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Comparative Behaviour of FRP Confined Square Concrete Columns under Eccentric Loading

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ABSTRACT: This study evaluates different methods of strengthening existing square concrete columns under eccentric loading. Sixteen reinforced square concrete columns were cast. The columns were made from normal strength concrete and the reinforcement was kept at minimum simulating columns needing retrofitting. Four columns were modified with round corners and wrapped with three layers of CFRP, four were circularised by circular segments and wrapped with three layers of CFRP, and the last four columns were circularised and confined with steel straps. Specimens from each group were tested under concentric, eccentric (15 or 25 mm) and flexural bending. Results from the study showed that part-circular concrete covers dramatically reduce stress concentration at the corners. FRP wrapped columns with circular segments showed significant increase in load-carrying capacity compared to columns with only round corners. Columns confined with steel straps showed comparable increase in both ultimate load and ductility.

1 INTRODUCTION

Retrofitting existing columns in bridges and buildings have become an indispensable requirement in recent decades. Strengthening existing columns using Fibre Reinforced Polymer (FRP)-confined concrete have been demonstrated as an excellent method. Its benefits range from high strength and stiffness to enhanced ductility. The behaviour of FRP-confined concrete was investigated through both experimental tests and theoretical studies, which led to the evaluation of many stress-strain models for FRP-confined concrete columns. These tests were mainly based on circular columns under concentric load, which showed that the experimental data matches very well with the stress-strain models. However, gaps exist between the experimental data and the existing models in predicting the behaviour of FRP confined square columns. For example: (1) the effect of stress concentration at the corners on the efficiency of FRP confinement, (2) effect of eccentricity on confinement, (3) alternative confining materials comparing the confinement efficiency using FRP and a cheaper material than FRP, for instance, steel straps.

It is obvious that most of existing columns are square or rectangular in section; early research indicate that FRP confined square or rectangular columns with sharp corners do not give enhancement on confinement efficiency. Some suggestions were proposed to modify the existing columns: (1) rounding the corners of columns, (2) preliminary bonding longitudinal FRP strips along each corner before adding transverse FRP hoop. Nevertheless, the first method requires additional cost and is too complicated to implement due to restriction of position of the existing longitudinal steel. In terms of the second technique, only some tests were conducted and the early research studies found out that little enhancement can be witnessed for columns with sharp corners.

Some investigations on FRP strengthened reinforced concrete (RC) columns under concentric load (Mander et al. 1988; Kumutha et al. 2007; Ilki & Peker 2008) have been reported. Further, RC columns under eccentric load were tested to study the combination of compression and bending behaviour (Li & Hadi 2003; Hadi & Li 2004; Hadi 2006a; Hadi 2006b; Hadi 2007a; Hadi 2007b). These studies concluded that the use of FRP increases the capacity of columns. Following the same direction, this study focuses on the retrofitting compressive structural members comparing three different approaches of strengthening.

Many existing research studies use behaviour of small plain concrete cylinders under concentric load to study the behaviour of confined concrete (Xiao & Wu 2000; Pessiki & Harries 2001; Chaallal et al. 2003; Harajli et al. 2006; Jiang & Teng 2007), which can create a gap between FRP-confined plain concrete and FRP-confined concrete with the given amount of longitudinal reinforcement. Eid et al. (2009) have conducted a test containing 36 cylinders (D=152mm, h=305mm) and 21 RC large scale columns (D=303mm, h=1200mm), which were wrapped with FRP. Different behaviour between plain concrete cylinders and large scale RC columns was found. This study uses reinforced concrete columns to report experimental results which should be closer to real RC columns than the existing research.

The existing structures built in 1970s until now use normal strength concrete, it requires to be retrofitted after a long time of servicing period. As such, experiments of this study use normal strength concrete with some methods to modify the configurations of sections, which address the current issue. In this paper, an experimental investigation into the behaviour of square reinforced concrete columns externally bonded with CFRP under different loading configurations was conducted. Steel straps confinement were evaluated to explore alternative confinement approach which is cheaper and more convenient than commonly used materials such as FRP.

2 EXPERIMENTAL PROGRAM

The experimental program was carried out at the High Bay Civil Engineering Laboratory at the University of Wollongong. All materials were purchased from local suppliers and then prepared in the laboratory.

2.1 *Design of Experiments*

A total of sixteen square reinforced concrete columns were cast. The dimensions of the columns were 150 mm by 150 mm in cross-section and 800 mm in length. The columns were categorised into four groups and each group consisted of four specimens simulating a specific technique of strengthening. Group N was used as a reference group with no external strengthening and no modification in the columns themself. Group RF columns were cast to leave 20 mm round corners then wrapped with three layers of CFRP. Group CF and CS simulate a new type of strengthening method. All columns in Group CF and Group CS were bonded with four pieces of circular segments which are made from concrete of the same strength as concrete covers to modify the shape of cross-section from square to circular using epoxy resin. This process is here and after called circularisation of cross-section. After the circularisation, columns in Group CF were wrapped with three layers of CFRP and columns in Group CS were bonded with steel straps at 30 mm spacing. From each group, one column was concentrically loaded, while the second and the third columns were subjected to eccentric loading of 15 mm and 25 mm eccentricity, respectively. The fourth specimen was tested under four-point loading as a beam to observe the flexural behaviour. Therefore the notation of each column consists of two parts: the group name in which the column belongs and the loading conditions, namely 0, 15 and 25 for axial tests and F for flexural tests. Table 1 depicts the configuration of the experiment and Figure 1 shows the plan view of specimens.

Table 1. Test Matrix

Specimen	Modification	Internal Reinforcement	External Reinforcement	Eccentricity
N-0 N-15 N-25 N-F	None	4N12 R6@120	None	0 15 25 Flexural
RF-0 RF-15 RF-25 RF-F	20 mm Round Corners	4N12 R6@120	Three layers of CFRP	0 15 25 Flexural
CF-0 CF-15 CF-25 CF-F	Concrete Covers	4N12 R6@120	Three layers of CFRP	0 15 25 Flexural
CS-0 CS-15 CS-25 CS-F	Concrete Covers	4N12 R6@120	Steel Straps	0 15 25 Flexural

2.2 *Design of Columns*

Normal strength concrete was used with nominal compressive strength of 32 MPa. 20 mm concrete cover was maintained in accordance with AS3600 (2009). The reinforcement was designed according to AS 3600 (2009). The reinforcement was kept as minimum which is guided by the standard simulating columns with which structures need to be strengthened. The reinforcement was identical for all columns in all groups. Four N12 bars (12 mm deformed bars with 500 MPa nominal yield strength) were provided at each corner as longitudinal reinforcement and R6 bars (6 mm plain bars with 250 MPa nominal yield strength) were provided as transverse reinforcement with 120 mm spacing. Complying with AS3600 (2009), the ties were hooked with longitudinal bars with 135° hooks. All the reinforcing steels were purchased from a local supplier and were cut, bent and tied together using handy tools in the laboratory.

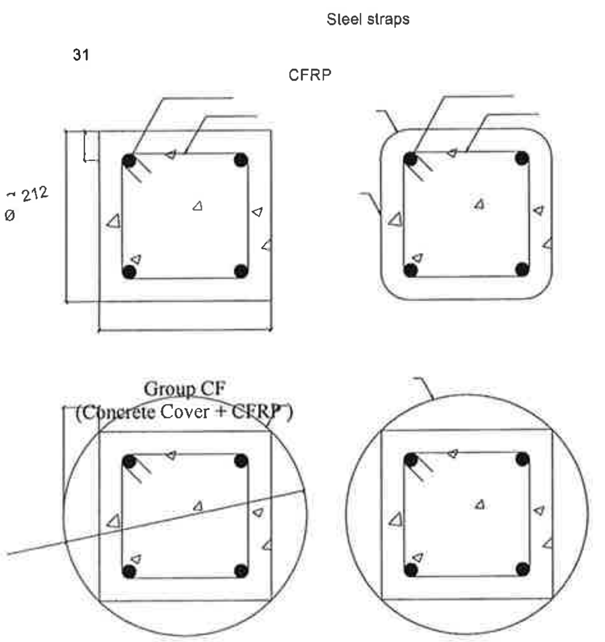


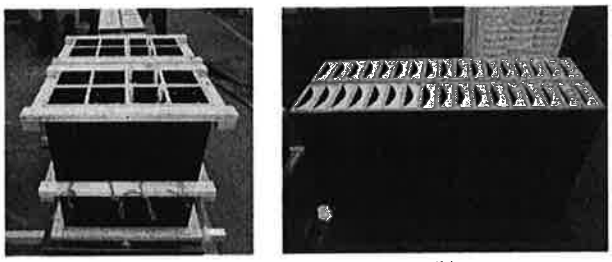
Figure 1. Plan View of Specimens (all units in mm)

2.3 *Casting of Columns*

The concrete used in the experiments was ready-mixed concrete purchased from a local supplier. The concrete was poured into two formworks when arrived. The first one was made for the columns and the second for the circular segments. All formworks were made from plywood and were screwed together with timber. Specially shaped foam was glued to the formwork in order to generate round corners for Group RF and also the circular segments for Group CF and CS. The details of the formwork are given in Figure 2. All formworks were covered with moisture burlap which was watered each day. All columns and concrete covers were taken out of the formwork after 28 days and further preparation was then carried out.

2.4 *Bonding of Concrete Covers*

The concrete covers used for Groups CF and CS were removed from the formwork after 28 days. The foam on the concrete covers was firstly removed and the surface of the covers was ground using an electric grinder to ensure smooth contact when bonding with FRP. After the concrete covers and the surface of original columns were cleaned, the covers were bonded to the columns using epoxy resin which was mixed with 15% of thickener. The columns were then left to dry for 14 days as specified by the suppliers. For the columns in the Group N, four pieces of segmental circular concrete covers with the width of 100 mm were bonded at each end and wrapped with three layers of CFRP in order to strengthen the ends of the columns to prevent buckling and damage at the ends.



(a) (b)

Figure 2. Formworks for (a) columns; (b) concrete covers

2.5 *External Reinforcement of Columns*

Before wrapping with FRP, the surface of the columns was cleaned by water and left to dry. The adhesive was a mixture of epoxy resin and hardener at 5:1 ratio. Before the first layer of CFRP was attached, adhesive was spread onto the surface of the column, and then CFRP was attached onto the surface. After the first ring, adhesive was spread onto the surface of the first layer of CFRP and the second layer was bonded. The same procedure was followed until three layers of CFRP were bond continuously on the surface. The main fibre orientation was perpendicular to the longitudinal axis of the column. For each ring, 100 mm of overlap was maintained. One additional layer of CFRP was wrapped at both ends of the columns to prevent buckling at the ends. For the same purpose, one layer of CFRP was used to strengthen both ends of the columns in Group N. All the FRP confined specimens were cured in room temperature at the laboratory for seven days.

2.6 *Preliminary Tests*

The average cylindrical compressive strength of concrete at 28 days was 26.81 MPa. Properties of CFRP were determined by FRP coupon tests which were conducted in accordance with ASTM D3039 (2008). Three coupons were made with a width of 25 mm. Each coupon was made of three individual layers of CFRP and bonded with epoxy resin. The coupons were capped at both ends and a gauge length of a least 150 mm was maintained. The actual width and thickness was measured before the tensile tests and the ultimate tensile load and displacement were recorded during the tests. The calculated material properties are given in Table 2.

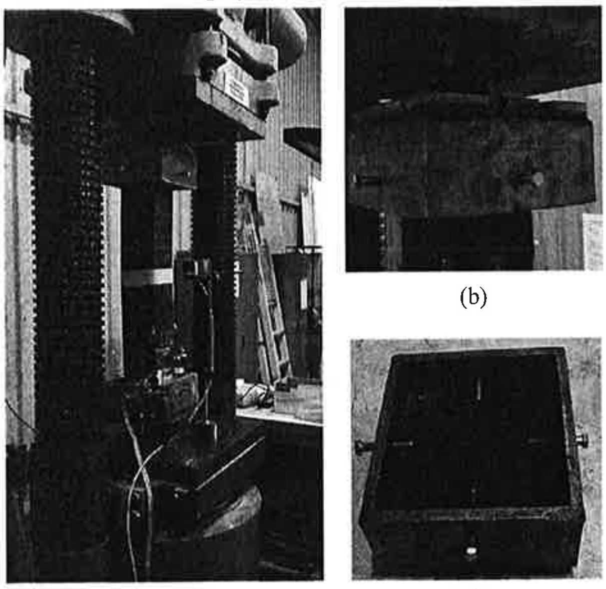
Table 2. FRP Coupon Tests

Properties	Three layers of CFRP
Average Thickness (mm)	1.13
Average Width (mm)	27.97
Maximum Load (kN)	54.97
Ultimate Stress (MPa)	1733.81
Ultimate Strain (mm/mm)	0.025
Modulus of Elasticity (GPa)	69.35

Coupon tests for reinforcing steels and steel straps were also conducted. Three specimens of N12 deformed bar and R6 plain bars with 250 mm in length were prepared and tested according to AS 1391 (2007). Three coupons of steel straps which were used in confining columns in group CS were prepared and tested according to ASTM D3953 (2007). The average yield strength for N12 deformed bars was 568.35 MPa, for R6 plain bars, 477.88 MPa and for steel straps, 598.21 MPa.

2.7 *Column testing*

All columns were tested using the Denison compression testing machine with an ultimate compression capacity of 500 Tonnes. The eccentricity was achieved by a special loading head with a gauge located 25 mm off centre. The loading head was paired with a steel plate with overhang edge. The details of the loading system are given in Figure 3.



(a) (b) (c)

Figure 3. (a) Loading system (b) Loading head and overhang edges (c) Loading head

Before putting the columns on the testing machine, the columns were capped with high strength plaster at both ends to ensure full contact between the loading head and the column. Calibration was then carried out to ensure that the columns were placed at the centre of the testing machine. For both 15 mm and 25 mm eccentric loading tests, the overhang edges were placed in the 25 mm off-centre gauge on the loading heads but for the 15 mm eccentric loading test, the columns were located 10 mm off centre against the axial direction same as the eccentricity in order to create 15 mm eccentricity. For the flexural tests, a four-point loading device was used as shown in Figure 4.

Before the tests, in order to measure the lateral displacement for eccentrically loaded columns and the deflection for the flexural tests, a laser LVDT was used and connected to the data-logger as well. For the column tests, the laser LVDT was fixed at the mid-height of the column, and for the beam tests, the laser LVDT was fixed on the hole which is located at the mid-span of the bottom loading plate.

All the tests were controlled by position. For compression tests, the loading rate was set at 0.5 mm/min, while for flexural tests the test rate was set at 0.3 mm/min.

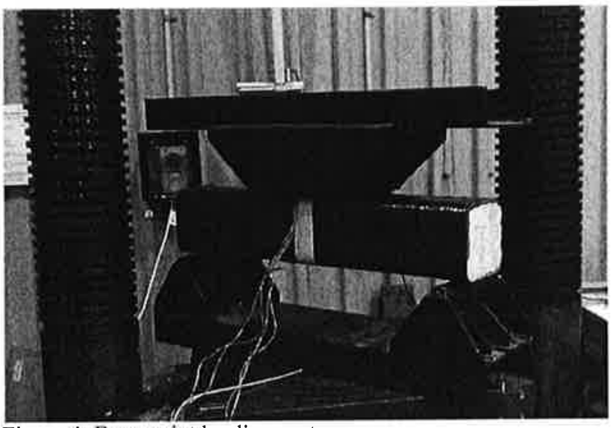


Figure 4. Four-point loading system

3 EXPERIMENTAL RESULTS AND DISCUSSION

During the tests, the axial load and displacement were measured by an LVDT located on the bottom loading plate of the compression machine, and the transverse displacement was measured by the laser LVDT. The ultimate load was taken as the peak load that the columns achieved and the yield load was taken at the point when the curve in the load – displacement graph started level off. The ductility was calculated using the following formula (Hadi 2009):

$$\mu = \frac{\Delta_{85}}{\Delta_{yield}} \qquad (1)$$

where Δ_{85} is the displacement at 85% of ultimate load after peak and Δ_{yield} is the displacement at yield load.

3.1 *Columns under Concentric Loading*

One column from each group was tested under concentric loading until failure. Results of the tested columns are given in Table 3 and the load-displacement diagram is given in Figure 5.

Table 3. Summary of Test Results, e=0

Specimen	N-0	RF-0	CF-0	CS-0
Ultimate Load (kN)	717.3	1588.6	2907.4	1112.9
Corresponding Axial Disp. (mm)	1.63	24.51	13.63	2.13
Yield Load (kN)	717.3	829.5	1390.8	935.7
Corresponding Axial Disp. (mm)	1.56	1.83	2.28	1.85
Ductility	1.22	13.42	7.00	2.38

Specimen N-0 failed by concrete spalling on the surface and buckling of longitudinal reinforcement. Specimens RF-0 and CF-0 failed by rupture of CFRP at mid-height of the column. The concrete was completely crushed but was held by the FRP. Specimen CS-0 failed by rupture of straps and crush of concrete at the upper-end. Significant increase in ultimate load and ductility can be witnessed for confined columns compared to unconfined columns. As can be seen on Figure 5, all columns showed similar behaviour during the first stage where concrete was not crushed. However, Specimens N-0 and CS-0 showed a descending branch at the second stage while confined Specimens RF-0 and CF-0 showed an ascending branch which is achieved by the confinement effect of FRP. For the confined columns, each sudden drop of load was caused by the rupture of one ring of CFRP or steel strap, and after four to six steel rings were ruptured, the column failed. Figure 6 demonstrates the mode of failure of concentrically loaded columns.

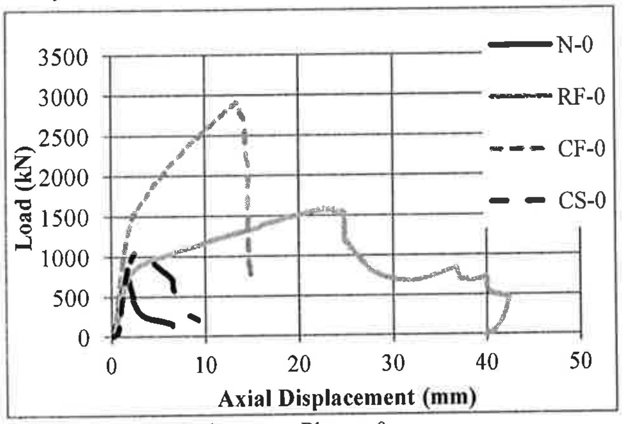
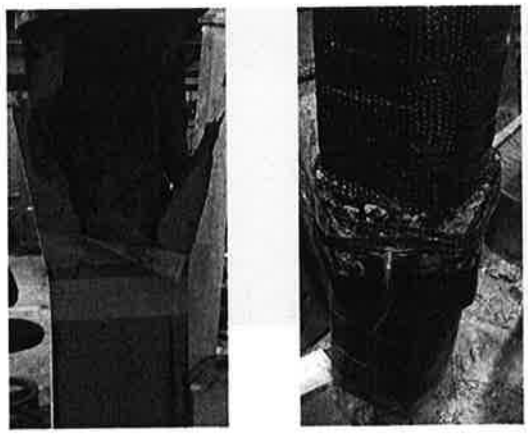


Figure 5. Load-Displacement Plot, e=0


(a) Specimen N-0 (b) Specimen RF-0

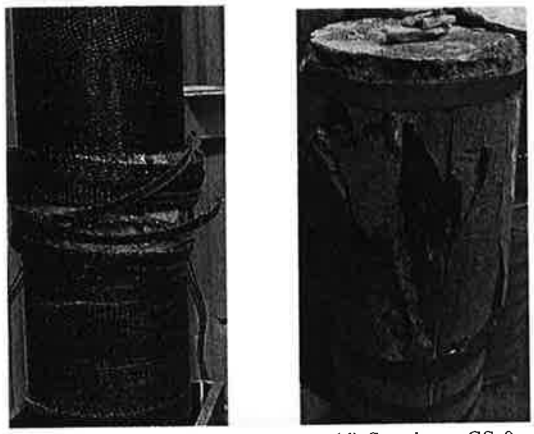

(c) Specimen CF-0 (d) Specimen CS-0

Figure 6. Failure modes of concentrically loaded columns

3.2 *Columns under Eccentric Loading*

The second and third columns in each group were subject to 15 mm and 25 mm eccentric loading, respectively. Table 4 depicts the results of eccentric loading tests; Figure 7 and Figure 8 show the load-displacement graph of the eccentrically loaded columns.

For unconfined columns, both N-15 and N-25 failed by spalling of concrete and buckling of longitudinal steels in the compression region. RF-15 failed by crushing of concrete in the compression region. Cracking of the column in the tension region occurred between two rings of FRP at the mid-height. Specimen RF-25 failed by rupture of longitudinal steels in the tension region. No FRP rupture was observed in both cases. However, cracking occurred between each ring of FRP confinement showed the negative effects of inconsistent confinement. Specimens CF-15 and CF-25 failed by rupture of FRP at mid-height, CS-15 and CS-25 failed by rupture of steel straps at the upper-height, all with concrete crushed in the compression region and cracked in tension region. Figure 9 depicts the mode of failure of eccentrically loaded columns.

Table 4. Summary of Test Results, e=15 mm and e=25 mm

Specimen (e=15)	N-15	RF-15	CF-15	CS-15
Ultimate Load (kN)	587.69	701.64	1489.92	917.09
Corresponding Axial Disp. (mm)	1.82	2.96	6.81	2.43
Corresponding Lateral Disp. (mm)	2.29	5.62	24.79	3.19
Yield Load (kN)	579.04	693.56	1488.12	859.11
Corresponding Axial Disp. (mm)	1.67	2.15	2.38	2.21
Ductility	1.63	5.22	4.85	3.23

Specimen (e=25)	N-25	RF-25	CF-25	CS-25
Ultimate Load (kN)	435.48	564.06	1170.62	778.10
Corresponding Axial Disp. (mm)	1.41	3.51	6.50	1.77
Corresponding Lateral Disp. (mm)	2.33	8.10	22.39	3.14
Yield Load (kN)	427.13	564.06	1170.62	762.40
Corresponding Axial Disp. (mm)	1.26	2.28	2.06	1.24
Ductility	1.33	4.73	5.11	2.10

Compared to Group N, Group RF showed a 20% to 32% increase in load-carrying capacity and 110% to 220% increase in ductility; Group CF showed a 157% to 174% increase in ultimate load but less than 30% increase of ductility; Group CS demonstrated 58% to 82% increase in ultimate load and more than 100% increase in ductility. The load-displacement behaviour for both confined and unconfined columns were similar at the beginning but confined columns reached higher peak load and ultimate displacement than unconfined columns. For eccentrically loaded columns, a descending branch is witnessed after peaking and thus weak confinement of FRP can be observed.

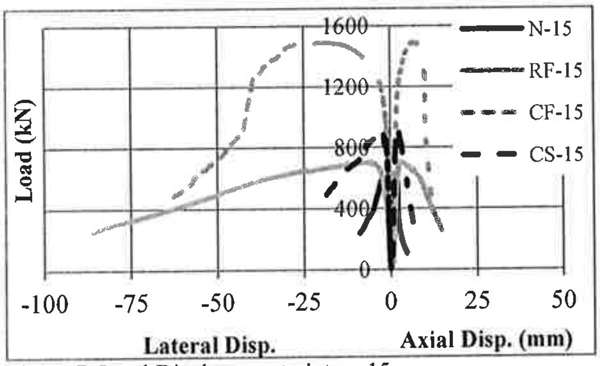


Figure 7. Load-Displacement plot, e=15

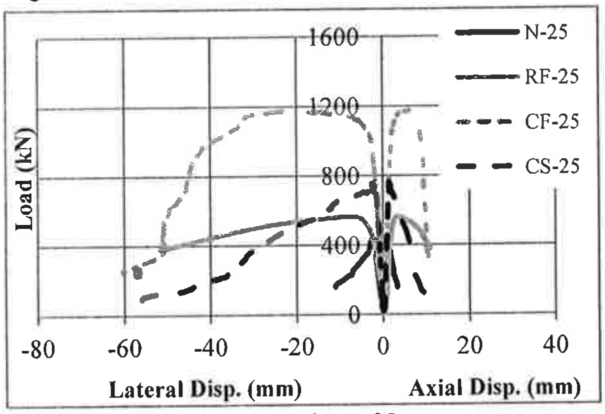


Figure 8. Load-Displacement plot, e=25

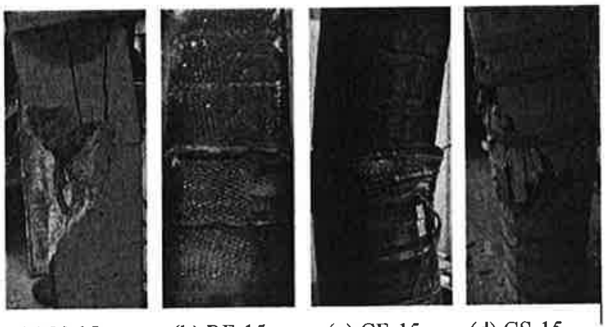
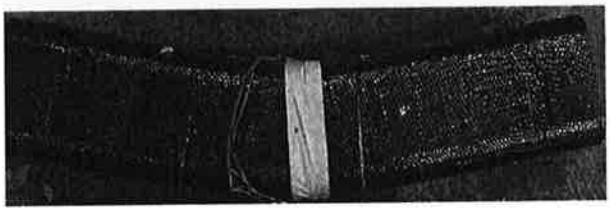

(a) N-15 (b) RF-15 (c) CF-15 (d) CS-15

Figure 9. Failure modes of eccentrically loaded columns

3.3 *Columns under Flexural Tests*

The last column in each group was tested under four-point bending. Table 5 summarises the test results and Figure 10 demonstrates the load-midspan deflection graph. Specimen N-F failed by separation of concrete and longitudinal reinforcement. The concrete widely spalled but the reinforcing steels did not buckle. Specimen RF-F failed by rupture of longitudinal reinforcement. No FRP rupture was observed. Specimens CF-F and CS-F failed by cracking of concrete at the tension region. Only minor rupture of confinement was observed. For FRP-confined Specimens RF-F and CF-F, an ascending branch after yield can be observed showing that FRP was effectively holding the concrete and prevented cover spalling. Significant rise in load-carrying capacity and ductility can be observed. Compared to Specimen N-F, RF-F showed 210% increase in ultimate load and 310% rise in ductility and for Specimen CF-F, 210% and 400% increase were observed for ultimate load and ductility, respectively.


(a) Specimen N-F


(b) Specimen N-F


(c) Specimen N-F


(d) Specimen CS-F

Figure 10. Failure modes of columns under flexural tests

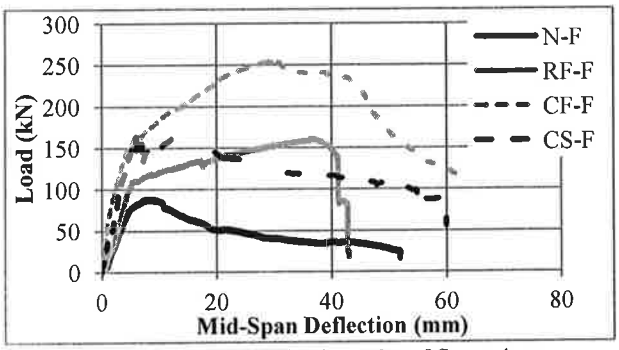


Figure 11. Load-midspan deflections plot of flexural tests

Specimens confined with steel straps demonstrated about 100% increase in ultimate load and 300% in ductility but only softening branch after yield can be observed.

Table 5. Summary of Flexural Test Results

Specimens	N-F	RF-F	CF-F	CS-F
Ultimate Load (kN)	81.70	159.80	253.92	163.19
Corresponding Axial Disp. (mm)	7.78	36.50	30.40	5.96
Yield Load (kN)	81.70	107.70	139.58	163.19
Corresponding Axial Disp. (mm)	7.78	5.25	4.04	5.96
Ductility	1.50	8.65	11.29	3.50

4 CONCLUSIONS

Based on the results of the experimental program, the following conclusion can be drawn:

1. For concentric and flexural tested columns, only columns in Group RF and CF provided ascending second branch showing strong confinement. Columns in Group CS showed descending second branch after peak which was described in Jiang & Teng (2007). This phenomenon indicates that steel straps confinement is less effective than FRP confinement. The reason for the ineffective confinement is mainly because the confinement was not continuous. For eccentrically tests, all columns showed descending second branch and therefore confinement is not effective in eccentrically loaded columns.

2. Circularisation is proven to be effective to increase the ultimate load-carrying capacity, as can be witnessed for Groups CF and CS. The enhancement can be largely attributed to the increase of cross-sectional area. The bonding of segmental circular concrete covers and the original columns were reliable and the modified columns can be treated as complete circular columns.

3. Concrete covers can effectively increase the efficiency of FRP confinement by reducing the stress concentration in the sharp corners. This phenomenon can be proved by observing the slope of the second branch in the load-displacement diagram. Group CF showed higher slope and thus the ultimate load-carrying capacity is higher than Group RF.

4. Steel strapping provides an alternative approach in strengthening the columns by increasing the ultimate load and ductility by a moderate amount compared to CFRP-confined columns. Nevertheless, this technique is relatively cheaper and easier to apply compared to CFRP wrapping. It is suggested that steel strap confining technique to be widely used in normal civil structure as an economical and convenient approach.

5. The efficiency of FRP confinement can be increased by continuously wrapping of FRP instead of wrapping ring by ring. All eccentrically loaded FRP-confined columns in the experimental program demonstrated that cracking of concrete between different rings of FRP can be observed.

Finally, the idea of modifying the cross-sectional area from square to circular by circularisation process is proved to be effective to maximise the load-carrying capacity of FRP-confined concrete columns. The efficiency of FRP-confinement can also be maximised compared to columns with round corners. This method can be considered as an effective and efficient method in strengthening columns in existing buildings and bridges.

5 ACKNOWLEDGEMENT

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