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Abstract

One of the methods for strengthening square concrete columns is shape modification. The method involves modification of the column cross section from square to circular by bonding concrete segments and then wrapping the column with fiber reinforced polymer (FRP). This paper investigates experimentally the applicability of the shape modification (circularization) for square hollow reinforced concrete (RC) specimens under different loading conditions. Five groups of four hollow RC specimens made from normal strength concrete were cast and tested. The specimens in the first group were RC hollow specimens, which served as reference specimens. The corners of the specimens in the second group were rounded to 20 mm and wrapped with two layers of carbon FRP (CFRP). The specimens in the third group were circularized and wrapped with two layers of CFRP. The specimens in the fourth group were bonded with one CFRP strap longitudinally on each side and then circularized and wrapped with two layers of CFRP. The specimens in the fifth group were wrapped with one layer of CFRP and then circularized and wrapped with two layers of CFRP. The results show that circularization increased the strength and ductility of the hollow specimen. Transverse wrapping with CFRP mainly improved the performance of the specimens under concentric axial loadings, while the longitudinal CFRP straps mainly improved the performance of the specimens under eccentric axial loading.

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Behavior of Circularized Hollow RC Columns under Different Loading Conditions

Muhammad N.S. Hadi¹, F.ASCE; Mohammed Jameel² and M. Neaz Sheikh³

ABSTRACT: One of the methods for strengthening square concrete columns is shape modification. The method involves modification of the column cross-section from square to circular by bonding concrete segments and then wrapping the column with fiber reinforced polymer (FRP). This paper investigates experimentally the applicability of the shape modification (circularization) for square hollow reinforced concrete (RC) specimens under different loading conditions. Five groups of four hollow RC specimens made from normal strength concrete were cast and tested. The specimens in the first group (N) were RC hollow specimens, which served as reference specimens. The corners of the specimens in the second group (RF) were rounded to 20 mm and wrapped with two layers of carbon FRP (CFRP). The specimens in the third group (CF) were circularized and wrapped with two layers of CFRP. The specimens in the fourth group (VCF) were bonded with one CFRP strap longitudinally on each side and then circularized and wrapped with two layers of CFRP. The specimens in the fifth group (HCF) were wrapped with one layer of CFRP and then circularized and wrapped with two layers of CFRP. The results showed that circularization increased the strength and ductility of the hollow specimen. Transverse wrapping with CFRP mainly improved the performance of the specimens under concentric axial loadings, while the longitudinal CFRP straps mainly improved the performance of the specimens under eccentric axial loading.

CE Database subject headings: Carbon Fiber reinforced polymer; longitudinal CFRP straps; hollow concrete columns; eccentricity; ductility.

Author keywords: CFRP; Square concrete column; circularization; ductility, hollow.

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Introduction

Retrofitting and upgrading existing structures may be required due to the deterioration of the structures, adoption of new design code requirements and increase in the load demand. Fiber reinforced polymer (FRP) has been used for the last few decades for retrofitting and upgrading concrete structures. FRP is preferred to other materials as FRP possesses low weight with high strength and high corrosion resistance. FRP can be used to enhance the performance of concrete members of different shapes under various loads, as FRP can be wrapped around various shapes in different directions. Wrapping FRP materials transversely around columns provides confinement to the concrete, which increases the strength and ductility of the column (Yazici and Hadi 2009). The confinement effect subjects the concrete in a solid column into a tri-axial state of stress.

The RC columns and piers with hollow cross-sections maximize the strength-mass and stiffness-mass ratios and reduce the weight demand on foundation. Hollow RC columns possess high torsional and bending stiffness. Hollow RC columns are usually preferred when the construction of a tall column is required. The construction cost of the structure with hollow columns is considerably less (Sheikh et al. 2007). However, the behavior of hollow columns is different from the behavior of solid columns due to the presence of an inner hole.

It is well known that wrapping FRP transversely provides higher level of confinement in circular columns than non-circular columns (Rochette and Labossiere 2000; Harries and Carey 2003; Kusumawardaningsih and Hadi 2010; Silva 2011; Faustino et al. 2014; Colajanni et al. 2014). The higher confinement for circular column than non-circular column is due to the uniform distribution of confinement pressure around the circular cross-section. In contrast, for non-circular cross-sections, the confinement pressure is much higher at the corners than on the flat sides. The high confinement pressure at the corners causes premature failure of FRP due to stress concentrations. Similar to solid columns, wrapping the circular hollow columns results better enhancement in strength and ductility than the non-circular hollow columns (Yeh and Mo 2005; Kusumawardaningsih and Hadi 2010).

Several research studies investigated the modification of the non-circular columns into circular or elliptical columns before FRP wrapping (Priestley and Seible 1995; Saadatmanesh et al. 1997; Yan et al. 2006; Pantelides and Yan 2007; Yan and Pantelides 2011; Hadi et al. 2012a; Pham et al. 2013; Alsayed et al. 2014). These studies on shape modification revealed that changing the non-circular cross-section of the column into a circular cross-section before FRP wrapping enhanced the performance of the FRP wrapped columns.

Priestley and Seible (1995) investigated experimentally the shape modification by bonding precast concrete bolsters to the solid square column and wrapping the new circular column with FRP. Priestley and Seible (1995) found that the shape modification enhanced the performance of columns. Yan et al. (2006) and Yan and Pantelides (2011) also investigated the shape modification of the column cross-section from square to circular. Expansive cement was used to fill the gap between the square column and the circular FRP shell. Yan et al. (2006) and Yan and Pantelides (2011) reported that, after circularization, the concrete confinement changed from passive to active. Also the axial load-axial deformation behavior of the column changed from softening to hardening.

Hadi et al. (2012b) modified the square cross-section of the solid column into circular cross-section by adding four precast concrete segments on the sides of the square column and wrapped the modified column with FRP. Hadi et al. (2012b) used the same concrete batch for the column and the segments. Modifying the cross-section of the solid column from square to circular enhanced the performance of the column in terms of strength and ductility. Pham et al. (2013) found that increasing the strength of the concrete segments increased the load carrying capacity of the circularized solid columns. Moran and Pantelides (2012) analytically investigated the ultimate stress and strain of shape modified (elliptical and circular) FRP confined solid concrete sections and found that FRP reinforcement ratio required to change the behavior of concrete column from softening to hardening depended on the unconfined concrete strength, FRP modulus and the aspect ratio of the cross-section.

Columns may be subjected to eccentric loadings due to the position of the column in the structure. Increasing load eccentricity reduces the confined parts of the column cross-sectional area. As a result, the load eccentricity reduces the confinement level of the FRP

wrapped columns. Therefore, the confinement provided by FRP are achieved mainly when the column is loaded concentrically or when the load eccentricity is small (Li and Hadi 2003; Hadi 2006b; Hadi 2006a; Hadi 2007; Bisby and Ranger 2010). However, attaching FRP straps longitudinally on the columns enhances the flexural strength of columns under eccentric loading (Chaallal and Shahawy 2000; Hadi 2007; Fitzwilliam and Bisby 2010; Hadi and Widiarsa 2012; Hadi and Le 2014).

The above literature review shows that shape modifications were carried out only on square or rectangular solid columns. This study investigates the applicability of the circularization technique on square hollow columns under different loading conditions.

Experimental Program

Design of Specimens

A total of twenty square hollow RC specimens were cast and tested in the High Bay Laboratory at the University of Wollongong, Australia. The specimens were 800 mm height and 150 mm x 150 mm cross-section with a square hole of 50 mm x 50 mm at the center. The dimensions of the tested specimens were chosen to suit the capacity of the laboratory testing facilities. The RC compression member with a ratio of the clear height to the maximum plan dimension of the support equal to or greater than 2.5 is considered as column in Canadian Highway Bridge Design Code CAN/CSA S6-06 (CSA 2006). Also, in ACI 318-11 (ACI 2011), RC columns are defined as RC members that sustain axial load with height-to-least lateral dimension ratio greater than 3. The height-to-lateral dimension of the specimens tested in this study was about 5.3. The unsupported wall length to thickness ratio was 1, which ensured that the mode of failure of the compression flange is the crushing of concrete instead of the local buckling (Taylor et al. 1995). Hence, the results presented in this paper should be translated with caution for thin wall and very slender hollow RC columns.

The specimens were divided into five groups of four specimens. The first group (Group N) served as reference square hollow RC specimens. The specimens in the second group (Group

RF) were constructed with 20 mm round corners and afterwards wrapped with two layers of CFRP. The specimens in the third group (Group CF) were circularized by bonding four precast concrete segments on the sides and afterwards wrapped with two layers of CFRP. The specimens in the fourth group (Group VCF) were bonded with one longitudinal CFRP strap on each side and then circularized by bonding four precast concrete segments. Afterwards, the specimens were wrapped with two layers of CFRP. The specimens in the fifth group (Group HCF) were wrapped with one layer of CFRP and then circularized with four precast concrete segments. Afterwards, the specimens were wrapped with two layers of CFRP. Three specimens from each group were tested as columns under concentric, 25 mm eccentric and 50 mm eccentric axial loadings. The eccentricity of axial load has been chosen based on the available test apparatus at the laboratory. The last specimen from each group was tested as a beam under four-point loading.

The specimen labels consist of two parts in Table 1. The first part (N, RF, CF, VCF and HCF) refers to the name of the group. The second part refers to the loading conditions: 0 refers to concentric loading, 25 refer to 25 mm eccentric loading, 50 refers to 50 mm eccentric loading and F refers to four-point loading. For example, Specimen VCF-0 refers to the concentrically loaded hollow specimen, which was strengthened with longitudinal CFRP straps (one on each side of the specimen). Specimen VCF-0 was circularized with concrete segments and afterwards wrapped with two layers of CFRP. Specimen HCF-50 refers to the 50 mm eccentrically loaded hollow specimen, which was wrapped with one layer of CFRP. Specimen HCF-50 was circularized with concrete segments and afterwards wrapped with two layers of CFRP. The test matrix of all specimens is shown in Table 1 and the details of the specimens are shown in Fig. 1.

The specimens were reinforced with 4N12 bars (12 mm deformed steel bars) as the longitudinal reinforcement. The R6 bars (6 mm plain steel bars) were used as transverse reinforcement with a pitch of 60 mm. The reinforcement arrangement has been chosen considering that the specimens require retrofitting according to AS 3600 (2009). The concrete clear covers were 17 mm on the sides and 20 mm at the top and bottom of the specimens.

The formwork of the square hollow specimens was made from plywood. The square hole was created from foam with 800 mm height and 50 mm x 50 mm cross-section. The foam was aligned longitudinally in the center of the specimens by inserting a 16 mm steel rod through the foam. The foam was fixed in the center of the base plate. The base plate had a square hole to prevent the foam from rotating. The round corners of Group RF were created by gluing arched parts made from foam with 20 mm radius and 800 mm height on the inner corners of the square formwork. The concrete segments were made by fitting square frames into polyvinyl chloride (PVC) pipes of 212 mm inner diameter and 800 mm height. The square frames were made from plywood with 800 mm height and 150 mm x 150 mm cross-section. Each PVC pipe created four precast concrete segments. The details of the formworks are shown in Fig. 2.

Material Properties

The ready mix concrete with nominal compressive strength of 40 MPa at 28 days was provided by a local supplier. The maximum aggregate size of concrete was 10 mm. Three standard solid concrete cylinders of 100 mm diameter and 200 mm height were tested to determine the compressive strength of concrete according to AS1012.9 (1999). The average compressive strength of concrete on the 28th day was 40 MPa and the average compressive strength of concrete during testing was 47 MPa.

Unidirectional CFRP of 100 mm width and 0.45 mm thickness was used for wrapping the specimens. The mechanical properties of the CFRP were determined by flat coupon tests according to ASTM D7565 (2010). The average width of the coupons was 25.4 mm. The average maximum tensile force per unit width and the average strain at the maximum tensile force were 1102 N/mm and 0.016 mm/mm, respectively. The average modulus of elasticity was 67.5 kN/mm.

To determine the mechanical properties of the reinforcing steel, three specimens of 500 mm length from each of the N12 deformed steel bars and R6 plain steel bars were tested

according to AS 1391 (2007). The average tensile yield strength of the N12 and R6 steel bars was 570 and 478 MPa, respectively.

Preparation of Specimen

The surfaces of the specimens and concrete segments were cleaned to ensure clean and smooth surfaces. Longitudinal CFRP straps were attached to the sides of the specimens of Group VCF by epoxy resin and hardener at a ratio of 5:1 (one longitudinal CFRP strap on each side of the square specimen). The specimens of Group HCF were wrapped with one layer of CFRP. Afterwards, the square cross-section of the specimens in Groups CF, VCF, and HCF were changed into circular cross-section by bonding four precast concrete segments on the sides of the specimens. The segments were held onto the sides of the specimens by using steel rings. All specimens, except the specimens of the reference group (Group N), were wrapped with two layers of CFRP.

The specimens were wrapped with CFRP by wet-layup method. The adhesive used was a mixture of epoxy resin and hardener at a ratio of 5:1. A 100 mm overlap was maintained at the second layer. To prevent premature failure at the top and bottom of the specimens during testing, the top 100 mm and bottom 100 mm of all specimens were wrapped with two layers of CFRP. Fig. 3 shows the specimen preparation.

Testing of Specimens

Three specimens from each group were tested as columns under concentric, 25 mm eccentric and 50 mm eccentric axial compression. One specimen from each group was tested as a beam under four-point loading. The universal Denison testing machine with 5000 kN capacity was used to determine the axial load-axial deformation behavior of the specimens. The specimens tested as columns were capped at both ends with high-strength plaster to ensure an even distribution of the applied load on the loaded face. The beam specimens were tested under four-point loading over a clear span of 700 mm with a shear span of 233 mm. It is noted that the response of the beam specimens might not be due to the pure bending, as the shear span-to-depth ratio of specimens was low. However, the dimensions of the specimens tested under

four-point loading were kept the same as the other specimens tested under concentric and eccentric axial loads for uniformity and consistency. Due to the relatively small span-to-depth ratio of the tested specimens, two layers of CFRP sheets were applied in the shear span of Specimens RF-F, CF-F, VCF-F and HCF-F to avoid shear failure and to minimize the effect of the shear-induced deflection at midspan. The CFRP sheets were also applied in the shear span of the reference Specimen N-F to ensure consistent comparisons.

The eccentric loadings were applied through special loading heads. The details of the loading head can be found in Hadi and Widiarsa (2012). Circular loading heads were used for testing the circular column specimens while square loading heads were used for testing the square column specimens. Two loading systems were used for testing the specimens as beams under four-point loading. The circular system developed by Yazici and Hadi (2009) was used for testing the circular beam specimens. The square system developed by Hadi and Widiarsa (2012) was used for testing the square beam specimens. The details of test setup and instrumentation are as shown in Fig. 4.

To determine the displacement of the column specimens during the testing, two Linear Variable Differential Transducers (LVDTs) were attached to the corners of the lower moving plate of the compression testing machine. The lateral deflection of the eccentrically loaded column specimens and the midspan deflection of the tested beam specimens were measured by using a laser triangulation. The laser triangulation was located at the mid-height of the specimens tested as columns and under the midspan of the specimens tested as beams. The laser triangulation and LVDTs with an accuracy of 0.2% were connected to a data logger which was connected to a computer. The specimens were preloaded under a force controlled load application at 2 kN/s to 10% of the estimated ultimate load. The specimens were then unloaded to 20 kN at the same rate. Afterwards, all specimens were tested to failure under a displacement controlled load application at 0.3 mm/minute.

Experimental Results

Failure Modes of the Tested Specimens

All specimens were tested to failure. For the concentrically loaded specimens, the failure of Specimen N-0 was brittle and marked by spalling of concrete cover and buckling of longitudinal steel reinforcement.

The failure of Specimens RF-0, CF-0, VCF-0 and HCF-0 was initiated by stretching of the CFRP followed by a snapping sound due to the rupture of CFRP when the axial load approached the ultimate axial load. The rupture of the CFRP was in the corners of Specimen RF-0, while the rupture of the CFRP was distributed around the circular cross-section of Specimens CF-0, VCF-0 and HCF-0. The failure of Specimens CF-0, VCF-0 and HCF-0 at ultimate axial load was sudden and accompanied by an explosive sound. It was observed by visual inspection that after testing the dilation of concrete in Specimens CF-0, VCF-0 and HCF-0 was more than the dilation of Specimen RF-0, which revealed the higher confinement of the circularized column specimens. Fig. 5 shows the failure mode of the concentrically tested specimens.

For the eccentrically loaded specimens, the failure of Specimen RF-25 did not show any rupture of the CFRP except the appearance of CFRP ripples in the compression side. For Specimen RF-50, the failure was initiated by the rupture of the CFRP in the compression side which revealed the buckling of longitudinal steel reinforcement and crushing of concrete in the compression side. Cracking of concrete in the tension side of Specimens RF-25 and RF-50 was observed during the testing. The failure of Specimens CF-25, CF-50, VCF-25, VCF-50, HCF-25 and HCF-50 was initiated by the rupture of the CFRP, crushing of concrete and buckling of longitudinal steel in the compression side. Afterwards, cracking of concrete appeared in the tension side when the axial load approached to the ultimate axial load.

The failure of Specimens CF-25, CF-50, VCF-25, VCF-50, HCF-25 and HCF-50 occurred in the mid-height of the specimens. The rupturing and debonding of the CFRP layers revealed the expansion of the concrete. Fig. 6 and Fig. 7 show failure mode of the 25 mm and 50 mm eccentrically tested specimens, respectively.

For Specimens VCF-25 and VCF-50, the failure in the tension side was observed to be initiated with kinking sounds before the appearance of any cracks. The kinking sound was

due to the rupture of the longitudinal CFRP straps. After the appearance of concrete cracks, the kinking sounds continued with the drop in the axial load due to the subsequent rupture of CFRP straps in the sides of the columns.

The failure of Specimen N-F was initiated by cracking of concrete in the tension side and crushing of concrete and spalling of concrete cover in the compression side. The failure of Specimens RF-F, CF-F, VCF-F and HCF-F was initiated by cracking of concrete in the tension side and rippling of the CFRP in the compression side. The load of Specimen VCF-F fluctuated after the first peak load due to the subsequent rupturing in the fibers of the CFRP in the sides of the specimen. Fig. 8 shows the failure mode of the specimens tested under four-point loading.

Load-Deformation Behavior

Table 2 summarizes the results of the specimens tested under concentric axial compression. The axial load-axial deformation behavior of the concentrically loaded specimens is shown in Fig. 9. The results show that the CFRP wrapping enhances the performance of the specimens in terms of ultimate load and ductility. Ductility of the specimens was determined as the ratio of the axial deformation at 85% of the post ultimate load (δ_u) to the deformation at the yield (δ_y) (Sheikh and Légeron 2014). The (δ_y) is defined as the yield deformation corresponding to the intersection point of a horizontal line from the first peak load and an extension line between the origin and the point representing 0.75 times the peak load. The yield load corresponding to the yield deformation represents the approximate limit of the elastic behavior of the specimens (Foster and Attard 1997).

Specimens CF-0, VCF-0 and HCF-0 achieved higher ultimate axial load and higher ductility than Specimen RF-0. However, Specimen RF-0 achieved only 17% higher ultimate axial load than Specimen N-0. The increases in the ultimate axial load of Specimens HCF-0, VCF-0 and CF-0 were 121%, 119% and 119%, respectively, higher than the ultimate axial load of Specimen N-0. The increase in the ultimate axial load of Specimens CF-0, VCF-0 and HCF-0 was mainly due to the increased cross-sectional area after circularization. Specimens HCF-0

and VCF-0 showed bilinear axial load-axial deformation curve with ascending branch in the second part in which the axial load increased after the yield.

The axial load-axial deformation curve of Specimens RF-0 and CF-0 showed two peak axial loads because of the decrease in the axial load after the first peak load. The slight decrease in the axial load after the first peak axial load of Specimens RF-0 and CF-0 was because of the rate of confinement activation was less than the degradation in concrete due to the presence of the hole. The axial load of Specimen RF-0 decreased after the first peak axial load from 1147 kN to 1084 kN. Then the axial load increased to the failure load of 1160 kN. The second peak axial load was only 1% higher than the first peak axial load. The axial load-axial deformation curve of Specimen CF-0 showed a slight decrease in the axial load after the first peak axial load where the axial load dropped from 1848 kN to 1826 kN. Then the axial load increased to the failure load of 2169 kN. The second peak axial load was 17% higher than the first peak axial load.

Specimen HCF-0 showed the highest yield load followed by Specimen VCF-0. However, Specimen VCF-0 achieved slightly higher yield load than Specimen CF-0. The gain in the yield load of Specimen VCF-0 compared to Specimen CF-0 might be due to the presence of the longitudinal CFRP straps, which was attached on the sides of the square hollow column specimen. Tan (2002) and Li et al. (2006) also reported that the longitudinal FRP straps enhance the load carrying capacity of the axially loaded columns if adequately confined by transverse FRP. The axial load-axial deformation curve of Specimen VCF-0 showed an increase in the axial load after the yield load up to the failure load. The ultimate axial load was 43% higher than the yield axial load. The highest yield axial load of Specimen HCF-0 was due to the confinement provided by the CFRP. However, a slight increase in the ultimate axial load achieved by Specimen HCF-0 compared to Specimen CF-0 was due to the sharp corners of the square column which might have led to premature rupturing of the CFRP. The axial load-axial deformation curve of Specimen HCF-0 showed an increase in the axial load after the yield load up to the failure load. The ultimate axial load was 34% higher than the yield axial load. The circularized specimens were considered to be more efficiently confined compared to the rounded corner specimen as the axial load increased after the yield load. The

ductility of Specimens RF-0, CF-0, VCF-0 and HCF-0 were 3.2, 4.3, 3.2 and 3.1 times, respectively, of the ductility of Specimen N-0 (Table 2).

Table 3 reports the results of specimens tested under 25 mm eccentric axial loads. Fig. 10 shows the axial load-axial deformation and axial load-lateral deformation behavior of the 25 mm eccentrically loaded specimens. Specimen HCF-25 showed the highest ultimate axial load followed by the Specimen VCF-25, Specimen CF-25, and Specimen RF-25. The highest ultimate axial load of Specimen HCF-25 was due to wrapping the square hollow specimen with one layer of CFRP. The CFRP wrapping provided confinement in the compression side of Specimen HCF-25. While the higher ultimate axial load of Specimen VCF-25 than Specimen CF-25 was due to the contribution of the longitudinal CFRP straps in the tension side. The higher ultimate axial load of Specimen HCF-25 than Specimen VCF-25 might be because the most parts of concrete of the column specimens under 25 mm eccentric axial loads were under compression. Therefore, the contribution of the transverse CFRP in confining the concrete of Specimen HCF-25 in the compression side was more effective than the contribution of longitudinal CFRP straps in enhancing the tensile strength in the tension side of Specimen VCF-25. Specimen VCF-25 achieved the highest ductility followed by Specimen CF-25 and Specimen HCF-25 then Specimen RF-25. The ductility of Specimens RF-25, CF-25, VCF-25 and HCF-25 were 2.6, 4.7, 4.9 and 3.6 times, respectively, of the ductility of Specimen N-25 (Table 3).

Tables 4 reports the results of the specimens tested under 50 mm eccentric axial compression. Fig. 11 shows the axial load-axial deformation and axial load-lateral deformation behavior of the 50 mm eccentrically loaded specimens. Specimen VCF-50 achieved the highest ultimate axial load followed by Specimen HCF-50, Specimen CF-50 and Specimen RF-50. The higher ultimate axial load of Specimen VCF-50 than Specimen HCF-50 might be because the most parts of concrete of the specimens under 50 mm eccentric axial loads were under tension. Therefore, the contribution of longitudinal CFRP straps in enhancing the tensile strength in the tension side of Specimen VCF-50 was more effective than the contribution of the transverse CFRP in confining the concrete of Specimen HCF-50 in the compression side.

Specimen VCF-50 showed different axial load-axial deformation behavior compared to the other eccentrically loaded specimens. After reaching the yield load, the axial load of Specimen VCF-50 decreased from 902 kN to 846 kN. Then the axial load increased up to the failure load of 975 kN. The behavior of Specimen VCF-50 was comparable to that of the concentrically loaded specimens and was due to the existence of the longitudinal CFRP straps. In other words, with the increase in the secondary bending moment, the longitudinal CFRP straps were activated in the tension side. The activation of the longitudinal CFRP straps was found to be significant after the yielding of compression concrete. It is clear that the load carrying capacity and the performance of the tested specimens decreased with the increase in the applied load eccentricity. Specimen VCF-50 achieved the highest ductility followed by Specimen CF-50, Specimen HCF-50, and Specimen RF-50. The ductility of Specimens RF-50, HCF-50, VCF-50 and CF-50 were 1.7, 2.8, 3.3 and 2.4 times, respectively, of the ductility of Specimen N-50 (Table 4). It is evident from Table 2-Table 4 that the ductility of the CFRP confined concrete specimens decreases with the increase in the load eccentricity.

Table 5 summarizes results of the specimens tested under four-point loading. Fig. 12 shows the load-midspan deflection behavior of the specimens. Specimen VCF-F achieved the highest ultimate load followed by Specimen HCF-F, Specimen CF-F and Specimen RF-F. Specimen VCF-F showed three peak loads in the load-midspan deflection diagram. The three peak loads of Specimen VCF-F were due to the consequence of rupturing of the longitudinal CFRP straps bonded on the sides of the square hollow specimen. The first rupture of the CFRP straps, which was mainly in the longitudinal CFRP sheet at the bottom of the specimen in midspan, resulted in a sudden decrease in the load. Afterwards, the load increased with the increase in the midspan deflection until reaching the second peak load. Afterwards, the load dropped suddenly after the second rupture of the CFRP straps which was mainly in the longitudinal CFRP sheets at the bottom and at the sides of the specimen in midspan. Then, the load increased until failure. The load-midspan curves of all circularized and CFRP wrapped specimens showed an ascending branch after the yield. Specimen VCF-F achieved the highest ductility followed by Specimen CF-F, Specimen HCF-F, and Specimen RF-F. The ductility of Specimens RF-F, HCF-F, VCF-F and CF-F were 1.1, 1.4, 1.5 and 1.3 times, respectively, of the ductility of Specimen N-F (Table 5).

Effect of Circularization

Circularization enhances the performance of the hollow square RC specimens in terms of strength and ductility. The circularized specimens showed a significant increase in the ultimate load. The significant increase in the ultimate load was mainly due to the enlargement of cross-section area and the increased level of the CFRP confinement due to the corner mitigation. The axial stress-axial deformation diagram of the concentrically loaded specimens was plotted to exclude the contribution of the cross-section area enlargement to the enhancement of the circularized specimens and to reveal the effect of the circularization only on the confinement efficiency. Fig. 13 shows the axial stress-axial deformation curves of the specimens tested under concentric axial compression. The ascending behavior of the axial stress-axial deformation curve of Specimens CF-0, VCF-0 and HCF-0 after yielding and also the higher ultimate axial stress of Specimens CF-0, VCF-0 and HCF-0 than Specimen RF-0 confirm the attainment of enhanced confinement by circularization. Specimen RF-0 achieved yield strength of 41 MPa, which is similar to the yield strength of 43 MPa of Specimen CF-0. The similar yield strength revealed the insignificant effect of corners on the confinement efficiency of the CFRP wrapped hollow column specimens at yield. Specimen RF-0 achieved less yield strength than the yield strength of Specimen VCF-0, as Specimen VCF-0 was strengthened with longitudinal CFRP straps before the circularization. Specimen RF-0 achieved less yield strength than the yield strength of Specimen HCF-0, as Specimen HCF-0 was wrapped with one layer of CFRP before the circularization.

The ultimate axial stress of Specimens HCF-0, VCF-0 and CF-0 were 1.4, 1.3 and 1.3 times, respectively, of the ultimate axial stress of Specimen N-0. The ultimate axial stress of Specimen RF-0 was 1.2 times of the ultimate axial stress of Specimen N-0. The effect of hole on the behavior of the hollow specimens is reduced after circularization especially when the square hollow specimen was bonded with longitudinal CFRP straps or transverse CFRP wrapping. However, bonding the square hollow specimen with longitudinal or transverse CFRP were more effective in enhancing the yield axial load rather than the ultimate axial load, as shown in Fig. 13 for Specimens HCF-0 and VCF-0. Specimens HCF-0 and VCF-0

were considered to be effectively confined as they showed increased axial load from the yield load up to the failure load.

Axial Load and Bending Moment Interactions

Eccentric load subjects the column specimen to axial load and bending moment. The axial load-bending moment interaction diagrams for the tested specimens were drawn in Fig. 14 to illustrate the effect of the load eccentricity on the behavior of the specimens. The experimental ultimate bending moment (M_u) at the ultimate axial load (P_u) at the midheight of the eccentrically loaded specimens was calculated as:

$$M_u = P_u (e + \delta) \quad (1)$$

where δ is the lateral deformation corresponding to the ultimate axial load and e is the applied initial eccentricity. The experimental ultimate bending moment (M_u) at the ultimate load (P_u) at the midspan of the specimens tested under four-point loading was calculated as:

$$M_u = \frac{1}{2} P_u a \quad (2)$$

where a ($a=233$) is the length of span between the support and the loading point.

It is clear from Fig. 14 that the load carrying capacity of all specimens was reduced with the increase of the bending moment. The circularized specimens achieved the highest ultimate axial load and bending moment. The presence of the longitudinal CFRP straps reduces the effect of bending moment on the ultimate load of Specimens VCF-25, Specimen VCF-50 and Specimen VCF-F. Hence, Specimens VCF-25, VCF-50 and VCF-F achieved the highest ultimate load and the highest bending moment compared to the corresponding specimens in Groups HCF, CF, RF and N.

The theoretical axial load and bending moment of the tested specimens under concentric, eccentric and flexural loads were determined by using the equivalent rectangular stress block

according to AS 3600 (2009). The equivalent rectangular stress block is based on the strain compatibility in the concrete cross-section between steel bars and concrete. Eq. (3) was used to determine the area of concrete in compression for circular specimens. Eq. (4) and Eq. (5) were used to calculate the centroid of the concrete in compressive zone for circular specimens (Fig. 15).

$$A_c = (\theta - \sin\theta\cos\theta)(D/2)^2 \quad (3)$$

$$y = \frac{4R(\sin\theta)^2}{3(2\theta - \sin 2\theta)} \quad \text{For } \gamma d_n < D/2 \quad (4)$$

$$y = \frac{2R(\sin\theta)^3}{3(\pi - \theta + \sin\theta\cos\theta)} \quad \text{For } \gamma d_n > D/2 \quad (5)$$

where y , R and θ are as shown in Fig. 15.

The capacity of the specimens under concentric axial compression was calculated as:

$$P_a = 0.85 f'_{co} (A_g - A_s) + f_{sy} A_s \quad (6)$$

where f'_{co} is the unconfined concrete strength, A_g is the gross-sectional area of column and f_{sy} is the yield strength of longitudinal steel bars, and A_s is the total area of longitudinal steel bars.

The compressive strength of confined concrete was calculated based on the FRP confined concrete model proposed by Lam and Teng (2003) for circular and non-circular solid columns.

In this study, the Lam and Teng (2003) confinement model for solid columns was extended to determine the compressive strength of FRP confined hollow columns by multiplying with a coefficient β as in Fam and Rizkalla (2001) and Lignola et al. (2008):

$$\frac{f'_{cc}}{f'_{co}} = (1 + k_1 k_a \frac{f_l}{f'_{co}}) * \beta \quad (7)$$

$$\beta = 1 - \frac{r_i^2}{(D/2)^2} \quad (8)$$

For non-circular hole:

$$r_i = \sqrt{b_{hole}^2 + h_{hole}^2} \quad (9)$$

where f'_{cc} represents the compressive strength of FRP confined concrete, f_l represents the effective confining pressure, r_i represents the equivalent radius of the inner hole, D represents the diameter of a column, k_a represents the shape factor of non-circular columns, k_1 was taken as 3.3 and b_{hole} and h_{hole} are the length and width, respectively, of the non-circular cross-sectional hole.

The effect of transverse CFRP around the square specimens in Group HCF was neglected due to the sharp corners of the square specimens. Therefore, the theoretical axial load and the bending moment of Specimens CF and HCF are the same. The effect of longitudinal CFRP straps was also neglected for concentrically loaded specimen in Group VCF. Table 6 shows the experimental and theoretical axial load and bending moment of the tested specimens. The larger difference in the experimental and theoretical load-bending moments for the specimens tested under four-point loading might be because the shear span of the circularized beam specimens was shorter than twice the effective depth of concrete cross section.

Conclusions

From the results of the experimental investigation of 20 hollow RC specimens carried out in this study, the following conclusions can be drawn:

1. Circularization proved to be an effective technique in strengthening square hollow RC specimens in terms of strength and ductility.
2. Wrapping the square hollow RC specimens transversely with CFRP before circularization is more effective in enhancing the strength and ductility of the concentrically loaded circularized column than the eccentrically loaded circularized column.
3. Bonding longitudinal CFRP straps on the sides of the square hollow RC specimens before circularization increased the strength and ductility of the eccentrically loaded circularized hollow RC specimens.
4. Circularization and rounding the corners technique enhanced the strength and ductility of the square hollow RC specimens. However, the circularization is more effective in improving the behavior of the hollow RC specimens after the yield load.
5. The circularized specimens (specimens in Groups CF, VCF and HCF) achieved the highest axial load and bending moment followed by the rounded corner CFRP wrapped specimens (specimens in Group RF) under eccentric axial loads.
6. Bonding the specimens with longitudinal CFRP straps (specimens in Group VCF) increases the load carrying capacity and bending moment of the specimens under eccentric axial loads.

The above conclusions are based on experimental investigations of 20 hollow RC specimens with an unsupported wall length to thickness ratio of 1. Hence, the conclusions may not be directly applicable for the behavior of thin wall RC hollow columns with an unsupported wall length to thickness ratio higher than 1.

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References

548 ACI (American Concrete Institute). (2011). "Building Code Requirements for Structural
549 Concrete and Commentary." *ACI 318M-11*, Farmington Hills, MI 48331, USA.

550 Alsayed, S. H., Almusallam, T. H., Ibrahim, S. M., Al-Hazmi, N. M., Al-Salloum, Y. A. and
551 Abbas, H. (2014). "Experimental and numerical investigation for compression
552 response of CFRP strengthened shape modified wall-like RC column." *Construction
553 and Building Materials*, 63, 72-80.

554 AS1012.9. (1999). "Methods of testing concrete." *Standard Australia International Ltd.*,
555 NSW.

556 Australian Standard (AS 1391). (2007). "Metallic materials—Tensile testing at ambient
557 temperature." *1391:2007*, Sydney, NSW, Australia.

558 Australian Standard (AS 3600). (2009). "Concrete structures." *3600:2009*, Sydney, NSW,
559 Australia.

560 ASTM 7565. (2010). "Standard test methods for determining tensile properties of fiber
561 reinforced polymer matrix composites used for strengthening civil structures."
562 *D7565:2010*, West Conshohocken, PA.

563 Bisby, L. and Ranger, M. (2010). "Axial–flexural interaction in circular FRP-confined
564 reinforced concrete columns." *Construction and Building Materials*, 24, 1672-1681.

565 Chaallal, O. and Shahawy, M. (2000). "Performance of fiber-reinforced polymer-wrapped
566 reinforced concrete column under combined axial-flexural loading." *ACI Structural
567 Journal*, 97, 659-668.

568 Colajanni, P., Fossetti, M. and MacAluso, G. (2014). "Effects of confinement level, cross-
569 section shape and corner radius on the cyclic behavior of CFRCM confined concrete
570 columns." *Construction and Building Materials*, 55, 379-389.

571 CSA (Canadian Standards Association). (2006). "Canadian highway bridge design code."
572 *CAN/CSA S6-06*, Rexdale, ON, Canada.

573 Fam, A. Z. and Rizkalla, S. H. (2001). "Confinement model for axially loaded concrete
574 confined by circular fiber-reinforced polymer tubes." *ACI Structural Journal*, 98.

575 Faustino, P., Chastre, C. and Paula, R. (2014). "Design model for square RC columns under
576 compression confined with CFRP." *Composites part B-engineering*, 57, 187-198.

577 Fitzwilliam, J. and Bisby, L. A. (2010). "Slenderness Effects on Circular CFRP Confined
578 Reinforced Concrete Columns." *Journal of Composites for Construction*, 14, 280-288.

579 Foster, S. J. and Attard, M. M. (1997). "Experimental tests on eccentrically loaded high-
580 strength concrete columns." *ACI Structural Journal*, 94, 295-303.

581 Hadi, M. N., Pham, T. M. and Lei, X. (2012a). "New method of strengthening reinforced
582 concrete square columns by circularizing and wrapping with fiber-reinforced polymer
583 or steel straps." *Journal of Composites for Construction*, 17, 229-238.

584 Hadi, M. N. and Widiarsa, I. B. R. (2012). "Axial and flexural performance of square RC
585 columns wrapped with CFRP under eccentric loading." *Journal of Composites for
586 Construction*, 16, 640-649.

587 Hadi, M. N. S. (2006a). "Behaviour of FRP wrapped normal strength concrete columns under
588 eccentric loading." *Composite Structures*, 72, 503-511.

589 Hadi, M. N. S. (2006b). "Comparative study of eccentrically loaded FRP wrapped columns."
590 *Composite Structures*, 74, 127-135.

591 Hadi, M. N. S. (2007). "Behaviour of FRP strengthened concrete columns under eccentric
592 compression loading." *Composite Structures*, 77, 92-96.

593 Hadi, M. N. S. and Le, T. D. (2014). "Behaviour of hollow core square reinforced concrete
594 columns wrapped with CFRP with different fibre orientations." *Construction and
595 Building Materials*, 50, 62-73.

596 Hadi, M. N. S., Pham, T. M. and Lei, X. (2012b). "New method of strengthening reinforced
597 concrete square columns by circularizing and wrapping with fiber-reinforced polymer
598 or steel straps." *Journal of Composites for Construction*, 17, 229-238.

599 Harries, K. A. and Carey, S. A. (2003). "Shape and "gap" effects on the behavior of variably
600 confined concrete." *Cement and Concrete Research*, 33, 881-890.

601 Kusumawardaningsih, Y. and Hadi, M. N. S. (2010). "Comparative behaviour of hollow
602 columns confined with FRP composites." *Composite Structures*, 93, 198-205.

603 Lam, L. and Teng, J. G. (2003). "Design-oriented stress-strain model for FRP-confined
604 concrete in rectangular columns." *Journal of Reinforced Plastics and Composites*, 22,
605 1149-1186.

606 Li, G., Maricherla, D., Singh, K., Pang, S.-S. and John, M. (2006). "Effect of fiber orientation
607 on the structural behavior of FRP wrapped concrete cylinders." *Composite Structures*,
608 74, 475-483.

609 Li, J. and Hadi, M. N. S. (2003). "Behaviour of externally confined high-strength concrete
610 columns under eccentric loading." *Composite Structures*, 62, 145-153.

- Lignola, G. P., Prota, A., Manfredi, G. and Cosenza, E. (2008). "Unified theory for confinement of RC solid and hollow circular columns." *Composites Part B*, 39, 1151-1160.
- Moran, D. A. and Pantelides, C. P. (2012). "Elliptical and circular FRP-confined concrete sections: A Mohr–Coulomb analytical model." *International Journal of Solids and Structures*, 49, 881-898.
- Pantelides, C. P. and Yan, Z. (2007). "Confinement Model of Concrete with Externally Bonded FRP Jackets or Posttensioned FRP Shells." *Journal of Structural Engineering*, 133, 1288-1296.
- Pham, T. M., Doan, L. V. and Hadi, M. N. S. (2013). "Strengthening square reinforced concrete columns by circularisation and FRP confinement." *Construction and Building Materials*, 49, 490-499.
- Priestley, M. J. N. and Seible, F. (1995). "Design of seismic retrofit measures for concrete and masonry structures." *Construction and Building Materials*, 9, 365-377.
- Rochette, P. and Labossiere, P. (2000). "Axial testing of rectangular column models confined with composites." *Journal of Composites for Construction*, 4, 129-136.
- Saadatmanesh, H., Ehsani, M. and Jin, L. (1997). "Seismic retrofitting of rectangular bridge columns with composite straps." *Earthquake Spectra*, 13, 281-304.
- Sheikh, M. N. and Légeron, F. (2014). "Performance based seismic assessment of bridges designed according to Canadian Highway Bridge Design Code." *Canadian Journal of Civil Engineering*, 41, 777-787.
- Sheikh, M. N., Vivier, A. and Legeron, F. (2007). "Seismic assessment of hollow core concrete bridge piers." In *Proceedings of the Ninth Canadian Conference on Earthquake Engineering*, The Canadian Association for Earthquake Engineering, Ottawa, Ontario, Canada, 1631-1640.
- Silva, M. A. G. (2011). "Behavior of square and circular columns strengthened with aramidic or carbon fibers." *Construction and Building Materials*, 25, 3222-3228.
- Tan, K. H. (2002). "Strength Enhancement of Rectangular Reinforced Concrete Columns using Fiber-Reinforced Polymer." *Journal of Composites for Construction*, 6, 175-183.

- 641 Taylor, A. W., Rowell, R. B. and Breen, J. E. (1995). "Behavior of thin-walled concrete box
642 piers." *ACI Structural Journal*, 92, 319-333.
- 643 Yan, Z. and Pantelides, C. P. (2011). "Concrete column shape modification with FRP shells
644 and expansive cement concrete." *Construction and Building Materials*, 25, 396-405.
- 645 Yan, Z., Pantelides, C. P. and Reaveley, L. D. (2006). "Fiber-reinforced polymer jacketed and
646 shape-modified compression members: I - Experimental behavior." *ACI Structural*
647 *Journal*, 103, 885-893.
- 648 Yazici, V. and Hadi, M. N. (2009). "Axial load-bending moment diagrams of carbon FRP
649 wrapped hollow core reinforced concrete columns." *Journal of Composites for*
650 *Construction*, 13, 262-268.
- 651 Yeh, Y. K. and Mo, Y. L. (2005). "Shear Retrofit of Hollow Bridge Piers with Carbon Fiber-
652 Reinforced Polymer Sheets." *Journal of Composites for Construction*, 9, 327-336.

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Fig. 15. Centroid of the compression zone of circular column

Table 1. Test matrix

Specimen	strengthening square specimen with CFRP	Cross- section (mm)	Gross concrete area (mm ²)	Height (mm)	Modification	External wrapping with CFRP	Eccentricit y (mm)
N-0							0
N-25							25
N-50	–	150x150	19547	800	None	–	50
N-F							Four-point loading
RF-0						Wrapping with two layers of CFRP	0
RF-25	–	150x150	19204	800	20-mm rounded corners		25
RF-50							50
RF-F							Four-point loading
CF-0							0
CF-25					Circularization by bonding	Wrapping with two layers of CFRP	25
CF-50	–	Φ 212	32360	800	four precast concrete segments		50
CF-F							Four-point loading
VCF-0	Bonding				Circularization	Wrapping	0
VCF-25	longitudinal				by bonding	with two	25
VCF-50	CFRP straps	Φ 212	32360	800	four precast	layers of	50
VCF-F	one on each side				concrete segments	CFRP	Four-point loading
HCF-0	Wrapping				Circularization	Wrapping	0
HCF-25	with one				by bonding	with two	25
HCF-50	layer of	Φ 212	32360	800	four precast	layers of	50
HCF-F	CFRP				concrete segments	CFRP	Four-point loading

Table 2. Results of the concentrically loaded specimens

Specimen	N-0	RF-0	CF-0	VCF-0	HCF-0
Axial load at yield (kN)	800	800	1403	1508	1631
Axial deformation at yield (mm)	2.2	2.2	2.3	2.5	2.4
Ultimate axial load (kN)	989	1160	2169	2162	2190
Axial deformation at ultimate axial load (mm)	2.5	9.5	12.7	10.5	9.8
Ductility	1.4	4.4	5.9	4.4	4.2
Increase in the ultimate axial load relative to the reference specimen (%)	–	17	119	119	121

Table 3. Results of the 25 mm eccentrically loaded specimens

Specimen	N-25	RF-25	CF-25	VCF-25	HCF-25
Axial load at yield (kN)	582	610	985	1011	1045
Axial deformation at yield (mm)	2.2	2.4	2.5	2.3	2.9
Axial load at ultimate load (kN)	642	692	1209	1279	1409
Axial deformation at ultimate axial load (mm)	2.4	3	6.2	5.7	4.2
Lateral deflection at ultimate axial load (mm)	2.3	4	9	8.6	5
Ductility	1.2	3.1	5.6	5.8	4.3
Increase in the ultimate axial load relative to the reference specimen (%)	—	8	88	99	120

Table 4. Results of the 50 mm eccentrically loaded specimens

Specimen	N-50	RF-50	CF-50	VCF-50	HCF-50
Axial load at yield (kN)	315	460	680	726	741
Axial deformation at yield (mm)	2.1	2.9	2.4	2.5	2.7
Ultimate axial load (kN)	393	505	885	975	955
Axial deformation at ultimate axial load (mm)	2.7	3.4	3.5	9.7	4.2
Lateral deflection at ultimate axial load (mm)	4	5	5	12.5	5.5
Ductility	1.5	2.6	4.2	4.9	3.6
Increase in the ultimate axial load relative to the reference specimen (%)	—	29	125	148	143

Table 5. Results of specimens tested under four-point loading

Specimen	N-F	RF-F	CF-F	VCF-F	HCF-F
Yield load (kN)	116	113	158	270	188
Midspan deflection at yield (mm)	4.2	4.3	4.5	3.0	4.2
Ultimate load (kN)	139	162	263	338	278
Midspan deflection at ultimate load (mm)	7.6	21	32	19	21.5
Ductility	6.2	6.8	8.4	9.4	8.0
Increase in the ultimate load relative to the reference specimen (%)	–	17	89	143	100

Table 6. Theoretical and Experimental Results of specimens tested under different loading eccentricities

Specimen	Load (kN)		Theo./exp. (%)	Bending moment (kN-m)		Theo./exp. (%)
	Experimental	Theoretical		Experimental	Theoretical	
N-0	989	1039	1.05	-	-	
N-25	642	641	1.00	17.5	16	0.91
N-50	393	431	1.10	21.3	21.5	1.01
N-F	-	-	-	16	15	0.94
RF-0	1160	1097	0.95	-	-	-
RF-25	692	709	1.02	20	17.7	0.89
RF-50	505	489	0.97	27.5	24.5	0.89
RF-F	-	-	-	19	15.3	0.81
CF-0	2169	1865	0.86	-	-	-
CF-25	1209	1207	1.00	41	30.5	0.73
CF-50	885	832	0.94	48.5	42	0.87
CF-F	-	-	-	30.5	21.5	0.70
VCF-0	2162	1865	0.86	-	-	-
VCF-25	1279	1229	0.96	43	31.5	0.73
VCF-50	975	867	0.89	61	43	0.71
VCF-F	-	-	-	40	30	0.75
HCF-0	2190	1865	0.85	-	-	-
HCF-25	1409	1207	0.86	42.5	30.5	0.73
HCF-50	955	832	0.87	53	42	0.80
HCF-F	-	-	-	32.5	21.5	0.66

Fig. 1. Plan view of specimens (units in mm)

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Fig. 7. Failure modes of the specimens tested under eccentric axial load ($e = 50$ mm)

Fig. 8. Failure modes of the specimens tested under four-point loading

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(a) Axial load-bending moment interaction diagrams

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Note: P_u is the ultimate axial load, M_u is the ultimate bending moment, A_g is the gross section area, f'_c is the compressive strength of concrete, D is the diameter of circular specimens and h is the side length of the cross section of square specimens

Fig. 14. Experimental axial load-bending moment interaction diagrams of the tested specimens.

Fig. 15. Centroid of the compression zone of circular column