Experimental Work on Columns Confined with CFRP Sheets

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Abstract— Concrete behaves superiorly when confined, so columns are confined and studied their behavior. Plain control concrete column 6no's, reinforced column with a minimum longitudinal steel 0.8% of cross section 6no's and 18no's plain confined column with one, two and three layers of CFRP in transverse direction for different grades of concrete. The axial load –Shortening, load carrying capacity, ductility index, toughness index, and failure pattern of each specimen are studied. Results of the experimental program showed that concrete confined with CFRP transversely increases load carrying capacity effectively increases up to the two layers , whereas ductility increases up to the three layers of confinement as compared to control concrete . Toughness index of the strengthened column increases with increase in grade of concrete, increases with increasing the number of CFRP sheet layers.

Key words: CFRP, columns, concrete, confinement

I. INTRODUCTION

The use of externally bonded fiber reinforced polymer (FRP) composites has become increasingly popular for the repair and retrofitting of concrete structures. The popularity of FRP composites is due to their well-known advantages, including a high strength-to-weight ratio and excellent corrosion resistance. One important application of FRP composites is as a confining material for the retrofitting of existing reinforced concrete (RC) columns with FRP jackets. The confinement effectiveness of FRP jackets in concrete columns depends on several Parameters namely concrete strength, types of fibers and resin, fiber volume and orientation, jacket thickness, shape of cross section, length-to-diameter (slenderness) ratio of the column, and the interfacial bond between the concrete core and the jacket. The confinement prevents lateral expansion under axial load, adding to the stiffness of the concrete column [Manuel A.G. Silva 2011]. Indeed, well dimensioned lateral confinement can also increase lateral deflection capability of the columns and FRP composites have been used for instance for seismic upgrades. Confinement of concrete is an efficient technique to increase the load-carrying capacity and ductility of RC concrete columns [Carlos Chastre al., 2010]. Under the lateral confining pressure provided by the confinement material, the concrete column is subjected to a triaxial stress state, thereby increasing the ultimate stress and strain. Carbon fiber reinforced plastics sheets or plates are well suited to this application because of their high strength-to-weight ratio, good fatigue properties, and excellent resistance to corrosion. Their application in civil engineering structures has been growing rapidly in recent years, and is becoming an effective solution for strengthening deteriorated concrete members [N. Chikh, et al., 2012]. Because CFRPs are quickly and easily applied, their use minimizes labor costs and can lead to significant savings in the overall costs of a project.

II. LITERATURE REVIEW

Lei-Ming Wang et al. (2007) has studied effect of corner radius on the performance of CFRP confined square column. The result indicates that stiffness is higher for columns with larger corner radius. The ductility of column increases with sharp corners, confinement is effective for increasing the ductility of columns of any corner radius; higher confinement produces higher ductility with smaller corner radius but smaller ductility of columns with large corner radius. **Manuel A.G. Silva (2011)** has studied the behavior of square and circular columns strengthened with aramidic or carbon fibers. The experimental part of study includes reinforced square and circular column strengthened with CFRP and AFRP the size of the specimen is 150 x 150 x 750mm and reinforced with longitudinal steel 8 ø 6 mm and stirrups ø3mm @ 100mm c/c. Based on the experimental work it was concluded that the increase in axial capacity for rounding chamfer, R=20 & 38mm by 20%, 96% & 153% cause a significant increase in axial shortening. The square column of corner radius equal to 38mm improved axial strength by factor 1.29 as compared to square section of corner radius 20mm.

N.Chikh et al. (2012) has studied the structural performance of high strength concrete columns confined with CFRP sheets. The study includes total 48 specimens were tested in axial compression. Both circular and square column were used the parameter were number of wrap layers, slenderness of the column. Based on the experimental work it was concluded that circular columns the average ratio of concrete strength of confined to unconfined member increases by 20% ÷ 51% for one layer and 38% ÷ 73% for three layer of CFRP, square column 9% ÷ 17% for one layer and 8% ÷26% for three layers of CFRP. The strength of composite column depends upon materials properties like strength of concrete, geometric properties like sharp and rounding corner and shapes like circular, square and rectangular. The orientation of fibers such as transverse, longitudinal and diagonal direction, number of layers of carbon fibers sheets.

A. *Present Work:*

So the present study is externally strengthening or confining of concrete columns with CFRP jackets, wrapping of fibers in the transverse direction for one, two and three layers of CFRP sheets for low, medium and high strength concrete. The corners of strengthen columns are rounded to one forth to one eight of the width or thickness. Since the transverse fiber sheets lead to increase the strength and ductility of columns (Kiang Hwee Tan 2002).The load carrying capacity, shortening and failure pattern of confined concrete column is compared with the reinforced column and plain column for different grade of concrete and number of CFRP layers.

III. EXPERIMENTAL DETAILS

A. Raw Materials:

1) Cement:
OPC 43 Grade cement was used.

2) Coarse Aggregates:
20 mm down size crushed granite aggregates are used in the present work.

3) Fine Aggregate:
Natural river sand is used confirming to Zone II as per IS: 383—1970.

4) Water:
Potable water free from solids.

5) Cold-Rolled Steel Bars:
The cold rolled steel bars are produced from strip steel.. Yield stress fy = 415 N/mm2
Modulus of elasticity Es = 2 x 105 N/mm^2 (values areas per data provided by suppliers)

6) Superplasticizer:
Glenium B233 is the type of superplasticizer used for our experimental work supplied by BASF manufacturer Bangalore.

7) Carbon Fibers And Epoxy Adhesive:
The carbon fiber used in this study is readily available in the market under the trade name "Nitowrap". The fibers are wrapped around the column with the help of the epoxy adhesive. The engineering properties of the fibers are as given below.

a) Properties of Nitowrap Carbon Fiber

- Fiber orientation - Unidirectional
- Weight of fiber - 200 g/m^2
- Fiber thickness - 0.11mm
- Ultimate elongation -1.5%
- Tensile strength - 4900 N/mm^2
- Tensile modulus - 285 x $10^3 N/mm^2$

8) Epoxy Sealer Cum Primer:
The primer used for binding between the carbon fibers and the concrete surface for external wrapping properties as follows.

a) Nitowrap 30, Primer:

- Density - 1.14g/cc
- Pot life - 25 min @ 27°C
- Full cure – 7 days

b) Nitowrap 410, Saturant:

- Color - Pale yellow
- Application temp - 15°C-40°C

B. Concrete Mix Design:

1) Mix Design:
Concrete Mixes with targeted characteristic strengths of M20, M30 and M40 MPa using locally available ordinary Portland Cement (OPC), crushed granite jelly (20 mm down) and river sand and Glenium B233 are used in the present investigation. Mix designs of these three grades of concrete are based on the guidelines of IS: 10262-2009. Standard cubes (150mmX150mmX150mm) were used to determine the compressive strength of the concrete. Based on the test results with number of trial mixes the mix proportions are finalized. The final mix proportions adopted for three grades are as shown in Table 3.1.

Sl. No	Mix Designation	Proportion C:FA:CA	W/B Ratio	Super plasticizer % by wt of cement	Compressive strength at 28 Days (N/mm^2)	Slump (mm)
1.	M1	1:1.8:3.3	0.5	-	28.66	75
2.	M2	1:1.6:3.1	0.45	-	38.25	65
3.	M3	1:1.4:2.7	0.4	0.5	46.69	60

Table 3.1: Details of Concrete Mix Proportions

C. Preparations of Test Specimens:

In the present experiment tests are conducted on plain and reinforced concrete column of square section with different grades of concrete. The plain concrete columns are wrapped with the carbon fibers of one; two and three layers. A total of 30 concrete columns specimens were tested.

1) Preparation Of Cube Samples:
Standard cast iron moulds of size 150 X 150 X 150mm are used in the preparation of cubes. The moulds have been cleaned to remove dust particles and applied with mineral oil on all sides before the concrete is poured into the mould. The admixture is mixed with the constituents of concrete at the time of adding water. Full blending of the admixture and the concrete should be ensured by mixing for a period of at least two minutes. Thoroughly mixed concrete is filled into the mould and compacted in three equal layers. Excess concrete is removed with trowel after proper compaction and top surface is smoothened. Overdose may also cause increase in air entrainment, which will tend to reduce the strength of the mix. After casting, the specimens are stored in the laboratory for 24 hours from the time of addition of water to the ingredients. After this period, the specimens are removed from the moulds, immediately submerged in the water tank. Three samples of every grade of concrete were tested for 28 days compressive strength.

2) Preparation Of Concrete Columns:
The moulds of size 150 X 150 X 750 mm are used in the preparation of column. The moulds have been cleaned to remove dust particles and applied with mineral oil on all sides before the concrete is poured into the mould. The admixture is mixed with the constituents of concrete at the time of adding water and the concrete should be ensured by mixing for a period of at least two minutes. Thoroughly mixed concrete is filled into the mould and compacted in three equal layers. Excess concrete is removed with trowel after proper compaction and top surface is smoothened. After casting, the specimens are stored in the laboratory for 24 hours from the time of addition of water to the ingredients. After this period, the specimens are removed from the moulds, immediately submerged in the water tank. Two columns specimen of every grade of plain concrete are casted and two columns specimen of each grade of reinforced column are prepared.

Fig. 3.1: Concrete columns specimen in the mould

D. Tests On Columns And Hardened Concrete Cubes:

1) Compression Test Set-Up And Test Procedure For Concrete Columns:

The column specimens are tested at 28 days of age for control specimen for CFRP wrapped column are tested after 7 days of application of CFRP. The tests are conducted in a 1000 kN capacity Column Testing Machine. Least count of the load that can read on the digital display of loading unit of UTM is 0.1kN and in dial gauge least count of axial shortening is 0.1mm.

Prior to the actual tests, a pre-load of 15 kN is applied so that the platens of the testing machine are firmly attached to both ends of the specimen. The axial load is then applied slowly by careful manipulation of the loading-valves. The readings of the applied load and axial shortening are recorded at appropriate load increments.The arrangement of the specimen in the UTM as shown in the figure 3.5.

IV. RESULTS AND DISCUSSIONS

A. Load -Shortening Curve Of Column:

Concrete columns with outer confinement provided by fiber reinforced polymers have their properties enhanced especially increased ductility and maximum load carrying capacity. These effects are achieved as a result of lateral pressure applied by external jackets. The confinement prevents the lateral expansion under axial load adding to the stiffness to the concrete column.

The effectiveness of confinement is known to be greater for circular section than square and rectangular sections due to singularity and stress concentration introduced at the edges, the mitigation of this shape effect may be achieved by rounding the corner of column.

It is observed that better performance were obtained for the corner radius between 15 and 25mm, an increase in the sharpness of the corners of the cross section results in a lower ultimate strength (Yu-Fei Wu, 2007), the smaller corner radius can significantly reduce the ultimate strength of the FRP laminate due to stress concentration around the corner area. This stress concentration factor increases when the corner radius decreases.

The nature of the curve for specimens M2 and M3as flows the same but the specimen M3 curve is slightly higher side as compared to M1, the specimen M1 curve is slightly higher side as compared to M2 at the initial stage up to the axial shortening of 3.8mm than it takes the path lower side.

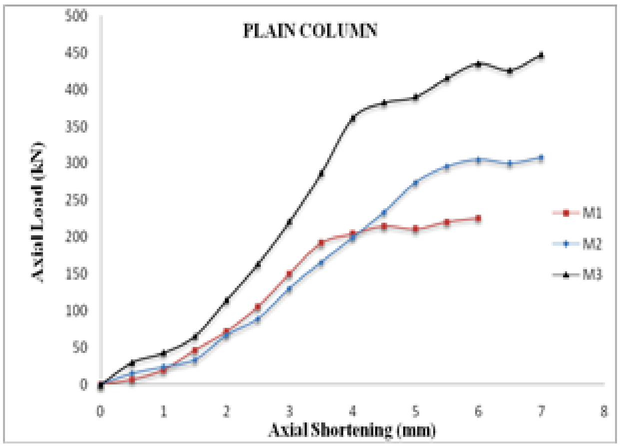

Fig. 4.1: Axial Load v/s Axial Shortening for Unconfined Column

All the plain columns are failed brittle only, the specimen M1 failed by crush of concrete in the middle part at the more compressive side, due to higher compressive stresses at the extreme top and bottom faces of the column as shown in the figure 4.2. The specimen M2 is failed by crushing of concrete in the upper part at the more compressive side and its failure is less as compared to specimen M1 As shown in the figure 4.2 .The columns showed very little warning signs of failure and cracked approximately from the top of the column. The specimens M3 is failed smaller than M1 and M2 because as the grade of concrete changes i.e higher grade of concrete will be able to sustain higher compressive stress at the extreme faces of the column as shown in the figure 4.2.

M1

M2

M3

Fig. 4.2: Failure Pattern of Unconfined Different Grades of Concrete Columns

B. Axial Load-Shortening For Reinforced Column:

The axial load axial shortening values for reinforced column as tabulated in the table 4.2.

Axial load v/s axial shortening for reinforced column curves as shown in the figure 4.3, from the table 4.2 shows that specimen M3RC was able to attain the maximum axial load 522.50 kN for a maximum axial shortening of 6.5mm, the percentage increase in axial load for M3RC as compared to M1RC 53.13% for a maximum axial shortening of 5.5 mm due to the Additional transverse strengthening implies delay in deboning the strips from concrete (T. Trapko, 2011). The interaction of Both CFRP materials entail the reduction of strains increase velocity which transfers to the Increase of load-bearing capacity. And for M2RC is 20.22% for a maximum axial shortening of 7.0 mm.

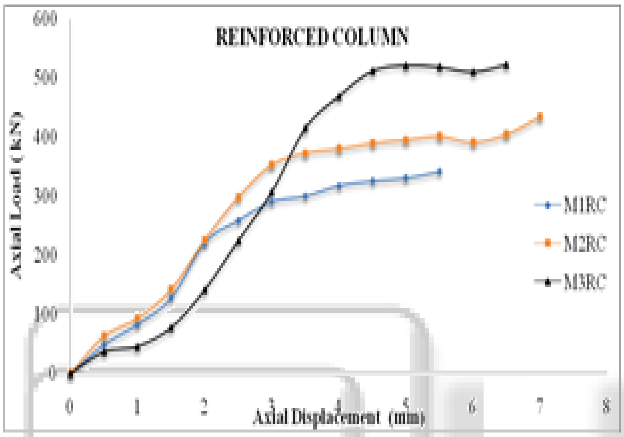

Fig. 4.3: Axial Load v/s Axial Shortening for Reinforced Column

The difference between members confined with internal steel spiral and external FRP Jacket is that in case of composite reinforcement the whole cross-section is strengthened and composite material works elastically till failure, whereas in case of the steel spiral reinforcement the confinement concerns only the core of cross-section. Moreover, when stress in steel reaches a yield strength strains increase under constant level of load (T.Trapko, 2011).

The nature of the curve for specimen M1RC and M2RC follows the same path up to the yielding point after that specimen M2RC have higher side as compared to the specimen M1RC, the nature of the specimen M3RC initially at the lower side as compared to M1RC and M2RC up to the yielding point but after yielding point maximum load and shortening of specimen higher as compared to M1RC and M2RC as shown in the figure 4.3.

The ultimate load of a column does not vary appreciably with the history of loading. When the load is increased, the steel will normally reach the yield strength before the concrete reaches its full strength. However at the stage the column has not reached its ultimate load the column can carry further load because the steel sustains the yield stress while shortening and load increase until the concrete reaches its full strength (R.Park and T.Paulay), the concrete approaches its strength before the steel yields so the ultimate load of an axially loaded reinforced concrete column is the sum of the yield strength of steel plus the strength of the concrete.

The reinforced columns are failed by crushing of concrete in the upper part at the more compressed and yielding of longitudinal steel reinforcement, the specimen M1RC are failed by crushing of concrete at the more compression side than yielding of steel as shown in figure 4.4, the specimen M2RC crushing of concrete is slightly less as compared to specimen M1RC as shown in figure 4.4 and the specimen M3RC instead of crushing delaying of concrete patches occurred at the top side due to higher grade of concrete as shown in fig 4.4. The RC specimen failed by spalling of concrete cover at the upper height. The concrete cover began to spall when the specimen achieved its ultimate load and spalling kept occurring as the load dropped steadily. After the concrete cover was completely spalled, it was seen that longitudinal bars were bent between two ties of transverse confinement.

M1RC

M2RC

M3RC

Fig. 4.4: Failure Pattern of RC Column with Different Grade

C. Axial Load –Shortening For Single Layer Strengthened Column:

Axial load v/s axial shortening curve for plain column strengthened with single layer of CFRP as shown in the figure 4.5, from the table 4.3 shows that specimen M3, 1L was able to attain the maximum axial load 690.40 kN for a maximum axial shortening of 8.0mm, the percentage increase in axial load for M3,1L as compared to M1,1L is 24.12% for a maximum axial shortening of 8.0 mm and for M2,1L is 18.54% for a maximum axial shortening of 7.0 mm.

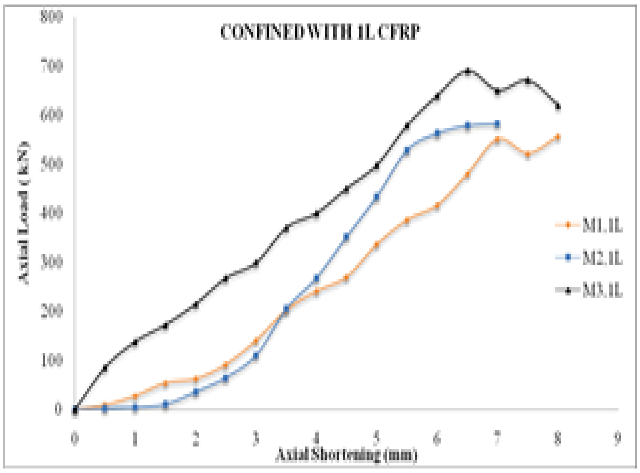

Fig. 4.5: Axial Load v/s Axial Shortening for One Layer CFRP Confined Column.

The axial load versus axial shortening relationship is almost linear up to the value of axial compressive strength of an unwrapped concrete column, after this the slopes of the load- shortening relationships decrease due to the reduction of the stiffness of the concrete columns. The stiffness of the columns has decreased because of the cracking and expansion of the confined concrete. At this stage the confining effect of FRP wraps starts to increase the compressive strength of the columns (M.Reza Esfahani, 2005). All the strengthened columns exhibited stiffness similar to that of the unstrengthen columns initially, indicating the contribution of fiber sheets to the column stiffness at low loads was not significant

1) Axial Load –Shortening For Two Layers CFRP Strengthened Column:

Axial load v/s axial shortening curves for plain column strengthened with two layer of CFRP as shown in the figure 4.6, from the table 4.4 shows that specimen M3, 2L was able to attain the maximum axial load 749.08 kN for a maximum shortening of 8.0mm, the percentage increase in axial load for M3,2L as compared to M1,2L is 14.31% for a maximum axial shortening of 5.5 mm and for M2,1L is 10.45% for a maximum axial shortening of 6.0 mm.

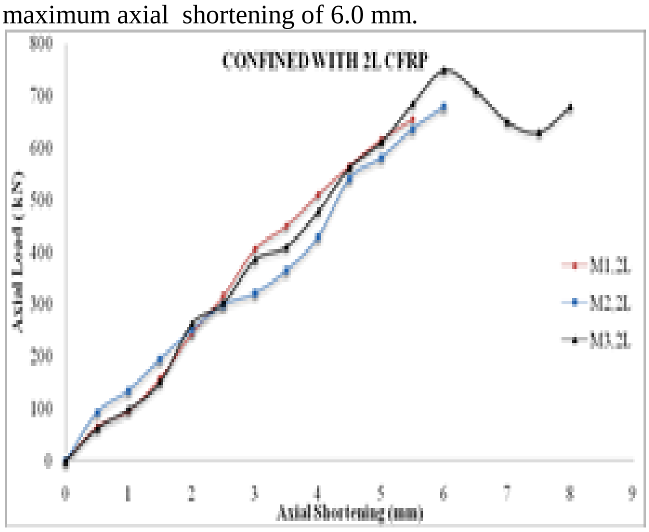

Fig. 4.6: Axial Load v/s Axial Shortening for Two Layers CFRP Confined Column

The load- shortening relationships of the confined columns are still linear but with the smaller slopes. This may be because of the linear behavior of the FRP wrap against the radial stresses in the confined concrete (M.Reza Esfahani, 2005), the linear behavior of the confined columns continues, with a smaller stiffness, until failure.

The nature of the curve for specimens M1, 2L, M2, 2L and M3, 2L almost linear up to the maximum load carrying capacity after that the specimen M3, 2L takes decline path but the other two specimen M1, 2L and M2, 2L are almost behaves same up to the maximum point due to the effectiveness of confinement pressure on the lateral side of the column as shown in the figure 4.6.

2) Axial Load –Shortening For Three Layers CFRP Strengthened Column:

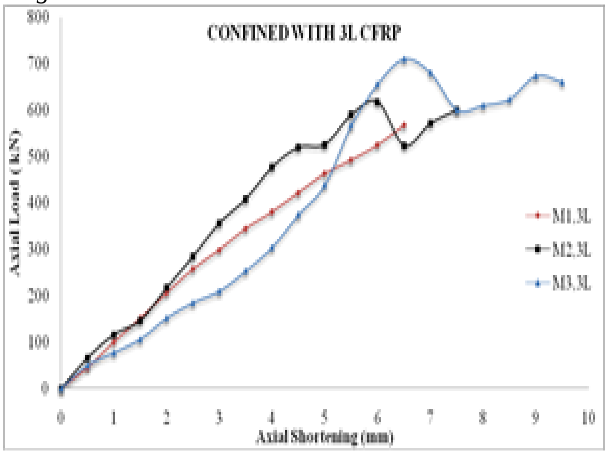

Fig. 4.7: Axial Load v/s Axial Shortening for Three Layers CFRP Confined Column.

Axial load v/s axial shortening curves for plain column strengthened with three layer of CFRP as shown in the figure 4.7, from the table 4.5 shows that specimen M3, 3L was able to attain the maximum axial load 710.20 kN for a maximum axial shortening of 9.5mm, the percentage increase in axial load for M3,3L as compared to M1,3L is 25.31% for a maximum axial shortening of 6.5 mm and for M2,3L is 14.98% for a maximum axial shortening of 7.5 mm

The nature of the curve for specimens M1, 3L, M2, 3L and M3, 3L are different for three layered strengthened column due to the variation of lateral pressure provided by the carbon fibers. The specimen M1,3L follows linear up to it's maximum load carrying capacity but the specimen M2,3L is slightly higher side than M1,3L up to the yield point and it's behavior is linear after that it undergoes parabolic shape and the specimen M3,3L at the initial stage slightly lower side as compared to the M1,3L and M3,3L up to the yield point after that it follows parabolic curve over the specimen M1,3L and M2,3L as shown in the figure 4.7.

The failure pattern of the CFRP wrapped column divided into three groups 1st tensile rupture of CFRP jacket usually near the corner due to the stress concentration, the clicking sound is heard during the loading stage after that CFRP rupture is takes place as shown figure 4.8. In order to prevent this failure the corner of the column are rounded to a corner radius of 20 mm to increase both load carrying capacity and ductility of columns.

The column wrapped with two layers of CFRP jacket the failure occurred as the combination of Delamination and tensile rupture of CFRP jacket this is due two plies of confinement as 1st layer rupture it causes the second layer to Delamination instead of rupture due to high tensile strength of CFRP jacket as shown in the figure 4.8. The columns wrapped with three layers of CFRP jacket the failure occurred as the Delamination of CFRP jacket this is due to the insufficient bonding strength between the CFRP and the specimen as shown in the figure 4.8.

The columns showed warning signs of failure and cracked approximately 200 mm from the top of the column. Failure was not sudden, yet not very many warning signs were evident. The number of layers, and by way of consequence the confinement stiffness, has direct impact on the axial load and axial shortening at failure due to the initially low confining effect of the columns a softening behavior was observed (Pierre Rochette,2000).

The carbon –wrapped specimens, there was insignificant Delamination between adjacent plies observed at failure. The breakage line was generally clean and perpendicular to the external plies of the specimens occurred. The breakage line appeared at a corner, exactly at the end of rounding. Macro cracks expanded in the concrete but the concrete remained solid and no concrete block came off when the test was stopped. The composite breakage was initiated at a corner and then propagated to the next one following a line that coincided with the fiber orientation.


1L


2L


3L

Fig. 4.8: Failure Pattern of CFRP Strengthened Column with Different Layers.

The column strengthened with two layers of CFRP sheets shows a slope of 94.12,the one layer strengthened column shows a slope of 87.39 column than it takes the lower side due to the steel reaches yield strength and strain increases under constant load. The column wrapped with the two layers of CFRP sheets shows the slope of 110.2 as compared to the specimen wrapped with one 102.3, three 84.33, and plain 52.15 and reinforced column 59.56. This shows that the slopes of two layer strengthened column is two times higher than the plain column for the same grade of column.

D. Load Carrying Capacity Of Column:

Specimen	Ultimate Axial Load (kN)			Axial Shortening at Ultimate Axial load (mm)		
	M1	M2	M3	M1	M2	M3
PCC	225.60	307.80	447.80	6.0	7.0	7.0
RCC	341.2	434.60	522.50	5.5	7.0	6.5
CF-1 Lyr.	556.20	582.40	690.40	8.0	7.0	6.5
CF-2 Lyr.	655.30	678.20	749.08	5.5	6.0	6.0
CF-3 Lyr.	566.75	617.62	710.20	6.5	6.0	6.5

Table 4.4: Summary of the Experimental Results

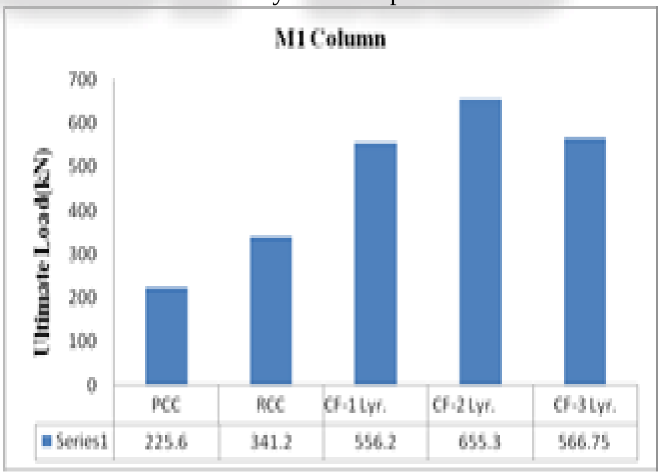

Fig. 4.9: Ultimate Axial Load of M1 Column

The figure 4.12 shows the ultimate axial load carrying capacity corresponding to M1 grade of concrete it includes plain, reinforced and CFRP column strengthen with one, two and three layers. The above graph it shows that percentage increase in load carrying capacity for M1, 2L as compared to M1 190.46%, M1 RC is 92.05%, M1, 1L is 17.18% and for M1, 3L decreases about 15.62% due to the ineffectiveness of confinement provided by the CFRP sheets and poor interfacial bond between concrete core and the jacket, a non uniform stress distribution in the FRP jacket due to shortening localization of the cracked concrete and thus premature rupture of the FRP. The increase in the column strength is directly related to the level of concrete confinement.

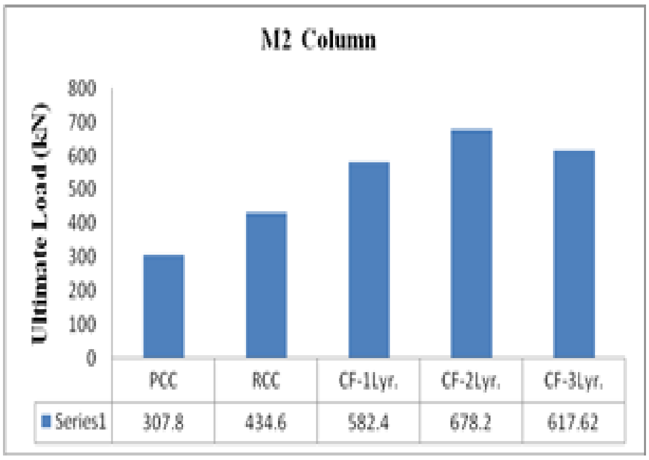

Fig. 4.10: Ultimate Axial Load of M2 Column

The figure 4.13 shows the ultimate axial load carrying capacity corresponding to M2 grade of concrete it includes plain, reinforced and CFRP column strengthen with one, two and three layers. The above graph it shows that percentage increase in load carrying capacity for M2, 2L as compared to M1 120.34%, M2RC is 56.05%, M2, 1L is 16.45% and for M2, 3L decreases about 9.81% due to the externally bonded FRP laminates have to be bent when they when they are wrapped around the columns bending affects the performance and efficiency of the FRP laminate (Wang. 2007) and corresponding confinement action depends upon the curvature of the corners. The effective confinement from the CFRP jacket which occurs at the column strength tends to be proportional to corner radius ratio. The axial shortening is usually large in experimental investigations due to local nature shortening measurement and non-uniform local cracking of concrete and local debonding of FRP.

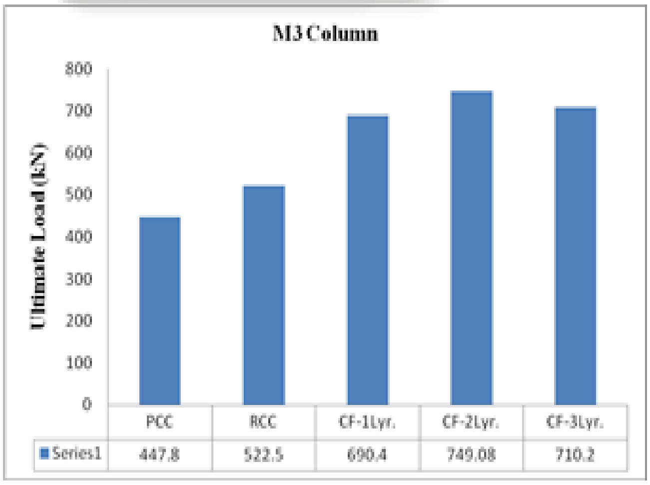

Fig. 4.11: Ultimate Axial Load of M3 Column

The figure 4.14 shows the ultimate axial load carrying capacity corresponding to M3 grade of concrete it includes plain, reinforced and CFRP column strengthen with one, two and three layers. The above graph it shows that percentage increase in load carrying capacity for M3, 2L as compared to M2 67.28% , M3RC is 43.4% , M3, 1L is 8.5% and for M3,3L decreases about 5.47% due to the ineffectiveness of confinement provided by the CFRP sheets, The confining causes three-axial state of stress in cross-section of compressed members and reduces the increase of transverse strains (Trapko and Musial. 2011), the effective confinement at the onset of the column strength is much lower than that at the ultimate failure. Therefore jacketing does not provide much confinement to columns when they reach their load carrying capacity and much higher confinement is provided at the ultimate failure.

The increase in strength of the column depends directly on the thickness of concrete cover which creates many fall backs such as increase in self-weight and cross-sectional area, the damage severity included crush of concrete and buckling of longitudinal bars. The strength enhancement for various levels of confinement and inefficiency of low lateral pressure.

E. Ductility Index:

Ductility is a technical measure of the shortening of a structural member before it fails. It is a desirable feature for a structural member to be safe against unpredicted overload such as earthquake. A structural member with high ductility gives warning before it fails hence it is a general rule for a structural member to be ductile

As per (Wang. 2007) Ductility ratio can be defined as the ultimate axial shortening (δ_u) divided by the yield axial shortening (δ_y). The ultimate axial shortening is defined as the point at which the load drops 20% from peak load; the yield axial shortening is the yield point of an equivalent bilinear response curve that provides an equal area to that response curve.

SL.No	Specimen	δ_y	δ_u	DI
1	M1	3.9	6	1.54
2	M2	4	6.5	1.36
3	M3	3.7	5.4	1.08
4	M1,RC	2.9	6.1	1.89
5	M2,RC	4	6.5	1.62
6	M3,RC	3.9	5.5	1.41
7	M1,1L	3.4	6.4	1.88
8	M1,2L	3.4	6.5	1.91
9	M1,3L	3.3	7.6	2.3
10	M2,1L	3	5.5	1.83
11	M2,2L	3.2	6	1.87
12	M2,3L	2.8	6	2.14
13	M3,1L	4	6.5	1.62
14	M3,2L	3.8	6.4	1.68
15	M3,3L	3.6	6.5	1.8

Table 4.5: Ductility Index Column Specimens

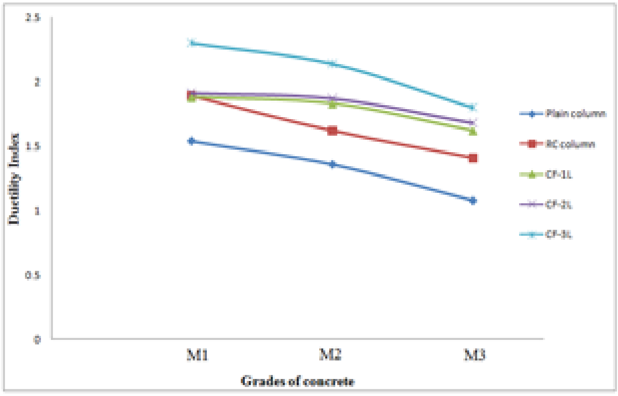

Fig. 4.12: Ductility Indices of Column for Different Grades of Concrete and Layers of Wrapping.

The figure 4.15 shows the ductility indices of plain, RC and strengthened column for the plain column the ductility decreases linearly with increase in grade of concrete due to the higher grade of concrete undergo less shortening due to its brittle nature. The RC columns ductility index for M1RC specimen is higher than that of M2RC and M3RC due to the early development of cracks in the specimen. Where as the ductility index for strengthened column increases with respect to the number of increase in wrapping of CFRP layer and decreases with respect to the increase in grade of concrete due to the brittle nature of concrete once concrete fails inside the CFRP sheets tends to fails in buckling but further increases due to increase in wrapping of CFRP.

The yielding of the confining steel contributes to increased ductility in the case of RC column. The material to enter into the plastic phase imparting additional strength to the structure by means of redistribution of stress. The ductility helps in reducing induced forces and in dissipating some of the input energy it also demands larger deformation accommodated by the structure.

Due to the increase in ultimate compressive strain, the ductility capacity and energy absorption capacity are also considerably improved. The use of FRP in this particular application is similar to that in the rehabilitation due to deteriorating infrastructure. The stiffness of the confining material is prime importance in improving the ductility of the structural element (Rochette and Labossiere. 2000). The higher confinement produces the higher ductility for column with smaller corner radius; however it leads smaller ductility for columns with a large corner radius. The increase in ductility depends on the reinforcement of the cover and connection between the cover and column.

F. *Toughness Index:*

Toughness is a measure of energy absorbing capacity of the composite. Increased toughness means – improved performance in fatigue, impact and impulse loading and it also provides ductility, i.e. the ability to undergo larger shortenings before failure, it is often measured using a toughness index.

Toughness index, I_t is given by -

$$\text{Toughness Index} = \frac{\text{Area under the load deflection curve untill load reaches zero for fiber composite}}{\text{Area under the load deflection curve untill load reaches zero for plain matrix}}$$

Specimen	Toughness (N-mm) x 10^3	Toughness Index
M1	1780.72	-
M2	1142.65	-
M3	777.4	-
M1,1L	1864.05	1.05
M1,2L	2191.17	1.23
M1,3L	2231.15	1.25
M2,1L	1724.5	1.51
M2,2L	2089.54	1.83
M2,3L	2858.21	2.51
M3,1L	1879.62	2.41
M3,2L	1981.71	2.54
M3,3L	2032.55	2.61

Table 4.6: Toughness Index of Strengthened Column.

V. CONCLUSIONS

(1) The CFRP confined column up to two layers is effective for increasing axial load carrying capacity of column, enhance in the CFRP layers found ineffective.
(2) The ductility index of three layers confined column is more as compared to the two, one layer strengthen, reinforced and plain columns, ductility increases with increase in number of CFRP layers.
(3) The one layers confined columns are failed by the tensile rupture of CFRP jacket where as two layered strengthened column failed by the combination of Delamination and rupture of CFRP jacket and three layered strengthened columns failed by the Delamination of CFRP jacket.
(4) The average percentage increase in load carrying capacity for RC column is 36.37% as compared to plain column.
(5) The average percentage increase in load carrying capacity for one, two and three layers strengthened columns are 96.64%, 126.02% and 103.49% as compared to plain column.
(6) The average percentage increase in load carrying capacity for one, two and three layers strengthened columns are 43.04%, 63.82% and 48.04% as compared to RC column.
(7) Toughness index of the strengthened column increases with increase in grade of concrete, increases with increasing the number of CFRP sheet layers. .
(8) A single layer confined plain concrete column is able carry more axial load than reinforced column of minimum steel.

VI. SCOPE OF FURTHER STUDY

The present experimental investigation deals with the axial compressive strength of concrete columns of different grade strengthened with one, two and three layers CFRP in the transverse direction.

The study can be extended by choosing the following parameter.

- The present study can be extended by using the reinforced concrete instead of plain concrete strengthened with the CFRP to see the effect on load carrying capacity and ductility of column.
- The study can be extended to behavior of plain and reinforced column strengthened with the CFRP under eccentric loading to see the effect on load carrying capacity, failure pattern and ductility of column.
- The study can be extended to plain column with rounding of corner with different corner radius strengthened with the CFRP to study the effect of corner radius on load carrying capacity of column.
- The study can be extended to plain column of different grade of concrete strengthened with the CFRP and GFRP to see the effect on the load carrying capacity and ductility of the columns.

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