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Effect of ply configuration on hollow square reinforced concrete columns confined with Carbon fibre-reinforced polymer (CFRP)

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ABSTRACT: This paper presents results of testing twelve hollow square reinforced concrete specimens wrapped with Carbon fibre reinforced polymer CFRP. The effect of ply configuration on the behaviour of the specimens is investigated. All specimens were 800 mm high and had the dimensions of 200 mm × 200 mm in cross-section and a hollow core of 80 mm × 80 mm. The specimens were divided into four groups with three specimens each. The specimens in the first group without bonding CFRP served as references. While the remaining three groups of specimens were externally wrapped with CFRP in three different ply configurations of hoop, vertical and 45° angle with reference to the circumferential direction, respectively. The specimens in each group were tested as columns under three eccentricities (0, 25, and 50 mm). Experimental results show that all types of wrap configuration increased the strength of reinforced concrete columns. The columns wrapped exclusively with hoop configuration proved to show the greatest ductility properties.

1 INTRODUCTION

1.1 *Hollow columns*

In practice, structural concrete columns are always subjected to axial compression as well as bending moment caused by inevitable eccentricity. When a column is under eccentric loads, there will be one side in compression and the other in tension. This means the material on the outside is under the most loads, while the material at the centre of the cross-section is hardly loaded at all. That is why using hollow columns is reasonable to have an efficient use of material meanwhile not lose a lot of its strength.

1.2 *FRP in strengthening columns*

FRP has been verified by many studies to be effective in strengthening concrete columns by improving significantly the performance of the columns for both strength and ductility. Most of these studies were based on solid, circular cross-section, plain concrete columns and tested under concentric axial loading, in which FRP is wrapped transversely, with respect to column's axial axis. By this way, FRP provided considerable confinement pressure to the concrete core under compressive loads resulting in increasing the compressive strength and deformation capacity of the columns. When columns are subjected to eccentric loads, both axial action and bending action are induced. The increase in eccentricity causes the maximum load capacity of the columns to decrease. Li and Hadi (2003), Hadi (2006a), Hadi (2006b) conducted experiments on circular concrete columns under variable eccentricities. The results from these studies show that external confinement with FRP can improve the performance of the columns under eccentric loading. However, the strength is only enhanced to some extent with the application of an eccentric load. Meanwhile, the gain in ductility is much more distinctive. In fact, under eccentric compressive loading, a column is bent, that produces an additional bending moment termed secondary moment to the column. The increase in applied load results in an increase in lateral deflection, and the total eccentricity of the applied load is thereby increased. This in turn increases the internal moment in the column and causes a reduction in compressive strength. In addition, FRP confinement leads to greater slenderness in the column as has been demonstrated by Ranger and Bisby (2007), Fitzwilliam and Bisby (2010), this again leads to column can achieve more lateral bending. To resist such bending moment that come from eccentricity, vertical wrapped FRP layers are provided and the outcomes are shown to be very good from some experimental results. Hadi (2007) continued testing on cylindrical concrete columns externally confined with FRP but vertical FRP wraps were added. The author concluded that the presence of vertical CFRP straps improved significantly the performance of the columns for both strength and ductility under eccentric loading. Hadi and Widiarsa (2012) conducted testing on solid, square, reinforced concrete columns, and they got the same results. In fact, the benefit of longitudinal wraps is more obvious with the increase in eccentricity. Tan (2002) also confirmed that increasing the amount of longitudinal fibre sheets leads to enhancement in strength and ductility of the solid, square, concentric loading columns. However, this would be possible only if they are adequately restrained from outward buckling by transverse fibre sheets.

Wrapping FRP in an angle other than hoop and vertical directions is also studied by several researchers. Rochette and Labossiere (2000) used fibres oriented at ±15°/0° to wrap square concrete columns. Mirmiran and Shahawy (1997) employed ±15° fibres from the hoop direction in their concrete-filled FRP tubes. In the study by Pessiki et al. (2001), fibres oriented at 0°/±45° were used to wrap both small- and large scale square and circular concrete columns. However, there is no careful exams on the performance of these specimens compared to others in both of strength and ductility aspects. Li et al. (2006) conducted an intensive experiment to study the effect of fibre orientation on the structural behaviour of FRP wrapped concrete cylinders. In their study, variety of fibre orientations and two different thicknesses were used to wrap concrete cylinders with a diameter of 152.4 mm and a height of 304.8 mm. It is found that the strength, ductility, and failure mode of CRP wrapped concrete cylinders depend on the fibre orientation and wall thickness. Fibres oriented at a certain angle in between the hoop direction and axial direction may result in strength lower than fibres along the hoop or axial direction. However, only a slight increase in axial strain was gained for the 45° wrapped specimens. The reason is insufficient FRP that was provided by authors. Sadeghian et al. (2010) also investigated the effect of fibre orientation on concrete cylinders (a diameter of 150 mm by 300 mm in height) under uniaxial compressive loading. Again, longitudinal fibres have no significant effect on strength and ductility of columns under concentric loading. Meanwhile, the pure angle orientations have a significant influence on enhancement of ductility and energy dissipation of columns.

2 EXPERIMENTAL PROGRAM

2.1 *Specimens preparation*

In order to investigate the effect of ply configuration on the behaviour of hollow RC columns confined with FRP, a total of twelve specimens were designed and tested. All the specimens were made of reinforced concrete with the same amount of internal steel reinforcement and were designed according to the requirements of the Australian Standards (AS 3600-2009). The specimens had square section with the dimensions of 200 by 200 mm in cross-section, 800 mm in height, and had a hole of 80 × 80 mm inside. All corners of the columns were rounded by a radius of 32 mm to protect FRP wraps apart from premature failure due to the concentrated stress at the corners of non-circular section columns. Two types of steel reinforcement were used. N12 deformed bars of 12 mm diameter (500 MPa nominal tensile strength) was for longitudinal reinforcement. R6 plain bars of 6 mm diameter was for transverse reinforcement placed at 100 mm spacing. The specimen dimensions were chosen based on the testing machine capacity that was used in this experiment. As such, the specimens were considered to be short columns. The wall thickness of 60 mm was designed to ensure a clear concrete cover of 20 mm was maintained at both outer and inner faces of the column as specified in AS 3600-2009. With the wall width-to-thickness ratio of 1.33, which is less than 15, the failure mode of the compression flange will be controlled by crushing of the concrete instead of local buckling (Taylor et al. (1995)). The size effect, however, is not considered in this study. Details of dimensions and reinforcement of the specimens are given in Figure 1.

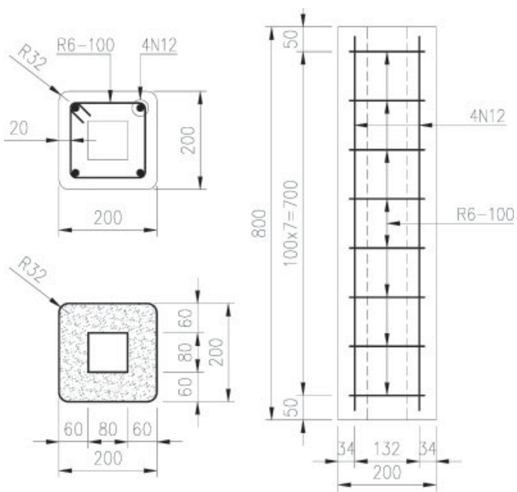

Figure 1. Details of dimensions and reinforcement.

A wooden formwork consists of twelve square holes was used to cast the test specimens. To create the inside hole, twelve 80 mm by 80 mm wooden boxes were also made and centred inside of each mould. Four foam arches with 32 mm radius were placed at four corners of each hole to make the round corners of the specimens. The 40 MPa nominal compressive strength concrete that was used in this experiment was supplied by a local supplier in one batch of concrete. Before pouring concrete, a slump test was conducted to make sure the workability of the concrete during pouring concrete process. A slump of 130 mm was achieved from the test. The concrete was then placed into the formwork by three stages. In each stage, vibration of specimens was carried out using two vibrators to ensure the compaction of concrete. Casting cylinders for concrete properties testing was also implemented.

After casting, the specimens were cured in their forms in moisture conditions. Wet Hessian rugs were placed on the top of all the specimens and were watered twice a day to keep the moisture in. The formwork was then removed after 14 days.

2.2 *Wrapping and curing FRP*

Before FRP wrapping, surface preparation was carried out carefully. The surface of the concrete was found to be intact after the removal of the formwork therefore there was no need to repair or patch, except the surface at corners because of using foam. These positions were then grinded using a grinder and a steel brush to make them flat.

The twelve specimens were then sub-divided into four groups with three specimens each to prepare to wrap with FRP. The specimens in the first group (RC Group) without any FRP wraps served as reference specimens. The specimens in the second group (HF Group) were all laterally wrapped with three layers of CFRP with respect to specimen axial axis. The specimens in the third group (VHF Group) were firstly vertically wrapped with one layer of CFRP along the specimen axial axis, and then horizontally wrapped with two layers of CFRP. All the specimens in the last group (AHF Group) were firstly wrapped with two layers of CFRP oriented at ±45° with respect to specimen axial axis, and then horizontally wrapped with one layer of CFRP.

Unidirectional fibre sheets of CFRP (CARBON-UNI340GM-75MM) were used in this experiment programme to wrap specimens using wet layup system. The nominal width and thickness of the CFRP sheet are 75 mm and 0.45 mm, respectively. The ultimate tensile strength and ultimate strain were determined from the FRP coupons tests shown in Table 1. The adhesive was mixed from epoxy resin and slow hardener at a 5:1 ratio as recommended by the manufacturer.

The wrapping procedure was done as follows. The surface of the specimens was coated with a thin layer of epoxy resin first, and then the first layer of CRRP was applied with an expected orientation. The first layer of FRP was then coated with epoxy again before the application of the second layer of FRP. The process was repeated until designed number of layers. An overlap of 100 mm was made in the last revolution and was applied only for the layers in the hoop direction. An extra two lateral FRP layers and 75 mm length vertical FRP layers were applied to the ends of all tested column specimens. The additional layers were placed in order to protect the two ends against premature failure due to the high partial pressures experienced under compressive loading. The layers also protect the ends from early cracking on the tensile sides of the columns due to eccentric loads. All specimens were then left for at least 14 days for FRP curing.

2.3 *Preliminary testing*

Preliminary testing included testing concrete cylinders, reinforcing bars and CFRP. Testing of concrete was conducted following AS 1012.8 (2000) and AS 1012.9 (1999) on cylinders with dimensions of 100 mm in diameter and 200 mm in height. The average day 28 compressive strength of concrete was 38.2 MPa. The tensile testing method according to AS 1391 (2007) was used to determine the properties of reinforcing steel. The average tensile strength of the N12 bars was 587 MPa, and that for R6 bars was 538 MPa. Tensile testing was carried out on CFRP coupons according to ASTM standard D7565/D7565M-2010. All FRP coupons consist of three layers of FRP representing for three types of wrapping FRP on specimens in each group. The summary of testing the FRP coupons is shown in Table 1.

Table 1. FRP coupon test results.

Coupons	Type 1	Type 2	Type 3
Configuration	3H	2H + 1V	1H + 2A
Maximum load (N)	38370	30858	15554
Maximum deflection (mm)	2.40	2.56	2.14
Width (mm)	25	25	25
Length (mm)	250	250	250
Maximum tensile force per unit width (N/mm)	1534.82	1234.33	622.16
Maximum strain	0.0174	0.0185	0.0155

Table 2. Configuration of specimens.

Specimen*	Configuration CFRP (layers)	Eccentricity mm
RC-0	None	0
RC-25	None	25
RC-50	None	50
HF-0	3 horizontal layers	0
HF-25	3 horizontal layers	25
HF-50	3 horizontal layers	50
VHF-0	1 vertical and 2 hoop	0
VHF-25	1 vertical and 2 hoop	25
VHF-50	1 vertical and 2 hoop	50
AHF-0	2 angle (±45°) and 1 hoop	0
AHF-25	2 angle (±45°) and 1 hoop	25
AHF-50	2 angle (±45°) and 1 hoop	50

*All specimens have dimensions of 200 × 200 mm in cross-section and 800 mm in height, and were internally reinforced with steel reinforcing.

2.4 *Test setup*

From each group, the three specimens were tested as columns at eccentricities of 0, 25 mm and 50 mm. These specimens were denoted by the name of the group accompanied with the notation 0, 25 and 50 at the end. For example, specimen RC-0, RC-25, RC-50 mean that these specimens are in Group RC (reference columns) and were tested under eccentric of 0, 25, and 50 mm, respectively. The test matrix is given in Table 2.

2.5 *Testing procedure*

Square, steel loading end caps were used in testing all specimens. High strength plaster was placed in the caps and left to set for at least 45 mins before testing. Bottom load caps were centred using a rig holding the column in place. A forklift was used to place the specimen in Denison 500 tonne testing machine. Top load caps were placed as the column was lifted into place.

Table 3. Summary of testing results.

Column	Maximum load kN	Deflection at maximum load		Increase in strength compare to reference %
		Axial mm	Lateral mm	
RC-0	1341	3.32	N/A	
HF-0	1485	21.99	N/A	10.8
VHF-0	1525	4.03	N/A	13.7
AHF-0	1417	3.81	N/A	5.7
RC-25	998	2.99	1.71	
HF-25	1245	3.75	1.48	24.7
VHF-25	1189	3.80	1.57	19.1
AHF-25	1083	3.73	2.29	8.5
RC-50	755	3.06	2.20	
HF-50	825	3.67	2.56	9.4
VHF-50	889	4.13	3.23	17.8
AHF-50	862	3.78	2.50	14.2

To measure lateral displacement of the columns, a laser LVDT was placed horizontally at the front of the protective Perspex shield with a small cutout hole for the laser. Testing commenced under displacement controlled condition. All tests were conducted at a rate of 0.3 mm/min.

3 RESULTS AND DICUSSIONS

Table 3 shows the results of testing all columns. It can be seen that similar to solid reinforced concrete column, CFRP external confinement can increase the strength and ductility of the RC hollow columns. The gain in strength is significant for HF columns under concentric loading and small eccentricity (25 mm). However, when the eccentricity is large (50 mm) the gain in strength is more considerable in the VHF and AHF columns. Meanwhile the gain in strength in the HF columns reduces. Also, wrapping columns with three layers of CFRP in the hoop direction allows columns to undergo a much larger axial deflection than unwrapped columns and the two other wrapping methods.

3.1 *Behaviour of unwrapped columns*

Unconfined columns showed the highest load carrying capacity when tested under concentric loading. When eccentricities were introduced, the maximum load carrying capacity decreased significantly. These columns did not suffer any large strain after reaching the peak load. In fact, they failed in a brittle manner charactered by the peeling off of concrete and the outward buckling of steel bars in the compression side for all columns. Horizontal cracks were also found in the tension sides of columns under eccentric testing.

3.2 *Behaviour of columns wrapped with three hoop layers of CFRP*

Wrapping columns with three layers in the hoop orientation is the most efficient method of increasing strength and ductility of columns for both concentric and eccentric loading. HF-0 column showed 10.8% increase in strength compared to reference RC-0 in concentric testing. HF-25 and HF-50 achieved 24.7% and 9.4% increases, respectively. Column HF-0 was expected to gain the highest applied load of the four columns tested concentrically, however a premature failure was observed. After examining the tested HF-0 column carefully, it was found that the concrete had spalled at a corner at the surface of the top end where the longitudinal steel bar was outcrop. The concrete cover on top of that longitudinal steel bar was just 4 mm instead of the required 20 mm. This caused high concentrated stress, leading to damage the top end of the column at this corner.

In terms of ductility, from the Figures 2–4, it can be seen clearly that hoop layers can substantially extend axial displacement as well as lateral displacement of the columns under concentric and eccentric loading. Table 4 shows the ductility for all columns. Hoop orientation wrapping allows HF-0 columns to achieve axial deflection 4.7 times larger than the reference, and around 2.4 times compared to VHF-0 and AHF-0 in the case of concentric loading. Under eccentric loading these comparisons are even larger. HF-50 showed ductility 7.4 times larger than RC-50 and about 3.4 times larger when compared to VHF-50 and AHF-50. The

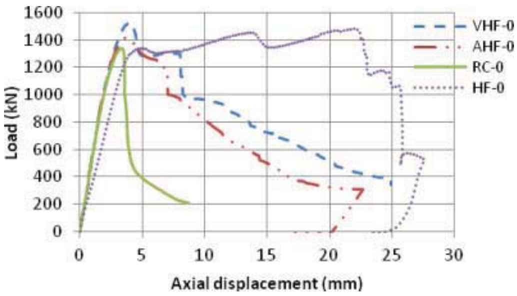

Figure 2. Load-axial deflection curves for concentrically loaded columns

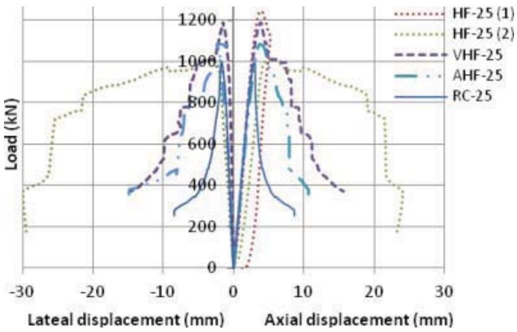

Figure 3. Load-deflection curves for 25 mm eccentrically loaded columns. Note: HF-25 (1) and HF-25 (2) refer to 1st and 2nd loading periods of column HF-25 due to an accident.

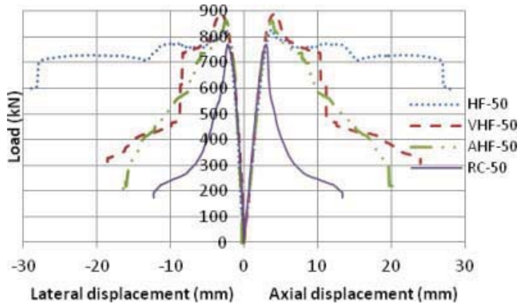

Figure 4. Load-deflection curves for 50 mm eccentrically loaded columns.

Table 4. Calculation of ductility.

Column	Axial deflection (mm) at yield load Δ_y	at 85% P_{max} $\Delta_{85\%Pmax}$	Ductility $\Delta_{85\%Pmax}/\Delta y$	Relative ductility compare to reference
RC-0	2.80	3.58	1.3	1.0
HF-0	3.83	22.98	6.0	4.7
VHF-0	2.92	8.05	2.8	2.2
AHF-0	2.75	6.76	2.5	1.9
RC-25	2.62	3.15	1.2	1.0
HF-25	N/A	N/A	N/A	N/A
VHF-25	2.92	6.07	2.1	1.7
AHF-25	3.05	5.87	1.9	1.6
RC-50	2.59	3.38	1.3	1.0
HF-50	2.78	26.89	9.7	7.4
VHF-50	2.78	8.52	3.1	2.3
AHF-50	2.94	7.89	2.7	2.1

ductility of HF-25 column is not applied herein due to an accident that occurred with the machine as testing commenced. The applied load suddenly increased with a very high speed rate and in about 16 seconds, 1250 kN was applied before the test was stopped. The load data recorded from the computer showed that the applied load reached the peak value and then started decreasing. It was decided to start testing of the column again, but some cracks were already found on FRP layers. The maximum load the column achieved was only about 80% of the previous value recorded during the accident. The axial and lateral displacements however, were still very large as shown in Figure 3. Therefore, CFRP layer in hoop direction is efficient in delaying the premature failure of columns due the spalling of concrete and buckling of steel bars at yield load.

It is worthy to note that when eccentricity is large, the gain in strength of HF columns decreases, whereas the gain in ductility increases. This result is due to FRP in this wrapping scheme only working in the hoop direction and there is no effect in preventing the loss of strength due to bending moment.

HF columns fail in a sudden, dangerous manner. When the applied load increased to large enough values, small crack sounds were heard. After the peak load, the load carrying capacity of the columns slightly reduced while the deflection significantly increased. This allows HF columns to achieve large ductility. When the deflection is large enough, the crack sounds increased and the FRP ruptured with a loud explosive noise as it reached its ultimate strain. The failure position of FRP layers of the HF-0 and HF-50 columns was determined to be about 160 mm–200 mm from the top end and that for the HF-25 column was near mid-height of the column. All of these FRP layers ruptured at a corner of the column due to the concentrated stress at corners of non-circular cross-section columns.

3.3 *Behaviour of columns with the presence of a vertical layer and ±45° layer wraps*

The behaviour of VHF and AHF columns are quite similar in both concentric and eccentric loading, especially with regards to ductility. Both these wrapping schemes improve slightly the ductility of the columns. The combination of two ±45° oriented CFRP layers and one hoop CFRP layer in AHF columns were expected to show the largest ductility compared to the other schemes, but their gain in ductility is only around 1.6 to 2.1 times larger than the references. These results are similar to those of Sadeghian et al. (2010) were conducted on solid plain concrete cylinders. The combination of transverse and angle oriented layers is not useful on enhancement of ductility and energy absorption. Meanwhile, Sadeghian et al. (2010) confirmed the significant increase in ductility for cylinders wrapped with pure ±45° orientations.

In the aspect of strength, as expected, the gain in strength of these columns increases when the eccentricity increases due to the contribution of vertical and angle wraps. When columns were tested concentrically, there was no contribution of vertical and angle layers resulting in only a slight increase in the strength which in fact comes from the hoop layers (Table 3). At an eccentricity of 50 mm, the contribution of vertical and angle layers become more clear. The increase in strength of VHF-50 and AHF-50 are even greater than that in HF-50 (i.e. 9.4% for HF-50, 17.8% and 14.2% for VHF-50 and AHF-50, respectively). The presence of vertical and angle CFRP orientation is clearly efficient in resisting bending moments due to eccentricities which result in premature failure of RC columns.

Similar to HF columns, the failure in VHF and AHF columns occur in a sudden and explosive manner. When the applied load is large enough, small crack sounds are heard. A bulging deformation on the outer hoop FRP layer in the compression side is also observed. After the peak load, the load carrying capacity of VHF and AHF columns reduced significantly. The rupture of the outer hoop layers caused a loud explosive noise and the load dropped.

All the VHF columns fail at a position approximately 130 mm from the top end. With the exception of column VHF-0, the rupture of FRP in VHF columns (VHF-25 and VHF-50) occurred in the middle, on the side of the column, not at the corner. When examining inside the hole of these columns, it is found that the concrete at the inner corners break in a way that tends to make the cross-section of the hole at failure position circular. This leads concrete at middle of compression side to expand outward causing the breaks of FRP near the middle side of the column.

For AHF columns, the rupture of FRP started from the corner and further developed into an approximate 45° downward angle in the compression side of the column.

4 CONCLUSION

In order to investigate the effect of fibre orientation on hollow square reinforced concrete columns confined with Carbon fibre-reinforced polymer, three varying orientations of fibre wrapping were made and tested on twelve specimens under both concentric and eccentric conditions. From the testing results, several conclusions can be made:

The fibre in hoop orientation can significantly increase strength and ductility of hollow square reinforced concrete columns. Compared to VHF and AHF columns, HF columns allow larger deformation before failure.

When columns were tested under eccentric loading, the contribution of vertical and ±45° angle layers are much more evident than in tests conducted under concentric loads.

The combination of two ±45° oriented CFRP layers and one hoop layer was expected to have the largest ductility. However, it did not show any significant increase in deflections of the columns under both concentric and eccentric testing. In fact, the behaviour of this wrapping scheme is nearly similar to the specimens with vertical wraps. The presence of one outer hoop layer is supposed prevented the deflection of the ±45° layers. When the applied load is large enough, due to only a single layer of hoop direction, the hoop layer sooner reaches its ultimate strain. The rupture of the one hoop layer results in the premature failure in the ±45° layers.

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