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Behaviour of CFRP Wrapped Square RC Columns under Eccentric Loading

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ABSTRACT

Fibre Reinforced Polymer (FRP) is an excellent material to strengthen existing structures. However, the confinement efficiency of FRP-confined square columns is relatively low compared to circular columns due to stress concentration at the sharp corners. This paper presents a new technique aimed to maximise the efficiency of FRP confinement for square concrete columns: circularisation using segmental circular concrete covers. Sixteen square reinforced concrete columns were cast. Four were used as a reference group; four were rounded 20 mm at each corner and wrapped with three layers of CFRP simulating the conventional methods; the rest eight columns were bonded with four pieces of segmental circular concrete covers simulating the proposed technique, after which four of them were wrapped with three layers of CFRP and the other four were confined with steel straps. From each group, one column was tested under concentric loading, one at 15 mm eccentricity, one at 25 mm eccentricity and the last specimen was tested under flexural loading. Results of the experimental program showed that circularisation significantly increases the efficiency of the FRP confinement compared to conventional methods which round the sharp corners. Meanwhile, steel straps had been demonstrated to be an excellent alternative for confining concrete.

KEYWORDS

Circularisation; FRP-Confined Reinforced Concrete Columns; Eccentric Loading; Square Columns.

INTRODUCTION

Fibre Reinforced Polymer (FRP) has, since its introduction, been widely used as an excellent confining material to strengthen the existing structures. The advantages of FRP include: light weight, adjustable shape, corrosion and fire resistance and most importantly, high tensile strength. The process of strengthening concrete columns is to wrap the columns with FRP layers using epoxy resin as adhesives. The columns tend to expand laterally when loaded axially, and confinement of FRP restraints such as expansion and provides lateral confining pressure which delays the growth of cracks and crushing of concrete cover. Recent experimental studies found out that FRP-confined circular concrete columns exhibit dramatically higher load-carrying capacity and ductility than unconfined columns which is extremely critical in extreme loading conditions such as earthquakes (Hadi, 2006, 2007). However, for square columns confined with FRP, little enhancement in strength can be witnessed due to premature rupture of FRP at the sharp corners, which is generally caused by stress concentration at the edges (Rochette & Labossiere, 2000). Therefore, modification is required for square concrete columns before being wrapped with FRP. The conventional method is to round the sharp corners, which reduces the stress concentration and delays the premature rupture of FRP.

However, the efficiency of FRP confinement of square columns with round corners is still significantly lower than circular columns (Al-Salloum, 2007).

In order to address the aforementioned problem, this study evaluates a new technique for FRP strengthening square RC columns. Before the wrapping of FRP, the columns are bonded with four pieces of segmental circular concrete covers to change the cross section from a square to a circular one. This technique is called circularisation hereafter. In the experimental program, columns FRP wrapped with the conventional techniques and the proposed circularisation process were tested and compared to evaluate the performance of the circularisation process. Meanwhile, steel straps confinement was also incorporated as an alternative confining material and compared to FRP. Apart from conventional concentric loading, eccentric loading and flexural four-point bending are also incorporated to fully examine the combined axial load and the bending behaviour of the columns to provide more useful and realistic data than studies which only focus on concentric loading.

EXPERIMENTAL PROGRAM

The experimental program was carried out at the High Bay Laboratory at the University of Wollongong. The purpose of the program was to examine the effectiveness of the proposed circularisation process, and compare the efficiency of FRP confinement and steel strap confinement.

Design of Specimens

Sixteen reinforced concrete columns were cast. The columns were square in cross-section with 150 mm in sides and 800 mm in height. All columns had identical internal steel reinforcement which was designed according to the minimum requirement set out in AS3600 (2009). Four 12 mm deformed bars with a nominal tensile strength of 500 MPa were provided as longitudinal reinforcement and 6 mm plain bars with a nominal tensile strength of 250 MPa were provided as transverse reinforcement with 120 mm spacing. The columns were made from normal strength concrete with a nominal compressive strength of 32 MPa. Concrete cover was maintained at 20 mm thick on the surface and 20 mm thickness at top and bottom. Carbon Fibre Reinforced Polymer (CFRP) was used as a primary confining material. The CFRP was 50 mm in width with a uni-directional fibre density of 340 g/m^2. Galvanised carbon steel straps were used as an alternative confining material. The steel straps had a nominal thickness of 0.78 mm and a width of 19.1 mm. The nominal tensile strength of the materials was not specified by the suppliers and therefore preliminary tests were carried out to investigate the mechanical properties of the aforementioned confining materials.

Test Configuration

The specimens were divided into four groups. The first group (Group N) was set as a reference group with no further modification and strengthening. The second group (Group RF) simulated the conventional method of strengthening square concrete columns with FRP. All specimens in Group RF were rounded 20 mm in the corners and wrapped with three layers of CFRP. The third and fourth groups simulated specimens strengthened using the proposed approach. Group CF was circularised and wrapped with three layers of CFRP, and Group CS was circularised and confined with steel straps with a clear spacing of 30 mm. From each group, three specimens were subjected to axial load with an eccentricity of either 0 mm, 15 mm or 25 mm. The last specimen from each group was tested under four-point loading. A detailed test matrix is given in Table 1 and the details of the specimens are given in Figure 1. All specimens were labelled with the respective group name and the loading condition in which the specimen was tested, where the number stands for the load eccentricity and ‘F’ stands for flexural tests. For instance, N-15 represents specimen in Group N under 15 mm eccentric loading while CS-F stands for specimen in Group CS under flexural test.

Table 1. Test Matrix

Specimen	Internal Reinforcement	External Modification	External Confinement	Test Eccentricity
N-0	Yes	-	-	0
N-15	Yes	-	-	15
N-25	Yes	-	-	25
N-F	Yes	-	-	Flexural
RF-0	Yes	Round corners	3 layers CFRP	0
RF-15	Yes	Round corners	3 layers CFRP	15
RF-25	Yes	Round corners	3 layers CFRP	25
RF-F	Yes	Round corners	3 layers CFRP	Flexural
CF-0	Yes	Circularisation	3 layers CFRP	0
CF-15	Yes	Circularisation	3 layers CFRP	15
CF-25	Yes	Circularisation	3 layers CFRP	25
CF-F	Yes	Circularisation	3 layers CFRP	Flexural
CS-0	Yes	Circularisation	Steel straps	0
CS-15	Yes	Circularisation	Steel straps	15
CS-25	Yes	Circularisation	Steel straps	25
CS-F	Yes	Circularisation	Steel straps	Flexural

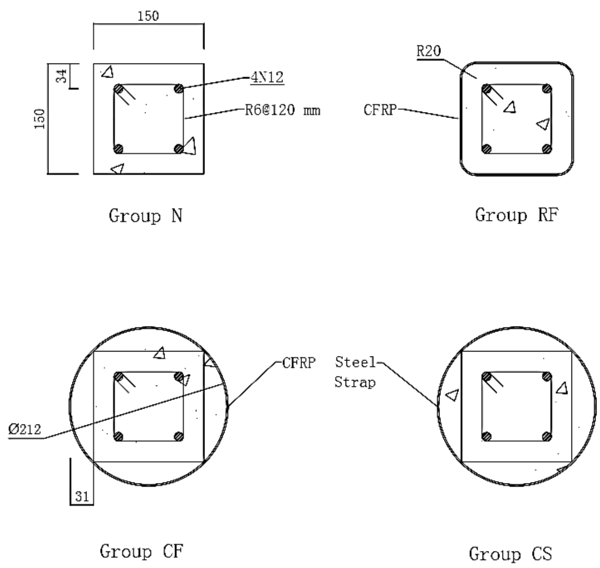


Figure 1. Cross-section of Specimens (Units in mm)

Preparation of Specimens

Ready-mixed concrete was purchased from a local supplier. Slump tests were carried out immediately after the arrival of the concrete. The results from the slump tests showed that the concrete had a slump of 117 mm. After that, the concrete was poured into two formworks made from plywoods and screwed by timbers. One of the formworks was for the columns and the other was specially made for the segmental circular concrete covers used in the circularisation process. In order to generate round corners for Group RF, corner arch made from foam was used and glued inside the formwork. A similar procedure was carried out for the segmental circular concrete covers with special shaped foam. Details of the formwork setup are shown in Figure 2. All specimens were then covered with wet hessian and cured in room temperature for 28 days before they were taken out of the formwork.

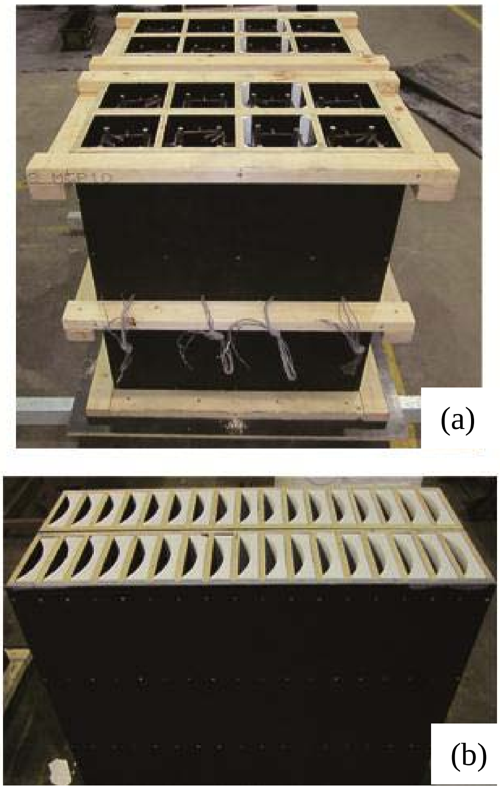


Figure 2. Details of the formworks for: (a) columns; (b) segmental circular covers

Circularisation Process

The segmental circular concrete covers were taken out of the formwork after 28 days. The foam on the covers was first removed and the surface of the covers was cleaned and ground to ensure they were flat and even. Before bonding of concrete covers, the surface of the columns was cleaned and any dust was removed. The adhesive used was a mix of epoxy resin, slow hardener and silica microsphere with a ratio of 5:1:10. The adhesive was evenly spread onto the surface of the concrete covers, which were then bonded onto the surface of the columns.

Four segmental circular concrete covers were bonded on the surface of the column to modify the shape of cross-section from a square to a circular one. After the concrete covers were bonded, an adjustable steel strap was used to hold the covers. The modified specimens were then left to dry for one week before they were externally confined. Figure 3 demonstrates the details of circularisation process.

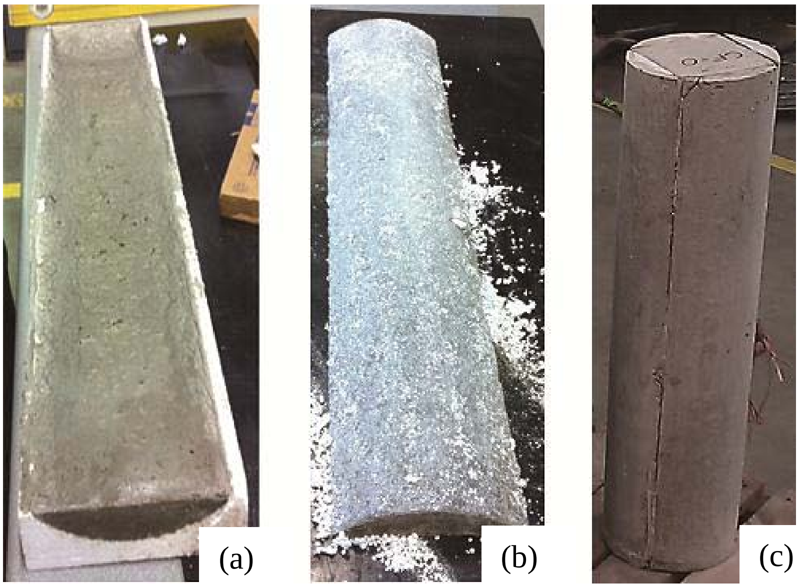


Figure 3. Details of circularisation process: (a) Removal of the segmental circular covers from formwork; (b) Removal of foams attached on the covers; (c) Bonding of segmental circular covers

Construction of External Confinement

For Groups RF and CF, all specimens were wrapped with three layers of CFRP. Wet-layup process was used to wrap the specimens with CFRP using epoxy resin. The specimens were confined with separate CFRP rings. Firstly, epoxy resin was spread onto the surface of the specimen and the first ring of CFRP was attached. After that, epoxy resin was spread again on the surface of the first layer of CFRP and the second layer was attached. The same procedure was followed until three layers of CFRP were bonded. An additional ring of CFRP was wrapped at both ends of the specimen to prevent damage in the ends. A 100 mm overlap was maintained for each ring. The specimens were then left to dry for 14 days as specified by the supplier. For Group CS, all specimens were confined with steel straps. The steel straps were tightened using a special tool provided by the supplier. Each ring of steel strap was clicked by a buckle. The first ring started at the top and each ring had 30 mm spacing.

Preliminary Tests

The average compressive strength of the concrete at 28 days was 26.81 MPa. Mechanical properties of CFRP and steel straps were determined according to ASTM D7565 (2010) and ASTM D3953 (2007), respectively. The ultimate tensile strength of CFRP was 1674.27 MPa with a corresponding strain of 0.025. The average tensile strength of steel straps was 598.21 MPa. For reinforcing steel, AS4671 (2001) was used to test specimens. The tests revealed that the average ultimate tensile strength for N12 deformed bars was 568.35 MPa and for R6 plain bars was 477.88 MPa.

Loading System

A specific loading system was used in order to conduct eccentric loading tests. The loading system consists of a steel loading head with a gauge and a top steel plate with an overhang edge. The gauge was 25 mm off centre and the top overhang edge was placed in the gauge in order to create 25 mm eccentricity. For 15 mm eccentric loading, the column was located 10 mm off centre against the eccentric direction. For flexural tests, a four-point loading system was used. All specimens were capped at both ends using high strength plaster to ensure even distribution of forces. Calibration was carried out to ensure the specimen was placed in the centre. For axial loading tests, the loading rate was set at 0.5 mm/min while for flexural tests, 0.3 mm/min. For eccentric loading tests, a laser linear variable differential transformer (LVDT) was placed at mid-height of the specimen to measure the lateral displacement and for flexural tests, the laser LVDT was placed at the middle of bottom loading plate to measure the midspan deflection.

EXPERIMENTAL RESULTS AND DISCUSSION

All Specimens were tested until failure. The load and displacement data was collected using a data-logger connected to the test machine.

Summary of Test Results

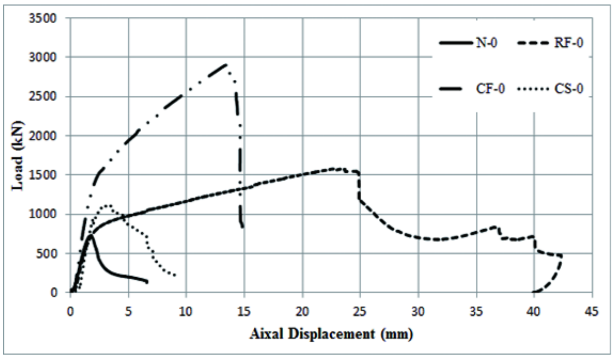
Table 2 summarises the test results of all specimens. All strengthened specimens showed significant increase in ultimate load, and in particular Group CF dramatically outperformed other groups in terms of ultimate load carrying capacity. Specimens subjected to eccentric loading showed considerably lower ultimate load compared to specimens under concentric loading. Notably, the lateral displacement of specimens in Group CF at ultimate load were significantly larger than that of other specimens, which indicates that the ductility of Group CF was outstanding.

Table 2. Summary of Test Results

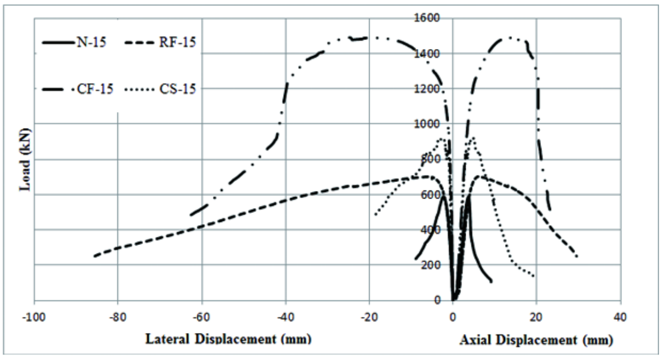
Specimen	Ultimate Load (kN)	Corres. Axial Defl. (mm)	Corres. Lateral Defl. (mm)	Yield Load (kN)	Corres. Axial Defl. (mm)
N-0	717.3	1.63	-	717.3	1.63
RF-0	1588.6	24.51	-	829.5	1.83
CF-0	2907.4	13.63	-	1390.8	2.28
CS-0	1112.9	2.13	-	935.7	1.93
N-15	587.69	1.82	2.29	587.69	1.82
RF-15	701.64	2.96	5.62	635.0	2.15
CF-15	1489.9	6.81	24.79	1202.0	2.38
CS-15	917.1	2.43	3.19	905	2.21
N-25	435.48	1.41	2.33	435.48	1..41
RF-25	562.05	3.51	8.10	515.05	2.28
CF-25	1170.6	6.50	22.39	1011.8	2.06
CS-25	778.1	1.77	3.14	766.4	1.24
N-F	81.70	7.78	-	81.7	7.78
RF-F	161.20	36.50	-	107.7	5.25
CF-F	253.92	30.40	-	139.58	4.04
CS-F	163.19	5.96	-	163.2	5.96

Load-Deflection Diagram

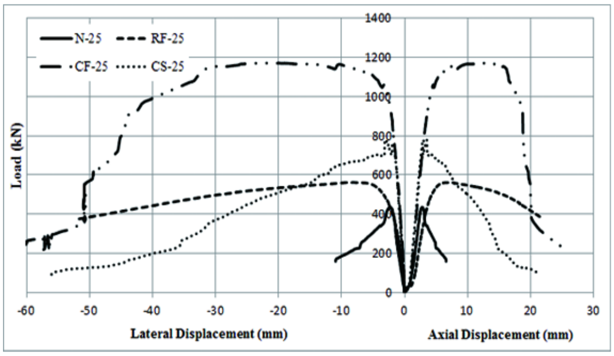
Figure 4 shows the load-deflection diagram for all specimens. It can be seen that all specimens showed similar behaviour during the first stage where the specimens were not yielded. For concentric tests, FRP-confined specimens RF-0 and CF-0 demonstrated ascending branch in the load-deflection diagram after the specimens yielded. As described by Lam and Teng (2003), this phenomenon indicates that the confinement of FRP is strong. Notably, the slope of curve in Figure 4(a) for Specimen CF-0 is higher than RF-0, which indicates that the confinement efficiency of the former is higher than the latter. In other words, circularisation increases the efficiency of FRP confinement. For eccentric loading tests, all specimens exhibited a descending branch in the diagram after yield which demonstrates weak confinement. Therefore, confinement efficiency for eccentrically loaded specimens is lower than that of concentrically loaded specimens.



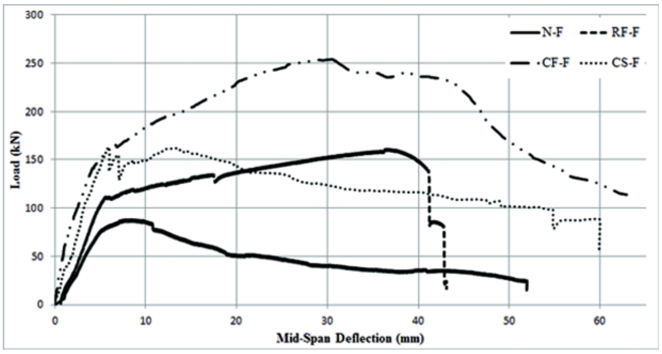
(a) Concentric Loading



(b) Eccentric Loading, e=15 mm



(c) Eccentric Loading, e=25 mm



(d) Flexural Tests

Figure 4. Load-Displacement Diagram

Table 4. Ductility of the Specimens

Specimen	Ductility	Normalised Ductility
N-0	1.40	1
RF-0	13.42	9.59
CF-0	6.98	4.99
CS-0	1.88	1.34
N-15	1.63	1
RF-15	5.22	3.20
CF-15	4.82	2.96
CS-15	3.23	1.98
N-25	1.33	1
RF-25	4.73	3.56
CF-25	5.11	3.84
CS-25	2.00	1.50

Ductility

Ductility is considered as one of the most critical parameters for structural members. Gangarao et al. (2007) described ductility as the ratio of axial deflection at 85% of ultimate load after peak and axial deflection at yield load. Table 4 summarises the ductility for axially loaded specimens. All confined specimens showed significant increase in ductility. For FRP-confined specimens, Group RF showed higher ductility performance compared to Group CF, which is mainly because the load achieved for Group CF was so high that the concrete was completely crushed. For Group CS, a moderate increase in ductility was witnessed.

CONCLUSIONS

Based on the above experimental program, the following conclusions can be drawn:

- Circularisation dramatically increases the efficiency of FRP confinement. Compared to conventional method which rounds the corners, FRP-confined columns which are circularised beforehand achieved substantially higher ultimate load. By circularising square concrete columns, the efficiency of FRP confinement can be maximised;
- Steel strap confinement provides higher load-carrying capacity and ductility at a moderate level compared to FRP confinement. Nevertheless, considering that steel straps are relatively low in material cost and easy to implement, steel straps confinement is an outstanding alternative of FRP confinement;
- Eccentricity dramatically reduced the ultimate load of all specimens, regardless of the technique incorporated. Theoretical models should take eccentricity into account in order to provide more accurate simulations.

Finally, test results showed that the proposed circularisation technique is a viable and efficient method for strengthening square RC columns

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