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Experimental Investigation for Circular Concrete Columns confined by FRP and Conventional Lateral Steel

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Abstract*—Fiber Reinforced Polymer (FRP) jacketing has emerged as a very effective way to retrofit concrete columns in recent years. FRP wrapping is used when lateral steel is not sufficient to confine the concrete core. This paper presents experimental results of testing twelve reinforced concrete columns externally confined with FRP subjected to loading (concentric and eccentric) and evaluates the effectiveness of two confinement materials (Carbon fiber – Glass fiber). The columns were wrapped with either carbon fiber or Glass fiber with different number of layers. Two reference columns were internally reinforced and tested. The results indicate that Carbon fibers provide the greatest amount of confinement and greater load carrying capacity and axial deflection without failure. Also by applying multiple layers, the tests proved the benefits of confinement to enhanced ultimate stress for concentric and eccentric loading. The Comparisons made between theoretical calculations and experimental results show that the model can be used to estimate the ultimate strength of externally reinforced columns under concentric load with accurate degree.

Index Terms— **Fiber reinforced concrete, Fiber reinforced polymer, Eccentricity, column wrapping, confinement column,**

I. INTRODUCTION

Fiber-reinforced polymer (FRP) has been commonly used in practice as a confining material for concrete columns to enhance significantly their strength and ductility. The use of FRP has been applied to both concentric and eccentric loads [1–5]. This use of FRP in industry has required design guidelines for these applications. Many confinement models for FRP confined concrete columns, therefore, were proposed to simulate the behavior of confined concrete columns [6–11].

FRP wrapping is typically used to confine the existing concrete members containing conventional lateral steel reinforcement (tie/ spiral). The confining effect of lateral steel reinforcement in analytical studies has been considered differently in different models. A majority of related models considers confinement due to FRP and ignore the effect of conventional lateral steel reinforcement. Shao et al. [12] used the model proposed by Samaan et al. [13], which was proposed for concrete confined only by FRP, in a fiber-based analysis of concrete specimen’s confined by FRP and tie. Although the amount of lateral steel reinforcement was not negligible in their test specimens, they ignored its confining effect and achieved a reasonably good agreement between experimental data and analytical results.

The use of fiber reinforced polymers (FRP) jackets as an external mean to strengthen existing RC columns has emerged in recent years with very promising results [14-17], among others. Several studies on the performance of FRP wrapped columns have been conducted, using both experimental and analytical approaches. Such strengthening technique has proved to be very effective in enhancing their ductility and axial load capacity. However, the majority of such studies have focused on the performance of columns of circular cross section. This field remains in its developmental stages and more testing and analysis are needed to explore its capabilities, limitations, and design applicability.

Fateman et al [18] was proposed a constitutive stress–strain model for concrete confined by FRP and conventional lateral steel reinforcement when they act simultaneously. The accuracy of the proposed model in predicting the monotonic stress–strain relationship of concrete confined by both FRP and conventional reinforcement is assessed compared to various experimental data from specimens tested under concentric load, and several representative models.

This study considers two types of external reinforcement; Namely Carbon fiber Reinforcement Polymer (CFRP) and Glass fiber Reinforcement Polymer (GFRP); and compares them with experimental results. The effects of the two types of external reinforcing material are evaluated. Two sets of tests in terms of eccentric loading and concentric loading are conducted. Then, the effectiveness of external reinforcement as a confining material under different loading conditions are investigated.

II. EXPERIMENTAL PROGRAM

A. Materials

Detailed information about the materials used and their characteristics are given in this section.

Cement :The type of cement used in this research was CEM I N 42.5, ordinary Portland cement, Amrya company production. Test result performed on the cement specimens according to ECP, 203/2007 [19] and E.S.S, 4756-1/2005 [20].

Fine Aggregate: The fine aggregate used in this research was natural siliceous sand. The sand used was clean, free from impurities, silt, loam and clay. The main physical and mechanical properties of the used sand were measured according to ECP, 203-2007 [21] and E.S.S, 1109-2002 [22].

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Coarse Aggregate: The coarse aggregate used in this research was natural gravel, clean, free from organic silts, loam, injurious matter and clay. The maximum nominal aggregate size of the used gravel was 9.51 mm (0.37 in). The main physical and mechanical properties of the used gravel were measured according to ECP, 203-2007 [20] and E.S.S, 1109-2002 [23].

High range water reducer:- (Superplastizer SP) complies with ASTM C494 type F was used.

Carbon Fiber Reinforced Polymer (CFRP) Sheet: The used CFRP sheet was cured in situ sheet, commercially called (MBrace CF130 sheet) manufactured by Master Builders Technologies (MBT). Table (1) shows the physical properties of the used CFRP sheet according to the manufacture's data sheet.

Glass Fiber Reinforced Polymer (GFRP) Sheet: The used GFRP sheet was cured in situ sheet, commercially called (MBrace E-Glass sheet) or EG sheet manufactured by Master Builders Technologies (MBT). Table (1) shows the physical properties of the used E-Glass sheet according to the manufacture's data sheet.

Primer: - The used primer is two-component epoxy primer manufactured by (MBT).

Saturant (Epoxy):- The saturant used was two-component epoxy resin saturant manufactured by (MBT).

Table (1) Physical properties of used CFRP and GFRP

Property	CFRP sheet	GFRP sheet
Fiber Reinforcement	Carbon – High tensile	E-Glass
Fiber density	1.7 gm/cm^3	2.6 gm/cm^3
Fiber tensile elastic modulus (E)	240 GPa	73 GPa
Fiber orientation	uni-directional	90/10 bi-directional
Sheet weight	200 gm/m^2	800 gm/m^2
Sheet thickness	0.117 mm	0.308 mm
Sheet tensile strength	3800 MPa	3400 MPa
Sheet tensile elongation, ultimate	1.55 %	4.5 %
Sheet roll length	150 m	50 m
Sheet width:	300 mm	670 mm

B. Design of experiments

Considering that a slender column might cause buckling and secondary bending moments, which are not part of the present study, all columns were designed as short columns. Twelve short cylindrical (900 mm high with 190 mm diameter) concrete columns were designed for testing. All columns were reinforced longitudinally with 5 φ16 steel bars. Helices were provided with 8 mm plain bars at 80 mm pitches shown in Fig.1. The clear cover to helices was 20 mm. There are two groups of columns one group was tested concentrically and the second group was tested with 50 mm eccentric load.

The concrete mix was designed for a target compressive strength (28 MPa). The weights of concrete constituent materials for one cubic meter of concrete are 350, 11260, 680, 150, 2 kg for Cement, coarse aggregate, fine aggregate water and superplastizer, respectively. The concrete mix was designed based on the absolute volume method. The concrete mixing was carried out mechanically by mixing the constituent material in dry state for two minutes, then mixing water and superplastizer were added gradually and the mixing was continued for further two minutes. The mixing was carried at room temperature of 25^{o}C.

Fig. 1 Fixing column with FRP

C. Preparing test specimens

The first stage of specimen construction was to prepare the circular PVC tubes. Twelev formworks were used in the experiment. In order to maintain a perfect environment for concrete columns, high pressure air was first used to clean the wooden platform. Then, the PVC tubes were fixed straight up on the wooden platform and were tested to make sure the tubes were level.

Reinforcement cage was tied for each column and then put into the formwork, then steel cages were used at the bottom of the reinforcement to ensure a 20 mm clearance. Next, the reinforcement cage was placed into the formwork (as shown in Fig. 1) and oil was brush inside of formwork in order to easily remove it from the concrete. The 28-day cube compressive strength, f_{cu} of the concrete was 28 N/mm^2. A slump test gave a reading of 120 mm. In the curing period, the concrete columns were covered by moist Hessian in order to give a suitable humidity. Seven days was required for the concrete to cure before removing the formwork. The specimens covered by moist Hessian to obtain further curing. After twenty eight days curing, the concrete columns were ready for start the programme.

D. FRP warping

The concrete surfaces of the columns to be strengthened with FRP were well scraped by an electric tool and carefully cleaned by removing dust and fine materials with compressed air by using an electric blower as shown in Fig. 1. Then epoxy primer was coated with brush over the columns surfaces to fill the irregulations on the surface as shown in Fig.1. Saturant was used to bond FRP with column, then rolling the FPR by special roller to ensure that the FRP is saturated with

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epoxy resin and there are no voids between the fibers and concrete surface as shown in Fig 1.

E. Test setup

Steel loading frame with hydraulic jack was used to apply vertical load on columns .Fig. 2 shows test setup for axially loaded columns. The hydraulically operated 3000 kN, located in the Strength of material Laboratory at the University of Mansoura was used to test all the columns in this study. All the columns were tested to failure. The value of applied load was appeared automatically on special monitor connected to the hydraulic jack.

Fig 2. Test setup

The axial deflection of the columns was measured by a deflection gauge placed on a corner of the platform and connected to Strain meter system. The peak loads of the tested columns were measured by monitor connected to the hydraulic jack.

Where eccentric loading differs from concentric loading is that it involves concentrating the load a certain distance from the neutral axis of the cross section. As shown in Fig. 2, two plates were designed and manufactured in order to apply eccentric loading on the columns. These plates were used on both top and end of the column during loading.

Five columns were eccentrically loaded until failure with an eccentricity of 50 mm. The testing matrix is summarized in Table 2.

Table (2) Test Matrix

Col	Confining Matrial	Loading pattern
N01	Helix	Concentric
N11	Helix	Eccentric
C01	Helix + Carbon 1 layer	Concentric
C11	Helix + Carbon 1 layer	Eccentric
C02	Helix + Carbon 2 layers	Concentric
C03	Helix + Carbon 3 layers	Concentric
C13	Helix + Carbon 3 layers	Eccentric
G01	Helix + Glass Fiber 1 layer	Concentric
G11	Helix + Glass Fiber 1 layer	Eccentric
G02	Helix + Glass Fiber 2 layers	Concentric
G03	Helix Glass Fiber 3 layers	Concentric
G13	Helix + Glass Fiber 3 layers	Eccentric

III. RESULTS AND DISCUSSION

A. Concentrically Loaded

Failure of strengthening columns was brittle, a very explosive failure. The snapping of fibers could be heard throughout the loading as the concrete tried to expand. Table 3 present the testing results of the concentrically loaded columns. For control columns (N01) the yield load was observed at 748 kN from load level and ultimate load equal 789 kN. Where for the columns (C01) the yield load equal 1164 kN and ultimate load equal 1346 kN. The yield load increased by 143%, the ultimate load increased 70% and deflection increased by 82% compared with the control column (N01).

For columns (C02) the yield load equal 1363 kN and ultimate load was 1590 kN, it was observed yield load and ultimate load was increased by 185% and 101% compared with control column (N01). Moreover, deflection for C02 was increased at yield and ultimate load by 118% and 103% respectively, compared with N01.

For columns (C03) the yield load equal 1800 kN and ultimate load was 2014 kN, it was observed yield load and ultimate load was increased by 276% and 155% compared with control column (N01). Moreover, deflection for C03 was increased at yield and ultimate load by 179% and 200% respectively, compared with N01.

For columns (G01) the yield load equal 851 kN and ultimate load was 1251 kN, it was observed yield load and ultimate load was increased by 78% and 58% compared with control column (N01). Moreover, deflection for G01 was increased at yield and ultimate load by 80% and 45% respectively, compared with N01.

For columns (G02) the yield load equal 1087 kN and ultimate load was 1408 kN, it was observed yield load and ultimate load was increased by 127% and 78% compared with control column (N01). Moreover, deflection for G02 was increased at yield and ultimate load by 122% and 57% respectively, compared with N01.

For columns (G03) the yield load equal 1327 kN and ultimate load was 1800 kN, it was observed yield load and ultimate load was increased by 170% and 128% compared with control column (N01). Moreover, deflection for G01 was increased at yield and ultimate load by 125% and 84% respectively, compared with N01.

Table (3)Testing results of concentrically loaded columns

Col	Yield Load (kN)	Displ. at yield load (mm)	Ult. Load (kN)	Displ. at ult. load (mm)	Strengthing relative to N01
N01	478	2.21	789	5.09	1
C01	1164	4.31	1346	9,27	1.7
C02	1363	4.5	1590	11.11	2.0
C03	1800	6.17	2014	15.28	2.55
G01	851	3.99	1251	7.39	1.58
G02	1087	4.92	1408	8.03	1,78
G03	1327	4.99	1800	9.39	2.28

The Carbon fiber confinement provided to columns resulted in higher ultimate load. The failure was very explosive. It can be concluded, increased the layers of confinement achieved significantly better results for both strength and deflection. It is of significance to note that the column was appeared to be fully intact after failure as shown in Fig. 3. This meant that after failure the column still had ability to withstand load and still maintain its integrity.

Fig. 3 Mode of failure for columns under concentric load

The glass fiber confinement was also achieving higher strength and ductility. However, there was not as much excess deflection achieved as the carbon fiber confinement. This specimen also remained intact after failure except for presence some fracture in glass fiber.

Table 3 and Fig 4- 6 shows the values of yield load recorded of each columns. It was noticed that there is increase in the yield load for all fiber confinement columns compared with control column (N01) the values of yield loads increases were ranged from (143 – 276)% for Carbon fiber and (78% 170) for Glass fiber. As shown in Table 3 and Fig. 4-6, It is clear that the values of ultimate loads increases for all fiber confinement columns by values ranged (70 -155)% for Carbon confinement and (58-128)% for Glass fiber confinement compared with control columns (without fiber confinement).

Table 3 and Fig. 4-6, show the effect of each strengthening columns on deflection behavior used in each columns.

For Fiber confinement column there is increase in deflection values ranged from (82 – 200) % for carbon confinement and (45 – 80) % for Glass fiber confinement, compare with control column (N01), this can attributed to, as the ductility of the fiber confinement columns increase the deflection increase, this results indicated that Carbon fibers confinement is more effective for external confinement compared with Glass fiber. Moreover, Comparison among the concentrically loading columns confirmed that the confinement significantly enhanced the strength, ductility of concrete, in particular when applied in multiple layers, as shown in Fig 7-8.

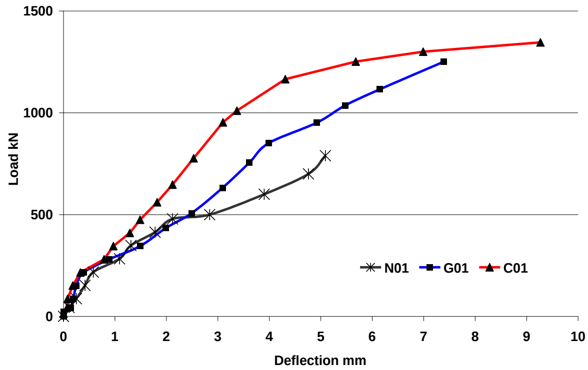

Fig. **4 Load-deflection of columns N01, G01 and C01**

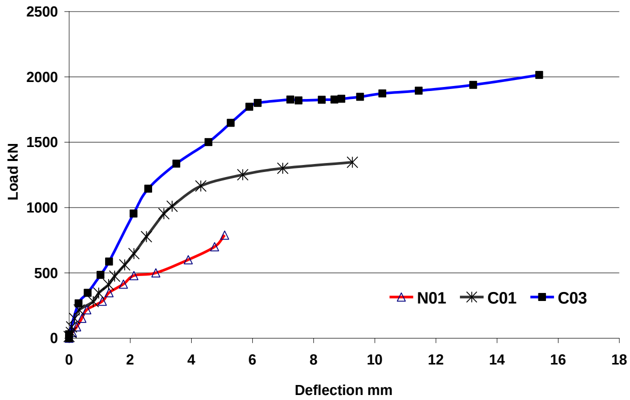

Fig. 5 Load-deflection of columns N01, C01 and C03

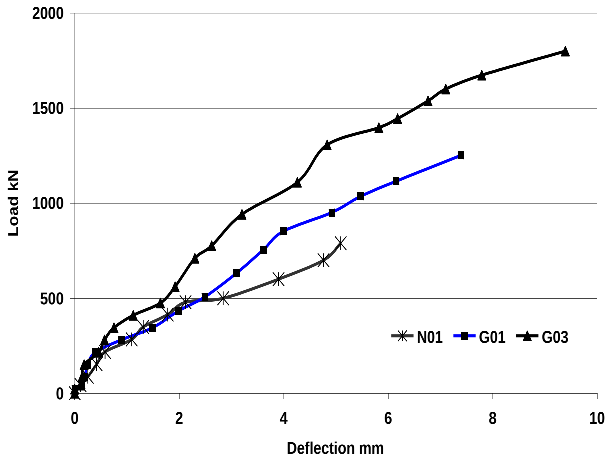

Fig 6 Load-deflection of columns N01, G01 and G03

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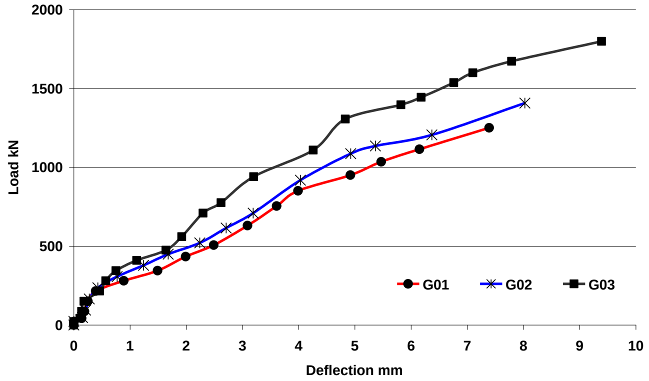

Fig 7 Load-deflection of columns G01, G02 and G03

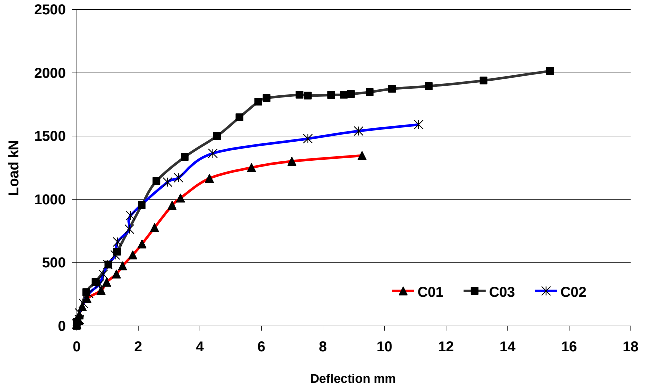

Fig 8 Load-deflection of columns C01, C02 and C03

B. Eccentrically Loaded Columns

Column N11 had internal reinforced only was tested at an eccentricity of 50mm. This column had ultimate load 225 kN as shown in Table 4 The columns continue buckle until the concrete cover broke away and internal reinforcement split. The column axial deflects to 1.9 mm at failure. Due to yielding of steel reinforcement the column remained bent after failure as shown in Fig. 9.

Fig. 9 Mode of failure for columns under eccentric load

Table 4 Results of testing eccentrically loaded columns

Col	Ult. Load (kN)	Displ. at ult. load (mm)	strengthing relative to N11
N11	225	1.9	1
C11	364	4.26	1.6
C13	584	7.22	2.6
G11	384	5.79	1.7
G13	543	7.4	2.4

Column C11was an internally reinforced column wrapped with one layer of carbon fiber and tested at 50 mm eccentricity. The ultimate load was 364 kN as seen in Table 4. Comparison between C11 and Control column N11, ultimate load and axial deflection for C11 was greater than N11 by 60% and 120%, respectively.

For C13 with three carbon fiber layers, the test results show that this column withstand much higher ultimate load than the internally reinforced (N11) and one layer carbon fiber wrapped (C11) by 158% and 60 % respectively this reveals that Carbon fiber wrapped could provide significantly greater confining pressure under eccentric loading..

Failure of carbon fiber wrapped column was marked by fiber rupture at the top column. Although it was sudden, the failure could be predicated by appearance of patches at the top of column as a result of the fiber stretching as shown in Fig. 9

The material used to wrap the column (G11) is one layer of glass fiber. The failure mode of this column was similar to that Carbon fiber specimen: fibers were ruptured at the top end of the column. This can be seen in Fig. 9. Cracking with the glass fiber could be heard throughout the testing with the failure of the column signified by a loud snap of the Glass fiber wrapping.

Comparison between N11, G11and G13, the ultimate eccentric load for G13 was greater than N11 and G1 by 140% and 41%, respectively. Also, the ultimate axial deflection for G13 was greater than N11 and G11 by 200% and 70% respectively.

Based on the experimental work undertaken in this study it can be concluded that the carbon fiber improves the load carrying capacity of the column more than when compared with glass fiber. The wrapped columns both having load carrying capacities greater than the unwrapped columns. For both, increasing the number of wrapping layers, increasing ultimate load and axial deflection.

IV. THEORETICAL CALCULATION

The ultimate strength is important parameters in the stress-strain model Some of the major parameters affecting the ultimate strength include (i) cross section dimension, (ii) Lateral steel reinforcement bar area, (iii) Lateral reinforcement spacing, (iv) FRP thickness, (v) FRP tensile Strength, (vi) compressive strength of unconfined concrete. The analytical model below [18] was used to calculate the confining stresses in column. It is to be noted that the model have been established for concentrically loaded specimens.

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To calculate the ultimate strength (f'_{cu}) applied to the concrete by confinement, the following relation relationship proposed by Fatemeh et al [18] is used:

$$\frac{f'_{cu}}{f'_{co}} = 1.1 + 2.5\left(\frac{f_{1f}}{f'_{co}}\right)^{0.8} \times \left(\frac{f_{1s}}{f'_{co}}\right) + 3.5\left(\frac{f_{1s}}{f'_{co}}\right)^{0.2}\left(\frac{d_c^2}{D^2}\right)^4 \qquad (1)$$

Where f'_{co}, D and d_c are maximum axial compressive strength of unconfined concrete, diameters of concrete gross cross section and concrete core, respectively. f_{1f} and f_{1s} are confining pressure provide by FRP and lateral steel reinforcement, respectively, given by

$$f_{1f} = \frac{2 \times t_f \times f_{yf}}{D} \qquad (2)$$

$$f_{1s} = \frac{2 \times A_{st} \times f_{ys}}{s \times d_c}$$

where: t_f, f_{yf}, A_{st}, f_{ys} and s are FRP thickness, ultimate strength of FRP, transverse steel cross section area, steel yield strength, and transverse steel spacing respectively.

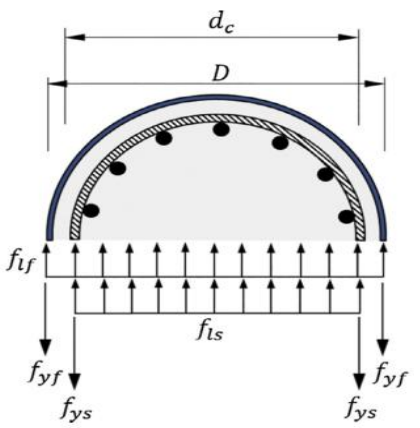

Fig. 10 Confining mechanism for concrete confined by FRP and steel [18].

Table 5 Comparison between theoretical and experimental results for the concentrically loaded columns

Col	Theoretical ult. Compressive Stress MPa (1)	Experimental ult. Compressive Stress (MPa)
C01	46.93	47.50
C02	53.39	56.16
C03	69.44	73.08
G01	44.88	44.35
G02	49.35	50.78
G03	60.46	64.11

The confining mechanism for concrete confined by FRP and lateral steel was shown in Fig.10.[18]. Table 5 compares the theoretical calculating results of all external reinforced columns under concentric loading with their experimental resulted. The theoretical ultimate stress was calculated based on Eq. (1). It shows that the theoretically determined confining stresses lower than the experimental results. This may be due the effect of good saturant and epoxy resin used to wrapping columns. It can be concluded the models prepared by Fatemeh et al [18] can be used to estimate the ultimate strength of externally reinforced columns under concentric loading with accurate degree.

V. CONCLUSIONS

This study used 7 internal reinforced columns with FRP wrapping under concentric loading and five columns under eccentric loading, which are mainly to evaluate effectiveness of various types of FRP wrapping and number of FRP layers. The results of tests allow the following conclusions to be drawn:

1) Using external FRP enhanced the properties of concrete column. The confinement of column prevents the concrete from expanding and allows the concrete to absorb higher stress, resulting a higher load carrying capacity.
2) The composite wrapping for steel reinforced columns improved the axial deflection capability of the column when compared with steel reinforced concrete column
3) By applying multiple layers, the tests proved the benefits of confinement to enhanced ultimate stress for concentric and eccentric loading.
4) Carbon fibers provide the greatest amount of confinement and greater load carrying capacity and axial deflection without failure.
5) The Comparisons made between theoretical calculations and experimental results show that the model prepared by Fatemeh et al [18] can be used to estimate the ultimate strength of externally reinforced columns under centric loading with accurate degree.
6) External confined FRP could undergo large deformation without rupture. The extent of deformation could be decided by strength of FRP composite.

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