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Axial and Flexural Behaviour of Circular Reinforced Concrete Columns Strengthened with Reactive Powder Concrete Jacket and Fibre Reinforced Polymer Wrapping

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Abstract

This paper investigates axial and flexural behaviour of circular reinforced concrete (RC) columns strengthened with reactive powder concrete (RPC) jacket and fibre reinforced polymer wrapping. The experimental results of 16 circular RC column specimens have been presented. The specimens were divided into four groups of four specimens. Column specimens of the first group were the reference RC specimens without any strengthening, specimens of the second group

were strengthened by wrapping with two layers of carbon fibre reinforced polymer (CFRP), specimens of the third group were jacketed with a 25 mm thick layer of RPC and specimens of the fourth group were jacketed with a 25 mm thick layer of RPC then wrapped with a single layer of CFRP. Test results demonstrated that jacketing with a thin layer of the RPC enhanced significantly the ultimate axial and flexural loads as well as energy absorption of circular RC column specimens. Wrapping the RPC jacketed specimens with CFRP improved the ultimate axial load, ductility and energy absorption of the specimens.

Keywords: Concrete columns; Reactive powder concrete; FRP; Jacketing; Wrapping.

1. Introduction

Reinforced concrete (RC) columns in buildings, highway bridges and other infrastructure may need to be strengthened in some cases. These cases include deterioration due to corrosion of steel reinforcement, damage after an earthquake event, inadequate design, functional changes and construction errors. Deficient RC columns have to be repaired before strengthening [1]. Jacketing is one of the most practical techniques used for restoring deficient RC columns [2]. The traditional reinforced concrete jacket probably no longer remains an effective jacketing technique as it is associated with several disadvantages including decrease in the available space of the strengthened structure, a significant increase of the dead load, slow construction process and practical problems for the required dowelling with the existing column as well as with the slab and foundation [1, 3, 4].

The other commonly used jackets for increasing the axial strength of RC columns are steel and fibre reinforced polymer (FRP) jackets [5]. Steel jacket has the problem of low corrosion resistance [6]. Hence, FRP is considered as one of the most suitable jacketing materials for strengthening RC columns. The FRP has a higher strength to weight ratio and superior durability compared to steel [7]. Wrapping RC columns with FRP increases the strength and ductility of the RC columns. However, FRP wrapping cannot be applied directly for strengthening a deteriorated RC column unless the surface of the RC column is suitably repaired. Also, the reliability of FRP wrapping decreases under freezing, thawing and temperature changes [8].

Similar to steel jacket, FRP jacket depends mainly on the principle of the lateral confinement pressure [6]. The efficiency of the confinement decreases when a column is subjected to an eccentric axial load [9-11]. Also, the confinement effect decreases when the diameter of the cylindrical concrete specimens increases [12]. Thus, several layers of FRP are required if only FRP wrapping is used for the strengthening of large diameter RC columns. Increasing the FRP layers is not only expensive but also causes bond failure [8]. Moreover, only slight improvement in the yield strength and flexural capacity of the RC column can be achieved by the FRP wrapping [13].

Reactive powder concrete (RPC) is a high performance concrete with high strength and high ductility [14]. The RPC has a dense structure, which is formed mainly by cement, silica fume, fine aggregate, water and superplasticizer. Steel fibre is usually used to improve the ductility of the RPC. The absence of the coarse aggregate in the RPC matrix is the main difference between the RPC and the other types of concrete. The high strength of the RPC reduces the required

reinforcement and cross-sectional dimensions for the RPC structural members compared to the conventional RC members [15]. Lee et al. [16] and Chang et al. [17] proposed using the RPC as a durable strengthening and repairing material. Lee et al. [16] and Chang et al. [17] used the RPC to strengthen cylinder and prism specimens exposed to hazardous conditions to increase the compressive and flexural strength of the specimens.

Even though RPC has a superior compressive strength compared to other types of concrete, studies on the use of RPC in the columns are still very limited. Malik and Foster [18] however, conducted an experimental study on circular RPC column specimens wrapped with carbon fibre reinforced polymer (CFRP). The study reported that the axial strength of the CFRP confined RPC column specimen was 19% higher than the axial strength of unconfined column specimen. Also, Huynh et al. [19] examined the behaviour of square RC specimens constructed of high strength concrete (HSC) and RPC under three-point bending. The test results indicated that the partial replacement of the HSC by the RPC enhanced the strength and energy absorption capacity of the tested specimens. However, strengthening of RC columns with RPC jacket has not been investigated yet. This study proposes using RPC jacket for strengthening existing deficient circular RC columns.

The objective of this study is to develop an effective strengthening technique with RPC jacket and FRP wrapping for the existing deficient circular RC columns. The experimental investigation results of circular RC column specimens strengthened with a thin layer of RPC jacket and wrapped with FRP tested under different loading conditions have been presented. The loading conditions included concentric axial load, eccentric axial loads and four-point bending.

The innovating strengthening technique of using RPC jacket and FRP wrapping has been found to be effective in increasing the yield load, ultimate load and energy absorption capacity of existing deficient circular RC columns.

2. Experimental program

2.1. Test matrix

The experimental program of this study included preparing and testing of 16 RC column specimens. These specimens were divided into four groups of four specimens based on the adopted strengthening technique. All base specimens (assumed to be existing columns) had a diameter of 150 mm with a height of 800 mm. Each base specimen was reinforced longitudinally with 6N10 (6 deformed steel bars of 10 mm diameter) and transversely with R6 (smooth steel bar of 6 mm diameter) helices at a centre to centre spacing of 50 mm. A clear concrete cover of 15 mm was provided at the sides and at the top and bottom of the specimen. All base specimens were cast with normal strength concrete (NSC) having a target compressive strength of 25 MPa. The NSC was supplied by a local company. The first group was the reference RC base specimens without any strengthening and was identified as Group C specimens. Specimens of the second group were wrapped with two layers of CFRP and were identified as Group CF specimens. The specimens of the third group were strengthened with a 25 mm thick RPC jacket and were identified as Group CJ specimens. The thickness of 25 mm was chosen for RPC jacket because the thickness of 25 mm was considered as the minimum practical thickness of the RPC jacket for the ease of cast and compaction. The specimens of the last group were strengthened with a 25 mm thick RPC jacket then wrapped with a single layer of CFRP. The specimens of the last group were identified as Group CJF specimens. The plan views of the reference and the

strengthened specimens are shown in Fig. 1. From each group, one specimen was tested under concentric axial load, two specimens were tested under 15 mm and 25 mm eccentric axial loads, respectively, and the remaining specimen was tested under four-point bending. To identify the loading condition, a number or a letter were added to the labels of the specimens. The first part of each specimen label refers to the group name and the second part refers to the loading condition. For instance, Specimen CF-25 refers to the specimen that was wrapped with two layers of CFRP and tested under 25 mm eccentric axial load. Specimen CJ-B was jacketed with 25 mm thick RPC and tested under four-point bending. The details of the specimens are presented in Table 1.

2.2. Preparation of RPC

Typical RPC mix usually includes cement, silica fume, fine sand, superplasticizer, water and steel fibre. General Purpose cement (Type GP) according to AS 3972-2010 [20] was used to prepare the RPC. Densified silica fume was used as a supplementary cementitious material. The silica fume was produced in SIMCOA silicon plant, Western Australia [21], and was supplied by Australasian (iron & steel) Slag Association [22]. The sand used for the RPC was washed fine river sand with particle size ranging between 150 μm and 600 μm . Master Glenium SKY 8700 used as a superplasticizer, which was supplied by BASF, Australia [23]. The steel fibres used in this study were straight and smooth with a length of 13 mm, a diameter of 0.2 mm, an aspect ratio (length/diameter) of 65, a density of 7.8 g/cm^3 and a nominal tensile strength of 2500 MPa [24]. The steel fibres are shown in Fig. 2. The steel fibres were supplied by Steel Wire Fibre in China [24].

The RPC mix design is presented in Table 2. The proportion of the steel fibre was 1.5% by volume. The proportion of steel fibre (1.5% by volume) was selected based on the experimental findings in Ju et al. [25]. Mixing of RPC batches was carried out using a vertical pan mixer in the Structural Engineering Laboratories at the University of Wollongong, Australia. Flow table test according to ASTM C230-14 [26] was used to evaluate the flowability of the RPC. The produced RPC achieved high flowability with 220 mm flow diameter.

2.3. Properties of materials

Engineering properties of the NSC and RPC were determined according to AS 1012-2014 [27-29] except the shear strength of the RPC which was determined according to JSCE SF6-1999 [30]. The details of the specimens and tests results for the RPC at 28 days are shown in Table 3. The average compressive strength of the RPC was 110 MPa at 28 days (start of the test) and 113 MPa at the end of the test. At age of 28 days, the average splitting tensile strength of the RPC was 9 MPa. The splitting tensile test was used to determine the tensile strength of the RPC, as recommended in AS 3600-2009 [31] for concrete. The average modulus of rupture of the RPC was 12 MPa and the average shear strength was 30 MPa. The NSC had an average compressive strength of 29 MPa and an average splitting tensile strength of 2.5 MPa at 28 days. The compressive strength of the NSC was 33 MPa at the start of the test and 35 MPa at the end of the test.

The tensile strength of both longitudinal and transverse steel reinforcement bars of the base specimens was determined according to AS 1391-2007 [32] using the Instron 8033 testing machine with a capacity of 500 kN. The deformed N10 steel bar had an average yield tensile

strength of 524 MPa and an average ultimate tensile strength of 660 MPa. The smooth R6 steel bar had an average yield tensile strength of 578 MPa and an average ultimate tensile strength of 613 MPa. The CFRP sheet had an average width of 100 mm and an average thickness of 0.3 mm. The coupon test according to ASTM D3039-08 [33] was used to determine the tensile strength of the CFRP. The specimens of the coupon test had an average width of 25 mm and an average length of 250 mm. The test was conducted using the Instron 8033 testing machine with a capacity of 500 kN. The average maximum tensile force per unit width of one layer of the CFRP sheet was 537 N/mm. The average maximum tensile force per unit width of two layers of the CFRP sheets was 1249 N/mm. Test results of the CFRP with one and two layers are reported in Table 4.

2.4. Preparation of test specimens

Formwork of the base specimens was prepared by using PVC pipes with a clear interior diameter of 150 mm and a height of 800 mm. The PVC pipes were supported by plywood frames at the top and the bottom. The bottoms of the PVC pipes were fixed with a plywood base by silicon glue. The longitudinal bars were cut and tied with the helix to form reinforcement cages. All reinforcement cages were placed inside the formworks. The NSC was cast inside the formwork then compacted using two small electric vibrators. The base specimens were left to cure for one day then covered with wet hessian rugs for six days. The base specimens were demoulded after seven days of the wet curing then left to cure under the laboratory conditions until the day of the RPC jacketing (26-day age). Eight base specimens were jacketed with RPC (Groups CJ and CJF) and the remaining eight specimens were left without jacketing. Later, four of the unjacketed

specimens were wrapped with two layers of CFRP (Group CF) and the remaining four specimens were left without any wrapping as reference specimens (Group C).

During the curing period of the base specimens, surface preparation and the formwork of the RPC jacket for eight base specimens (Groups CJ and CJF) were completed. To ensure sufficient bond strength between the surface of the base specimen and the RPC jacket, adequate care was taken to make the surface of the base specimen rough. At first, the base specimen was sandblasted inside a closed sandblasting chamber. Afterwards, a small chipping hammer was used to prickle the zones of the base specimen which were not adequately sandblasted (Fig. 3). Then, a steel wire brush was used to remove all the weak particles from the surface of the base specimen. The specimens were then cleaned by an air jet. At last, the surface of the base specimen was cleaned with a piece of wet cloth and left to dry in the laboratory.

The formwork of the RPC jacket was prepared by using an easy form cardboard with a 200 mm clear interior diameter. After the surface preparation was done, the eight base specimens were placed on a plywood base then each cardboard formwork was installed on a specimen and glued with the plywood base. The cardboard formwork was supported vertically by plywood frames at the top, mid-height and bottom. The RPC jackets were then cast. Two small electric vibrators were applied on the outer surface of the formwork to compact the RPC. The flowability of the produced RPC was high enough to achieve an efficient pouring for the RPC between the formwork and the base specimen. Figure 4 shows the formwork of the base and RPC jacketed specimens before and after jacketing. The RPC jacketed specimens (Groups CJ and CJF) were left to cure for one day then covered with wet hessian rugs for six days. Afterwards, the eight

jacketed specimens were demoulded. Four specimens (Group CJF) were prepared for wrapping with CFRP.

The specimens of Groups CF and CJF were wrapped with CFRP sheets by the wet layup technique. First, the CFRP sheets were cut into pieces of specified lengths equal to the specimen circumference (or twice the specimen circumference in case of two layers wrapping) plus 100 mm for the circumferential overlap. The CFRP sheet was coated with epoxy resin on both sides. The epoxy resin was prepared by mixing epoxy and hardener at a ratio of 5:1 by volume. The specimen surface was also coated with the epoxy resin. The coated CFRP sheet was wrapped gently on the surface of the specimen without adding any additional epoxy resin between the layers. Lastly, the surface of the CFRP sheet was coated with a very thin layer of epoxy resin, especially at the overlap zone. This technique was found to be effective in preventing de-bonding failure between the CFRP layers during testing. The CFRP sheets were wrapped with a vertical overlap of 10 mm. The specimens of Groups CF and CJF were wrapped entirely with CFRP. Specimens of Group CF were wrapped with two layers of CFRP, whereas the Specimens of Group CJF were wrapped with one layer of CFRP.

All specimens which were tested under the concentric and eccentric axial loads were wrapped at the ends with two layers of CFRP of 100 mm wide to prevent any premature failure at the ends of the specimen during testing. The four specimens which were tested under four-point bending were wrapped with two layers of CFRP from the two ends up to the mid one-third (up to the pure bending moment zone) of the specimen. This was done to avoid shear failure for Specimen CJ-B.

The same wet layup technique was used to wrap the ends of the specimens. All wrapped specimens were left to cure in the laboratory for at least seven days before testing.

2.5. Instrumentation and test procedure

All reference and strengthened RC specimens were tested using the Denison testing machine with a capacity of 5000 kN under displacement control load application at 0.5 mm per minute. The data of the axial load were captured directly from load cell of the testing machine, while the data of the axial deformation were recorded from average readings of two Linear Variable Differential Transducers (LVDTs). The two LVDTs were connected with the lower plate of the test machine and attached vertically with the two opposite corners of the upper plate of the test machine. The mid-height lateral deformation of the eccentrically loaded specimens and the midspan deflection of the four-point bending test specimens were captured by a laser triangulation. Loading heads similar to those used by Hadi et al. [34] were used to apply the eccentric axial load. The specimens were capped at the top and bottom using high strength plaster and left to dry for about one hour before the test. The test setup of the eccentrically loaded specimen is shown in Fig. 5. The steel frame that was used for the four-point bending test of Specimens CB, CFB, CJB and CJFB was similar to that used by Hadi et al. [35]. The shear span provided for all the specimens tested under four-point bending was 233 mm.

3. Results of testing

3.1 Definition of strengthening ratio, ductility and energy absorption ratio

To investigate the influence of the proposed strengthening method, the strengthening ratio was calculated at both yield and ultimate loads. The yield strengthening ratio was expressed as the

ratio of the yield load of the strengthened specimen to the yield load of the corresponding reference specimen in Group C. The ultimate strengthening ratio was expressed as the ratio of the ultimate load of the strengthened specimen to the ultimate load of the corresponding reference specimen in Group C.

The ductility was calculated by dividing the deformation corresponding to the 85% of the peak load in the descending part of the load-deformation curve by the deformation at yield load (δ_y) [36]. The δ_y was determined by the intersection point of two straight lines. The first straight line is the best-fit regression line to the linear segment of the load-deformation curve and the second line is a horizontal straight line passing through the ultimate load [37].

Energy absorption was calculated as the area under the load-deformation curve. In this study, energy absorption for the specimens tested under concentric and eccentric axial loads was expressed as the area under the load-deformation curve at $3\delta_y$ [38]. However, energy absorption at $3\delta_y$ for the specimens tested under four-point bending was considered misleading, because the deflection $3\delta_y$ occurred at a flexural load before the specimen reached the ultimate flexural load. Therefore, energy absorption of the specimens tested under four-point bending was expressed as the area under the load-deflection curve up to $10.5\delta_y$ [38]. The energy absorption ratio was expressed as the ratio of the energy absorption of the strengthened specimen to the energy absorption of the corresponding reference specimen in Group C.

3.2. Behaviour of the concentrically loaded specimens

Figure 6 shows the axial load-axial deformation response of the reference specimen and the strengthened specimens under concentric axial load. Specimen C-0 experienced premature concrete cover spalling at the mid-height followed by large cracks at different locations in the specimen. The premature concrete cover spalling was probably due to the relatively small pitch of the transverse reinforcement, which formed a plane of separation between the concrete core and the concrete cover. Final failure of Specimen C-0 occurred due to the buckling of the longitudinal steel bars, as shown in Fig. 7. The yield axial load of Specimen C-0 was 536 kN and the yield axial deformation was 2.9 mm (Table 5). Specimen C-0 achieved an ultimate axial load of 615 kN. After the spalling of concrete cover, the confinement of the transverse reinforcement was activated and the specimen carried the applied axial load with a ductility of 5.7. This high ductility was due to the high yield strength and the relatively small pitch of the transverse reinforcement which generated high confinement to the concrete core. However, this high ductility may not be representative of the existing deteriorated RC columns. The energy absorption of the specimen was 4297 kN.mm. The axial deformation at the final failure of Specimen C-0 was 19 mm.

Specimen CF-0 failed suddenly by the rupture of the CFRP and by the crushing of concrete at the mid-height segment of the specimen, as shown in Fig. 7. The ultimate axial load of 1245 kN was achieved by a quasi-bilinear behaviour with an increase in the axial load with the increase in the axial deformation (hardening response). Yield strengthening ratio of 1.33 and ultimate strengthening ratio of 2.02 were achieved by Specimen CF-0 (Table 5). Specimen CF-0 demonstrated a lower ductility compared to Specimen C-0. The ductility of Specimen CF-0 was

4. However, the energy absorption ratio was 1.43. The lower ductility of Specimen CF-0 compared to that of Specimen C-0 was due to the sudden rupture of the CFRP and crushing of concrete which caused the final failure of the specimen before the buckling of the longitudinal steel bars at an axial deformation of 18 mm, which was only 5% lower than that of Specimen C-0. No residual axial load capacity for the Specimen CF-0 was observed after the ultimate axial load.

The failure of Specimen CJ-0 started with a vertical crack along the length of the specimen then inclined and vertical cracks were developed in several locations in the specimen (Fig. 7). This was because of the inadequate lateral tensile strength of the RPC jacket, which was not able to resist the expansion of the concrete core. The ultimate axial load of Specimen CJ-0 was only 6% higher than the yield axial load as the confinement of the RPC jacket on the concrete core was not significant. After reaching the ultimate axial load, the axial load dropped to about 80% of the ultimate axial load due to the vertical splitting in the RPC jacket. This was followed by a softening phase, as the RPC jacket did not entirely fail. Later, the axial load dropped to about 55% of the ultimate axial load due to the inclined splitting in the RPC jacket. Afterwards, the confinement provided by the steel helices prevented further expansion of the concrete core and the specimen showed a decrease in the axial load with the increase in the axial deformation (softening response). The final failure occurred when some parts of the RPC jacket were separated from the body of the specimen (Fig. 7). Specimens CJ-0 had a gradual failure during the test and the concrete core of the specimen demonstrated resistance and integrity up to the end of the test. Axial deformation of Specimens CJ-0 at failure was 21 mm, which was about 10% higher than the axial deformation of Specimen C-0 at failure. Specimen CJ-0 achieved a

significant enhancement in the axial load capacity with a yield strengthening ratio of 2.78 and an ultimate strengthening ratio of 2.55 (Table 5). The ductility of Specimen CJ-0 was 1.4, which is less than the ductility of Specimen C-0. This can be attributed to the considerable enhancement in the axial stiffness due to the RPC jacket, which decreased the deformability and thereby decreased the ductility. Nevertheless, the energy absorption ratio of Specimen CJ-0 was 1.6.

Specimen CJF-0 failed by the rupture of the CFRP at the upper one-third segment of the specimen followed by crushing of RPC jacket (Fig. 7). The axial load of the specimen increased up to the ultimate axial load due to the wrapping of the CFRP. Afterwards, a drop in the axial load occurred due to the rupture of the CFRP, which decreased the axial load to about 75% of the ultimate axial load. The subsequent drop in the axial load decreased the axial load to about 50% of the ultimate axial load, which occurred due to the crushing in the RPC jacket. This was followed by a ductile behaviour with softening response due to the confinement of the steel helices up to the end of the test. The test was stopped when the axial deformation of Specimen CJF-0 reached to 25 mm. It is noted that Specimen CJF-0 did not entirely fail at the axial deformation of 25 mm. Specimen CJF-0 had a yield strengthening ratio and an ultimate strengthening ratio of 3.69 and 3.4, respectively. The ductility of Specimen CJF-0 was 1.8 and the energy absorption ratio was 3.07 (Table 5).

It is apparent that Specimens CJ-0 and CJF-0 had higher ultimate axial load and energy absorption capacity than Specimen CF-0. In addition, the yield strengthening ratio of Specimens CJ-0 and CJF-0 was 109% and 177%, respectively, higher than the yield strengthening ratio of Specimen CF-0. This indicates that the strengthening of circular RC columns with RPC and RPC

plus CFRP is more effective than strengthening with CFRP only to achieve a higher yield strength. This can be explained by the fact that confinement has a marginal beneficial effect on the yield strength. Furthermore, the ductility of Specimen CJF-0 was 28% higher than the ductility of Specimen CJ-0 and energy absorption of Specimen CJF-0 was 92% greater than energy absorption of Specimen CJ-0. Wrapping of the RPC jacket for Specimen CJF-0 not only increased the ultimate axial load and the ductility but also prevented the expansion of the concrete core, which was the major cause of the failure of Specimen CJ-0.

3.3 Behaviour of the eccentrically loaded specimens

Axial load-axial deformation response of the specimens tested under eccentric axial load with 15 mm eccentricity is shown in Fig. 8. Specimen C-15 failed by outward buckling and tensile cracks at the tension side followed by the crushing of concrete at the compression side, as shown in Fig. 9. The yield axial load of Specimen C-15 was 393 kN and the yield axial deformation was 2.2 mm. Specimen C-15 achieved an ultimate axial load of 436 kN, which was followed by a softening response. The ductility of Specimen C-15 was 1.9, which was achieved due to the confinement provided by the transverse reinforcement. The energy absorption of Specimen C-15 was 2057 kN.mm (Table 6).

Specimen CF-15 failed initially by outward buckling on the tension face and later by rupture of the CFRP with crushing of concrete on the compression face at the mid-height of the specimen. Specimen CF-15 exhibited initial axial load-axial deformation behaviour similar to that of Specimen C-15. However, the yield strengthening ratio of Specimen CF-15 was 1.18 and the ultimate strengthening ratio was 1.31. Specimen CF-15 achieved a higher ductility than

Specimen C-15. The ductility and energy absorption ratio of Specimen CF-15 were 4.3 and 2, respectively (Table 6).

The failure of Specimen CJ-15 occurred by tensile-flexural cracking with splitting vertical cracks at the upper one-third segment of the specimen, as shown in Fig. 9. The axial load of Specimen CJ-15 increased up to the ultimate axial load then dropped to about 50% of the ultimate axial load due to the splitting of the RPC jacket. Later the specimen showed a softening response due to the confinement provided by the internal steel helices. Specimen CJ-15 achieved a higher yield strengthening ratio and a higher ultimate strengthening ratio than Specimen CF-15. The specimen achieved a yield strengthening ratio of 3.72 and an ultimate strengthening ratio of 3.53. The ductility of Specimen CJ-15 was 1.3 and the energy absorption ratio was 3.73 (Table 6).

Specimen CJF-15 failed by the rupture of CFRP and the crushing of concrete at the mid-height of the specimen at the compression side (Fig. 9). General axial load-axial deformation behaviour of Specimen CJF-15 was similar to that of Specimen CJ-15. However, Specimen CJF-15 achieved higher yield axial load, ultimate axial load, axial ductility and energy absorption compared to Specimen CJ-15. The yield strengthening ratio of Specimen CJF-15 was 3.95 and the ultimate strengthening ratio was 4.07. The ductility and the energy absorption ratio of Specimen CJF-15 were 1.4 and 4.5, respectively (Table 6).

Figure 10 shows the axial load-axial deformation response of the specimens tested under the eccentric axial load of 25 mm eccentricity. Specimen C-25 failed by the crushing of concrete at the mid-height segment of the specimen followed by concrete cracking on the tension face at the

upper one-third segment of the specimen (Fig. 11). The axial load-axial deformation response of Specimen C-25 was characterized by a yield axial load of 295 kN with a yield axial deformation of 2.6 mm and an ultimate axial load of 338 kN. The ultimate axial load was followed by a softening response. The ductility and energy absorption of Specimen C-25 were 2.3 and 1916 kN.mm, respectively (Table 7).

The failure of Specimen CF-25 occurred by outward buckling at the tension face then by rupturing of CFRP and crushing of concrete at the compression face, as shown in Fig. 11. The axial load of Specimen CF-25 gradually increased up to the ultimate axial load, which was followed by a softening response up to the final failure, which occurred by the rupture of CFRP. Specimen CF-25 achieved a yield strengthening ratio of 1.33 and an ultimate strengthening ratio of 1.41. The ductility of Specimen CF-25 was 3.5 and the energy absorption ratio was 2.1 (Table 7).

Specimen CJ-25 failed by typical tensile-flexural failure at the mid-height segment of the specimen with crushing and splitting of RPC, as shown in Fig. 11. Specimen CJ-25 achieved ultimate axial load of 1276 kN then the axial load dropped to about 45% of the ultimate axial load. Afterwards, the specimen exhibited a softening response due to the confinement provided by the internal lateral steel reinforcement. For Specimen CJ-25, the yield strengthening ratio was 3.92 and the ultimate strengthening ratio was 3.77. Ductility of Specimen CJ-25 was 1.2 and energy absorption ratio was 2.3 (Table 7).

Specimen CJF-25 failed by the rupture of the CFRP and the crushing of the RPC at the upper one-third segment of the specimen (Fig. 11). The initial axial load-axial deformation response of Specimen CJF-25 was similar to that of Specimen CJ-25. However, Specimen CJF-25 demonstrated higher yield strengthening ratio, ultimate strengthening ratio, ductility and energy absorption ratio compared to Specimen CJ-25. The yield strengthening ratio of Specimen CJF-25 was 4.34 and the ultimate strengthening ratio was 4.05. Ductility of Specimen CJF-25 was 1.5 and energy absorption ratio was 3.17 (Table 7).

3.4. Behaviour of the specimens under four-point bending

The flexural load-midspan deflection curves of the specimens tested under four-point bending are shown in Fig. 12. All the specimens tested under four-point bending failed by typical vertical flexural cracks at the midspan region of the specimen, as shown in Fig. 13. Initially, the first vertical crack was formed then the crack became wider when the applied load reached the ultimate load. Several cracks were observed after the ultimate load. All the cracks started from the tension side of the specimen and propagated upwards within the midspan region of the specimen.

Initial load-midspan deflection response of Specimen C-B was quasi-linear with a yield load of 115 kN and corresponding yield deflection of 7.7 mm. Afterward, the flexural load-midspan deflection response showed a slightly hardening response up to the ultimate flexural load of 157 kN with the corresponding deflection of 53 mm. The final failure of the specimen occurred suddenly by the rupture of the farthest tensile steel bar at the midspan deflection of 64 mm. Specimen C-B achieved a high ductility of 8.3 and an energy absorption of 8530 kN.mm (Table

8). The high ductility of Specimen C-B was due to the high ultimate tensile strength of the steel bars.

The initial part of the load-midspan deflection curve of Specimen CF-B was similar to that of Specimen C-B. However, Specimen CF-B showed a steeper hardening response after the yield load of 156 kN. Immediately after the ultimate load of 212 kN, the load dropped suddenly due to wide cracks that formed between the CFRP strips in the midspan region at the tension side of the specimen. Both the yield strengthening ratio and the ultimate strengthening ratio of Specimen CF-B was 1.35. The ductility of Specimen CF-B was 4.1 and the energy absorption ratio was 0.95. The low energy absorption ratio of Specimen CF-B was due to the sudden failure of the specimen after the ultimate load (Fig. 12).

The initial flexural load-midspan deflection response of Specimen CJ-B was steeper than the flexural load-midspan deflection response of Specimens C-B and CF-B. The initial steeper flexural load-midspan deflection response of Specimen CJ-B represented the higher initial effective stiffness of Specimen CJ-B. After the ultimate flexural load, the flexural load-midspan deflection showed a softening response until the final failure which occurred by a wide crack at the tension side and crushing of RPC at the compression side. The yield strengthening ratio and ultimate strengthening ratio of Specimen CJ-B were 2 and 1.89, respectively. Specimen CJ-B achieved a flexural ductility of 3.8 with an energy absorption ratio of 1.06 (Table 8).

The initial flexural load-deflection response of Specimen CJF-B was close to that of Specimen CJ-B. However, Specimen CJF-B achieved higher ultimate flexural load, ductility and energy

absorption than Specimen CJ-B due to the confinement effect of CFRP. The ultimate flexural load of Specimen CJF-B was only 5% higher than the ultimate flexural load of Specimen CJ-B. Specimen CJF-B failed by wide vertical cracks at the tension side and rupture of CFRP at the compression side. The yield strengthening ratio of Specimen CJF-B was 2.2 and the ultimate strengthening was 1.99. Specimen CJF-B exhibited a flexural ductility of 9.7 and an energy absorption ratio of 1.38 (Table 8).

3.5 Experimental axial load-bending moment interaction diagram

The axial load-bending moment interaction diagrams for the four groups of specimens are presented in Fig. 14. The axial load-bending moment interaction diagrams are drawn based on the four experimental points obtained for each group of specimens in this study. The first point represents the pure axial load. The second and the third points represent the axial loads and bending moments at axial load eccentricities of 15 mm and 25 mm, respectively. The last point represents the bending moment obtained from four-point bending test. The bending moments for the specimens under eccentric axial loads were calculated by using Eq. (1). The bending moment under four-point bending was calculated by using Eq. (2).

$$M = P(e + \delta) \quad (1)$$

$$M = \frac{PL}{6} \quad (2)$$

where M is the bending moment, P is the ultimate load, e is the eccentricity, δ is the midspan lateral deformation at the corresponding ultimate axial load and L is the span length of the specimen, which was 700 mm in this study.

The experimental axial load-bending moment interaction showed the superior performance of the Groups CJ and CJF specimens compared to Groups C and CF specimens. Group CJ specimens obtained greater ultimate axial load than Groups C and CF specimens under concentric axial load, 15 mm eccentric axial load and 25 mm eccentric axial load. In addition, Group CJF specimens achieved higher ultimate axial load than Group CJ specimens under concentric and eccentric axial loading. Similarly, Group CJ specimens obtained greater bending moment than Groups C and CF specimens under 15 mm eccentric axial load, 25 mm eccentric axial load and under four-point bending. Group CJF specimens achieved higher bending moment than Group CJ specimens under 15 mm eccentric axial load, 25 mm eccentric axial load and four-point bending. Table 9 presents the results of the axial-load bending moment interactions. For the eccentric axial load with the eccentricity of 15 mm, bending moments of Groups CF, CJ and CJF were 126%, 213% and 278%, respectively, higher than the bending moment of Group C. For the eccentric axial load with the eccentricity of 25 mm, bending moments of Groups CF, CJ and CJF were 84%, 208% and 238%, respectively, higher than the bending moment of Group C. Under four-point bending, the bending moments for Groups CF, CJ and CJF were 39%, 94% and 100%, respectively, higher than the bending moment of Group C.

Based on the above experimental results, it is apparent that jacketing with RPC only (without FRP wrapping) can be used to increase the maximum axial and maximum flexural loads of circular RC columns. Nevertheless, jacketing with RPC and FRP is recommended to achieve higher structural ductility and energy absorption capacity together with improved maximum axial load and maximum bending moment.

4. Conclusions

A new jacketing technique is proposed to retrofit existing deficient circular RC columns. The new jacketing technique consisted of jacketing the RC column with a thin layer of RPC then wrapping with CFRP. The behaviour of 16 RC column specimens under concentric axial load, eccentric axial loads and four-point bending was experimentally investigated. The load-deformation responses of the tested specimens under concentric axial load, eccentric axial loads as well as under four-point bending are presented. Also, ductility and energy absorption were calculated. Furthermore, the axial load-bending moment interaction diagrams for groups of the tested specimens are plotted. Based on the experimental results of the current study, the following conclusions can be drawn:

1. Under concentric axial load, eccentric axial loads and four-point bending, the yield and ultimate strengthening ratios of circular RC column specimens strengthened with RPC jacket were significantly higher than the yield and ultimate strengthening ratios, respectively, of the circular RC specimens strengthened with CFRP wrapping.
2. The specimens strengthened with CFRP wrapping achieved higher ductility compared to the specimens strengthened with RPC jacket. However, the specimens strengthened with RPC jacket achieved higher energy absorption ratios than the specimens strengthened with CFRP wrapping under concentric axial load, eccentric axial loads and four-point bending.
3. The ultimate strengthening ratios, ductility and the energy absorption ratios of circular RC specimens strengthened with RPC jacket and CFRP wrapping were higher than those of the circular RC specimens strengthened with RPC jacket under concentric axial load, eccentric axial loads and four-point bending.

4. The proposed jacketing technique of the circular RC columns with RPC jacketing and FRP wrapping was found to be an effective strengthening technique to increase the yield load, ultimate load and energy absorption capacity of the existing inadequate circular RC columns.

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664 bending

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669 **Table 1**

670 Test matrix

Specimen	Dimensions (mm)	Longitudinal reinforcement	Transverse reinforcement	Jacket type	Loading condition
C-0	Ø150 × 800	6N10	R6@50 mm	None	Concentric
C-15					15 mm eccentric
C-25					25 mm eccentric
C-B					Four-point bending
CF-0	Ø150 × 800			Two layers of CFRP	Concentric
CF-15					15 mm eccentric
CF-25					25 mm eccentric
CF-B					Four-point bending
CJ-0	Ø200 × 800			RPC	Concentric
CJ-15					15 mm eccentric
CJ-25					25 mm eccentric
CJ-B					Four-point bending
CJF-0	Ø200 × 800			RPC + One layer of CFRP	Concentric
CJF-15					15 mm eccentric
CJF-25					25 mm eccentric
CJF-B					Four-point bending

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674 **Table 2**

675 Components of RPC mix

Components kg/m ³ (by cement mass)					
Cement	Silica fume	River sand (150-600) μm	Superplasticizer	Water	Steel fibre 13 mm length
880 (1.00)	220 (0.25)	924 (1.05)	50.16 (0.057)	176 (0.20)	117 (0.13)

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681 **Table 3**

682 Mechanical properties of the RPC on the 28th day

Property	Specimen type	Specimen Dimensions (mm)	Test result
Compressive strength (MPa)	Cylinder	100×200	110
Splitting tensile strength (MPa)	Cylinder	150×300	9
Modulus of rupture (MPa)	Prism	100×100×500	12
Shear strength (MPa)	Prism	150×150×500	30

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688 **Table 4**

689 Properties of the CFRP sheets

Property	Number of layers	
	1	2
Average Width (mm)	25	25
Average maximum tensile strain (mm/mm)	0.0186	0.0247
Average tensile modulus per unit width (N/mm)	28871	50567
Average maximum tensile force per unit width (N/mm)	537	1249

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695 **Table 5**

696 Experimental results of specimens tested under concentric axial load

Specimen	C-0	CF-0	CJ-0	CJF-0
Yield axial load (kN)	536	714	1490	1977
Axial deformation at yield axial load (mm)	2.9	4.5	2.4	3.4
Ultimate axial load (kN)	615	1245	1573	2094
Axial deformation at ultimate axial load (mm)	4.5	17.6	2.7	6
Yield strengthening ratio	1	1.33	2.78	3.69
Ultimate strengthening ratio	1	2.02	2.55	3.4
Ductility	5.7	4	1.4	1.8
Energy absorption (kN.mm)	4297	6165	6867	13221
Energy absorption ratio	1	1.43	1.6	3.07

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701 **Table 6**

702 Experimental results of specimens tested under eccentric axial load (eccentricity = 15 mm)

Specimen	C-15	CF-15	CJ-15	CJF-15
Yield axial load (kN)	393	465	1463	1554
Axial deformation at yield axial load (mm)	2.2	3	3.5	3.5
Ultimate axial load (kN)	436	572	1542	1777
Axial deformation at ultimate axial load (mm)	2.9	8.2	3.8	4.8
Yield strengthening ratio	1	1.18	3.72	3.95
Ultimate strengthening ratio	1	1.31	3.53	4.07
Ductility	1.9	4.3	1.3	1.4
Energy absorption (kN.mm)	2057	4108	7683	9273
Energy absorption ratio	1	2	3.73	4.5

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708 **Table 7**

709 Experimental results of specimens tested under eccentric axial load (eccentricity = 25 mm)

Specimen	C-25	CF-25	CJ-25	CJF-25
Yield axial load (kN)	295	393	1158	1282
Axial deformation at yield axial load (mm)	2.6	3.6	2.8	3
Ultimate axial load (kN)	338	478	1276	1371
Axial deformation at ultimate axial load (mm)	3.8	8	3	4
Yield strengthening ratio	1	1.33	3.92	4.34
Ultimate strengthening ratio	1	1.41	3.77	4.05
Ductility	2.3	3.5	1.2	1.5
Energy absorption (kN.mm)	1916	4025	4424	6085
Energy absorption ratio	1	2.1	2.3	3.17

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715 **Table 8**

716 Experimental results of specimens tested under four-point bending

Specimen	C-B	CF-B	CJ-B	CJF-B
Yield flexural load (kN)	115	156	230	254
Deflection at yield flexural load (mm)	7.7	11.7	3.9	4
Ultimate flexural load (kN)	157	212	298	313
Deflection at ultimate flexural load (mm)	53	40	10	18
Yield strengthening ratio	1	1.35	2	2.2
Ultimate strengthening ratio	1	1.35	1.89	1.99
Ductility	8.3	4.1	3.8	9.7
Energy absorption (kN.mm)	8530	8100	9061	11787
Energy absorption ratio	1	0.95	1.06	1.38

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722 **Table 9**

723 Experimental axial load-bending moment interactions

Specimen	Ultimate load (kN)	Lateral deformation at ultimate axial load	Ultimate bending moment (kN.m)
C-0	615	-	-
C-15	436	3.7	8.1
C-25	338	7	10.8
C-B	157	-	18
CF-0	1245	-	-
CF-15	572	17	18.3
CF-25	478	16.6	19.9
CF-B	212	-	25
CJ-0	1573	-	-
CJ-15	1542	1.5	25.4
CJ-25	1276	1.1	33.3
CJ-B	298	-	35
CJF-0	2094	-	-
CJF-15	1777	2.2	30.6
CJF-25	1371	1.6	36.5
CJF-B	313	-	36

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Fig. 1. Plan view of the reference and the strengthened specimens

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Fig. 2. Steel fibres

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Fig. 3. Preparation of surface of base specimen: (a) sandblasting chamber with accessories and (b) use of chipping hammer

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Fig. 4. Formworks of the base and jackted specimens: (a) formwork of base specimen, (b) formwork of jackted specimen and (c) jacketed specimen after casting

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Fig. 5. Test setup of eccentrically loaded specimen

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813 **Fig. 6.** Axial load-axial deformation responses of the specimens tested under concentric axial
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Fig. 7. Failure modes of the specimens tested under concentric axial load

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830 **Fig. 8.** Axial load-axial deformation and axial load-lateral deformation responses of the
831 specimens tested under eccentric axial load (eccentricity = 15 mm)

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840 **Fig. 9.** Failure modes of the specimens tested under eccentric axial load (eccentricity = 15 mm)

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Fig. 10. Axial load-axial deformation and axial load-lateral deformation responses of the specimens tested under eccentric axial load (eccentricity = 25 mm)

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857 **Fig. 11.** Failure modes of the specimens tested under eccentric axial load (eccentricity = 25 mm)

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Fig. 12. Flexural load-midspan deflection curves of the specimens tested under four-point bending

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Fig. 13. Failure modes of the specimens tested under four-point bending

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Fig. 14. Experimental axial load-bending moment interaction diagrams

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