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Procedia Engineering 51 (2013) 240 – 249
Procedia Engineering
www.elsevier.com/locate/procedia

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

Behavior of GFRP wrapped RC Columns of different shapes

Rahul Raval[a], Urmil Dave[b]*

[a]*Structural Engineer ,VMS Engineering & Design Services (P) Ltd, Ahmedabad 380009, India*
[b]*Professor , Department of Civil Engineering, Institute of Technology, Nirma University, Ahmedabad 382481, India*

Abstract

In recent years, the use of externally bonded fiber-reinforced polymers (FRP) has become increasingly popular for civil infrastructure applications. The Glass fiber reinforced polymer has significantly enhanced the strength and ductility of concrete by forming perfect adhesive bond between concrete and the wrapping material. Present experimental investigation mainly emphasises on effectiveness of external GFRP strengthening for RC Columns of circular, square and rectangular shapes having same cross sectional area. Total 15 RC columns of 1 meter in height were cast. 9 columns were control and the rest 6 columns were strengthened with one layer of GFRP wrap having 20mm of corner radius. Columns were designed using IS: 456:2000 provisions. Design of GFRP wrapping was done using ACI 440.2R.08 provisions. All the test specimens were loaded to fail in axial compression and strain of the columns in the axial direction was investigated. The test results clearly demonstrated that the axial load carrying capacity increases from rectangular to square to circular shape of confined RC columns. No major impact on axial compressive strength is observed due to variation in shape for control columns, on the other hand, quite opposite behaviour was observed in case of RC columns confined by GFRP. GFRP wrapped circular column undergone more axial deformation as compared to that of square and rectangular columns. Stress-strain behaviour revealed that the strength gained from FRP confinement was prominent for circular columns. Square and rectangular-section columns are found to experience lesser increment in strength as compared to that of circular columns. This behaviour may be attributed to variation in lateral confining pressure distribution for rectangular columns from a maximum at the corners to a minimum in between, which is in contrast to even confining pressure observed for circular columns in order to achieve the full confinement effect.

Selection and peer-review under responsibility of Institute of Technology, Nirma University, Ahmedabad.

Keywords: RC column, Shape, GFRP, Axial compressive strength, Axial strain.

Nomenclature

B	Breadth of RC column
D	Width of RC column
RC	Reinforced Concrete
CC	Circular Column
SC	Square Column
REC	Rectangular Column
CW	Circular Column confined with GFRP wrap
SW	Square Column confined with GFRP wrap
RW	Rectangular column confined with GFRP wrap

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

Selection and peer-review under responsibility of Institute of Technology, Nirma University, Ahmedabad.
doi:10.1016/j.proeng.2013.01.033

Ø	Diameter of reinforcement
f_{co}	Compressive strength of unconfined concrete
f_{cc}	Compressive strength of confined concrete

1. Introduction

Column is the essential element in any structure. Strengthening and retrofitting of columns are very common. GFRP wrapping has significantly enhanced the strength and ductility of concrete by forming perfect adhesive bond between concrete and the wrap as observed by many investigators. The popularity is due to its well known advantages, including high strength-to-weight ratio and excellent corrosion resistance. Direction for FRP wrapping for RC columns is in horizontal direction to the length of the column. This kind of wrapping technique is identical to the horizontal stirrups provided for the reinforced concrete (RC) columns. Fiber Reinforced Polymer (FRP) composite constituents are resins (polymers), reinforcements, fillers & additives. The primary function of FRP is to carry load along the length of the fiber and it provides strength and stiffness in one direction. It can be oriented to provide properties in directions of primary loads. FRP is new generation material and in a short time it has gained tremendous popularity.

Hadi [1] wrapped RC columns with FRP straps both in vertical and horizontal directions and tested them under axial and eccentric loading. Seven RC columns of diameter 205 mm with height of 905 mm were used. One column was reinforced with steel reinforcement while another six columns were made up of plain concrete and then vertical straps were provided, followed by wrapping the column horizontally with FRP. Performance of CFRP straps was more effective compared to GFRP and conventional steel reinforcement. GFRP strengthened RC column performed better than steel reinforced concrete column. Sezen [2] evaluated the axial behaviour of strengthened circular RC columns with steel jackets and FRP. It was observed that FRP wraps increased the axial strength of the unretrofitted or base column by up to 140%. However, both methods resulted in a brittle failure immediately after the maximum axial capacity was reached. Smith et al. [3] investigated the behaviour of six 250 mm diameter concentrically loaded unreinforced CFRP confined concrete cylinders. Effect of the number of layers of the FRP and different overlap locations on the effectiveness of the FRP wrap was determined. Discontinuous versus continuous wrapping configurations to confine the cylinder were also investigated. All cylinders were 250 mm in diameter and 500 mm in height of which one cylinder served as a control (unwrapped) and five were wrapped with two layers of CFRP. All confined cylinders were found to fail by rupture of the FRP. Yu-Fei Wu[4] presented effect of cross-sectional aspect ratio on the strength of CFRP-confined rectangular concrete columns. Three series of uniaxial compression tests were conducted on 45 specimens. The parameters considered were the aspect ratio and the number of CFRP layers. The test results clearly demonstrate the strength gain in the confined concrete columns relative to the original unconfined columns, f_{cc}/f_{co} decreased as the aspect ratio increased, until it became insignificant when the aspect ratio reached. R. Kumutha et al.[5] studied the behavior of RC rectangular columns strengthened using GFRP. Three aspect ratios (a/b) where a and b are respectively, the longer and shorter sides of column cross-section, a/b = 1.0, a/b = 1.25, and a/b = 1.66 were considered. Specimens wrapped with 0, 1, and 2 layers of GFRP were investigated. Total nine specimens were subjected to axial compression. Effective confinement with GFRP resulted in improving the compressive strength. Better confinement was achieved when the number of layers of GFRP was increased, resulting in enhanced load carrying capacity of the column, in addition to the improvement of the ductility.

Most of the available studies [6-9] on the behavior of FRP confined RC columns have concentrated on circular columns, while relatively few studies have addressed rectangular and square columns. This is partly because FRP confined rectangular and square sections are not uniformly confined and the compressive pressure is unevenly distributed. However, the vast majority of all columns in buildings are rectangular columns. Therefore their strength and rehabilitation need to be given attention to preserve the integrity of building infrastructure. The use of externally bonded FRP composite for strengthening and repair can be a cost-effective alternative for restoring or upgrading the performance of existing concrete columns. Therefore, this paper is directed towards this endeavour.

The scope of work includes evaluation of the effectiveness of external GFRP strengthening on behaviour of circular, square and rectangular RC Columns in the present investigation. The columns were designed using IS: 456 [10] provisions. The columns strengthened with single layer of GFRP wrap were investigated. Design of GFRP wrapping for the columns was conducted using ACI 440.2 [11] provisions. Total fifteen columns were subjected to axial compression which includes nine columns as control and remaining six columns having 20mm of corner radius were confined with GFRP wrapping. All the columns were subjected to an axial compressive loading. Various parameters i.e. ultimate failure load, vertical deformation, axial strain, cracking pattern and failure mode were measured for the columns [12].

2. Experimental programme

2.1. RC Column Design

RC columns were designed as per IS: 456 [10] provisions. Total 15 columns of 1 meter height were cast. Design parameters are shown in Table 1. Reinforcement details of RC columns are presented in Fig. 1.

Table1. Details of RC columns

Columns	B (mm)	D (mm)	Area (mm^2)	Ties	Bars	No. of columns
CC	170 diameter		22707	6 ø-100c/c	6#8ø	5
SC	150	150	22500	6 ø-100c/c	4#8ø	5
REC	110	210	23100	6 ø-100c/c	4#8ø	5

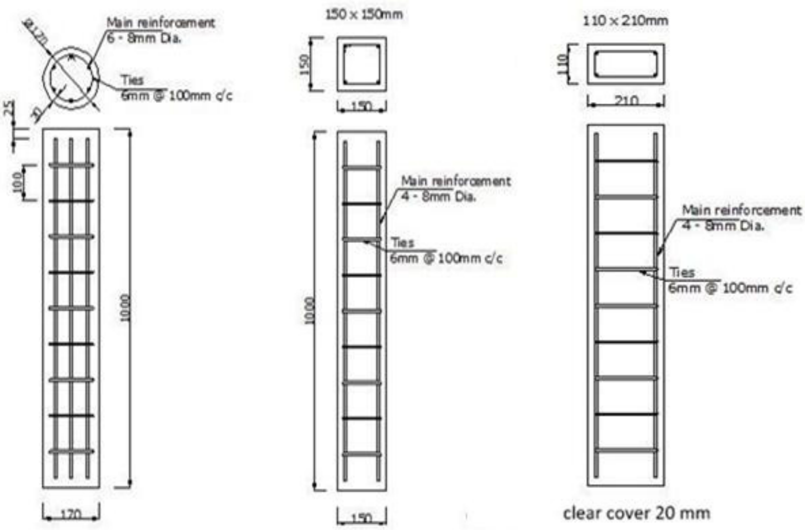

Fig. 1 Reinforcement details of circular, square and rectangular columns

2.2. Material properties

Concrete

The RC columns were cast using concrete mix with 28 days compressive strength of 15 MPa. Proportion of material as per weight batch was 0.60: 1: 3.25: 5 (water: cement: sand: coarse aggregate). The quantities of ingredients, used in the concrete mix 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 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

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 is more in longitudinal direction as compared to 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

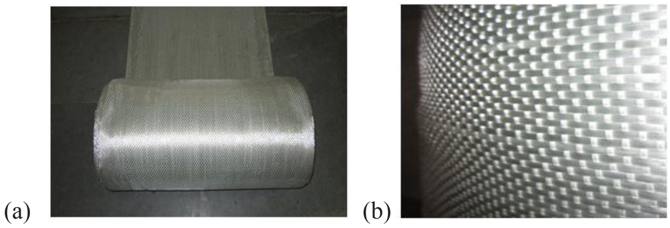

Fig. 2 GFRP Sheet (a) Sheet roll and (b) Unidirectional GFRP sheet

2.3. Casting of RC columns

Total three different shapes of formwork were used of 1 meter length. Concrete is prepared in the concrete mixture of half cement bag capacity. Clear cover was kept as 20mm for all the columns. In order to round of the corners of the square specimens, wooden patty inserts with 20mm radius are fixed with the help of screw and cello tape at the corners of the formwork before the time of casting as shown in Fig. 3.

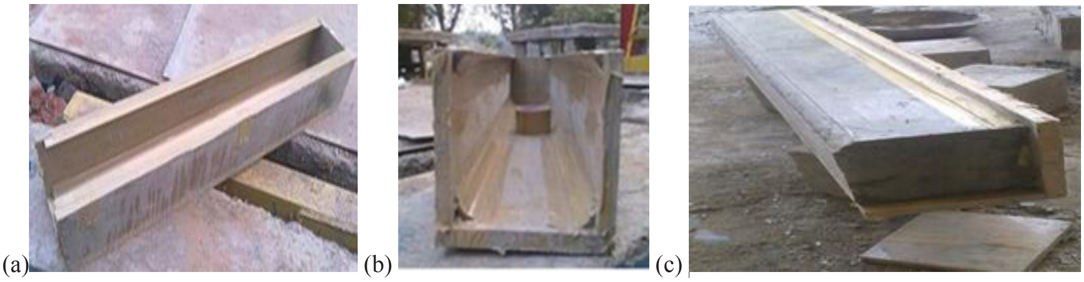

Fig. 3 (a) Formwork for column with corner radius 20 mm, (b) Completed formwork with corner radius patty and (c) Formwork with cast specimen.

2.4 *GFRP wrapping*

Fig. 4 (a) Grinding of RC column, (b) Application of Primer, (c) Application of saturant and (d) Application of GFRP sheet

The concrete surface needed to be cleaned with wire brush to remove all the loose dust particles. Girding machine was used for smooth even surface. Any voids on the surface of concrete are filled with putty. Primer coats are applied over the concrete surface after finishing of putty. Saturant is made from the two different parts i.e. base and hardener. They are taken in equal proportion and mixed together. 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 GFRP sheet was wrapped in the form of two pieces with overlap of one inch at mid height. GFRP wrapping procedure for RC columns stage wise is presented in Fig. 4.

2.5 Test setup

The vertical displacement of the column was measured by LVDT (linear variable differential transducers) with a travel of 50 mm which was mounted on aluminium frames that were attached to the specimen. Testing of the columns were carried out on loading frame in laboratory of 1000 kN capacity. The load was applied using hydraulic jack of capacity 2000 kN. The RC columns were tested on the loading frame under axial compressive loading as shown in Fig. 5. The axial load is applied through hydraulic jack of 2000 kN capacity. General arrangement of test setup is shown in Fig. 5. 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. Laboratory test setup is shown in Fig. 6.

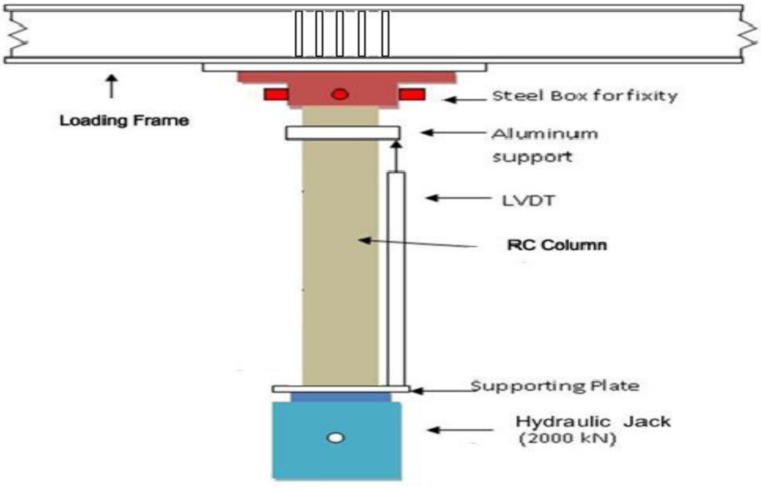

Fig.5. Test setup for application of axial load on columns

Fig.6. Laboratory test setup for RC columns

3. Test Results and discussion

To understand the behavior of RC columns of different shapes structural parameters like load, deformation & strain were evaluated for control and GFRP wrapped columns, respectively.

3.1 Ultimate load carrying capacity

Control circular columns exhibited higher axial load carrying capacity as compared to that for other columns. Axial load carrying capacity increases from rectangular to circular RC columns. Rectangular column exhibits lowest axial load carrying capacity. Results clearly demonstrated that variation in shape plays limited role in increasing the amount of axial load carrying capacity for control RC columns. Increase of 14% and 7% in axial load carrying capacity were observed for circular and square columns, respectively as compared to that of rectangular control columns. GRFP wrapped columns give considerable amount of increase in strength as compared to that of control columns for different shapes. GFRP wrapping for rectangular columns increases the axial load carrying capacity by 70-80%, on the other hand, for circular columns, the capacity increases to 158.75% as compared to that for control columns as shown in Fig. 6. Circular shape gives full confinement and therefore has resulted in to attainment of the the highest compressive strength.

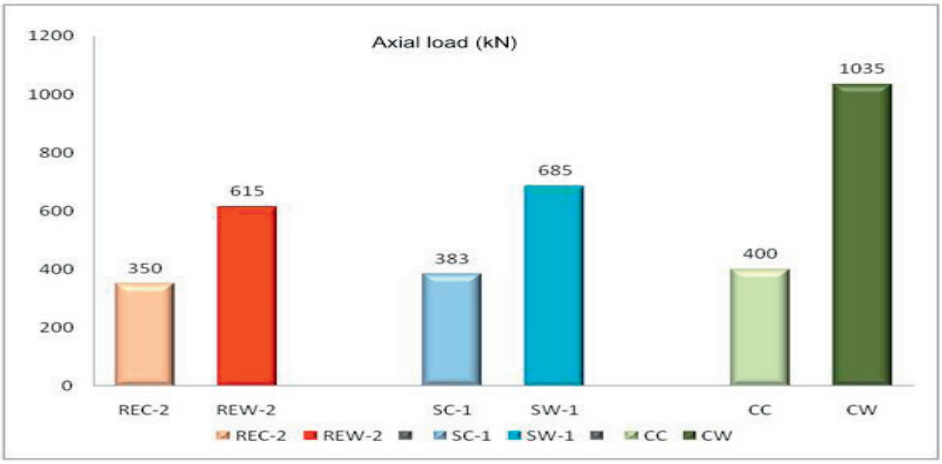

Fig. 7 Ultimate failure load for columns

3.2 Axial deformation

Load vs. axial deformation behaviour for all columns is presented in Fig. 8. The effects of geometry as well as effect of GFRP wrapping on load-deformation behaviour for columns are exhibited in Fig. 8. Minor difference in axial deformation behaviour is observed for control columns of different shapes. GFRP wrapped columns have exhibited higher axial deformation as compared to that of control columns. With the shape of column changes from rectangular to circular, strength and ductility of the columns increases considerably. Less effectiveness of GFRP confinement for rectangular columns may be attributed to the slenderness effect of the rectangular shape of the columns.

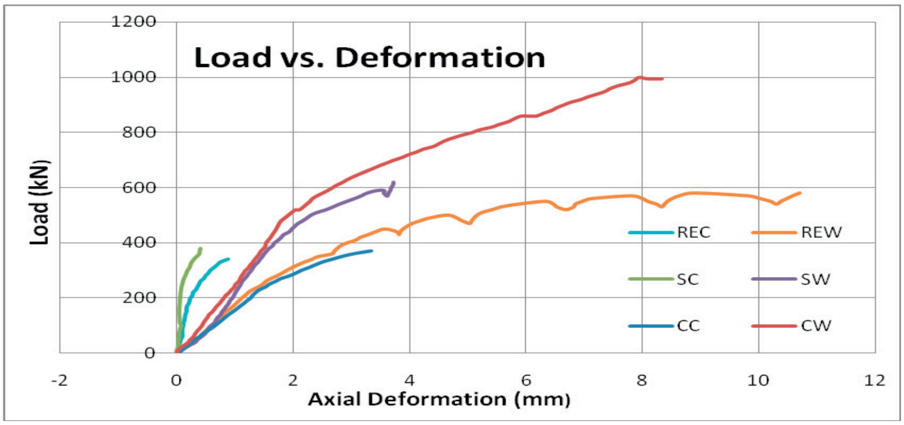

Fig 8: Load vs. deformation behaviour for columns

3.3 Axial Stress vs. Axial Strain

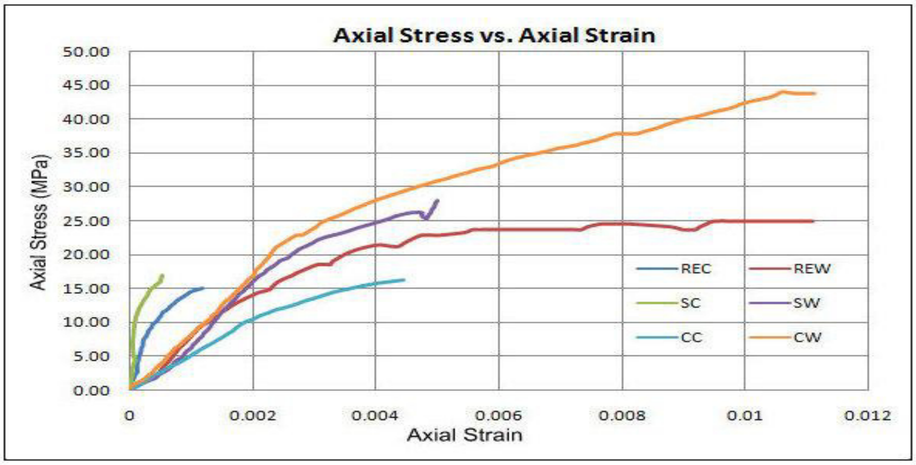

Fig 9: Axial stress vs. axial strain behaviour for columns.

Axial strain for columns was calculated from vertical deformation measured from LVDT. Axial stress for columns was calculated as load divided by cross sectional area. Average axial strain was evaluated from average axial deformation for the columns. Average axial stress and axial strain for control and GFRP wrapped columns is presented in Fig. 9. GFRP wrapped columns have exhibited higher axial strain as compared to that of control columns. It is evident from Fig. 9 that GFRP confinement is less effective in improving the axial strength of rectangular columns as compared to that of circular columns. Higher axial strain for GFRP wrapped rectangular columns as compared to other columns can be attributed to possibility of small eccentricity during testing resulting into bending effect exhibited by large deformation. Even stress distribution and full confinement effect has resulted into highest ultimate axial strength and strain for GFRP wrapped circular columns as compared to that for other GFRP wrapped columns. Up to the attainment of axial strain of 0.002 in concrete of circular and square GFRP wrapped columns exhibited similar behaviour. GFRP wrapped circular columns attained higher strain value as compared to that of other columns with further increase in load.

3.4 Effect of Shape

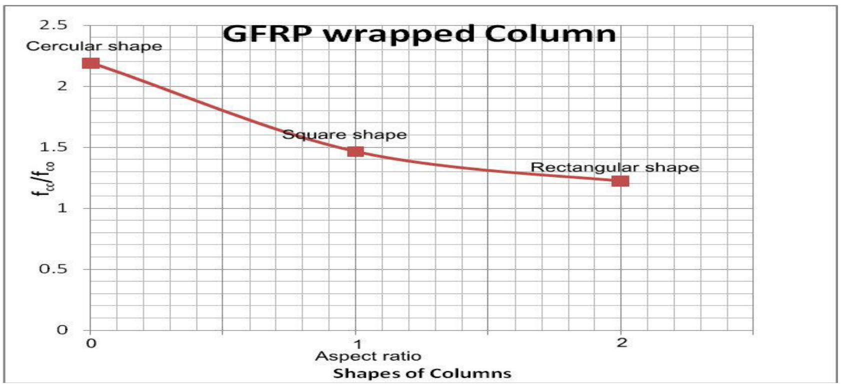

Fig 10: Effect of variation in shapes on confinement.

The effect of variation in shape for different columns have been studied and examined carefully. The ratio (f_{cc}/f_{co}) of GFRP confined concrete is defined as the ratio of the confining concrete strength to the unconfined concrete strength. Confinement ratio measures how effectively the concrete is confined for a given shape of RC column. It can be observed from Fig. 10 that with the change in shape for the columns from circular to rectangular, the confinement ratio f_{cc}/f_{co} decreases. Circular GFRP wrapped column shows best confinement as compared to that for other columns. Confinement by GFRP enhances the performance of circular columns much better as compared to that of square and rectangular columns.

3.5 Failure Modes and Crack patterns

Control RC columns have failed after reaching to their ultimate compressive strength and that resulted into splitting of concrete in between the stirrups. Majority of control columns were failed with blasting effect. The mode of failure has been characterized by shearing and splitting of the concrete in case of the control columns. Circular columns failed due to shearing effect under axial loading. Due to buckling of reinforcement at ultimate compression load the concrete pulled out in between two stirrups as shown in Fig. 11(a) & Fig.11(b), respectively. The failure of square column in shear can be observed. Lean concrete proportion was used in casting of these columns which could be attributed to this kind of failure. Fig.11(c) shows rectangular column failed from longer sides due to the slenderness effect. This is evident as less compressive load is required to break the concrete due to large variation in cross-sectional dimensions for rectangular column.

(a)

(b)


Fig.11 (a) Control circular column and (b) Control square column

(c)


Fig.11 (c) Control rectangular column

The failure of the GFRP wrapped RC columns have been divided into three modes: (i) tensile rupture of the GFRP layer usually observed near the corner; (ii) Delamination of the GFRP layer; and (iii) a combination of delamination and tensile rupture of the GFRP layer. The failure modes for the GFRP wrapped columns are shown in Fig. 12 & Fig. 13, respectively.

All the confined columns were failed by the rupture of the GFRP near the mid-height or near the corners. The GFRP and concrete at the top and bottom of the columns were still found intact at the time of failure. During the application of loading for the columns, typical sound was heard signifying the straining of the GFRP laminate and the cracking of the epoxy resin. Final failure for the column occurred suddenly with an explosive sound. GFRP wrapped circular columns failed from middle portion because of tensile rupture of GFRP material. There is no debonding observed over the surface of the column during the application of the axial load. Once the column reaches to the failure load, sudden rupture of GFRP wrapping was observed.

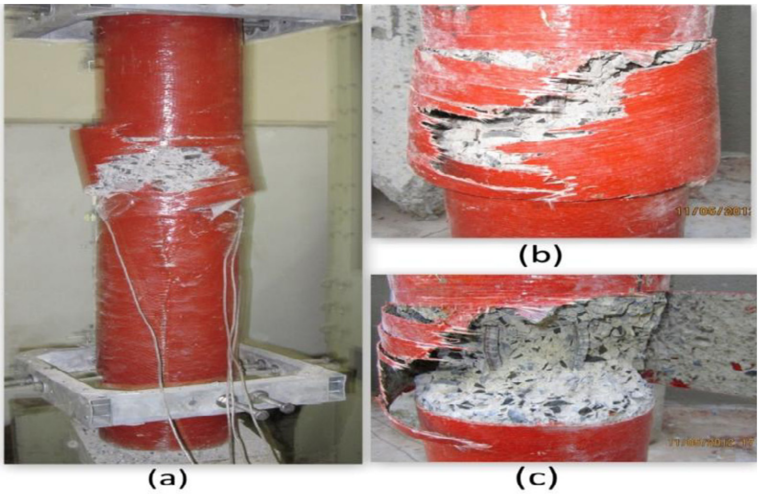

Figure 12: (a) Failure of GFRP wrapped circular column, (b) Closer view of failure portion & (c) Buckling of stirrups and failure shape

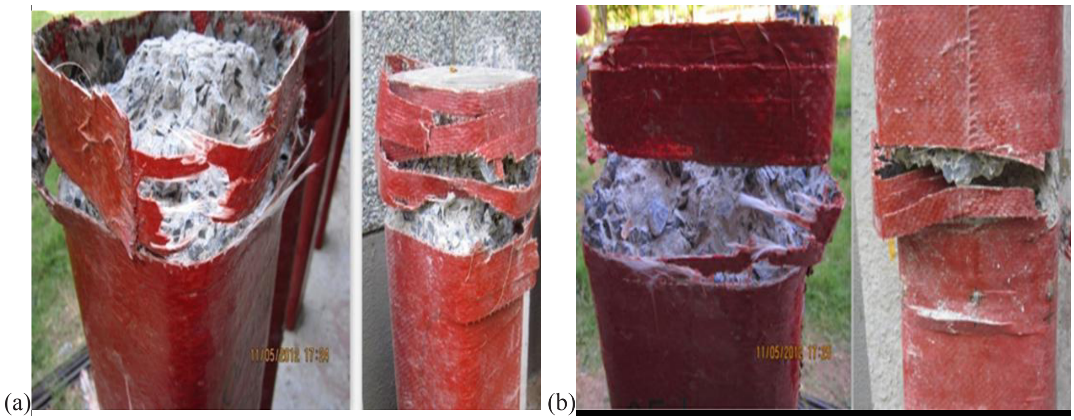

Figure 13: (a) Tensile rupture and delamination of GFRP wrapped square column and (b) Tensile rupture and Debonding of GFRP at mid height of rectangular column

Fig. 13(a) shows square column failure occurred at corner due to GFRP rupture. This is mainly because of unsaturated strands of fiber at corner of the column. Improper saturation of GFRP wrap during the wrapping can be attributed to this kind of failure. The square columns failed due to the combination of delamination and tensile rupture of the GFRP layer. GFRP wrapped rectangular columns failed due to combination of GFRP debonding and rupture from the corner. Fig. 13(b) demonstrates that GFRP rupture occurs due to unsaturated strands of GFRP layer at the corners. Small eccentricity during application of axial load for rectangular RC column caused bending effect which resulted into compression and tension zone on either side of the column face and as a result GFRP was torn from compression zone as it is weak in the compression.

4. Conclusions

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

- GFRP wrapping increases the axial load carrying capacity by providing addition confinement to the concrete without increasing the original column size.
- Effective confinement with GFRP wrapping resulted in improving the compressive strength. GFRP wrapping for circular columns produced highest increment in axial load of 159%. For square and rectangular columns, the enhancement in axial load was about 79% &76%, respectively due to GFRP confinement.
- Control and GFRP wrapped circular columns undergo higher axial deformation as compared to that for rectangular columns. Higher deformation was observed for GFRP wrapped rectangular columns as compared to that for square and circular columns because of slenderness effects having resulted into bending at the time of failure under small eccentricity.

- The axial stress-strain response changes from a monotonically increasing to strain-hardening type for GFRP wrapped columns. GFRP confined circular columns exhibited more ductile behavior as compared to that for GFRP wrapped square and circular columns.
- The GFRP wrapping is more effective for square columns as compared to that for rectangular columns. For GFRP wrapped columns, ultimate confined strength and compressive strain increased from rectangular to square and from square to circular shape of the columns.
- All control columns failed under brittle mode with blasting effect. GFRP wrapped circular column failed without any sign of debonding. The failure of square columns started at one of the corners by tearing of GFRP layers due to higher stress concentration. As the shape changes from square to rectangular for the columns, the failure zone shifted from corner onto the sides. The failure of rectangular columns occurred due to the combination of delamination/debonding as well as the rupture of GFRP material. The failure of GFRP columns was explosive in nature releasing tremendous amount of energy. Good contact between the GFRP layer and the column specimen was always noticeable for the damaged columns.

Confinement effect for GFRP wrapped columns becomes increasingly less effective with the change in shape from circular to square & from square to rectangular for the columns. Confinement by FRP for circular columns should be the ideal choice for axial load resistance as well as overall enhancement of the performance of the columns. However, at the same time, the sudden failure of the confined columns without any sign of debonding is undesirable from viewpoint of structural integrity. Thus, it can be recommended from the present study that FRP confinement will be a very good alternative for strengthening of circular and square RC columns, whereas, other methods are required to be employed for strengthening of rectangular RC columns.

Acknowledgements

Present experimental work was carried out at Department of Civil Engineering, Nirma University, Ahmedabad, India. Authors are thankful to management and Director, Institute of Technology, Nirma University, Ahmedabad for giving permission for the work.

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