Available online at www.sciencedirect.com
SciVerse ScienceDirect
ELSEVIER
Procedia Engineering 51 (2013) 220 – 229
Procedia Engineering
www.elsevier.com/locate/procedia

Chemical, Civil and Mechanical Engineering Tracks of 3rd Nirma University International Conference on Engineering (NUiCONE-2012)

FRP Wrapping for RC Columns with Varying Corner Radii

Sushil S. Sharma[a], Urmil V. Dave[b]*, Himat Solanki[c]

[a]*Structural Engineer, MaRs Planning and Engineering Services Pvt Ltd , Ahmedabad, India*
[b]*Professor , Department of Civil Engineering, Institute of Technology, Nirma University, Ahmedabad 382481, India*
[c]*VistingFaculty, Department of Civil Engineering, Institute of Technology, Nirma University, Ahmedabad 382481, India*

Abstract

Existing reinforced concrete (RC) columns may be structurally deficient due to variety of reasons such as improper transverse reinforcement, flaws in structural design, insufficient load carrying capacity, etc. Carbon/Glass fibre reinforced polymer (FRP) confinement can be effectively used for strengthening the deficient RC columns. The effectiveness of FRP wrapping for RC columns mainly depend upon corner radius of the specimens as well as number of FRP layers used for the confinement. An attempt has been made hereby to investigate the experimental behaviour of GFRP wrapped small scale square RC columns with varying corner radii. Experimentally evaluated behaviour of GFRP wrapped RC columns is compared with the performance observed for non-wrapped RC columns. 15 RC columns having cross-sectional dimensions 125 mm × 125 mm and length of 1200 mm have been tested under axial compression. Three columns are unwrapped and have been designated as control specimens. Three columns each with corner radius equivalent to cover of 25 mm are wrapped with one and two layers of GFRP, respectively. To avoid a premature rupture of the GFRP composite, remaining six columns with corner radius of 5 mm have been wrapped with one and two layers of GFRP, respectively. GFRP wrapped columns go under higher axial displacement in order to gain higher compressive strength over the control column. The results showed that smoothening of the edges of square cross-section of RC columns play a significant role in delaying the rupture of the FRP composite at the edges. Corner radius equal to concrete cover gives better results in terms of ultimate load carrying capacity than the corner radius less than cover for confined RC columns.

Keywords: RC column, Corner radius, GFRP, Number of Wrap, No. of FRP layers, Axial compressive strength

Nomenclature

r	Corner radius of the square RC column
b	Cross-section dimension of the square RC column
L	Height of the RC column
S0R0	Control column
S1R1	Column having 5 mm corner radius strengthened using one GFRP layer
S2R1	Column having 5 mm corner radius strengthened using two GFRP layers
S1R2	Column having 25 mm corner radius strengthened using one GFRP layer
S2R2	Column having 25 mm corner radius strengthened using two GFRP layers

* Corresponding author. Tel.: +91-2717-241911-15; fax: +91-2717-241917.
E-mail address: sushil701@gmail.com, urmil.dave@nirmauni.ac.in, himatsolanki@yahoo.com

doi:10.1016/j.proeng.2013.01.031

1. Introduction

Over the last few years, there has been a worldwide increase in the use of composite materials for the rehabilitation of deficient reinforced concrete (RC) structures. One important application of this composite retrofitting technology is the use of fibre reinforced polymer (FRP) jackets or sheets to provide external confinement to RC columns when the capacity of existing structure is inadequate. RC columns need to be laterally confined in order to ensure large deformation under load before failure and to provide an adequate load resistance capacity. In the case of a seismic event, energy dissipation allowed by a well-confined concrete core can often save lives. On the contrary, a poorly confined concrete column behaves in a brittle manner, leading to sudden and catastrophic failures.

Benzaid et al. [1] evaluated load-carrying capacity and strains by testing square prismatic RC column strengthening with external GFRP composites. Variables like number of composite layers and the corner radius for a square shape were considered. Twenty-one prisms of size 100 x 100 x 300 mm were tested under strain control rate of loading. It was suggested that a larger radius can expand the strong constraint zone and diminish the stress concentration. So the reduced confining pressure in a square section due to the concentration of stresses at the corners is solved by using a square section with corner radius. Silva [2] performed tests on axially loaded square RC columns, with and without FRP jackets. Square cross-section was divided into three groups i.e. sharp edged corner; corner radius equal to 20 mm; corner radius equal to 38 mm. The FRP jackets were made either of CFRP or AFRP wraps and the geometry of the specimens included square and circular cross-sections. Comparison of gains of axial strength and ductility were presented and aspects of the variation of the lateral pressure and rupture of FRP jackets were examined. The improvement of axial load capacity gained, either from jackets of AFRP, or CFRP was almost equal for cylindrical columns. CFRP jacketed square column with sharp corner evidenced neither improvement of capacity, nor ductility. In the case of AFRP confinement there was improvement of load capacity, but no significant improvement on ductility. El-Hacha and Mashrik [3] experimentally evaluated the effectiveness of steel fibre reinforced polymer (SFRP) sheets to confine small-scale plain concrete circular and square columns. Parameters were investigated including: number of SFRP layers (1, 2, and 3), target concrete compressive strength (25, 30, and 35 MPa), cross-section of the columns (circular and square), and corner radius for square columns (3, 6, 10, and 25 mm). 36 circular specimens 150 mm diameter x 300 mm height and 36 square specimens 150 mm side length x 300 mm height were tested. Three specimens were tested without wrapping for comparison purposes, and three specimens for each number of layers. 12 SFRP wrapped (one layer) square specimens were tested to investigate the effect of varying the corner radii on the confined compressive strength. The specimens were tested under monotonic concentric uniaxial compression load. SFRP confinement improved the performance of both circular and square specimens in terms of axial strength and ductility; however, the improvement for square specimens was not as prominent as that for circular specimens. Rounding the corners of the square specimens improved the situation for square specimens and performance enhances with increasing corner radius. Al-Salloum [4] investigated the influence of the radius of the cross-sectional corners (edges) on the strength of square RC columns confined with FRP laminates. 20 specimens under uniaxial compression were tested. Depending on the selected radius of the edges, the section varied from square to circular. Intermediate radii were about 1/6, 1/4, and 1/3 of the side dimension. The sharpest square specimens had a corner radius of 5 mm to make composite application easier and to avoid a premature rupture of the composite. The results showed that smoothening the edges of square cross-section plays a significant role in delaying the rupture of the FRP composite at these edges, and the efficiency of FRP confinement is directly related to the radius of the cross-section edges.

Use of externally bonded FRP composite for strengthening can be a cost effective alternative for upgrading the performance of existing RC columns [5-10]. Even though a lot of research has been directed towards circular columns, relatively less work has been performed on square and rectangular columns, to examine the effects of FRP confinement on the structural performance. However, a vast majority of all columns in buildings are square or rectangular. Therefore, their strength and rehabilitation needs to be given attention to preserve the integrity of building infrastructure. Up till now a less amount of research has been carried out on effect of corner radius for improving performance of the confined columns. The decision about keeping the corner radius less than cover, equal to cover or greater than cover is a critical one for the square confined columns. With the increase in the confinement layers, the repair of RC columns becomes a costly affair. Hence, the number of confinement layers to be added to the columns to upgrade the performance of columns is also a difficult question to deal with while deciding the repair strategy for the columns. Therefore, an attempt has been made to upgrade the performance of square RC columns by confining with GFRP wraps in the present investigation. A total of 15 RC columns are cast and tested under axial loading. Three columns are unwrapped and have been designated as control specimens. Three columns each with corner radius less than cover of 5 mm and equivalent to cover of 25 mm are wrapped with one and two layers of GFRP, respectively. The effect of variation in corner radius on the effectiveness of GFRP confinement is evaluated for RC columns. The test variables included different corner radius and number of GFRP layers. The parameters i.e. ultimate failure load, axial strain and lateral strain for RC columns are recorded [11].

2. Experimental programme

2.1. Test specimens

Notations for RC columns, dimensional details and number of wraps considered are presented in Table 1. GFRP was used to confine the column specimens. Fig. 1 shows the cross-sections and dimensions of the column specimens tested.

Table1. Details of RC columns

Column	b (mm)	L (mm)	r (mm)	No. of wraps	No. of column specimens
S0R0	125	1200	0	0	3
S1R1	125	1200	5	1	3
S2R1	125	1200	5	2	3
S1R2	125	1200	25	1	3
S1R2	125	1200	25	2	3

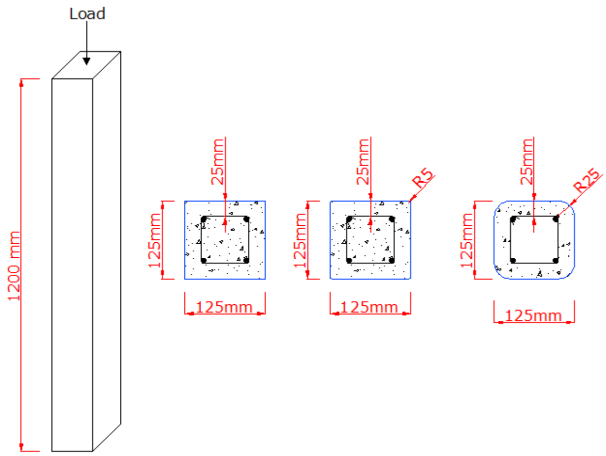


Fig. 1. RC column with different corner radii

2.2. Material properties

2.2.1. Concrete

Casting of all columns is conducted by using M15 grade concrete mix. Concrete mix proportion selected after mix design is Water: Cement: Sand: Coarse Aggregate, 0.60: 1: 3.25: 5, respectively. The quantities of ingredients, used in the concrete mixes are shown in Table 2.

Table 2. Proportion of ingredients used for concrete mix ($1m^3$)

Ingredients	Quantity
Cement	270 kg/m^3
Sand	877.5 kg/m^3
10 mm down size aggregate	945 kg/m^3
20 mm down size aggregate	405 kg/m^3
water	162 kg/m^3

2.2.2. GFRP sheet

The glass fiber sheets used in present investigation were unidirectional as shown in Fig. 2. The properties of GFRP sheet are presented in Table 3. The resin system used to bond the glass fabrics over the columns is an epoxy resin made of two-parts, resin and hardener. Fig. 2 Shows GFRP sheet in roll form and defines the direction of layers of fibers which are more in longitudinal direction as compared to that for the transverse direction.

Table 3: GFRP properties supplied by manufacturer

Fiber weight(g/m^2)	Sheet width (mm)	Fiber thickness (mm)	Ultimate tensile strength (MPa)	Elastic modulus (MPa)	Ultimate elongation (%)
900	500	0.324	3400	74500	4.3

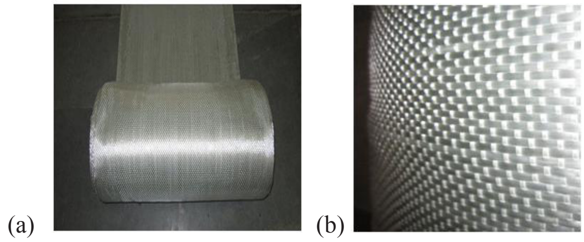


Fig. 2. GFRP Sheet (a) Sheet roll and (b) Unidirectional GFRP sheet

2.3. Casting of columns

A total of 15 square columns with a 125 mm x 125 mm cross-section and 1200 mm height with corner radius of 0 mm, 5 mm and 25 mm, respectively have been cast. Concrete is prepared in the concrete mixture machine of half cement bag capacity. The columns are reinforced with 4 number of 8 mm diameter bars in longitudinal direction and 6 mm diameter ties in the transverse direction spaced at 125 mm c/c as small scale RC column, designed based on IS:456 provisional [12]. The selection of 8 mm diameter main reinforcement in place of minimum 12 mm diameter as per codal provisions is based on available testing facilities for the RC columns. In order to round of the corners of the square columns, wooden patty inserts with the desired radius are fixed with the help of screw and cello tape at the corners of the boxes. Different types of corner wooden patty which is fixed into the formwork before the time of casting to get the desired radius on the columns as shown in Fig. 3.

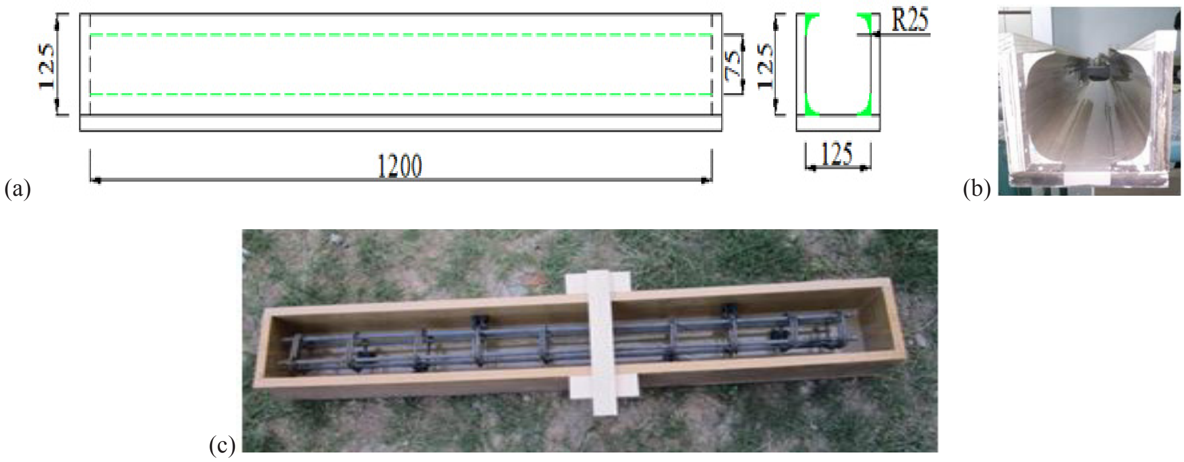
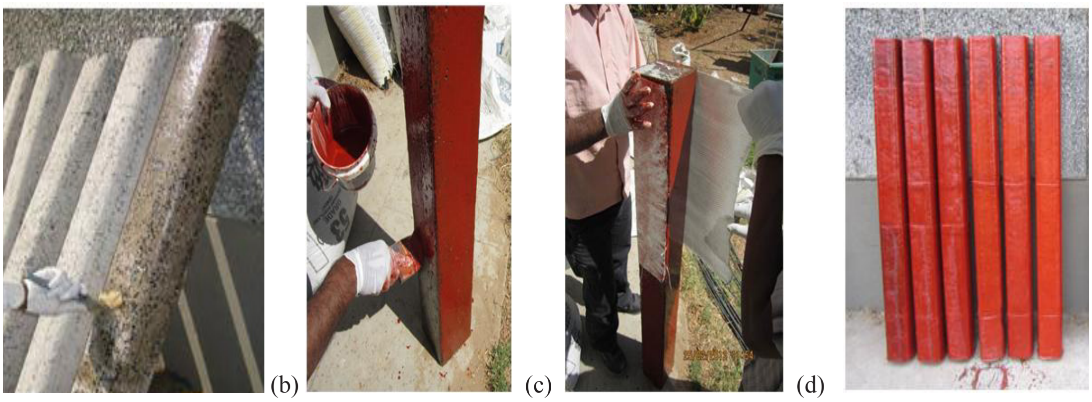


Fig. 3 (a) Schematic view of formwork for column with corner radius 25 mm, (b) Completed formwork with corner radius patty and (c) Formwork with reinforcement cage.

2.4 GFRP wrapping

Voids and deformities on the surface of the column specimens were filled using putty after 28 days of curing. The two-part epoxy system (Saturant and Primer) used, consisting of resin and hardener, was thoroughly hand-mixed for at least 5 minutes before use. The GFRP Sheets were then applied directly onto the surface of the specimens providing unidirectional lateral confinement in the hoop direction. The process of wrapping is shown in Fig. 4. Special attention was taken by the installers to eliminate any voids between the FRP laminates and the concrete surfaces. Overlap is kept 75 mm in the column to ensure the development of tensile strength of full composite.

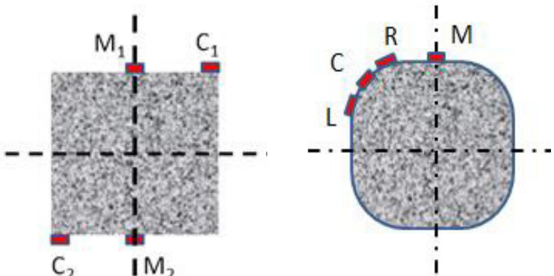


(a) (b) (c) (d)

Fig. 4. (a) Application of Primer, (b) Application of saturant, (c) Application of GFRP sheet and (d) After application of GFRP sheet and saturant

2.5 Instrumentation

Load, displacement and lateral strain for the column specimens are measured using hydraulic jack, LVDT and electrical strain gauge, respectively. The Model P3 Strain Indicator and recorder are used for measuring lateral strain on the column. The strain gauges were mounted at multiple points at the mid-height of the columns to measure the strain for unconfined and confined column specimens. The gauge length of the electrical strain gauges is 5 mm. Fig. 5 shows the locations of the transverse strain gauges, where M, C, L and R refer to positions on the side face, the centre of the corner, and the curvature changing point on the left and right-hand sides, respectively. LVDT (linear variable differential transducers) was mounted to capture the vertical displacements. The wires for strain gauges and the LVDTs were attached to data acquisition system and checked for readings.



(a) (b)

Fig. 5. (a) Strain gauges on sharp edges specimen (b) Strain gauges on corner radius specimen

2.6 Test procedure

The column specimens are tested on loading frame under axial compressive loading. The axial load is applied through hydraulic jack of 2000 kN capacity and the capacity of the frame is 1000 kN. General arrangement of test setup is shown in Fig. 6. All columns were capped with steel plate to ensure parallel surface and to distribute the load uniformly in order to reduce eccentricity. The LVDT was installed in preparation to start the test, and then the load was applied at a loading rate equal to 10 kN. This loading rate is kept constant up to the complete failure of the column specimen.

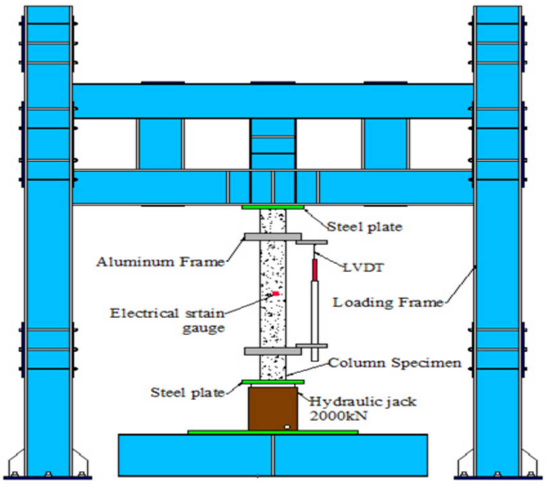


Fig. 6. Schematic view of test setup for RC column

3. Results and discussion

3.1 Axial Load

Ultimate failure load of all the columns and percentage increment of ultimate failure load over unconfined columns are presented in Table 4.

Table 4. Experimental results for columns

Sr. No.	Notation	Ultimate failure Load (kN)	Average ultimate failure load (kN)	% Increase of average ultimate failure load over unconfined
1	S0R0	310	303.33	-
		310		
		290		
2	S1R1	460	446.67	47%
		440		
		440		
3	S2R1	590	596.67	96%
		570		
		630		
4	S1R2	630	573.33	89%
		540		
		550		
5	S2R2	800	756.67	149%
		730		
		740		

Higher load carrying capacity has been observed for all wrapped columns as compared to that of unwrapped columns. Percentage increment in ultimate failure load is ranging from 47% to 149% for all wrapped columns as compared to that of unwrapped columns. 47%, 96%, 89% and 149% increment in ultimate failure load is observed for the columns S1R1, S2R1, S1R2 and S2R2, respectively as compared to that for column S0R0. This behaviour confirms upgrading of column performance due to provision of GFRP confinement on them. The comparison of ultimate failure load for columns confined with single and double wrap having 5 mm and 25mm radius, respectively also is evident from Table 4. Ultimate failure load for column S1R2 is increased by 28% as compared to that for column S1R1. Similarly, 26% increase in load carrying capacity is observed for column S2R2 as compared to that for column S2R1. Thus it is clearly evident from the above comparison that higher load carrying capacity is achieved for RC columns having 25 mm corner radius as compared to RC columns having 5 mm corner radius. This behaviour indicates importance of provision of corner radius equivalent to cover for RC columns in order to enhance their capacity.

3.2 Strain measurements

Strain is measured in axial direction and lateral direction for the columns. For measuring axial strain the gauge length for LVDT setup is considered as 800 mm. Strain is measured in lateral direction on mid height of the column which is 600 mm. Fig. 7 shows the average axial stress vs. axial strain plot the columns. The columns S0R0, S1R1, S2R1, S1R2 and S2R2 are subjected to total stress of 18.56 N/mm^2, 27.34 N/mm^2, 36.96 N/mm^2, 35.79 N/mm^2 and 41.09 N/mm^2 and corresponding strain observed is 0.0007, 0.0100, 0.0125, 0.0097 and 0.0089, respectively. From the plot for columns S1R1 and S2R1, the axial strain is at par up to axial stress of 25 N/mm^2. Increase in axial strain is observed for columns with increase in number of GFRP layers used for the confinement.

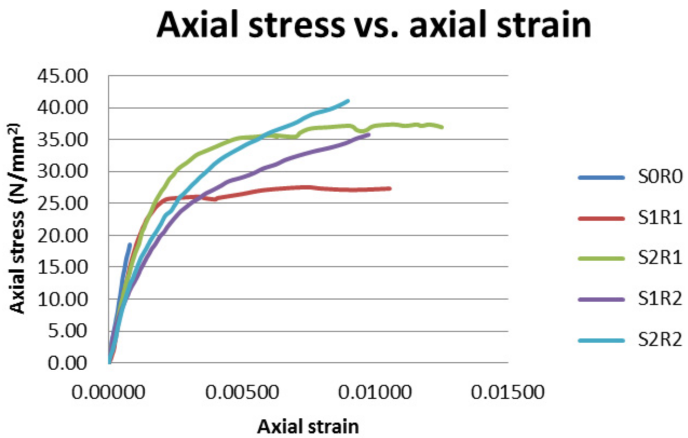


Fig. 7. Ultimate failure load of all specimens

Lateral strain is measured using electrical strain gauges positioned as shown in Fig. 5 for the columns. Strain measured at the mid of side face and at left, centre and right on the corner radius for column S2R2 is presented in Fig. 8. Higher strain is observed at mid of side face and then in decreasing order at left, right points and at the centre for the column S2R2. Column S2R2 is subjected to total stress of 41.09 N/mm^2 and corresponding strain observed at mid of side face, left, centre and right on the corner radius is 0.0045, 0.0029, 0.0017 and 0.0050, respectively. Due to debonding of FRP at an axial stress 30 N/mm^2, the strain developed on right side for the column S2R2 is more as shown in Fig. 5. Strain developed at mid for the column is more from the beginning of the variation in axial stress. From the strain results it is clear that strain developed for column S2R2 at mid point is more as compared to that for left and right points and the results of left and right points are more than the center one, which shows the reasonable distribution of strain for the column S2R2.

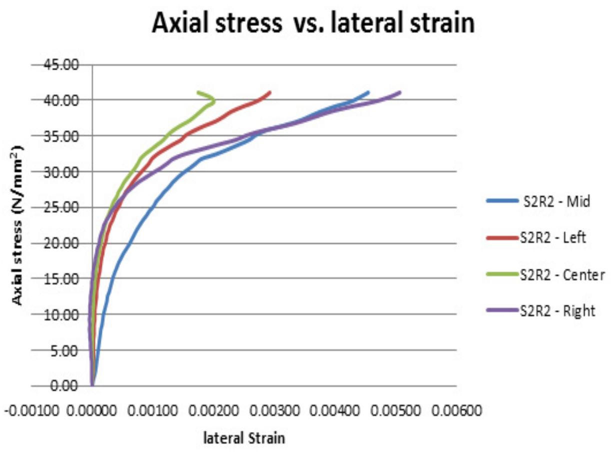


Fig. 8. Ultimate failure load of all specimens

3.3 Failure mode and crack patterns

Failure modes for unwrapped and wrapped column specimens are presented in Fig. 9 to Fig. 13, respectively. Crack propagation is visible before the crushing of the unconfined columns. GFRP wrapped columns typically failed by a fracture of GFRP composite near the corner due to the stress concentration in those regions. During the loading, clicking sounds is heard signifying the tearing of the FRP sheet and the cracking of the epoxy resin. The final failure occurred suddenly with an explosive sound.

Fig. 9 shows the failure of column S0R0 at quarter height from top. Failure occurs between two ties which mean the lack of confinement in that region which is responsible for the failure of the concrete.

(a)  (b)  (c)  (d) 

Fig. 9. Failure mode of control column S0R0

Fig.10 shows failure of the column S1R1. Failure of FRP has been observed at edges which is indicative of high stress concentration at the edges for the column. Along the compressed side near the mid height the wrinkles for the FRP confined column are visible due to the shrinkage effect. These wrinkles are representative of the debonding of the FRP which is anticipated to lead the column to the failure.

(a)  (b)  (c)  (d) 

Fig. 10. Failure mode of column S1R1

Fig. 11 shows the failure of the column S2R1.The failure occurs at corner due to the stress concentration for the column. Fig. 11 (b), (c) and (d) show step by step progression of rupture of FRP at the corner of the column.

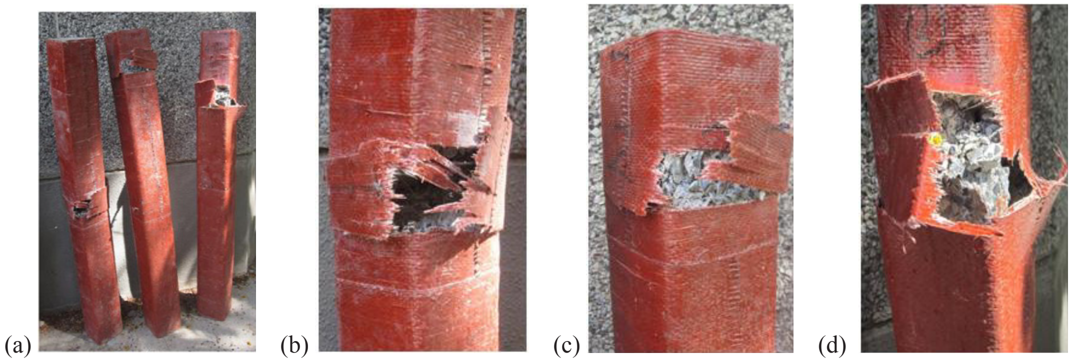


Fig. 11. Failure mode of Column S2R1.

Fig. 12 shows the failure of Column S1R2. Two columns failed from the mid height. Fig. 12(b) shows the premature failure of the column. Fig. 12 (b), (c) and (d) shows the shifting of rupture zone from corner to mid portion of sides for the column, respectively.

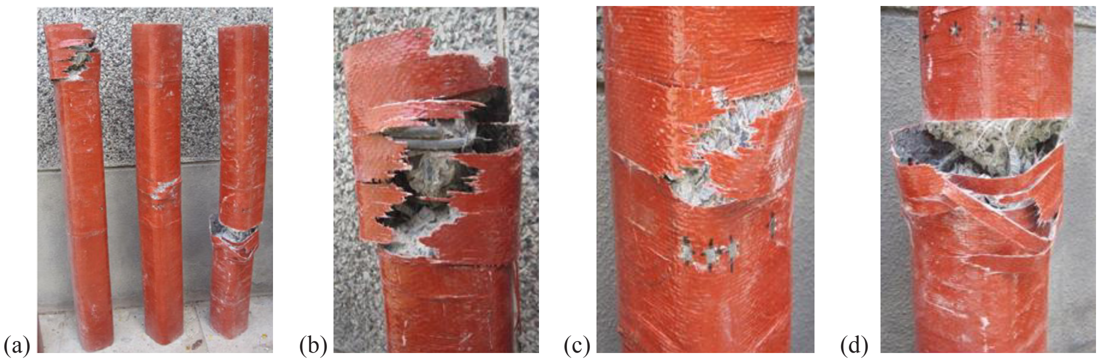


Fig. 12. Failure mode of Column S1R2.

Fig.13 shows the failure of the column S2R2. The column fails from the top due to premature failure. Fig.13 (b) and (d) shows the premature failure of the column. The reinforcement bar for the column can also be seen in Fig.13 (d).

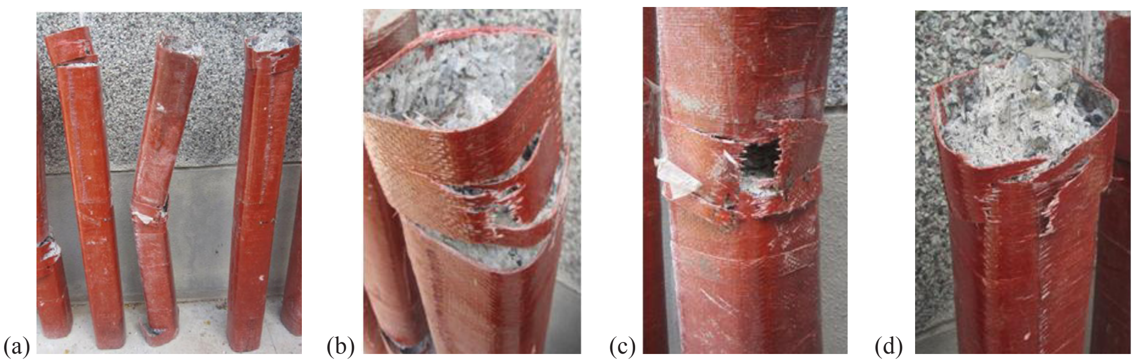


Fig. 13. Failure mode of Column S2R2.

Overall, the failure is observed in between the top end to the mid height for the majority of the confined columns. The failure occurring near top end of the columns can be attributed to medium quality of concrete mix proportioning as well as the debonding of the FRP confinement. The failure of the columns occurring at the mid height may be attributed to the development of the compressive stresses because of application of the axial load.

3. Conclusions

Based on the experimental results, the following conclusions are drawn:

- The experimental results clearly demonstrate that GFRP wrapping can enhance the structural performance of RC columns under axial loading, in terms of both maximum strength and strain.
- Percentage increment in ultimate failure load is ranging from 47% to 149% for all confined columns as compared to that of unconfined columns.
- Increasing the number of GFRP layers increases the axial compressive strengths of the columns. However, the strength increase is not in linear proportion with the number of GFRP layers.
- Higher ultimate failure load capacity is achieved for the columns having corner radius of 25 mm as compared to the columns having 5 mm corner radius which further proves the importance of the corner radius.
- The column having corner radius of 25 mm performed superior as compared to the column with corner radius of 5 mm.
- Higher strain is observed at the middle of the column and it reduces from starting of curvature to center of curvature.
- Increase in axial strength and axial strain of column is observed with increase in number of GFRP layers.

To enhance overall performance of RC columns confinement with GFRP is strongly recommended. Corner radius equivalent to the cover plays a prominent role in increasing the axial load carrying capacity of the column. Increase in the number of GFRP confinement layers improves the performance of the column. However, use of more number of confinement layers is recommended only looking to the viable cost benefit ratio for the overall strengthening job for the structure.

Acknowledgements

The work described in this paper was conducted at the Civil Engineering Department of Nirma University, Ahmedabad, India. Authors are grateful to the Management and Director of Institute of Technology, Nirma University for extending the permission for the work.

References

[1] Riad Benzaid at el., "Study of The Compressive Behavior of Short Concrete Columns Confined by Fiber Reinforced Composite", The Arabian Journal for Science and Engineering, Volume 34, Number 1B, (2009), pp. 15-26.
[2] Manuel A.G. Silva, "Behavior of square and circular columns strengthened with aramidic or carbon fibers", Construction and Building Material 25(2011), pp. 3222-3228.
[3] Raafat El-Hacha and Mohammad A. Mashrik, "Effect of SFRP confinement on circular and square concrete columns", Engineering Structures 36 (2012), pp. 379 -393.
[4] Yousef A. Al-Salloum, "Influence of Edge Sharpness on The Strength of Square Concrete Columns Confined with FRP Composite Laminates", Composites: Part B 38 (2007), pp. 640-650.
[5] M. Reza Esfahani and M. Reza Kianoush, "Axial Compressive Strength of Reinforced Concrete Columns Wrapped with Fibre Reinforced Polymers (FRP)", International Journal of Engineering Transactions B: Applications, Vol. 18, No.1 (2005), pp. 9-19.
[6] Yung-Chih Wang and K. Hsu, "Design of FRP-wrapped reinforced concrete columns for enhancing axial load carrying capacity", Composite Structures, 82 (2008), pp. 132-139.
[7] Lei-Ming Wang and Yu-Fei Wu, "Effect of corner radius on the performance of CFRP-confined square concrete columns: Test", Engineering Structures, 30 (2008), pp. 493-505.
[8] Yu-FeiWu and You-YiWei, "Effect of cross-sectional aspect ratio on the strength of CFRP-confined rectangular concrete columns", Engineering Structures 32 (2010), pp. 32-45.
[9] H. Toutanji et al., "Behavior of Large-Scale Rectangular Columns Confined with FRP Composites", Journal of Composites for Construction - ASCE (2010), pp.62-71.
[10] Antonio De Luca at el., "Structural Evaluation of Full-Scale FRP-Confined Reinforced Concrete Columns", Journal of Composites for Construction – ASCE (2011), pp.112-123.
[11] Sharma Sushil S., 2012. "Improving Behaviour by Change in Radius and Number of FRP Wraps on Behaviour of Rectangular RC Columns", M. Tech. Dissertation, Nirma University, Ahmedabad, India.
[12] IS 456:2000, "Plain and Reinforced Concrete - Code of Practice", Bureau of Indian Standards, New Delhi, India.