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Axial behavior of CFRP wrapped RC columns of different shapes with constant slenderness ratio

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Abstract. In composite materials technology, the fiber-reinforced polymers (FRP) have opened up new horizons in infrastructural engineering field for strengthening existing structures and components of structure. The Carbon fiber reinforced polymer (CFRP) sheets are well suited for RC columns to this application because of their high strength to weight ratio, good fatigue properties and excellent resistance to corrosion. The main focus of present experimental work is to investigate effect of shapes on axial behavior of CFRP wrapped RC columns having same cross-sectional area and slenderness ratio. The CFRP volumetric ratio and percentage of steel are also adopted constant for all the test specimens. A total of 18 RC columns with slenderness ratio four were cast. Nine columns were control and the rest of nine columns were strengthened with one layer of CFRP wrap having 35 mm of corner radius. Columns confined with CFRP wrap were designed using IS: 456:2000 and ACI 440.2R.08 provisions. All the test specimens were loaded for axial compression up to failure and failure pattern for each shaped column was investigated. All the experimental results were compared with analytical values calculated as per the ACI-440.2R-08 code. The test results clearly demonstrated that the axial behavior of CFRP confined RC columns is affected with the change in shapes. The axial deformation is higher in CFRP wrapped RC circular column as compared to square and rectangular columns. Stress-strain behaviour revealed that the yield strength gained from CFRP confinement was significant for circular columns as compare to square and rectangular columns. This behaviour may be credited due to effect of shape on lateral deformation in case of CFRP wrapped circular columns at effective confinement action.

Keywords: CFRP wrapped RC columns; effect of shapes; axial behavior; confinement action; failure pattern

1. Introduction

In construction industry, the use of fiber reinforced polymer composites for Civil Engineering applications, especially in structural up gradation has become increasingly popular due to its strength properties. CFRP are widely used for retrofitting and rehabilitation of columns to reduce structural deficiencies and enhance the service life of structures. Columns are strengthened by means of confinement actions. The confining strength of CFRP wraps largely varies with the shape of the column. The confinement imparted by FRP composites to columns of non-circular cross section is not as efficient as that imparted to columns of circular cross sections as observed by many investigators. CFRP wrapping for RC columns is in horizontal direction to the length of the columns. The primary function of this kind of CFRP wrapping technique is carry load along the length of the fibre and it improves strength and stiffness in one direction. Mirman (1997) tested twelve square and thirty cylindrical concrete filled GFRP tube columns to investigate the effect of cross-section under uniaxial compression. Square cross section columns were observed less effective in confining concrete than their circular counterparts and measured confinement effectiveness by modified confinement ratio. Pessiki *et al.* (2001) presented the results of an experimental investigation of axial behavior of small scale circular and square plain concrete specimens and square reinforced concrete columns confined with FRP composite jacket to monotonic, concentric axial loads. The test results clearly demonstrate the improvements in concrete axial stress and strain capacity, relative to that of unconfined concrete, increase with increasing FRP jacket strength and stiffness. Toutanji *et al.* (2007) studied the behavior of large-scale square and rectangular columns width (b)=250,350 mm and depth (d)=500,355 mm) externally confined with GFRP wrapping. It was observed that higher aspect ratio usually results in a reduction in the confinement pressure and also the compressive strength of a confined column increases as the corner radius increases. This study investigated the strength models of FRP confined concrete columns, the effect of increasing confining pressure and the effective circumferential FRP failure strain. Esfahani and Kianosh (2005) presented the effect of the FRP wrap on axial strength of RC circular and square columns. Three RC circular column of diameter 203 mm and three RC square columns of 180 mm side length with similar height 850 mm were used for testing. The corners of one of the square columns were rounded in order to study the effect of corner shape of square columns on load resistance. It was observed that FRP wrap increased the axial strength and ductility of circular column significantly. The square column with rounded corners exhibited a higher strength and ductility

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Table 1 Proportion of ingredients used for concrete mix (1m^3)

Ingredients	Quantity
Cement	395 kg
Fine aggregate	738.7 kg
Coarse aggregate	1165 kg
Water	197.5 Litre

compared to those with sharp corners. Chikh *et al*. (2012) presented the experimental study on axially loaded short and slender high strength concrete columns confined with carbon fiber reinforced polymer sheets. The number of wrap layers (1 and 3) and the slenderness ratio of column length (L)/diameter (D) (2, 5.08 and 6.45) for circular shape and length (L)/least dimension of cross-section (a) (2, 4 and 7.14) for square shape were considered as main parameters in this study. A total of 48 PC and RC were loaded to failure in axial compression. Results demonstrated that the efficiency of confinement was very sensitive to the specimen cross section geometry but increased in number of CFRP layers and slenderness ratio of column.

Most of the existing studies such as Chaallal *et al.* (2000), Benzaid *et al.* (2008), Mirmiran (1998), Xiao *et al.* (2008), Rahai *et al*. (2008),Widiarsa *et al.* (2013), Siddiqui *et al.* (2014), Sadeghian *et al.* (2014), Kabashi *et al.* (2014), Ozbakkaloglu *et al.* (2013), Sezen *et al.* (2011), Pham *et al.* (2011), Song *et al*. (2013), on the axial behavior of FRP confined small-scale plain concrete columns with variable slenderness ratio have concentrated on circular columns, while relatively few studies have addressed on RC rectangular and square columns. This is partly because confinement pressure distribution is not uniform in case of FRP wrapped rectangular and square shape column as compare circular column. However, the circular shape columns rarely used in building constructions as compare to square and rectangular column. Therefore, their comparative behavioral study need to be given attention to preserve the reliability of building infrastructure while repair and rehabilitation. The use of externally bonded CFRP composite RC columns of different shape for strengthening and repair can be a cost-effective alternative to reduce structural deficiencies and enhance the service life of existing columns. Therefore, this paper is focused towards this effort.

The scope of work includes evaluation of the confinement effectiveness of CFRP wrapping on axial behavior of circular, square and rectangular shape RC columns in the present investigation. The columns of same cross-sectional areas were designed using IS: 456(2000) provisions. The columns confined with single layer of CFRP wrap with constant volumetric ratio and percentage of reinforcement were investigated. Design of CFRP wrapping for the columns was conducted using ACI 440.2R (2008) provisions. Total eighteen columns were subjected to axial compression which includes nine columns as control and remaining nine columns having 35 mm of corner radius were confined with CFRP wrapping. All the columns were subjected to an axial compressive loading. Various parameters i.e., yield load, ultimate failure load, vertical deformation, axial strain, effect of confinement, bulking, cracking pattern and failure mode were measured for the columns.

Table 2 CFRP Properties Supplied by Manufacturer

	Fiber sheet Fiber weight(g/m^2)	Sheet width(mm)	Fiber thickness(mm)	Ultimate tensile strength (MPa)	Elastic modulus(MPa)	Ultimate elongation (%)
CFRP$_W$*	300	500	0.171	3800	242000	1.43

*CFRPw: Carbon fiber reinforced polymer

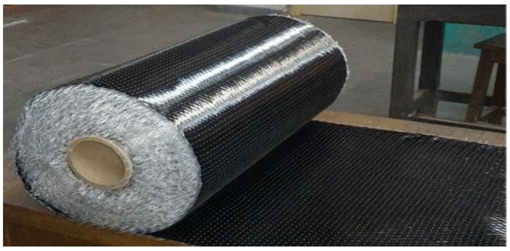


Fig. 1 Carbon fiber reinforce polymer sheet roll

Table 3 Details of RC columns of different shapes with constant slenderness ratio

Shape of column B(mm)		D(mm)	Length(mm)	Area(mm^2)	Ties	Main Bars	No. of Columns
CC*	250 mm	Diameter	1000	49087.39	6ϕ	6₦10ϕ	06
SC	225	225	900	50625.00	6ϕ	4₦12ϕ	06
RC	200	250	800	50000.00	6ϕ	4₦12ϕ	06

*CC: Circular reinforced concrete column; SC: Square reinforced concrete column;

RC: Square reinforced concrete column; ϕ: Diameter in mm; ₦: Number of bars

Reinforced Concrete columns were designed as per IS: 456 (2000) provisions. Total 18 columns of slenderness ratio four were cast.

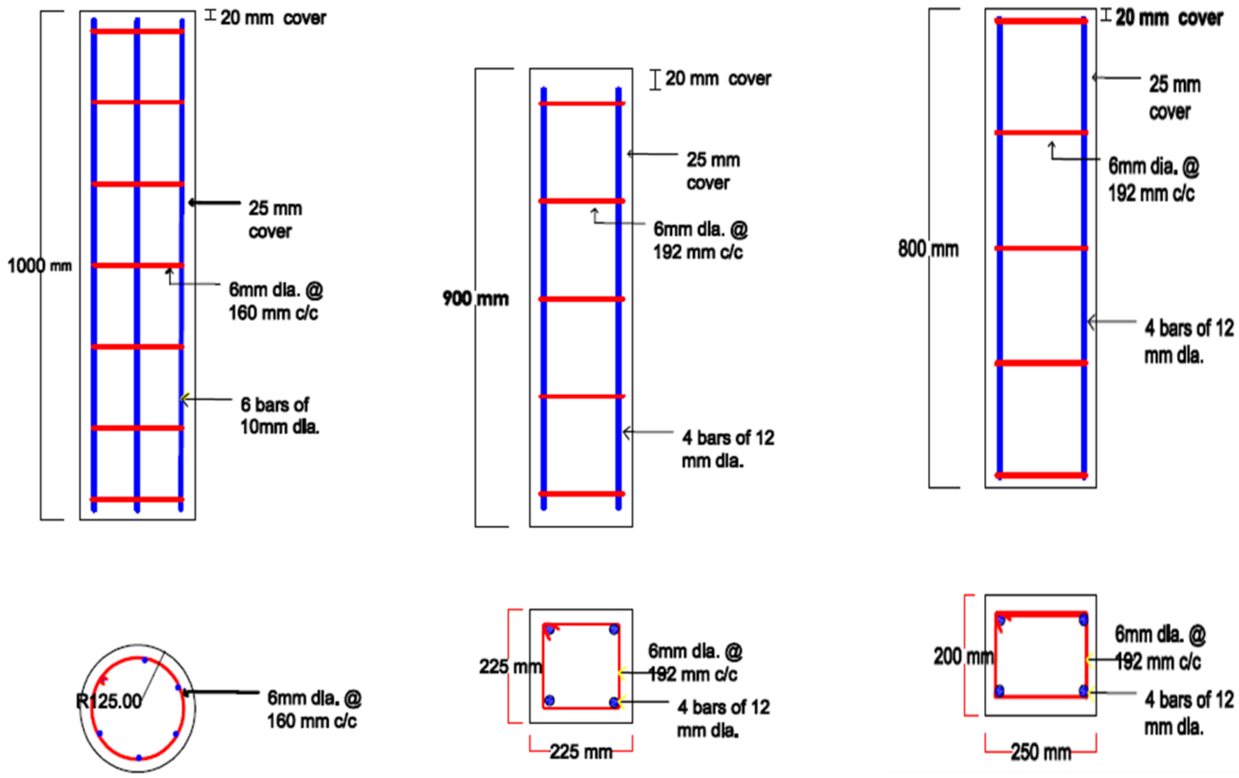
2. Experimental work

2.1 Material properties of concrete

The RC columns were cast using concrete mix with 28 days compressive strength of 20 MPa. Proportion of material as per weight batch was 0.5: 1: 1.87: 2.95 (W: C: FA: CA) (water: cement: fine aggregate: coarse aggregate). The quantities of ingredients, used in the concrete mix are shown in Table 1.

2.2 Material properties of carbon fiber reinforced polymer sheet

All specimens were wrapped with one layer of



(a) Reinforcement details of circular and square (b)Reinforcement details of rectangular column

Fig. 2 Reinforcement details of circular, square and rectangular columns

Fig. 3 Formwork for circular, rectangular and square column

unidirectional CFRP wraps. The properties of CFRP sheet are presented as per manufacturer's data sheet (R&M International Pvt. Ltd., Mumbai) in Table 2. Resin epoxy was used as matrix and had two components (base and hardener) mixed in the ratio of 100:35 as suggested by the manufacturer. All specimens were pre-treated with resin primer-11 in order to achieve a smooth surface and good bond between FRP and the specimen surface. Fig. 1 shows CFRP sheet in roll form and defines the direction of layers of fibers which is more in longitudinal direction as compared to the transverse direction. CFRP wraps were applied on both top and bottom portion of unwrapped and wrapped column of width one tenth length of column to avoid local failure of column for axial compression load.

2.3 Design of reinforced concrete columns

Design parameters are shown in Table 3. Reinforcement details of RC columns are presented in Fig. 2.

2.4 Casting of reinforced concrete columns

Total three different shapes of formwork were used of length 1meter, 0.9 meter and 0.8 meter respectively. Concrete is prepared in the concrete mixture of half cement bag capacity. Side clear cover to reinforcement was kept as 25 mm for all the columns. Concrete cover to longitudinal reinforcement at Top and bottom faces of columns was provided 20 mm along with 5 mm epoxy capping. The formwork for square and rectangular column is prepared using plywood of 18mm.The steel formwork of thickness 3 mm is used to cast circular column as shown in Fig. 3.

2.5 Carbon fiber reinforced polymer wrapping

(a) Grinding of RC column (b)Application of primer (c) Application of saturant (d) Application of CFRP sheet

Fig. 4 Process of carbon fiber reinforce polymer sheet wrapping on reinforced concrete columns

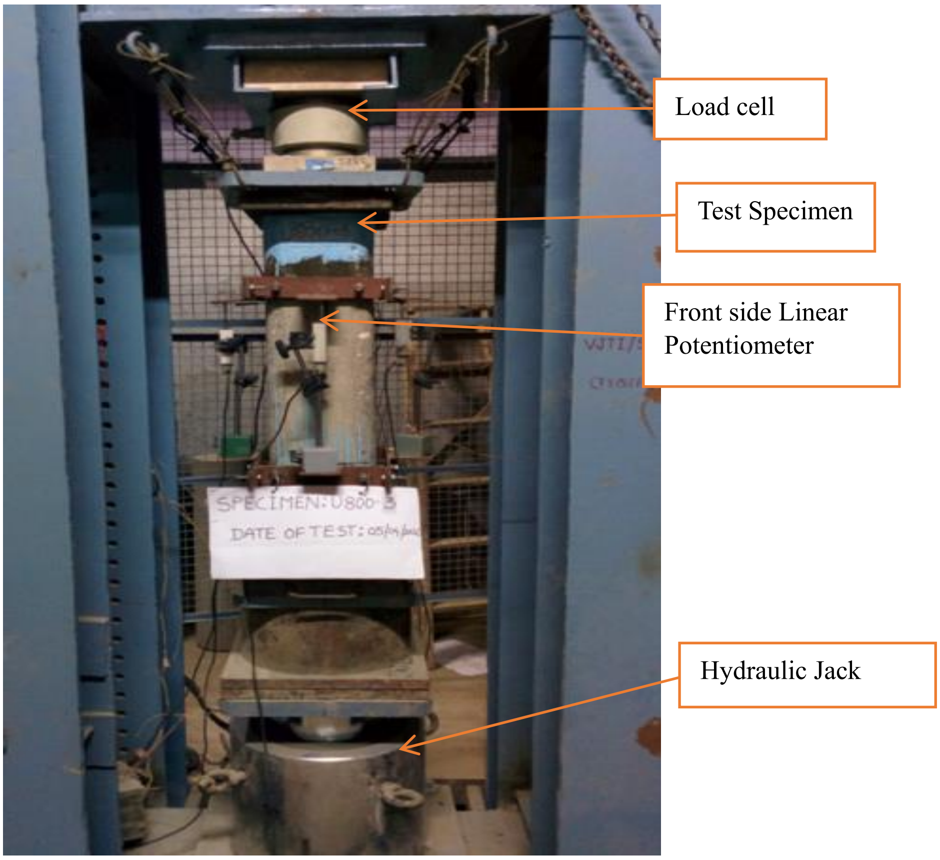


Fig. 5 Laboratory test setup for RC columns

The concrete surface needed to be cleaned with wire brush to remove all the loose dust particles. Grinding machine was used to make curved corner 25mm radius of non-circular columns and also for smooth even surface. Any voids on the surface of concrete are filled with putty. Primer coats are applied over then concrete surface after finishing of putty. Saturant matrix-20 is made from the two different parts i.e., base and hardener in proportion of 0.35:1. Saturant is applied over the surface with hand brush. After application of the saturant simultaneously the fibers are wrapped around the columns. Care was taken during wrapping to make sure that fibers remain in hoop direction so that it can give proper confinement effects at the time of loading. The CFRP sheet was wrapped in the form of single

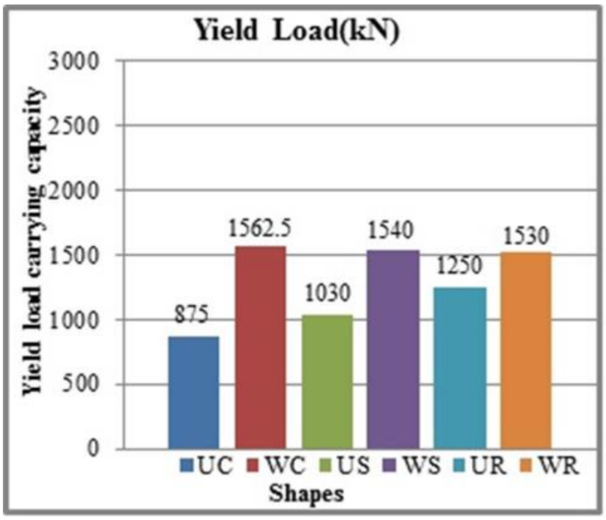


Fig. 6 Yield load carrying capacity for RC columns UC: Unconfined circular RC column; WC: Wrapped circular RC column; US: Unconfined square RC column; WS: Wrapped square RC column; UR: Unconfined rectangular RC column; WR: Wrapped rectangular RC column

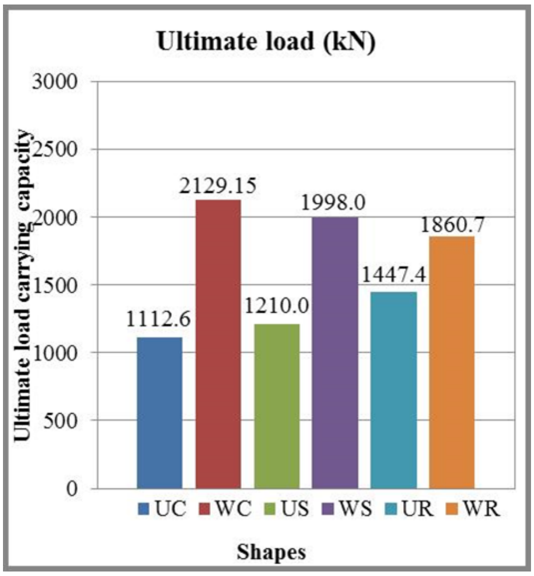


Fig. 7 Ultimate load carrying capacity for RC columns

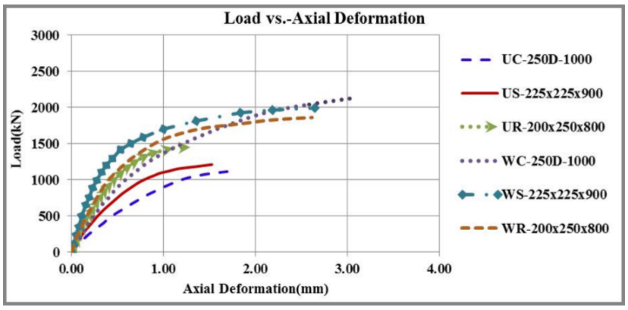


Fig. 8 Load vs. deformation behavior for RC columns

piece with overlap of 150 mm. CFRP wrapping procedure for RC columns stage wise is presented in Fig. 4.

2.6 Test setup

Testing of the columns were carried out on loading frame in laboratory of 4000 kN capacity. The axial load was applied using hydraulic jack of capacity 5000 kN. The RC columns were tested on the loading frame under axial compressive loading as shown in Fig. 5. All columns were capped with layer of dry cement and steel plate to ensure levelled surface and to distribute the load uniformly in order to reduce eccentricity. The four LVDTs (linear voltage displacement transducers) were installed on front, back, right and left side of each test specimen with a travel of 50 mm to measure vertical deformation of column. Special fabricated steel frames with bolting arrangement were attached to test specimen to mount the LVDT. The axial load was applied at a constant loading rate equal to 5 kN/mm up to the complete failure of the column specimen.

3. Test results and discussion

Structural parameters like load, vertical deformation, stress & strain were evaluated for control and CFRP wrapped columns respectively to understand the behavior of RC columns of different shapes with constant slenderness ratio.

3.1 Yield load carrying capacity

Control circular columns exhibited higher yield load carrying capacity as compared to square and rectangular shape columns. Yield load carrying capacity increases from rectangular to circular RC columns. Results clearly demonstrated that variation in shape plays significant role in increasing the amount of yield load carrying capacity for wrapped RC columns. Increase of 78%, 49% and 22% in yield load carrying capacity were observed for circular, square and rectangular shape CFRP wrapped columns, respectively as compared to that of unwrapped columns as shown in Fig. 6.

3.2 Ultimate load carrying capacity

CFRP wrapped RC circular columns exhibited higher axial load carrying capacity as compared to RC square and rectangular wrapped columns. Axial load carrying capacity increases from rectangular to circular RC columns. CFRP wrapped RC Rectangular column exhibits lowest axial load carrying capacity. CFRP wrapped columns give considerable amount of increase in strength as compared to that of control columns for different shapes. CFRP wrapping for Square columns increases the axial load carrying capacity by 65 %, on the other hand, for circular columns, the capacity increases to 91% as compared to that for control columns as shown in Fig. 7. Rectangular shape gives less confinement and therefore has resulted in to attainment of the lower increase in compressive strength.

3.3 Axial deformation of columns

The effects of shapes on load-deformation behaviour of

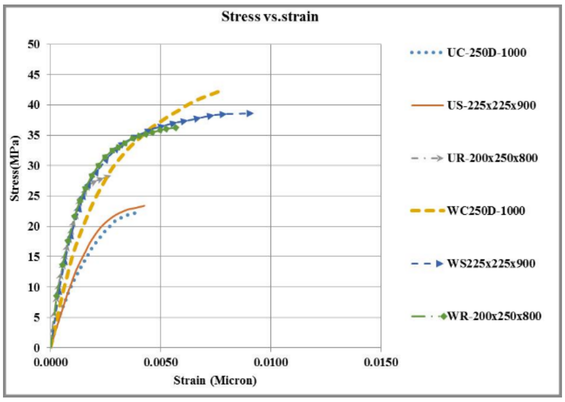


Fig. 9 Axial stress vs. axial strain behavior for RC columns

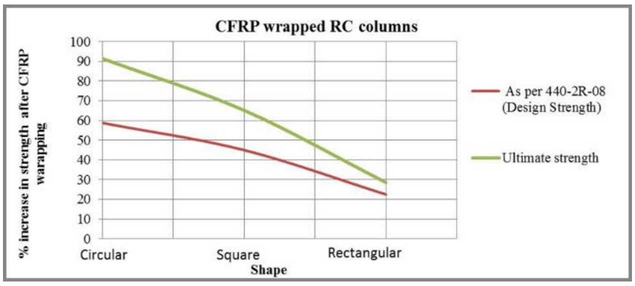


Fig. 10 Effect of variation in shapes on confinement

Table 4 Average vertical displacement of RC wrapped and unwrapped columns

Test specimen	At front side LVDT	At left Side LVDT	At back side LVDT	At right side LVDT	Avg. Vertical Displacement
UC-250-1000*	-0.98	-1.02	-1.60	-1.75	-1.34
WC-250-1000*	-2.64	-2.05	-3.34	-3.65	-2.92
US-225x225x900*	-0.52	-0.42	-1.24	-1.45	-0.91
WS-225x225x900*	-2.24	-2.51	-2.61	-2.20	-2.64
UR-200x250x800*	-1.44	-0.48	-1.28	-1.50	-1.18
WR-200x250x800*	-0.98	-1.08	-3.50	-3.75	-2.33

*UC: Unconfined circular RC column; WC: Wrapped circular RC column; US: Unconfined square RC column; WS: Wrapped square RC column; UR: Unconfined rectangular RC column; WR: Wrapped rectangular RC column. LVDT: Linear voltage displacement transducer

columns are exhibited in Fig. 8. CFRP wrapped columns have exhibited higher axial deformation as compared to that of control columns. CFRP wrapped RC rectangular columns have exhibited higher axial deformation as compared to confined square and circular columns. Ductility of confined column increases considerably with the shape of column changes from rectangular to circular.

3.4 Axial stress vs. axial strain

Average axial strain was evaluated from average axial deformation for the columns measured from LVDTs. Axial stress for columns was calculated as load divided by cross sectional area. Average axial stress and axial strain for control and CFRP wrapped columns of different shapes with constant slenderness ratio is presented in Fig. 9. CFRP wrapped RC circular columns have exhibited higher axial strain as compared to that of rectangular confined columns. CFRP wrapped circular columns have resulted into highest ultimate axial strength as compared to that for other CFRP wrapped columns. The CFRP confinement effectiveness improving the axial strength for RC rectangular columns is less as compared to other wrapped columns.

3.5 Effect on confinement

The effect of variation in shape of columns with constant slenderness ratio have been studied carefully to examine axial behaviour of RC wrapped columns. It is evident from Fig. 10 that increase in percentage of axial strength with CFRP confinement is higher for RC circular columns than RC square and rectangular columns. The confinement effectiveness on strength attainment decreases with the change of shape from circular to rectangular. Confinement by CFRP enhances the performance of circular columns much better as compared to that of square and rectangular columns.

3.6 Bulking behavior

Vertical displacements of control and wrapped columns were recorded from LVDTS installed on four sides of test specimens as shown in Table 4. It is evident that confined RC circular columns exhibited uniform vertical displacement and less bulking as compared to square and rectangular columns. Wrapped RC rectangular column undergoes more bulking along short side of cross section for ultimate compressive load than other columns.

3.7 Failure modes and crack patterns

Unwrapped RC columns have failed after reaching to their ultimate compressive strength and that resulted into splitting and crushing of concrete simultaneously in between the stirrups. Majority of control columns were failed due to crushing of concrete. The mode of failure has been identified with effect of shear cracking and crushing of the concrete in case of the unwrapped columns. RC circular columns failed at mid-height due to propagation of shear cracks and crushing of concrete by bending of vertical reinforcement. The failure started near mid-height with bending of main reinforcement and cracking due to dilation of concrete between stirrups as shown in Fig. 11(a) & Fig. 11(b), respectively. The failure of square column observed due to shear cracking with bending of vertical reinforcement. Fig. 12 shows rectangular column failed from longer sides due to crushing of concrete. All the CFRP wrapped columns have failed by tearing of CFRP wrap near the mid height. The CFRP and concrete at the top and bottom of column were still found intact at the time of failure. Typical sound was heard while the application of loading on columns signifying the straining of CFRP wrap and cracking of epoxy resin. Final failures of wrapped columns were observed suddenly with bursting sound. CFRP wrapped RC columns have been failed into three modes:(i) tensile rupture of CFRP wrap at the corner (ii)

(a) Failure of unwrapped RC circular column (b) Failure of unwrapped RC square column

Fig. 11 Failure modes and crack patterns of RC circular column and RC square column

Fig. 12 Failure modes and crack patterns of unwrapped RC rectangular column

debonding of CFRP wrap due to tearing and (iii) combine effect of tensile rupture and tearing of CFRP wrap. The failure of wrapped RC circular column took place due tensile rupture of wrap with bursting noise between one third heights of column to mid height of column as shown in Fig.13. The bending of main reinforcement was observed after debonding the CFRP confinement due to tearing. The process of tearing wrap is continued from portion of bent up main reinforcement to mid height of column due to propagation of internal shear cracks and transvers dilation of concrete. The CRRP confined square and rectangular columns failed due to the combination of delamination and tensile rupture of the CFRP wrap at corner due to stress concentration as shown in Fig. 14.

4. Conclusions

Influence of shapes of column section on the axial behavioral response of wrapped RC columns is investigated. A comparison of the axial behavioral response of the different shapes RC columns with constant slenderness ratio for strengths and deformations is studied. In addition, the effects of the shape of RC columns on yield strength, bulking and failure behavior are also investigated. From the trends of the results of the present study,

(a) Failure of CFRP wrapped circular column (b) Failure of CFRP wrapped square column

Fig. 13 Failure modes and crack patterns of CFRP wrapped circular column and square column

Fig. 14 Tensile rupture and debonding of CFRP at mid height of rectangular column

following conclusions are drawn:

- RC Circular columns exhibited highest increment in axial strength and yield strength with CFRP wrapping compared to square and rectangular RC columns.
- Enhancement of yield strengths of RC columns with the CFRP wrapping is significant as compared to improvement in ultimate axial strengths of RC columns.
- CFRP confinement effectiveness improves stress vs. strain behaviour drastically in case of circular RC column as compared to that of other columns.
- Higher axial deformation was observed for unwrapped RC circular columns from load vs axial deformation behavioral response of RC columns.
- Wrapped RC circular columns undergo higher axial deformation as compared to that for rectangular and square columns.
- CFRP wrapped RC rectangular columns evaluated more bulking from vertical displacements measured with LVDTs mounted on four sides of column section.
- Failure of all unwrapped columns was observed in brittle mode and all wrapped columns in bursting mode.

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References

(ACI) 440.2R, (2008), *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*, American Concrete Institute, Farmington Hills, MI, U.S.A.

Amir, M. (1998), "Effect of column parameters on FRP confined concrete", *J. Compos. Constr.*, **2**(4), 175-185.

Benzaid, R., Chikh, N. and Mesbah, H. (2008), "Behavior of square concrete column confined with GFRP composite warp", *J. Civil Eng. Manage.*, **14**(2), 115-120.

Chaallal, O.M., Shahawy, M. and Adnan, A.S. (2000), "Behavior of axially loaded short rectangular columns strengthened with CFRP composite wrapping", Technical report, FDOT Structures Research center, E. Paul Dirac Drive Tallahassee, FL 32310.

Chikh, N., Gahmous, M. and Benzaid, R. (2012), "Structural performance of high strength concrete columns confined with CFRP sheets", *Proceedings of World Congress on Engineering*, London, U.K.

Esfahani, R. and Kianosh, M.R. (2005), "Axial compressive strength of reinforced concrete columns wrapped with fiber reinforced polymers (FRP)", *IJE Trans. B: Appl.*, **18**(1), 9-19.

IS 456 (2000), *Plain and Reinforced Concrete-Code of Practice*, Bureau of Indian Standards, India.

Kabashi, N., Krasniqi, C. and Nushi, V. (2014), "Analysis and behaviour the concrete columns strengthening with the carbon polymer fibres", *Civil Eng. Archit.*, **2**(9), 317-322.

Mirmiran, A. and Shahawy, M. (1997), "Behavior of concrete columns confined by fiber composites", *J. Struct. Eng.*, **123**(5), 583-590.

Ozbakkaloglu, T. and Lim, J.C. (2013), "Axial compressive behavior of FRP-confined concrete: Experimental test database and a new design-oriented model", *Compos. Part B: Eng.*, **55**, 607-634.

Pessiki, S., Harries, K., Kestner, J., Sause, R. and Ricles, J. (2001), "Axial behavior of reinforced concrete columns confined with FRP jackets", *J. Compos. Constr.*, **5**(4), 237-245.

Pham, T.M., Doan, L.V. and Hadi, M.N.S. (2011), "Strengthening square reinforced concrete columns by circularisation and FRP confinement", *Constr. Build. Mater.*, **49**, 490-499.

Rahai, A.R., Sadeghian, P. and Ehsani, M.R. (2008), "Experimental behavior of concrete cylinder confined with CFRP composites", *Proceedings of the 14th World Conference on Earthquake Engineering*, China.

Sadeghian, P. and Fam, A. (2014), "Rational approach toward strain efficiency factor of fiber reinforced polymer wrapped concrete columns", *ACI Struct. J.*, 113-S13,135-144.

Sezen, H. and Miller, E.A. (2011), "Experimental evaluation of axial behavior of strengthened circular reinforced-concrete columns", *J. Brid. Eng.*, **16**(2), 238-247.

Siddiqui, N.A., Alsayed, S.H., AlSalloum, Y.A., Iqbal, R.A. and Abba, H. (2014), "Experimental investigation of slender circular RC columns strengthened with FRP composites", *Constr. Build. Mater.*, **69**, 323-334.

Song, X., Gu, X., Li, Y., Chen, T. and Zhang, W. (2013), "Mechanical behavior of FRP-strengthened concrete columns subjected to concentric and eccentric compression loading," *J. Compos. Constr.*, **17**(3), 336-346.

Toutanji, H.A., Meng, H. and Matthys, S. (2007), "Axial load behavior of rectangular concrete columns confined with FRP composites", FRPRCS-8 University of Patras, Greece.

Widiarsa, I.B. and Hadi, M.N. (2013), "Performance of CFRP wrap square reinforced concrete column subjected to eccentric loading", *Proc. Eng.*, **54**, 365-376.

Xiao, Y. and Wu, H. (2008), "Compressive behavior of concrete confined by carbon fiber composite jackets", *J. Mater. Civil Eng.*, **12**(2), 139-146.

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