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Ductility Behaviour of Rectangular Compression Members Retrofitted by Modified Technique of FRP Wrapping

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Abstract: This paper presents an experimental investigation on ductility behaviour of reinforced concrete compression members, rectangular in cross section, modified to elliptical shape in cross section by bonding precast segment covers followed by Carbon Fiber Reinforced Polymer wrapping (CFRP) under concentric and eccentric loading conditions. Eighteen reinforced concrete rectangular compression members of size 100mm×150mm in cross section and 300mm in height were prepared using normal-strength concrete. Reinforcement ratio was kept at minimum, to simulate compression members that need retrofitting. Out of eighteen specimens, nine specimens were converted to elliptical shape in cross section. From nine remaining rectangular specimens, three specimens retained as it is without wrapping FRP and designated as Group1, remaining six specimens were wrapped with one and two layers of CFRP and designated as Group2. Out of nine elliptical specimens, three specimens were retained as it is without wrapping FRP and designated as Group3, remaining six elliptical specimens were wrapped with one and two layers of CFRP and designated as Group4. Specimens were tested upto failure under monotonic axial compression with concentric and eccentric load conditions. From the experimental results, it is observed that rectangular compression members shape modified to ellipse in cross section and then wrapped with CFRP show outstanding increase in the ultimate load carrying capacity which may be due to increased cross sectional area and effective confinement of FRP wrapping. As the number of layers of CFRP increases the ultimate load carrying capacity increases. With increase in eccentricity, the ultimate loads of the compression members were found to be decreased. Elliptical specimens wrapped with one and two layers of CFRP reported exponential increase in deformation ductility under concentric load condition and considerable increase under eccentric load condition compared to rectangular specimens wrapped with CFRP.

Keywords: Compression Members, CFRP Wrapping, Precast Segments, Elliptical Columns

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I. INTRODUCTION

Fibre Reinforced Polymer (FRP) application for retrofitting existing deficient columns is very common now a days. Vast research has been undertaken to evaluate the behaviour of FRP wrapped Square and Rectangular columns(Eid & Paultre, 2017; M. N.S. Hadi, 2006; Ilki et al., 2008; Lin & Teng, 2017; Pessiki et al., 2001; Teng & Lam, 2002) . From these studies it is understood that, in square columns and rectangular columns though there is considerable increase in the load carrying capacity and strength, the failure is mainly due to stress concentration at the corners of the columns. This made the method of retrofitting square and rectangular columns very less effective. Several researchers attempted to increase the efficiency of confinement by rounding of the corners of the columns (Luca et al., 2011; Saleem et al., 2017; Wang et al., 2016).It is proved that the confinement efficiency increases with increase in the corner radius. However, it is a fact that this increase in corner radius is limited by the presence of longitudinal and lateral reinforcement which becomes an obstruction during rounding of corners and also increase in corner radius reduces the cross-sectional area there by reducing load carrying capacity though confined compressive strength is high. On the contrary, wrapping FRP transversely provides a higher level of confinement in circular columns than in noncircular columns(Chastre & Silva, 2010; M. N.S. Hadi, 2007; Muhammad N.S. Hadi, 2006; Harries & Carey, 2003; Parvin & Schroeder, 2008; Teng et al., 2016; Teng & Lam, 2002). Several research studies investigated the modification of the square columns into circular columns before FRP wrapping (Muhammad N.S. Hadi et al., 2013, 2017; Pham et al., 2013; Zeng et al., 2017)

These studies on shape modification revealed that changing the square cross section of a column into a circular cross section before FRP wrapping enhanced the performance of the columns after FRP wrapping. In practice rectangular columns are more commonly provided in buildings especially in residential apartments. Hence it is interesting to investigate the performance of rectangular column converted into elliptical columns and followed by FRP wrapping. There is only one study carried out (Yan et al., 2011) on the performance of rectangular columns without reinforcement converted to elliptical shape and Expansive cement filled in FRP Shells.

The study covers limited number of parameters. Inserting FRP shell around the existing column is impractical and filling the cement in the gaps and ensuring the compaction will be very difficult. In the present study as an alternative to cast in situ expansive cement, precast segments are used to convert the rectangular cross section to elliptical cross section (introduced by Hadi et al. 2013 for square columns) followed by FRP Wrapping.

Use of precast segments for shape modification reduces the time for process of retrofitting from 45 days to 10 days against the former required by cast-in situ concrete.

This paper aims to investigate ductility the behaviour of rectangular columns converted to elliptical followed by CFRP wrapping. In the present study a total of 18 compression members were prepared and tested for concentric and eccentric loading conditions. The test results in terms of the failure modes and ductility are investigated.

II. SCHEME OF RETROFITTING

In present study, to overcome the reduction in effectiveness of FRP wrapping in rectangular columns due to stress concentration at the corners, a method of inducing the uniform confinement by FRP by changing cross section shape is adopted. Compression members rectangular in cross section were converted to elliptical shape in cross section by the bonding precast segment covers on all four sides of specimen using cementitious adhesive and followed by CFRP wrapping (Fig.1) which provides uniform confinement to the concrete.

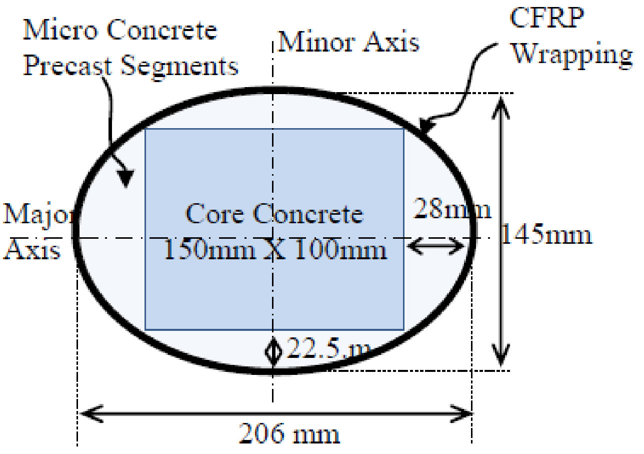


Fig. 1.Cross section of rectangular specimens modified to elliptical shape by bonding precast segments followed by FRP wrapping

III. EXPERIMENTAL PROGRAM

A. Design of Experiments

A total of 18 reinforced concrete rectangular specimens of size 100 mm X 150 mm in cross section and 300mm in length, were divided into 4 groups are cast. First group consists of FRP unwrapped rectangular specimens which serve as control specimens with which all comparisons are made. Second group consists of FRP wrapped rectangular specimens with corners rounding. Third group consists of unwrapped rectangular specimens converted to elliptical shape by four precast segments. Details of the elliptical cross section adopted in the present study are shown in Fig.3.b. Fourth group consist of FRP wrapped rectangular specimens converted to elliptical shape obtained by bonding precast segments. First group consisting of three rectangular specimens without FRP wrapping are named as (R0-eX) where "R" indicates Rectangular Cross Section, "0" Indicates absence of FRP wrapping, "e" indicates eccentricity, "X" indicates the value of eccentricity of loading (0mm, 25mm and 50mm). Second group consisting of six FRP wrapped rectangular specimens (corners rounded by 25mm) named as Rn-eX, in which "n" indicates number of layers of CFRP (one and two layers) other notations mean the same as that of previous group. Third group consisting of three unwrapped specimens shape modified from rectangle to elliptical in cross section named as (E0-eX), where "E" indicates Elliptical cross section. Fourth group consists of six rectangular specimens converted to elliptical shape wrapped with FRP named as En-eX. All specimens are reinforced with 6 bars of 8 mm diameter high strength deformed bars and 6 mm diameter mild steel ties at 100mm c/c in the middle region at 25mm c/c at the ends. Table 1 shows the details of test specimens considered in the investigation.

B. Preparation of Specimens

The rectangular specimens were cast using steel moulds with normal concrete mix made of coarse aggregates 12 mm down size, natural river sand as fine aggregates and 53 Grade OPC cement. Specimens were cured for 28 days and compressive strength is after 28 days was found to be 30.5 N/mm2. Out of 18 rectangular specimens 3 specimens were retained as it is without any modification and are designated as Group 1(R0-eX-control specimens). 6 rectangular specimens were corner rounded with corner radius of 25mm and wrapped with one and two layers FRP (3 specimens with one layer and other 3 with two layers), which are designated as Group 2 (Rn-eX) specimens.

Before the application of FRP, the surface irregularities on the specimen were removed using grinding machine and using flexible Nylon brush, dust was removed

Table 1: Details of the test specimens

Group	Specimens	External Reinforcement	Eccentricity (mm)
Group 1 (R0-eX)	R0-e0	None	0
	R0-e25		25
	R0-e50		50
Group 2 (Rn-eX)	R1-e0	One Layer of CFRP	0
	R1-e25		25
	R1-e50		50
	R2-e0	Two Layers of CFRP	0
	R2-e25		25
	R2-e50		50
Group 3 (E0-eX)	E0-e0	None	0
	E0-e25		25
	E0-e50		50
Group 4 (En-eX)	E1-e0	One Layer of CFRP	0
	E1-e25		25
	E1-e50		50
	E2-e0	Two Layers of CFRP	0
	E2-e25		25
	E2-e50		50

On the prepared surface one layer of primer was applied, which is obtained by mixing base and hardener in proportions 3.1 liter (base): 0.4 liter (hardener) by volume. Mixed primer was applied using brush. In case of very porous surfaces a second coat was applied. The primer was allowed to cure overnight. After 24 hours as primer becomes tack free, Epoxy Saturant which comes as 2 parts, base and hardener was mixed as per specification and applied to the surface of the specimen.

As per the need one or two layers of CFRP was wrapped over the specimen in the hoop direction as shown in Fig-4. A lap length of 150 mm is adopted on each on each layer. After the wrapping of a single ply fiber sheet, one more layer of epoxy saturant was applied and the plastic roller was used again to work the resin into the fibers. The second layer of CFRP was then wrapped tightly on the first layer.

The precast segments prepared using Micro-concrete, with open moulds (Fig. 2) were cured for 28 days and compressive strength after 28 days was found to be 45 N/mm^2.

Nine rectangular specimens were bonded with precast segments using Nitowrap PC 40 cementitious adhesive (Fig.3a.). Nitowrap PC 40 comes as two part, one base and other hardener. Base and hardener are mixed in 2: 1 ratio. This material after hardening is designed to give Compressive Strength of 70 N/mm^2 (ASTM D695), Tensile Strength of 13 N/mm^2 (ASTM D638), % of Elongation of 31% (ASTM D638) and Bond Strength 14 N/mm^2(ASTM C882). The cross sectional details of modified specimens is as shown in Fig.1. Curved Precast segments of two different thicknesses at the centreal region were used, 22.5mm thick segment was bonded on the sides parallel to 150mm and 28 mm was bonded on sides parallel to 100mm. Out of these nine shapes modified specimens, three specimens retained as it is without wrapping with FRP and designated as Group 3 (E0-eX), remaining six specimens are wrapped (Fig. 4) with one and two layers of FRP and designated as Group 4 (En-eX)

Fig. 2. Preparation of precast segments

Fig. 3. . Bonding of precast segments

Capping of the specimen at top and bottom end faces was done using a cementitious grouting material (compressive strength 55-65 MPa after 7 days), to make the end surfaces smooth and perfectly perpendicular to the longitudinal axis of the compression members to ensure uniform distribution of applied compressive stress.

Fig. 4. Wrapping of CFRP

C. Experimental setup and Instrumentation

Compression Testing Machine of 2000 kN capacity available in the laboratory was used for both concentric and eccentric loads. To apply the Eccentric loading, a customized high strength steel ‘wedges and plate system’ was employed. The plate was provided with 3 triangular grooves to create eccentricities of 0 mm, 25mm and 50mm ad shown in Fig.5(a) and (b).

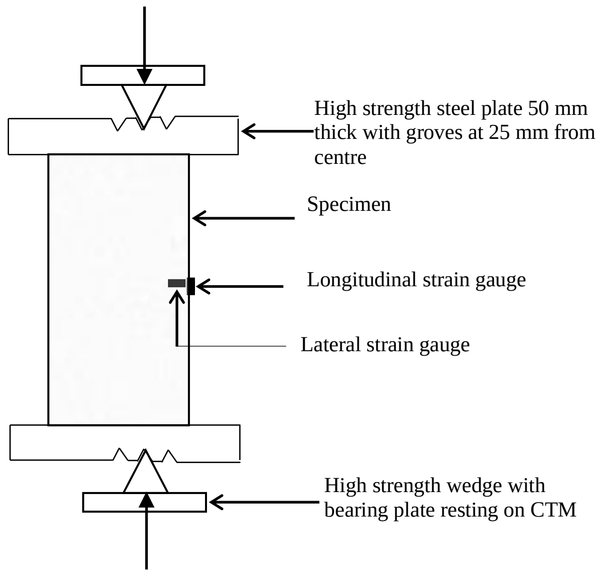


Fig. 5. a. **Loading arrangement using high strength steel plates and wedges**

Fig. 5. b. High strength steel wedges and plates

Fig. 6. Test set up in compression testing machine

All specimens were mounted in the Compression Testing Machine (2000kN Capacity) and compression load was applied upto failure at 50 kN interval. At each increment of load, axial deformations were measured using two dial gauges placed on two opposites sides of base. Strains were measured using strain gauges of gauge length 6mm placed at mid height of specimen one in longitudinal direction and other in lateral direction on the side of eccentricity. The test set up for the unwrapped elliptical specimen is as shown in the Fig. 6.

IV. RESULTS AND DISCUSSION

Some of the test results of the progressive compression test conducted on the all the four groups of the specimens mentioned earlier are presented in the Table 2. The behavior of different groups is compared and discussed.

Table 2: Ultimate loads of the and ultimate deformations of the compression members

Designation	Cross Sectional Area (mm^2)	Number of FRP Layers	Ultimate Load (kN)	Ultimate Deforma -tion (mm)	Factors by which Ultimate load increase compared to (R-0,e-0)
R0-e0	13714.16	0	400	0.90	1.00
R0-e25	13714.16	0	250	0.60	0.63
R0-e50	13714.16	0	113	0.97	0.28
R1-e0	13714.16	1	710	0.76	1.78
R1-e25	13714.16	1	550	1.58	1.38
R1-e50	13714.16	1	180	.38	0.45
R2-e0	13714.16	2	800	1.30	2.00
R2-e25	13714.16	2	650	2.43	1.63
R2-e50	13714.16	2	500	1.34	1.25
E0-e0	23680.24	0	550	4.47	2.38
E0-e25	23680.24	0	400	4.58	1.00
E0-e50	23680.24	0	350	3.55	0.88
E1-e0	23680.24	1	1065	1.03	2.66
E1-e25	23680.24	1	650	1.04	1.63
E1-e50	23680.24	1	462	1.06	1.16
E2-e0	23680.24	2	1200	1.14	3.0
E2-e25	23680.24	2	1015	1.45	2.54
E2-e50	23680.24	2	550	1.14	1.38

From the experimental results presented in the Table 2 , it is observed that specimens modified to elliptical shape and wrapped with CFRP show outstanding increase in the ultimate load carrying capacity compared to rectangular specimens. This increase in the load carrying capacity may be due to increased cross sectional area and uniform confinement provided by FRP wrapping in elliptical compression members compared to rectangular compression members. As the number of layers of FRP increased the ultimate load carrying capacity increased, highest ultimate load of 1200kN is reported for E2-e-0 specimen, which is thrice compared to R0-e0 specimen. With increase in eccentricity, the ultimate loads of the compression members were found to decrease. The lowest ultimate load of 113 kN is reported in R0-e50 specimen, which is only 28% compared to R0-e-0 specimen.

A. Ductility behavior of specimens under concentric loading

Results of specimens tested under concentric compressive loading are tabulated in Table.3 with the axial load-axial deformation diagrams shown in Fig. 7. From table. 3 and the Fig.7, it is observed that elliptical specimens obtained by modification of rectangular specimens by precast segments (E0-eX) deformed less and failed at higher ultimate load compared to the control specimens R0-eX which may be due to higher cross sectional area and uniform confinement.

CFRP confined shape modified elliptical specimens resisted ultimate loads of 1065 kN and 1200kN which are almost 1.5 times than rectangular counterparts for single and double layers of wrapping. Specimens with two layers of FRP compared to single layer of FRP deformed more at same load levels during initial stage but have shown higher stiffness after around 80% of ultimate load and failed at higher ultimate loads. This happened for both rectangular and elliptical columns with concentric loading.

Specimen R0-e0 (Fig.8.a) failed by concrete crushing and yielding of compression reinforcement. Specimens R1-e0 and R2-e0 failed by rupture of CFRP in the corners on the major compression side face of column as shown in Fig. 8.b and Fig.8.c. E0-e0 specimen (Fig.8.d) failed partially due to debonding of precast segment from the core concrete due to interfacial incompatibility. E1-e0 (Fig. 8.e) and E2-e0 (Fig. 8.f) specimens failed at the sharper side of elliptical cross-section due to stress concentration by crushing of concrete and tearing of CFRP at the ends, during which a loud bursting sound could be heard. The ultimate load has been increased 3 times for E2-e2 compared to R0-e0 (400kN to 1200 kN).

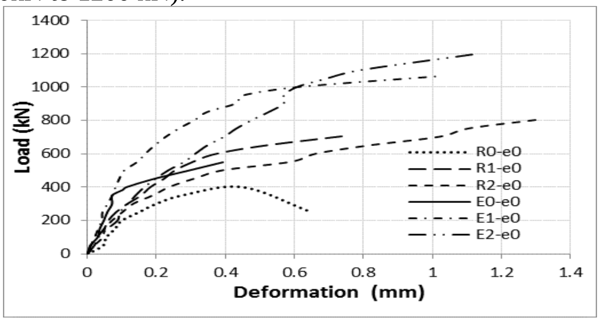
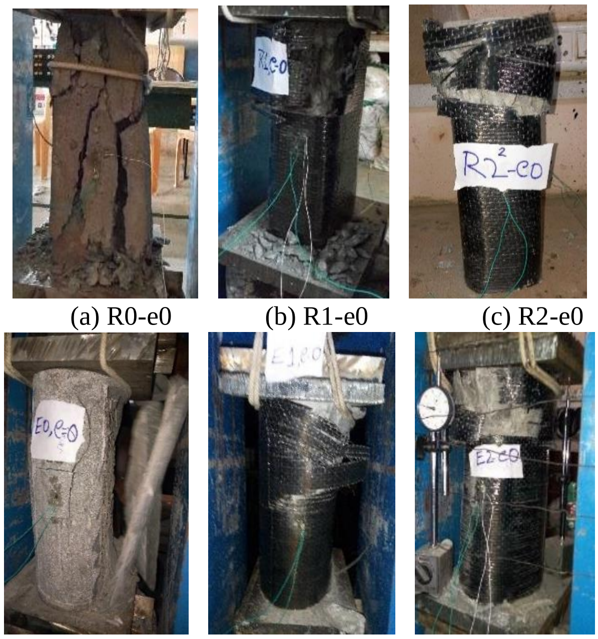


Fig. 7. Axial Load - deformation behavior of concentrically loaded specimens

Table 3: Results of specimens tested under concentric loading

Specimens	R0-e0	R1-e0	R2-e0	E0-e0	E1-e0	E2-e0
Yield load (kN)	380	491.5	500	400	500	450
Corresponding Axial Deformation(mm)	0.34	0.37	0.39	0.11	0.11	0.2
Ultimate load (kN)	400	710	800	550	1065	1200
Ultimate Axial deformation (mm)	0.45	0.75	1.3	0.39	1.03	1.13
Ductility (Method 1)	1.31	2.03	3.30	3.55	9.36	5.65
Ductility (Method 2)	1.46	5.48	5.39	6.14	35.98	16.74

In the present study ductility of the specimen is calculated using two methods. In the first method, the equation k = du/dy, is used to calculate the ductility where k = ductility, dy = yield deformation, du = ultimate deformation. In the second method the area under the load-axial deformation curve is used which represents total energy absorbed by the specimen. Two areas are calculated, A1 which represents the area under the curve up to the yield load and A2 which represents the area under the curve up to the ultimate deformation. The ductility is calculated by A2/A1(Muhammad N.S. Hadi, 2009).



(a) R0-e0 (b) R1-e0 (c) R2-e0

(d) E0-e0 (e) E1-e0 (f) E2-e0

Fig. 8. Modes of failure of concentrically loaded specimens

From results it is observed that rectangular specimens show more deformation ductility with 2 layers of FRP compared to single layer of FRP. But in elliptical specimens the ductility reduced in 2 layers of FRP mainly due to increase in stiffness and ultimate load carrying capacity.

B. Ductility behavior of specimens under eccentric Loading

Fig. 9 and 11 depict axial load- axial deformation variations of eccentrically loaded specimens while Table 4 and 5 show comparisons of yield load, ultimate load and corresponding deformations and ductility factors of all specimens tested under eccentric compression loading for eccentricity of 25mm and 50mm respectively.

Specimens R0-e25(Fig.10.a) failed by crushing of concrete at bottom of major compression side where as E0-e25 failed prematurely by debonding of precast segments without crushing of core concrete. Specimen R1-e25(Fig.10.b) failed by tearing of CFRP at bottom corner followed by crushing of concrete at same location. Specimen E1-e25(Fig.10.e) failed similar to R1-e25 but tearing of CFRP happened on the sharper face of ellipse which was on major compression side. It is interesting to observe that in specimens with two layers of FRP R2-e25(Fig.10.c) and E2-e25(Fig.10.f), the failure shifted from bottom to mid height of specimens in which tearing of FRP took place in R2-e25 specimen at one of the corner and in specimen E2-e25 tearing of CFRP occurred at 450.

All the Specimens Rn-e50(Fig.12.a to c) failed very prematurely at the top with partial crushing of concrete, Specimen En-e50(Fig.12.d to e) failed by partial debonding of precast segment. Specimens with one and two layers of FRP also failed at the top and was same for both rectangular and elliptical specimens.

Ductility of specimens tested under eccentric compressive load is also higher for specimens wrapped with single layer of FRP and decreased as the number of layers increase to 2 both in rectangular and elliptical specimens, mainly due to substantial increase in ultimate load and stiffness.

In case of E2-e-25 specimen with 25mm eccentricity the ultimate load observed was 930 kN, which is 3.72 times that compared to R0-e25 (ultimate load of 250 kN). Similarly, E2-e50 specimen has shown 4.86 times increase in the ultimate load compared to R0-e50. From the results it is clear that the CFRP wrapped shape modified elliptical specimens perform well even under eccentric compressive loads.

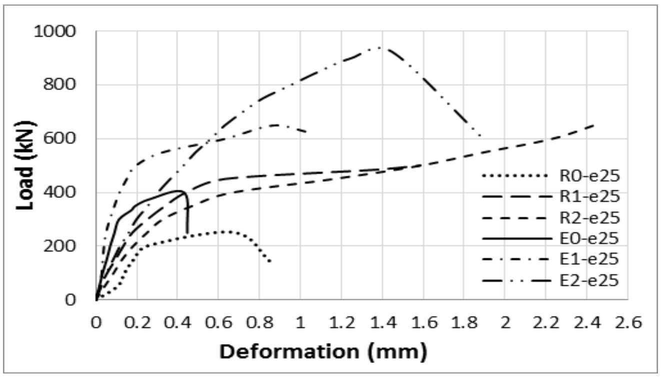


Fig. 9. Axial Load – axial deformation behavior of specimens loaded with an eccentricity of 25mm.

Table 4: Results of specimens tested under Eccentric loading of 25mm

Specimens	R0-e25	R1-e25	R2-e25	E0-e25	E1-25	E2-e25
Yield load (kN)	190	445	400	300	497.5	540
Corresponding Axial Deformation(mm)	0.62	0.57	0.66	0.12	0.2	0.48
Ultimate load (kN)	250	500	650	406.5	652	930
Ultimate Axial deformation (mm)	0.85	1.58	2.43	0.40	0.9	1.4
Ductility (Method 1)	1.37	3	3.68	3.33	4.5	2.91
Ductility (Method 2)	6.41	3.77	5.35	6.88	7.81	5.26

(a) R0-e25 (b) R1-e25 (c) R2-e25

(d) E0-e25 (e) E1-e25 (f) E2-e25

Fig. 10. Modes of failure of specimens loaded at 25mm eccentricity

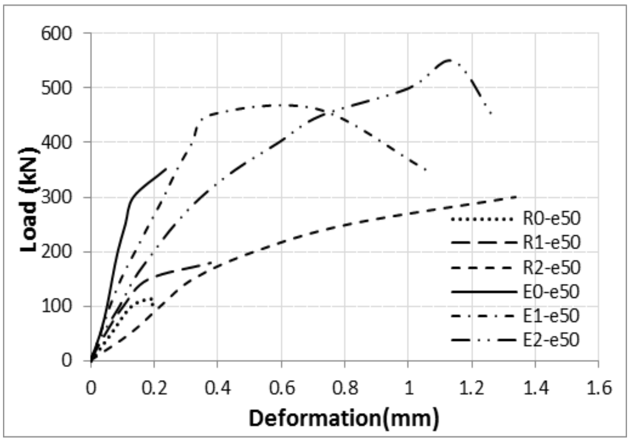


Fig. 11. Axial Load – axial deformation behavior of specimens loaded with an eccentricity of 50mm

Table 5: Results of specimens tested under Eccentric loading of 50 mm

Specimens	R0-e50	R1-e50	R2-e50	E0-e50	E1-50	E2-e50
Yield load (kN)	100	144	140	300	440	440
Corresponding Axial Deformation(mm)	0.129	0.16	0.30	0.135	0.35	0.69
Ultimate load (kN)	113	180	300	350	462	550
Ultimate Axial deformation (mm)	0.194	0.38	1.34	0.234	0.71	1.14
Ductility(Method 1)	1.50	2.375	4.45	1.73	2.03	1.65
Ductility(Method 2)	1.93	2.94	5.47	3.22	4.78	3.18

(a) R0-e25 (b) R1-e25 (c) R2-e25

(d) E0-e50 (e) E1-e50 (f) E2-e50

Fig. 12. Modes of failure of specimens loaded at 50 mm eccentricity

V. CONCLUSION

Based on the limited experimental investigation carried out, following conclusions are drawn,

1. The increase in load carrying capacity of shape modified elliptical specimens by bonding of precast segments to rectangular specimens and confined by CFRP wrapping is substantially high compared to rectangular specimens due to increased area of cross section and due to uniform confinement under both concentric and eccentric compressive loading.
2. The specimens with CFRP wrapping show increased load-carrying capacity for any eccentricity of compression compared to unwrapped specimens.
3. With the increase in number of layers of CFRP, the load carrying capacity increases both in case of shape modified elliptical and corner rounded rectangular specimens.
4. Elliptical specimens wrapped with one and two layers of CFRP exhibit considerable increase in deformation ductility both under concentric and eccentric compressive loads compared to rectangular specimens wrapped with CFRP.
5. In rectangular specimens wrapped with CFRP, deformation ductility factor increased with increase in number of layers of CFRP. But Elliptical specimens with single layer of FRP show higher deformation ductility compared to elliptical specimens wrapped with 2 layer of FRP, this may be due to increased stiffness of CFRP wrap with additional layer of FRP 6. The increase deformation ductility in the concentrically loaded elliptical specimens wrapped with CFRP is very high compared rectangular specimens wrapped with CFRP. But this increase is less in case of specimens loaded eccentrically.

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