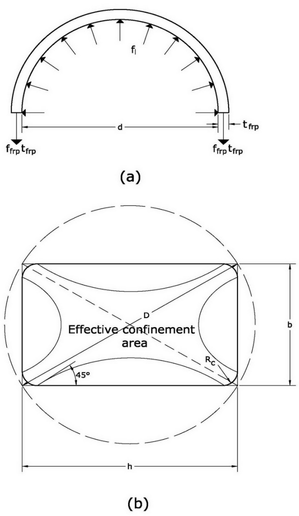

Figure 1. FRP confinement models in RC columns: (a) in solid circular section, (b) in solid square section.

area of column. While, for calculating f_l of FRP confined solid square RC column (see its effective confinement area in Figure 1b), the following formula is used:

$$f_l = \frac{2 f_{frp} t_{frp}}{D} = \frac{2 f_{frp} t_{frp}}{\sqrt{h^2 + b^2}} \quad (8)$$

where D= diagonal length of square cross section.

Warner et al. (1998) has proposed the formula for calculating the ultimate axial concentric load (N_{uo}) of unconfined RC column as following:

$$N_{uo} = 0.85 f'_{co} A_g + f_{sy} A_s \quad (9)$$

where f_{sy} = yield strength of steel reinforcement and A_s= total cross sectional area of steel reinforcement. While for calculating the N_{uo} of confined RC columns, Eq. (9) is modified by changing the variable f''_{co} to f''_{cc}.

Approach Models

Regarding to previous confinement models, models are proposed herein for hollow (either circular or square) RC column having either a circular or square hole. For calculating f_l of FRP confined hollow circular RC column having either a circular or square hole, Eq. (6) can be used. However, Eq. (7) is modified by changing the variable A_{column} to $A_{netcolumn}$. Similarly, for calculating f_l of FRP confined hollow square RC column having either a circular or square hole, Eq. (8) can also be used. However, Eq. (5) is modified by eliminating A_g with A_{hole}.

EXPERIMENTAL PROGRAM

Experimental program of this study was conducted in the Highbay Laboratory of the School of Civil, Mining and Environmental Engineering at the University of Wollongong, Wollongong, Australia.

In this study, columns were identified with acronyms as described in Table 1. A total of twelve RC columns made of HSC supplied by a local supplier, having a height of 925 mm were cast and tested. Six of the RC columns had a circular cross section (two solid circular columns, two hollow circular columns each having a circular hole, and two hollow circular columns each having a square hole) and the other six columns had a square cross section (two solid square columns, two hollow square columns each having a circular hole, and two hollow square columns each having a square hole). Three columns from each configuration (a total of six columns) were confined with two layers of FRP composite, while the other six were left unconfined as control specimens.

Table 1. Columns' labelling system

No.	Column Specimen Acronym	Abbreviation of
	Circular Columns	
1	CCC	Control Circular Column
2	CCCH	Circular Column with Circular Hole
3	CCSH	Circular Column with Square Hole
4	CCF	Circular Column confined with CFRP
5	CCCHF	Circular Column with Circular Hole confined with CFRP
6	CCSHF	Circular Column with Square Hole confined with CFRP
	Square Columns	
7	CSC	Control Square Column
8	SCCH	Square Column with Circular Hole
9	SCSH	Square Column with Square Hole
10	SCF	Square Column confined with CFRP
11	SCCHF	Square Column with Circular Hole confined with CFRP
12	SCSHF	Square Column with Square Hole confined with CFRP

By taking into account the availability of PVC pipes in the market (to form circular columns), a net column cross section of 29,252 mm^2 was chosen in order to cast columns having constant cross sectional area (except Columns CCC and CCF). The four corners of the square columns were rounded by a corner radius of 20 mm, in order to achieve a better efficiency and eliminating regions with ineffectively confined concrete (Mirmiran and

Shahawy 1997).

Deformed steel bars N12 and N16 (12 and 16 mm diameter) which had a nominal tensile strength of 500 MPa, were used as longitudinal reinforcement in the columns. While, for the ties and spirals (transversal reinforcement), a plain steel bar R8 (8 mm diameter) having a nominal tensile strength of 250 MPa, with a pitch of 50 mm were used.

The FRP material used in this study was the carbon fiber reinforced polymer (CFRP). CFRP is used since carbon fibers have more superior properties and durability performance in severe environments compared to glass and aramid fibers. Geometry of the columns' reinforcement detail in this study are illustrated in Figures 2 and 3. Parameters of HSC and FRP are explained in Table 2.

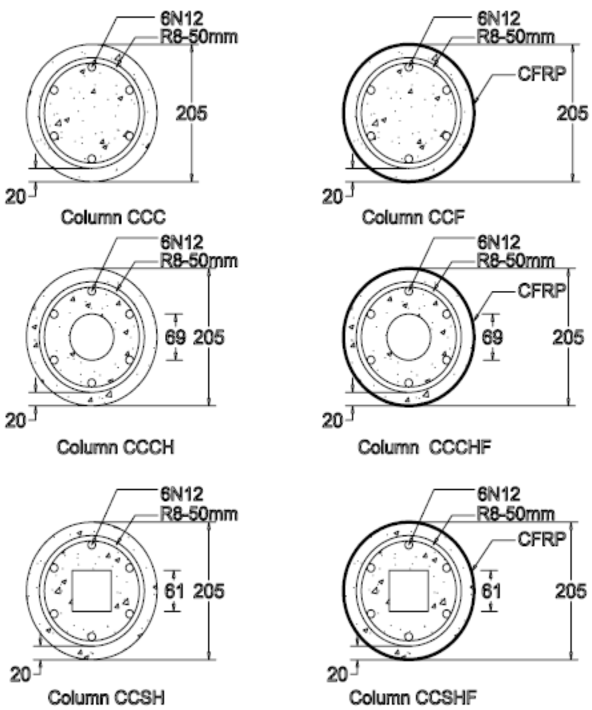

Figure 2. Reinforcement detail of circular columns (all units in mm)

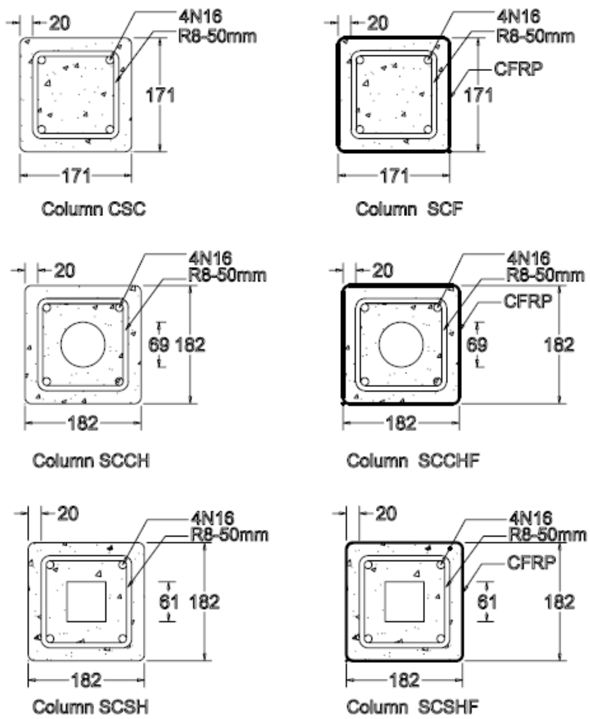

Figure 3. Reinforcement detail of square columns (all units in mm)

Table 2. Parameters of HSC and FRP

High Strength Concrete (HSC)		
Slump	:	155 mm
Modulus of rupture	:	0.72 MPa
Compressive strength	:	72 MPa
Indirect tensile strength	:	4.65 MPa
Carbon Fiber Reinforced Polymers (CFRP)		
Confinement technique	:	10^{o} angle to horisontal
Epoxy : hardener	:	5 : 1
Thickness	:	1.79 mm
Width	:	75 mm
Max. tensile stress	:	674.97 MPa
Strain at max. load	:	0.01 mm

EXPERIMENTAL RESULT AND DISCUSSION

Denison 5000kN compressive testing machine was used to identify the strength and to monitor the axial deflection of the RC column specimens. All columns were loaded under an increased axial concentric load applied under displacement control, using a displacement rate of 0.3 mm/minute and adjusted to 0.5 and 0.7 mm/minute once the load change was insignificant. The data was recorded every two seconds.

Failure Modes

All RC column specimens were tested to failure. Failure of RC columns without CFRP confinement was generally marked by spalling of concrete cover, followed by the rupture of lateral reinforcement and the buckle outwards of vertical reinforcement at or near the midheight of the columns. Failures, while sudden, were physically noticeable and foreseeable. In RC columns confined with CFRP, snapping sounds were heard before the ultimate failure, revealing the rupture of CFRP composites and debonding between the layers of CFRP confinement and concrete column. These failure were explosive but not sudden, and the reinforcements where the CFRP composites failed, experienced buckling outwards. As can be seen in Figure 4, an RC column with CFRP confinement remained intact after failure.

Figure 4. Failure mode

The typical load - axial deflection curves of columns in this study are shown in Figures 5, 6, 7 and 8. The summary of column testing results of this study, including the theoretical capacity analysis of the testing columns is shown in Table 3. Loads were simply obtained from the recorded applied load data of the loading test, while axial deflections were defined from the recorded column's axial deformation data.

According to Figures 5, 6, 7 and 8, columns confined with CFRP experienced higher ultimate load capacity and larger axial deflections compared to columns that are not confined with CFRP. However, circular columns have much better performance in load – axial deflection carrying capacity compared to square columns, and CFRP external confinement is more effective for circular columns rather than for square columns; it may be because the confining pressure in circular columns is uniformly distributed and the column's concrete is effectively confined (Mirmiran et al. 1998).

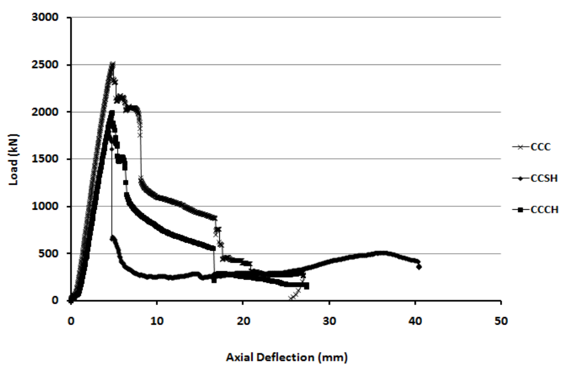

Figure 5. Load – axial deflection of circular columns without CFRP confinement

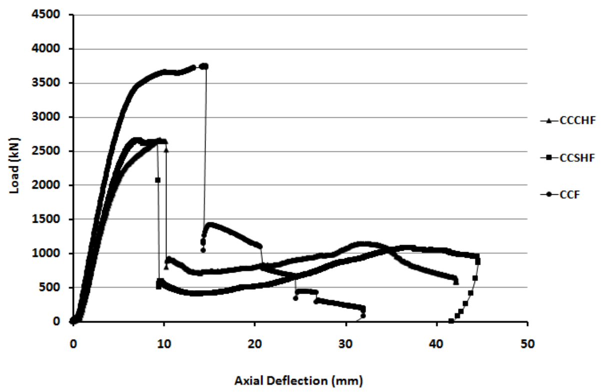

Figure 6. Load – axial deflection of circular columns with CFRP confinement

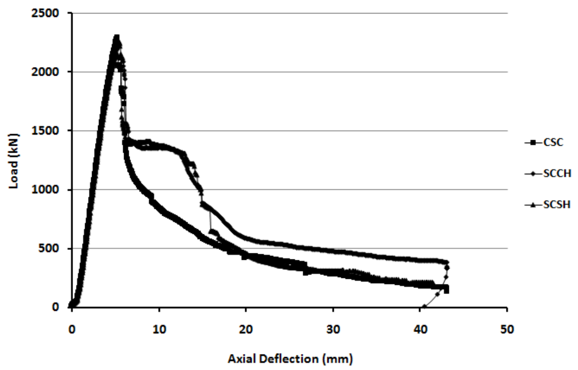

Figure 7. Load – axial deflection of square columns without CFRP confinement

In columns without CFRP confinement; when the applied load increases, the columns' axial deflections will also increase. However, once columns reach their ultimate load capacity, the columns will experience significant decreases in their ultimate load; and the columns' axial deflections still increase until they reach their ultimate capacity and then fail. Columns confined with CFRP have more capability to sustain repeated large loadings (demonstrating an increased ductility) before they finally reach their ultimate load capacity and experience significant vertical decreases in their load carrying capacity.

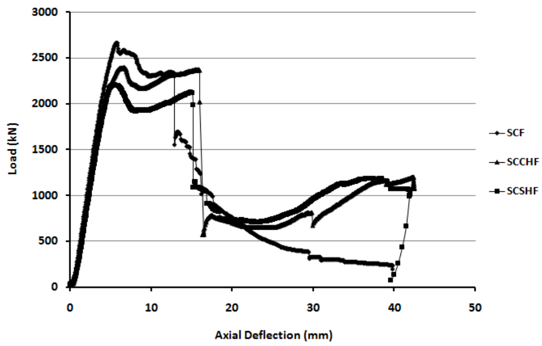

Figure 8. Load – axial deflection of square columns with CFRP confinement

Table 3. Summary of column testing results

Column Specimens	Ultimate Axial Load (kN) Experimental P_{exp}	Theoritical P_{the}	Difference (%) $\Delta = (\frac{P_{exp} - P_{the}}{P_{exp}})x100\%$	Axial Deflection at Ultimate Load (mm)	Axial Deflection (mm) At 85% Pmax ($\Delta_{85\%Pmax}$)	At Yield Load (Δ_y)	Ductility $\mu_\Delta = \frac{\Delta_{85\%P_{max}}}{\Delta_y}$	Relative Ductility
CCC	2507.20	2401.06	4.23	4.89	4.034	4.3	0.94	1.00
CCCH	1991.20	2172.93	-9.13	4.82	4.076	4.5	0.91	1.00
CCSH	1788.80	2172.93	-21.47	4.42	3.620	3.9	0.93	1.00
CCF	3782.70	3062.09	19.05	14.39	6.011	5.5	1.09	1.16
CCCHF	2667.60	2834.00	-6.24	9.56	5.764	4.8	1.20	1.32
CCSHF	2665.80	2835.00	-6.35	7.12	5.051	4.4	1.15	1.24
CSC	2291.80	2253.42	1.67	5.21	4.233	4.4	0.96	1.00
SCCH	2153.50	2253.42	-4.64	5.08	4.086	4.2	0.97	1.00
SCSH	2254.90	2253.42	0.07	5.42	4.334	4.2	1.03	1.00
SCF	2663.40	2691.70	-1.06	5.71	4.41	4.0	1.10	1.15
SCCHF	2394.40	2628.03	-9.76	6.61	4.416	4.0	1.10	1.13
SCSHF	2208.30	2629.42	-19.07	5.38	4.078	3.8	1.07	1.04

According to Figure 5 and Table 3, the highest ultimate load capacity in circular columns without CFRP confinement is reached by Column CCC (solid circular column) namely 2507.20 kN, followed by Column CCCH (circular column with a circular hole) namely 1991.20 kN , and Column CCSH (circular column with a square hole) namely 1788.80 kN. Similarly, after its ultimate load was reached, Column CCC also had the largest axial deflection of 4.89 mm, followed by Column CCCH (4.82 mm), and Column CCSH (4.42 mm).

Based on Figure 6 and Table 3, the highest ultimate load capacity in circular columns confined with CFRP is reached by Column CCF (solid circular column confined with CFRP) namely 3782.70 kN, followed by Column CCCHF (circular column with a circular hole, confined with CFRP) namely 2667.60 kN, and Column CCSHF (circular column with a square hole, confined with CFRP) namely 2665.80 kN. Next, after its ultimate load was reached; Column CCF experienced the largest axial deflection (14.39 mm), followed by Column CCCHF (9.56 mm) and Column CCSHF (7.12 mm).

According to Figure 7 and Table 3, the highest ultimate load capacity in square columns without CFRP confinement is reached by Column CSC (solid square column) namely 2291.80 kN, followed by Column SCSH (square column with a square hole) namely 2254.90 kN, and Column SCCH (square column with a circular hole) namely 2153.50 kN. After its ultimate load was reached; Column SCSH had the largest axial deflection of 5.42 mm, followed by Column CSC (5.21 mm), and Column SCCH (5.08 mm). While, based on Figure 8, the highest ultimate load carrying capacity in square columns confined with CFRP is reached by Column SCF (solid square column confined with CFRP) namely 2663.40 kN, followed by Column SCCHF (square column with a circular hole, confined with CFRP) namely 2394.40 kN, and Column SCSHF (square column with a square hole, confined with CFRP) namely 2208.30 kN. Next, after its ultimate load was reached; Column SCCHF experienced the largest axial deflection (6.61 mm), followed by Column SCF (5.71 mm), and Column SCSHF (5.38 mm).

These analyses clearly demonstrate that CFRP external confinement in both circular and square columns enhance the ultimate axial load and deflection of the columns by delaying rupture of the concrete and reinforcement.

Effect of Different Shape of Hole

Generally, in this study, hollow RC columns having circular holes showed higher ultimate load and axial deflection, compared to those having square holes. In hollow circular RC columns; columns having circular holes (Columns CCCH and CCCHF) had better performance in terms of ultimate load and axial deflection, compared to those of circular RC columns having square holes (Columns CCSH and CCSHF). Similarly, this behavior occurred in hollow square RC columns with CFRP confinement. However, different behavior occurred in hollow square RC columns without CFRP confinement, whereas Column SCSH had better performance in ultimate load and axial deflection, compared to Column SCCH.

Ductility of Columns

Ductility of HSC columns is an important structural design consideration due to the brittle nature of HSC, especially when HSC columns are subjected to high axial compression loadings. The CFRP confinement of HSC columns plays significant role in enhancing the ductility performance of HSC columns (Ozbakkaloglu and Saatcioglu 2007).

In this study, ductility was measured based on the columns' axial displacement behavior using Eq. (10), where μ_Δ=column's ductility; Δ=column's displacement at 85% of maximum load (at post-yielding, post-buckling) or ultimate displacement; Δ_y=yield displacement (GangaRao 2007):

$$\mu_\Delta = \frac{\Delta}{\Delta_y} \tag{10}$$

Generally, the ductility of RC columns in this study increases. The presence of two layers of CFRP confinement is the most beneficial for enhancing columns' ductility. According to Table 3, among circular columns, Column CCCHF had the largest increase of ductility with a relative ductility value of 1.2, followed by Column CCSHF (1.15), Column CCF (1.09), Column CCC (0.94), Columns CCSH (0.93), and Column CCCH (0.91). Among square columns, Column SCCHF and SCF had the largest increase of ductility with a relative ductility value of 1.1, followed by Column SCSHF (1.07), Column SCSH (1.03), Column SCCH (0.97), and Column CSC (0.96).

CONCLUSION

The following conclusions are drawn from the results of the experimental work:

1. CFRP external confinement in both solid and hollow columns allows columns to experience larger loadings and demonstrate an increased ultimate load and axial deflection carrying capacity.
2. Under axial concentric loading, external confinement of RC columns with CFRP can significantly enhance the columns' performance, by delaying rupture of the concrete and reinforcement.
3. Hollow columns having circular holes carry higher maximum load and axial deflection, compared to hollow columns having square holes.
4. Ductility of columns increase along with the application of two layers external confinement of CFRP.

Thus, research of the application of FRP confinement is strongly recommended to achieve more efficient and safer designs.

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