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Influence of Longitudinal FRP Straps on the Behaviour of Circularised and FRP Wrapped Square Hollow RC Concrete Specimens

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Abstract

This paper investigates the influence of longitudinal CFRP straps on the behaviour of circularised and FRP wrapped square hollow reinforced concrete (RC) columns. Twelve square hollow RC specimens were prepared and tested under concentric axial loads, eccentric axial loads and four-point bending. The specimens were divided into three groups of four specimens. The specimens in the first group were the non-strengthened square hollow RC specimens. The specimens in the second group were circularised by adding concrete segments to the sides of the square hollow RC specimens. Then the circularised specimens were wrapped with two layers of CFRP. The specimens in the third group were strengthened by attaching one longitudinal CFRP strap on each side of the square hollow RC specimens. Then the specimens were circularised with concrete segments and wrapped with two layers of CFRP. The test results showed that circularisation of the square hollow RC specimens enhanced the performance of the specimens in terms of ultimate axial load and ductility. The influence of the longitudinal CFRP straps was insignificant in increasing the ultimate axial load and ductility of concentrically loaded specimens. The presence of the longitudinal CFRP straps enhanced the axial load at yield of concentrically loaded specimens. The presence of the longitudinal CFRP straps enhanced the ultimate axial load and ductility of eccentrically loaded specimens. The contribution of the longitudinal CFRP straps to the ultimate axial load and ductility of the circularised square hollow RC specimens increased with the increase in load eccentricity. Also, the longitudinal CFRP straps increased the bending moment capacity of the circularised and CFRP wrapped square hollow RC specimens.

Keywords: Column, circularisation, CFRP, eccentricity.

1. INTRODUCTION

The Fibre Reinforced Polymer (FRP) materials have been used widely in strengthening concrete members in the last few decades. Strengthening concrete columns by wrapping with FRP increased the strength and ductility of the wrapped solid and hollow RC columns (Kusumawardaningsih and Hadi 2010). The increase in strength and ductility of the FRP wrapped columns is due to the confinement caused by FRP. The confinement brings the concrete in solid column into a triaxial state of stresses while FRP confinement brings the concrete in hollow columns into biaxial state of stresses.

The loading eccentricity and column cross-section can influence the efficiency of FRP confinement. The efficiency of FRP confinement decreases with the increase in the load eccentricity (Li and Hadi

2003). The presence of longitudinal FRP straps can reduce the effect of eccentricity and can increase the load and deformation capacities of eccentrically loaded hollow RC columns (Hadi and Le 2014). The FRP effectiveness of confinement is less for square columns than for circular columns. Changing a square cross section into circular cross section and then wrapping with FRP is an effective strengthening method for square solid and hollow concrete columns. (Hadi et al. 2012a; Jameel et al. 2017; Hadi et al. 2017). Hadi et al. (2017) showed that circularisation increased the strength, ductility and bending moment of the FRP wrapped square hollow RC specimens under different loading eccentricities. This paper investigates the influence of longitudinal CFRP straps on the behaviour of circularised and CFRP wrapped square hollow RC specimens under different loading eccentricities.

2. EXPERIMENTAL PROGRAM

Details of the experimental program of testing circularised and CFRP wrapped hollow RC specimens have been reported in Hadi et al. (2017). In this study, three groups are selected to investigate the influence of longitudinal CFRP straps on the behaviour of circularised and FRP wrapped hollow RC specimens under different loading conditions. For clarity, the experimental program is briefly reported herein.

The experimental program comprises twelve square hollow RC specimens of three groups. The specimens were constructed with square cross-section of 150 mm side dimension, square hole of 50 mm side dimension and 800 mm height. Four N12 deformed steel bars were used as longitudinal reinforcement and R6 plain steel bars were used as stirrups placed at 60 mm from centre to centre. The clear covers of concrete were 17 mm on each side and 20 mm on the top and bottom ends of the specimens. The specimens in the first group (Group R) were the non-strengthened hollow RC specimens. The specimens in the second group (Group CC) were the square hollow RC specimens circularised and wrapped with two layers of CFRP. The specimens in the third group (Group LCC) were the square hollow RC specimens strengthened with one longitudinal CFRP strap on each side then circularised and wrapped with two layers of CFRP. The first specimen from each group was tested as a column under concentric axial load. The second and third specimens were tested as columns under 25 mm and 50 mm eccentric axial loads, respectively. The fourth specimen was tested as a beam under four-point bending. Table 1 shows the test matrix of the tested specimens.

Table 1. Test matrix

Specimen	Cross-section (mm)	Gross area (mm^2)	Description of specimen	Eccentricity (mm)
N-0 **N-25** **N-50** **N-F**	150x150	19547	No strengthening	0 25 50 Four-point bending
CC-0 **CC-25** **CC-50** **CC-F**	Φ 212	32360	Circularised with four concrete segments and wrapped with two CFRP layers	0 25 50 Four-point bending
LCC-0 **LCC-25** **LCC-50** **LCC-F**	Φ 212	32360	Strengthened with one longitudinal CFRP straps on each side of square specimens then Circularised and wrapped with two CFRP layers	0 25 50 Four-point bending

The average compressive strength of concrete was 40 MPa and 47 MPa at 28 days and during the testing, respectively, determined according to AS1012.9 (1999). The mechanical properties of CFRP was 1102 N/mm maximum tensile strength per unit width and 0.016 mm/mm corresponding tensile strain determined according to ASTMD7565 (2010). The tensile yield strength was 478 MPa and 570

MPa, respectively, for the N12 and R6 steel bars determined according to AS 1391 (2007). The wet-layup method was used to wrap the specimens with CFRP by using an adhesive mixture of hardener and epoxy resin with ratio of 1:5. The top and bottom 100 mm of column specimens were wrapped with an extra two CFRP layers to prevent the premature failure at these regions. The beam specimens were wrapped with two CFRP layers at the shear span to reduce the shear failure. The Linear Variable Differential Transducers (LVDTs) were used to determine the vertical displacement of the tested specimens. The lateral deflection of the eccentrically tested specimens and the midspan deflection of the beam specimens were determined by using the laser triangulation. The specimens were subjected to displacement control loading of 0.3 mm/min. Figure 1 shows the details of specimens in Group LCC.

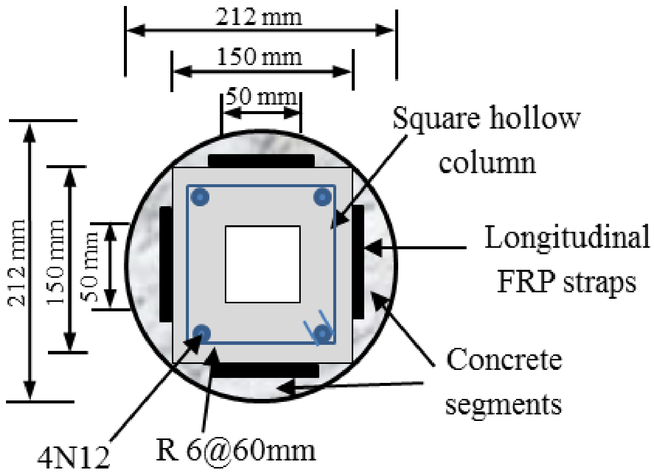


Figure 1. Design details of specimens in Group LCC

3. RESULTS AND DISCUSSIONS

3.1. Failure Mode

The failure of the reference specimens was sudden, brittle and initiated with spalling of concrete cover and buckling of longitudinal steel. The failure of the circularised column specimens was generally explosive and initiated by the rupture of CFRP at the midheight. It was observed that specimens in Group LCC experienced longer time up to failure than the specimens in Group CC.

3.2. Load-deformation Behaviour

Table 2 and Table 3 summarise the experimental results of the specimens tested as column specimens and beam specimens, respectively. Figures 2-5 show, respectively, the load-deformation behaviours of the specimens tested under concentric axial load, 25 mm eccentric axial load, 50 mm eccentric axial load, and four-point bending. Figure 6 shows a comparison of the normalised ultimate axial load and ductility between the tested specimens.

The normalised ultimate load and normalised ductility of specimens were calculated by dividing, respectively, the ultimate load and ductility of specimens by the ultimate load and ductility of the corresponding reference specimens. The ductility of the specimens was calculated by dividing the axial deformation corresponding to 85% of the post ultimate axial load by the deformation at the yield of the specimen.

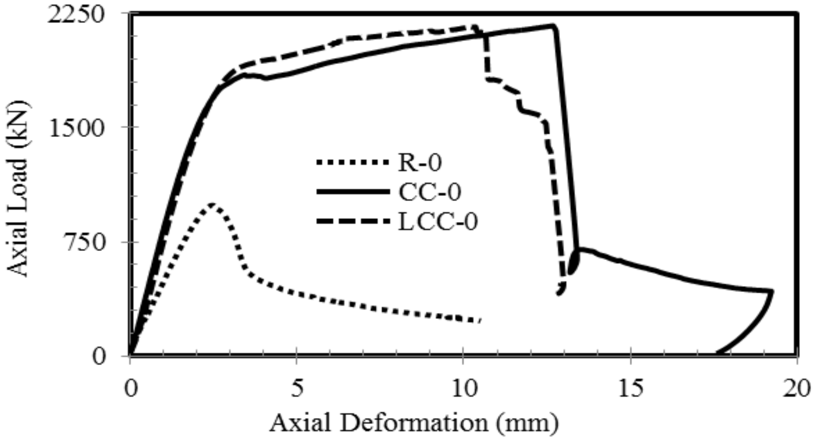


Figure 2. Axial load-axial deformation behaviour of concentrically loaded column specimens.

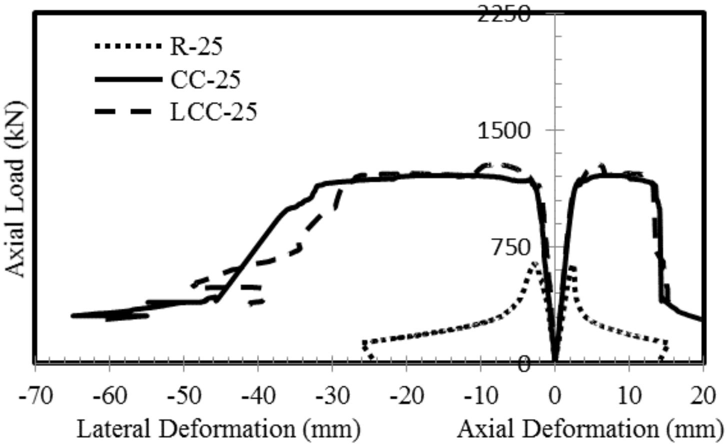


Figure 3. Axial load-deformation behaviour of eccentrically loaded column specimens (e = 25 mm)

The axial load-axial deformation behaviour of Specimen CC-0 showed two peak axial loads. After the first peak axial load of 1848 kN, the load dropped slightly to 1826 kN due to the presence of the hole that resulted in lower confinement gain compared to the degradation of concrete, then the load decreased to 2169 kN. While Specimen LCC-0 showed bi-linear axial load-axial deformation behaviour. Specimens CC-0 and LCC-0 showed similar increase in the ultimate axial load of 119% compared to that of Specimen R-0. Therefore, the contribution of the longitudinal CFRP straps to the ultimate axial load was negligible for the concentrically loaded specimens. Specimen LCC-0 achieved higher axial load at yield of 1508 MPa than that of Specimen CCC-0 of 1403 MPa.

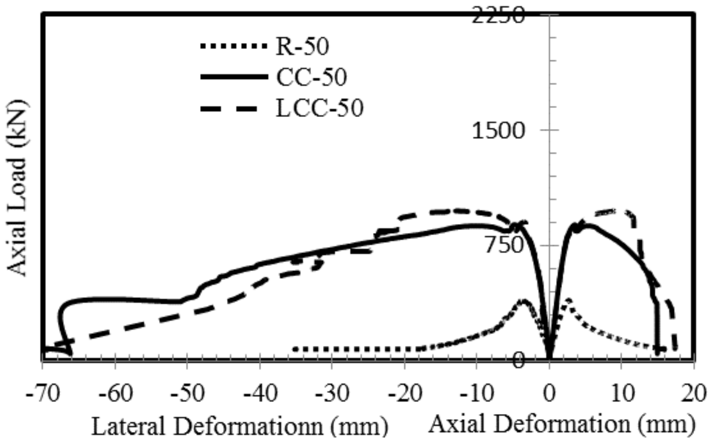


Figure 4. Axial load-deformation behaviour of eccentrically loaded column specimens (e = 50 mm)

The increase in the ultimate axial load was 99% and 88% for Specimens LCC-25 and CC-25, respectively, compared to that of Specimen R-25. The increase in the ultimate axial load was 148% and 125% for Specimens LCC-50 and CC-50, respectively, compared to that of Specimen R-50. The axial load-axial deformation behaviour of Specimen LCC-50 showed two peak axial loads due to the presence of the longitudinal CFRP straps. After the first peak load of 902 kN, the axial load of Specimen LCC-25 dropped to 846 kN then the axial load increased up to the ultimate axial load of 975 kN due to the activation of the longitudinal CFRP straps with the increased applied eccentric loading. The increase in the ultimate axial load was 89% and 143% for Specimens LCC-F and CC-F, respectively, compared to that of Specimen R-F. The load-deflection behaviour of Specimen LCC-F showed three peaks due to the subsequent rupture of the longitudinal CFRP straps in the bottom and the sides of the specimens.

Table 2. Experimental results of the column specimens

Specimen	Axial load at yield (kN)	Axial deformation at yield (mm)	Ultimate axial load (kN)	Axial deformation at ultimate axial load (mm)	Lateral deflection at ultimate axial load (mm)	Ductility	Moment at ultimate load (kN-m)
R-0	800	2.2	989	2.5	-	1.4	-
CC--0	1403	2.3	2169	12.7	-	5.9	-
LCC-0	1508	2.5	2162	10.5	-	4.4	-
R-25	582	2.2	642	2.4	2.3	1.2	17.5
CC--25	985	2.5	1209	6.2	9.0	5.6	41
LCC-25	1011	2.3	1279	5.7	8.6	5.8	43
R-50	315	2.1	393	2.7	4.0	1.5	21.3
CC--50	680	2.4	885	3.5	5.0	4.2	48.5
LCC-50	726	2.5	975	9.7	12.5	4.9	61

Specimen CC-0 achieved the highest ductility of 5.9 followed by Specimen LCC-0 of 4.4. Specimen LCC-25 achieved higher ductility of 5.8 than that of 5.6 for Specimen CC-25. Specimen LCC-50 achieved higher ductility of 4.9 than that of 4.2 for Specimen CC-50. Specimen LCC-F achieved higher ductility of 9.4 than that of 8.4 for Specimen CC-F.

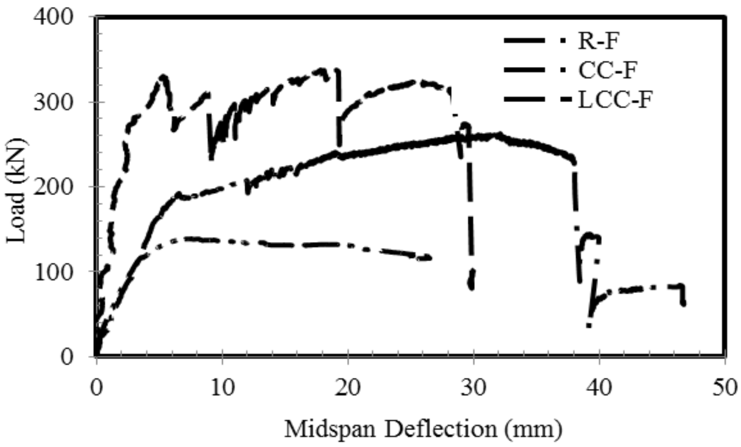


Figure 5. Load-midspan deflection behaviour of beam specimens

3.3. Position of the Longitudinal CFRP Straps

The test results showed that the longitudinal CFRP straps enhanced the performance of the circularised and CFRP wrapped hollow RC specimens subjected to eccentric axial loads and four-point bending. Also, there was no significant contribution of the longitudinal CFRP straps to the concentrically loaded specimens. Based on the above results, the longitudinal CFRP strap on the compression side was negligible. The longitudinal CFRP straps on the tension side contributed directly to the tensile resistance of the column specimens subjected to eccentric axial loads and four-point bending which increased the ultimate load of the specimens. After the rupture of the CFRP straps on the tension side, the CFRP straps on the left and right sides of the square hollow specimens in Group LCC contributed to the ultimate load of the specimens and ruptured as single fibres one after one towards the compression side with the increase in the applied eccentric load. The subsequence ruptures of the CFRP straps increased the ductility of the specimens and were more active for specimens with higher eccentricity. Therefore, it is believed that the longitudinal CFRP straps on the tension side of specimens were more effective in increasing the strength than increasing the ductility, while the longitudinal CFRP straps on the left and right sides of the specimens were more effective in increasing the ductility than increasing the strength of the tested specimens. Therefore, strengthening the circularised hollow RC specimens with longitudinal CFRP straps on the sides of the specimens is significant in increasing the ductility of eccentrically loaded column specimens.

Table 3. Results of specimens tested under four-point bending

Specimen	Yield load (kN)	Midspan deflection at yield (mm)	Ultimate load (kN)	Midspan deflection at ultimate load (mm)	Ductility	Moment at ultimate load (kN-m)
R-F	116	4.2	139	7.6	6.2	16
CC-F	158	4.5	263	32	8.4	30.5
LCC-F	270	3.0	338	19	9.4	40

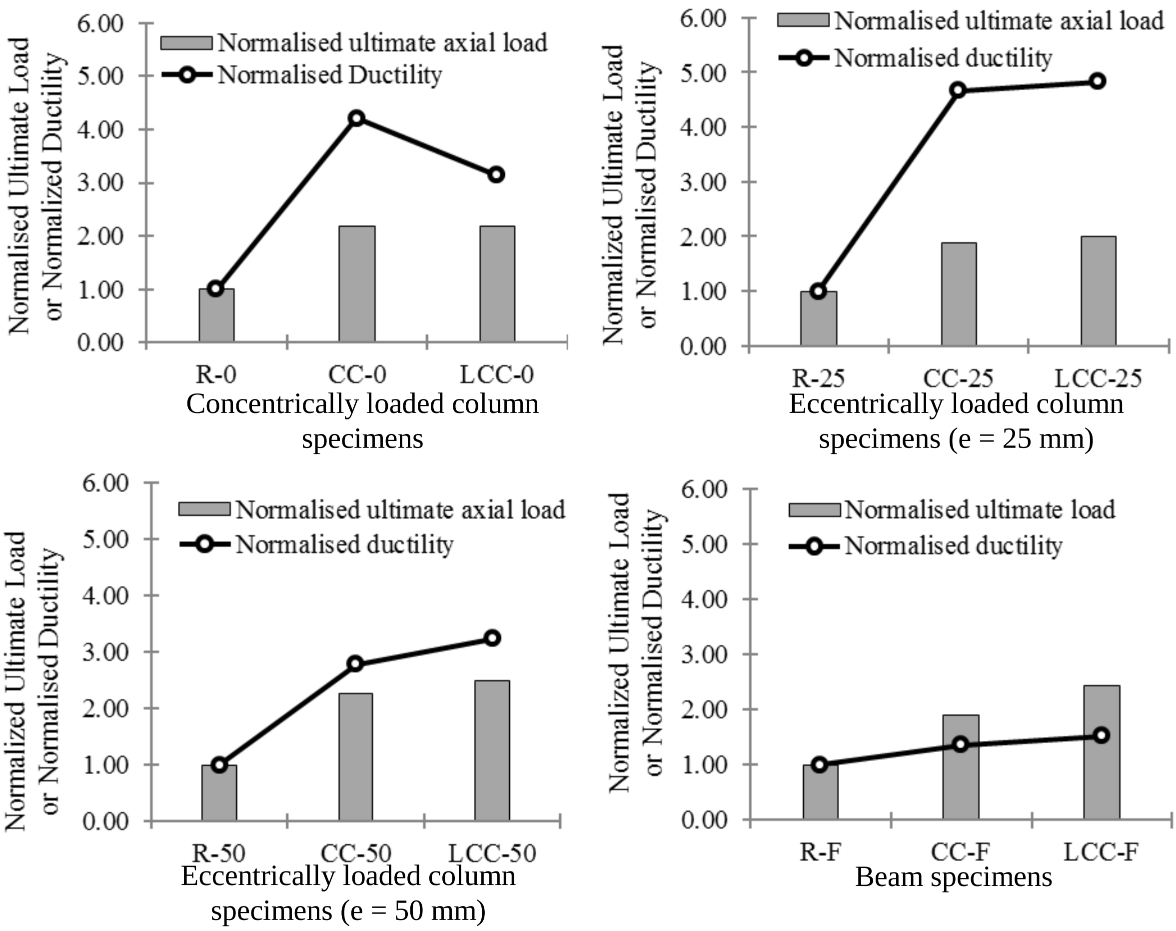
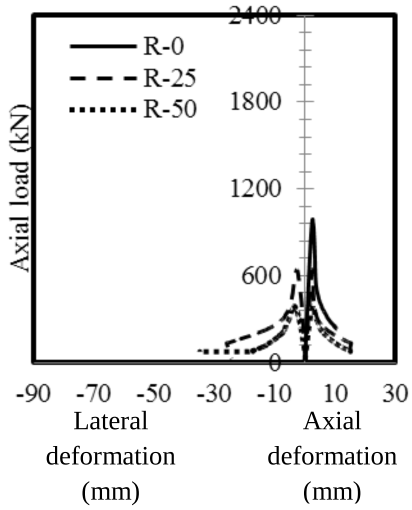


Figure 6. Comparison between specimens (normalised ductility and normalised ultimate load)

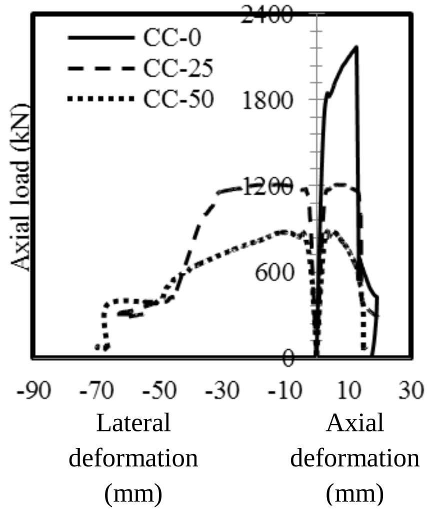
Figure 6 shows that the gain in ductility was higher than that of ultimate axial load for the circularised and CFRP wrapped column specimens relative to the reference column specimens. While the gain in ultimate load was higher than the gain in ductility for the circularised and CFRP wrapped beam specimens relative to the reference beam specimens. Also, the gain in ultimate axial load and ductility was higher for Specimens LCC-25 and LCC-50 than that of Specimens CC-25 and CC-50, respectively due to the increase in the effectiveness of the longitudinal CFRP straps with the increased load eccentricity.

3.4. Influence of Load Eccentricity

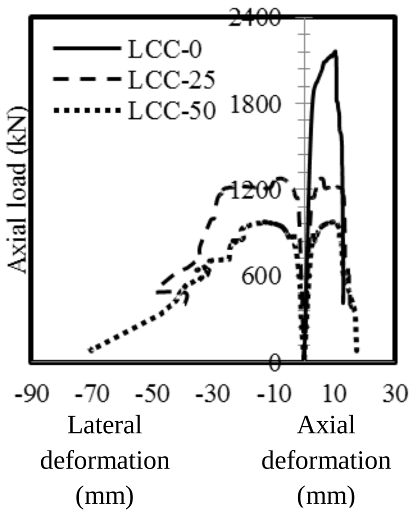
Figure 7 shows the axial load-axial deformation curves in relation to the eccentricity of the axial load of the tested specimens. The load and deformation capacities of column specimens decreased with the increase in the load eccentricity. The reduction in ultimate axial load of Specimens R-25 and R-50 relative to Specimen R-0 was respectively, 35% and 60%. The reduction in ultimate axial load of Specimen CC-25 and CC-50 relative to Specimen CC-0 was respectively, 44% and 59%. It can be seen that the influence of eccentricity is higher for the circularised and CFRP wrapped group compared to the reference group. This might be because the higher eccentricity increased the concrete area in tension zone and reduced the area of concrete in compression zone, hence, reducing the confined concrete area. The reduction in ultimate axial load of Specimens LCC-25 and LCC-50 relative to Specimen LCC-0 was respectively, 40% and 55%. It is clear that the longitudinal CFRP straps minimized the reduction in the ultimate axial load especially with the high load eccentricity.



(a) Group R



(b) Group CC



(c) Group LCC

Figure 7. Axial load-deformation behaviour of column specimens with different load eccentricities

3.5. Axial Load-Bending Moment Interactions

Figure 8 shows the axial load-bending moment interactions of the tested specimens. The bending moment (M_u) corresponding to the ultimate axial load of the specimens tested as column specimens was calculated as:

$$M_u = P_u (e + \delta) \tag{1}$$

where *e and* δ are the initial eccentricity and the lateral deformation at the ultimate axial load (P_u).

The bending moment corresponding to the ultimate load of the specimens tested as beam specimens was calculated as:

$$M_u = 0.5\, P_u\, a \tag{2}$$

where a = 233 mm, is length between the support and the nearest loading point of the beam specimens.

The axial load bending moment interactions comprises four points nominated as A, B, C and D for each group (Figure 5). The first point (A) represents the concentrically loaded column specimens. The second point (B) and the third point (C) represent, respectively, the 25 mm and 50 mm eccentrically loaded column specimens. The fourth point (D) represents the specimens tested under four-point bending. At Point A, the circularised and CFRP wrapped specimens achieved higher ultimate load compared to the reference specimens. At Point B, Specimen LCC-25 achieved slightly higher ultimate axial load and corresponding bending moment than that of Specimen CC-25. At Point C, Specimen LCC-50 achieved 10% higher ultimate axial load and 25% higher corresponding bending moment than that of Specimen CC-50. The increase in the ultimate axial load and the corresponding bending moment of specimens in Group LCC compared to specimens in Group CC was higher at Point C than that at Point B due to the presence of the longitudinal CFRP straps that increased the capacity of column specimens at ultimate load and lateral deformations.

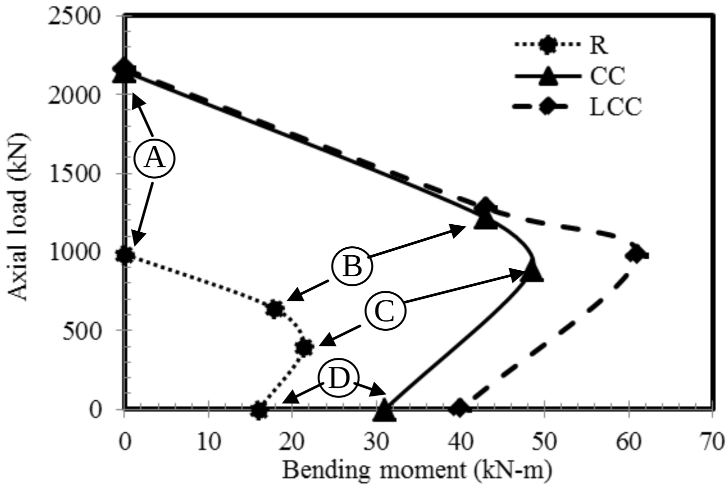


Figure 8. Experimental axial load-bending moment interactions for the tested specimens.

4. CONCLUSIONS

Circularisation and FRP wrapping proved to be an effective method in strengthening hollow RC column specimens subjected to different loading conditions. Strengthening square hollow RC column specimens with longitudinal CFRP straps increased the load capacity, ductility and bending moment capacity of the circularised and FRP wrapped square hollow RC specimens. The presence of longitudinal CFRP straps was insignificant for the concentrically loaded specimens. The effectiveness of the longitudinal CFRP straps increases with the increase in the eccentricity of the applied load. The presence of the longitudinal CFRP straps on the tension side of the eccentrically loaded column specimens and beam specimens was more significant in increasing the strength of the specimen than the ductility. The presence of the longitudinal CFRP straps on the left and right sides of the specimens was more significant in increasing the ductility of column specimens than the ultimate load.

5. ACKNOWLEDGMENTS

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