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Experimental and Analytical Study of Square Columns Strengthed and Repaired Using Cfrp Sheets Partially and Fully Wrapped

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--*ABSTRACT*--

The Egyptian code of practice for the use of fiber reinforced polymer (FRP) in the construction fields [16]allows full wrapping only for non-circular columns and permits partially wrapping only after providing proof of the efficiency of the system. Such permission is subject to providing proof of the efficiency of the system through carrying out a sufficient number of tests.

This paper presents an experimental and analytical program conducted to study the behavior of RC square columns strengthened and repaired with carbon fiber reinforced polymer (CFRP) sheets with full and partial wrapping under axial loading. The program consists of a total of fifteen columns. The columns were tested under monotonic uniaxial compression loading up to failure. One layer of CFRP sheets were wrapped around the columns with different intervals between the wraps.

An analytical model dependent on the stress-strain characteristics of concrete under tri-axial state of stresses is proposed to predict the deformational behavior as well as the ultimate capacity of square RC columns strengthened by CFRP sheets Different recommendations and design guidelines are introduced

Keywords: *Carbon Fiber Reinforced Polymers. Columns, Confinement, Reinforced Concrete, Strengthening, Uniaxial Tests. Wrapping*

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I. INTRODUCTION

Wrapping circular columns with CFRP sheets was proven to be a very effective method to increase both the axial capacity and ductility of columns [1],[2]. However, it is less effective for square columns and much less effective for rectangular columns [3]. This is attributed to less confinement of the columns due to the out-of-plane deformation of the sheets, induced by the axial loads on columns Behavior of square columns was improved by rounding the corners of columns before applying the composite wraps [4], but it is still less effective than circular columns. This paper presents different CFRP wrapping percentages (from zero to full wrap) which can be used to increase column axial load carrying capacity and ductility.

This paper comprises experimental and analytical phases to investigate the behavior of square RC columns strengthened and repaired by CFRP sheets under axial loading. The main variables of this study were: number of stirrups in columns, width of CFRP Sheets, Spacing between CFRP and percentage of CFRP Sheets. The analytical phase includes a rational analysis to predict the behavior of RC columns wrapped with CFRP sheets. The analysis is based on the stress-strain characteristics of concrete under triaxial state of stresses, which was presented by Mander et al 1988 [5] and modified Mander presented by Hosny 2002 [8], to predict the ultimate capacity of RC columns.

The Experimental Program

Group G1 consists of five columns without stirrups one column was tested as control specimen without CFRP Sheets and the remaining four columns are repaired using CFRP Sheets with different percentage of CFRP.

Group G2 consists of five columns with ϕ6 stirrups spaced (30 cm) each one column was tested as control specimen without CFRP Sheets and the remaining four columns were strengthened with CFRP Sheets with different percentage of CFRP

Group G3 consists of five columns with ϕ6 stirrups by spaced (15 cm) each one column was tested as control specimens without CFRP Sheets and the remaining four columns are strengthened by CFRP Sheets with different percentage of CFRP.

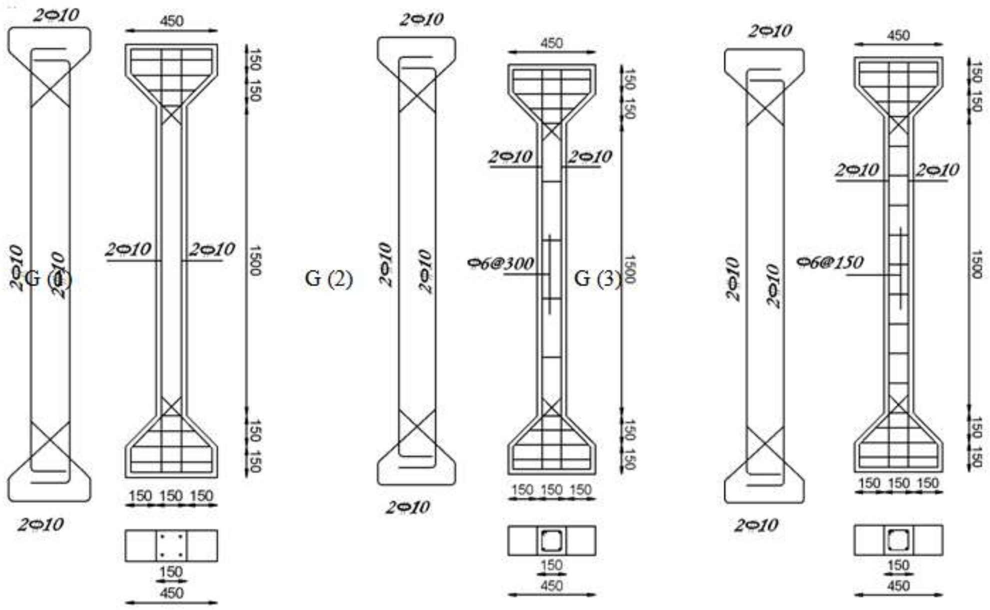

Fig.1: Reinforcement details of tested columns

Carbon fiber reinforced polymers (CFRP) Sheets were used to strengthen the columns. The Sheets were wrapped with the fibers in the horizontal direction to increase the confinement of concrete section. The thickness of CFRP laminates was 0.13 mm, while the tensile strength and modulus of elasticity of the laminates were 3450 MPa and 230 GPa, respectively. The characteristic compressive strength of concrete cubes are shown in Tabel.1, while the yield stress of longitudinal and transverse steel was 440 and 350 MPa, respectively.

2.1 Test Specimens

Table 1 and Fig.1 show the test specimen matrix

Table (1): Designation of experimental testing groups

NO.	Specimens designation	SHEETS WIDTH Mm	SHEETS SPACING mm	CFRP (%)
G1	CW-0-0	Control specimen		
	CW-1-5/10	50	100	33.5%
	CW-2-10/10	100	100	50%
	CW-3-20/10	200	100	66.5%
	CW-4-F	Full wrapping	----------	100%
G2	C30-0-0	Control specimen		
	C30-1-5/10	50	100	33.5%
	C30-2-10/10	100	100	50%
	C30-3-20/10	200	100	66.5%
	C30-4-F	Full wrapping	----------	100%
G3	C15-0-0	Control specimen		
	C15-1-5/10	50	100	33.5%
	C15-2-10/10	100	100	50%
	C15-3-20/10	200	100	66.5%
	C15-4-F	Full wrapping	----------	100%

2.2 Different Scheme of CFRP Wrapping:

- **First scheme (three specimens)**: CFRP sheets of 50-mm width were used in one layer with a clear distance between the sheets of 100-mm.
- **Second scheme (three specimens)**: CFRP sheets of 100-mm width were used in one layer with a clear distance between the sheets of 100-mm.
- **Third scheme (three specimens)**: CFRP sheets of 200-mm width were used in one layer with a clear distance between the sheets of 100-mm.
- **Fourth scheme (three specimens)**: Full wrapping by CFRP sheets on entire column was used in one layer.

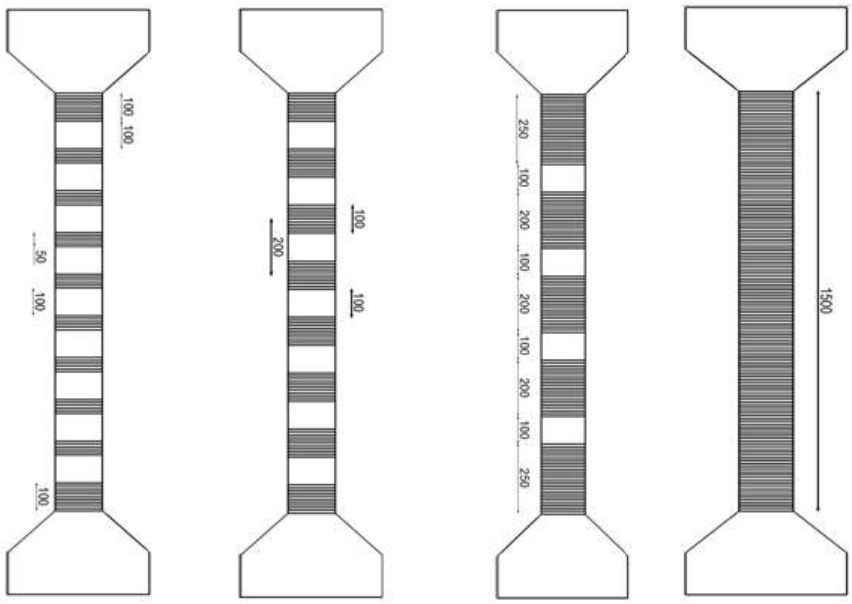

Fig.2: Details of different wrapping schemes

CFRP Sheets were wrapped after the concrete reached an age of 28 days, The corners of the columns were rounded at a radius of 15 mm. CFRP Sheets were attached to the concrete surface using epoxy paste and the epoxy resin as shown in Fig 2.

2.3 TEST SET-UP

The columns were subjected to a monotonic uniaxial compression loading up to failure using a hydraulic machine of 400-ton capacity. The load was measured using a load cell of 400-ton capacity, as shown in Fig.3. The specimens were loaded at a rate of 10-ton per minute using a load control system until a load of 100-ton was reached. The specimens were then loaded using a stroke control until the end of the test. The axial and transverse strains of the specimens were measured by two different methods; five linear variable distance transducers, (LVDT), and 4 electrical strain gauges. The strains of the steel and CFRP sheets were measured in the vertical directions, the strain of the longitudinal steel and stirrups were also recorded during the test. The data was collected using a data acquisition system

Fig.3: Test Set-up

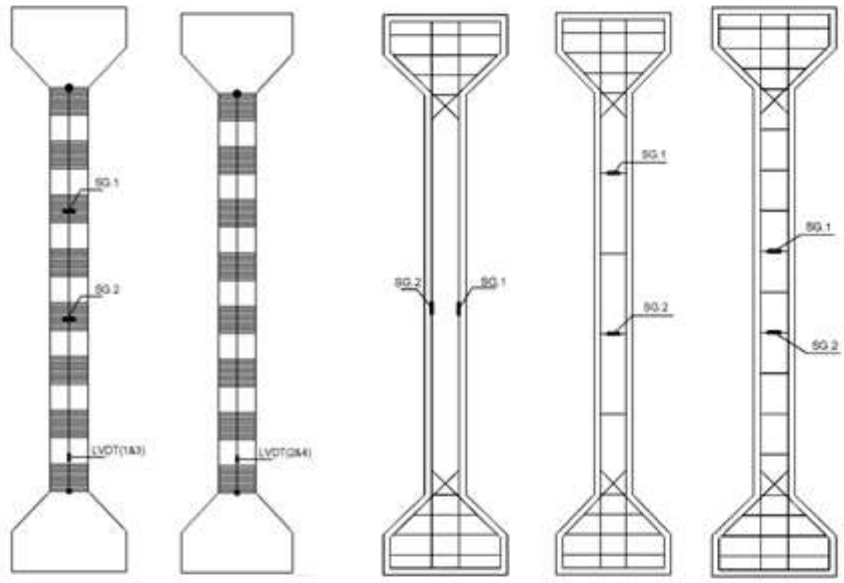

Fig.4: Strain Gauges and LVDT Locations on the Steel Reinforcement and CFRP

II. EXPREMENTAL RESULTS

The load versus longitudinal strain relation of columns with and without CFRP sheets was linear up to 75% of the maximum load, followed by a nonlinear behavior until failure. The load decreases gradually after it reaches the maximum load. The slope of the first pan of the load-defamation curve was the same for all the specimens with and without CFRP laminates. This indicates that the stiffness of the columns does not increase after wrapping it with CFRP. The longitudinal steel bars did not yield for the control specimen. The maximum measured load as well as the longitudinal strains, the maximum measured strains and the ductility for all the tested specimens are summarized in Table 2.

Table (2): Results of columns loading tests.

NO.	Specimens designation	CFRP (%)	Failure load (KN)	Increase of load (%)	Failure mode
G1	CW-0-0	0%	590	------	Compression
	CW-1-5/10	33.5%	630	7%	Rupture of CFRP
	CW-2-10/10	50%	660	12%	Rupture of CFRP
	CW-3-20/10	66.5%	690	18%	Rupture of CFRP
	CW-4-F	100%	730	24%	Rupture of CFRP
G2	C30-0-0	0%	600	-------	Compression
	C30-1-5/10	33.5%	640	7%	Rupture of CFRP
	C30-2-10/10	50%	670	12%	Rupture of CFRP
	C30-3-20/10	66.5%	700	18%	Rupture of CFRP
	C30-4-F	100%	730	22%	Rupture of CFRP
G3	C15-0-0	0%	650	-------	Compression
	C15-1-5/10	33.5%	700	8%	Rupture of CFRP
	C15-2-10/10	50%	740	15%	Rupture of CFRP
	C15-3-20/10	66.5%	780	20%	Rupture of CFRP
	C15-4-F	100%	810	25%	Rupture of CFRP

The Compression failure   The Rupture of CFRP failure

Fig.5: Different failure modes

3.1Concrete strain

The effect of the width of CFRP sheets, on the load versus concrete strain relationship, is presented in Fig.6. For same group it can be seen that increasing the width of CFRP sheets increases the axial load and longitudinal strain at failure and can be seen the more reading concrete strain at the same load because different confinement percentage by CFRP

Comparing the concrete strain of columns at the same load the concrete strain was inversely proportional to

1) Width of CFRP sheets. For column specimens G3C15-5/10, G3C15-10/10, G3C15-20/10 and G3C15-FULL having 5 cm,10 cm,20 cm, full width sheet respectively, it was found the concrete strain of columns and 0.001,0.0013,0.0015, 0.002respectively
2) Number of stirrups. For column specimens G3CW-10/10, G3C30-10/10, G3C15-10/10 and G3C15-FULL having 0 cm,30 cm,15 cm spacing between stirrups respectively, it was found the concrete strain of columns and 0.0005,0.001,0.0013respectively

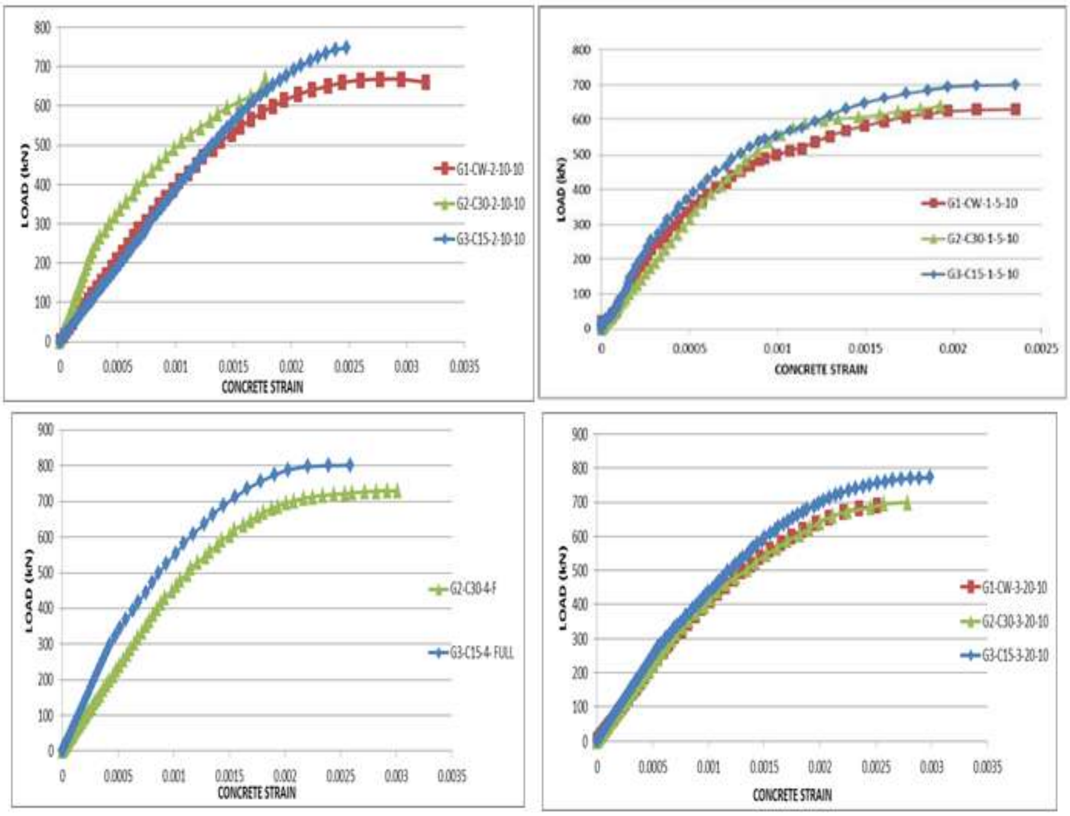

Fig.6: load-concrete strain relationship for tested specimens

3.2Steel strain

The effect of the width of CFRP sheets, on the load versus steel strain relationship, is presented in Fig.7. For same group It can be seen that increasing the width of CFRP sheets increases the axial load and longitudinal strain at failure can be seen the strain of full wrapping specimens is bigger than other specimens because that full wrapping by CFRP gave the specimens along time on loading due to increase the capacity of specimens

Comparing the steel strain of columns at the same load the steel strain was inversely proportional to

1) Width of CFRP sheets. For column specimens G3CW-5/10, G3CW-10/10, G3CW-20/10 and G3CW-FULL having 5 cm,10 cm,20 cm, full width sheet respectively, it was found the specimens G3C15-5/10, G3C15-10/10, G3C15-20/10 don't exceed the yield strain butG3C15-FULL is more than yield strain =0.01
2) Number of stirrups. For column specimens, G3C30-20/10, G3C15-20/10 and having,30 cm,15 cm spacing between stirrups respectively, it was found the steel strain of columns and 0.0002,0.0004 respectively

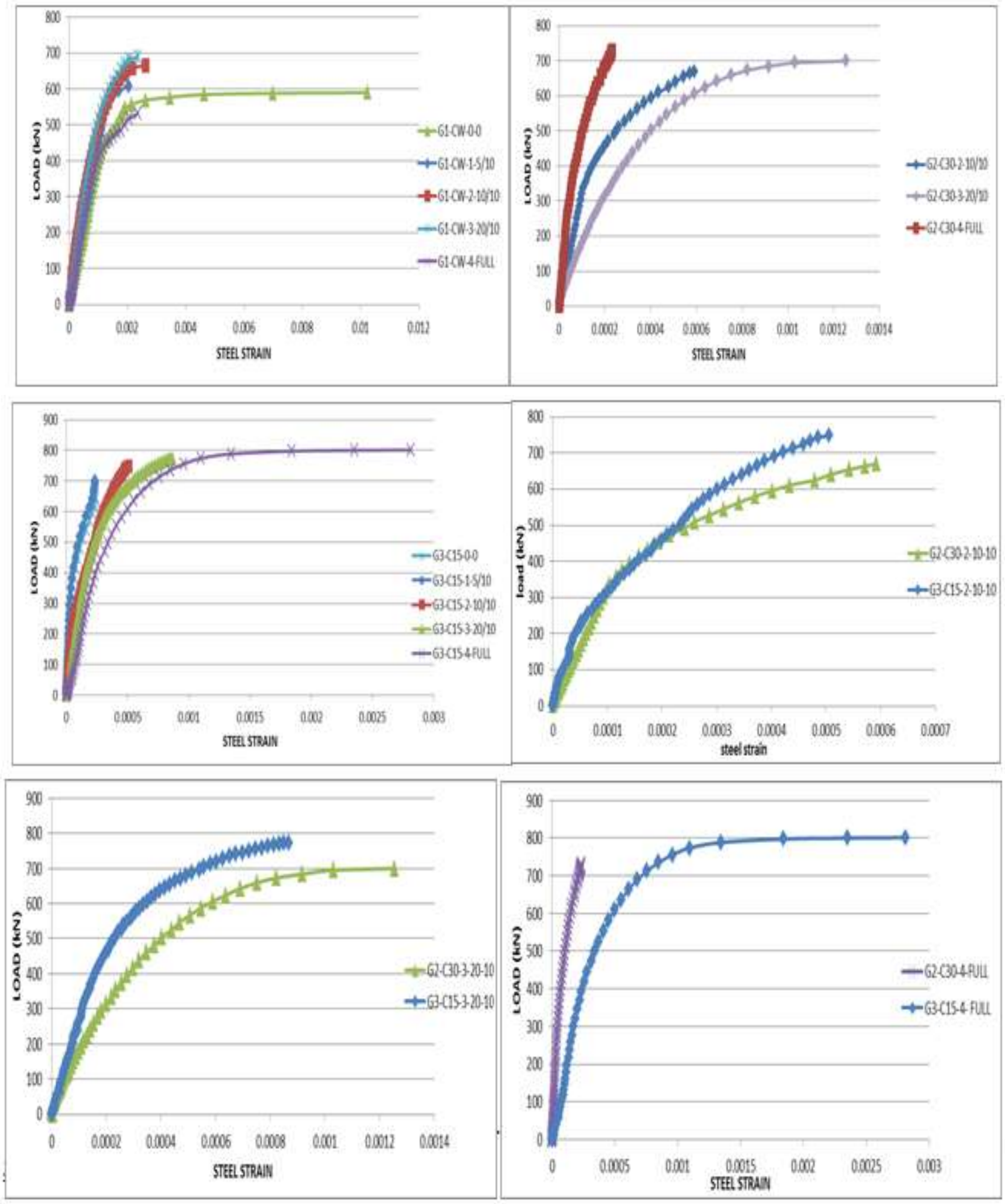

Fig.7: Load –Steel strain relationship for tested specimens

3.3 Fiber strain

The effect of the width of CFRP sheets, on the load- fiber strain relationship, is presented in Fig.8 For same group It can be seen that increasing the width of CFRP sheets percentage of CFRP increases the axial load and longitudinal strain at failure due to increase of confinement level by CFRP sheets.

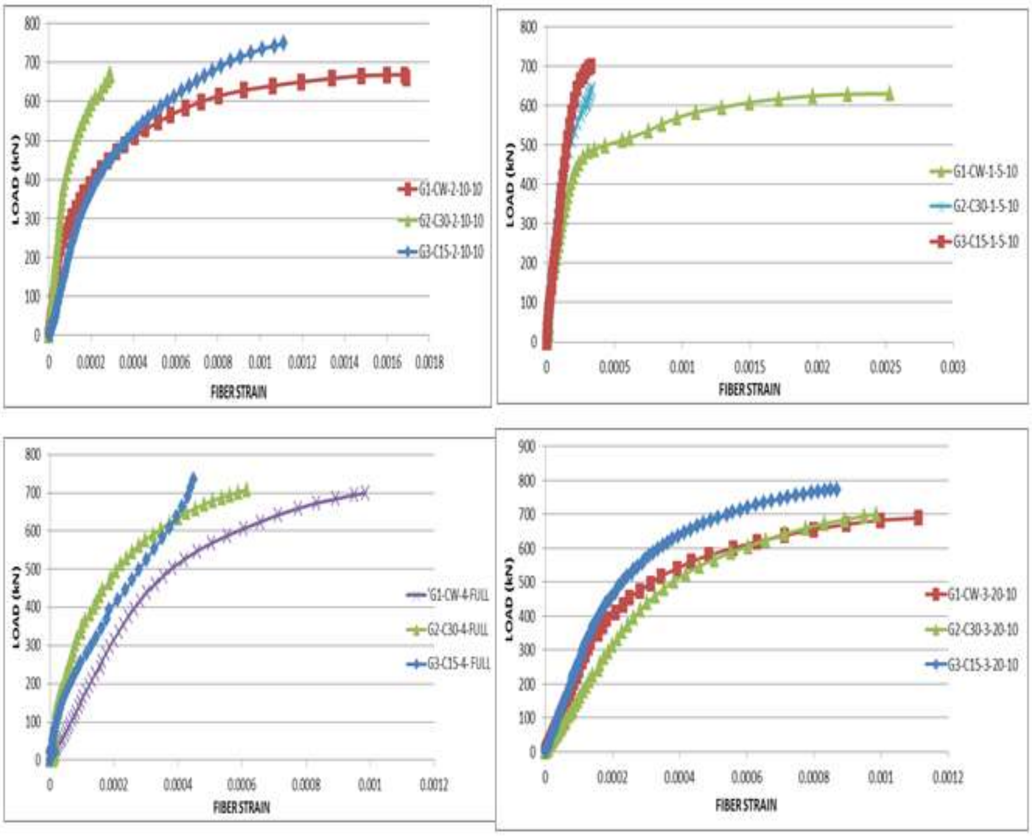

Fig.8: Load –Fiber strain relationship for tested specimens

4. The Analytical Study

The analytical study includes rational analysis to predict the behavior of RC columns wrapped with CFRP laminates. The used model is based on the stress-strain characteristics of concrete under triaxial state of stresses, which was presented by Mander [5] to predict the ultimate capacity of RC columns. Wang (6) and FamandRizkalla [7] accounted for the mechanical properties of CFRP in the model to predict the ultimate capacity of columns. The stress-strain relationship of confined concrete is given in Eqns. 1 to 6 For a slow quasi-static strain rate and monotonic loading, the longitudinal compressive concrete stress, f_c is given by:

$f_c = \frac{f`cc.x.r}{r-1-x^r}$ ....Eqn.1 $x = \frac{\varepsilon c}{\varepsilon cc}$ Eqn.2

$\varepsilon_{cc}=\varepsilon_{co}[1+5(\frac{f`cc}{f`co}-1)]$................Eqn.3 $r = \frac{Ec}{Ec-Esec}$ Eqn.4

$Ec=4700\sqrt{f`co}$MPa (ACI318M-95)...........Eqn.5 $E_{sec}=\frac{f`cc}{\varepsilon cc}$ Eqn.6

Where,
$f`_{cc}$: compressive strength of confined concrete.
ε_c. : longitudinal compressive strain.
$f`_{co}$: unconfined concrete strength.
ε_{co}: unconfined concrete strain (ε_{co}, was taken equal to 0.002).
E_c: modulus of elasticity of unconfined concrete.

Fig.9 shows a cross-section of a reinforced concrete rectangular column confined by an external CFRP wrap and internal reinforcing steel stirrups. Two different lateral confining pressures are acting on the cross-section. The first one is due to the effect of the transverse steel stirrups and the second one is due to the effect of CFRP sheets.

Since the behavior of CFRP sheets is different from that of steel due its linear characteristics and different elastic modulus a modified approach is adopted by the authors [81 to predict the resulting strain in the longitudinal direction and the inclined angle of the descending part.

The approach adopts the same equations proposed by Mander [5], however, different factors are proposed based on interpolation of the measured values for the different tested columns. The modified model is presented by Eqns 7 and 8, which should replace equations 2 and 3 respectively.

$x = (\frac{\varepsilon_c}{\varepsilon_{cc}})^K$ Eqn.7

where k = 1.0 for $(0 \leq \varepsilon c \leq \varepsilon cc)$
= 1.5 for $(\varepsilon cc \leq \varepsilon c \leq \varepsilon cu)$

$\varepsilon_{cc} = \varepsilon_{co}[1 + 2(\frac{f'cc}{f'co} - 1)]$..........Eqn.8

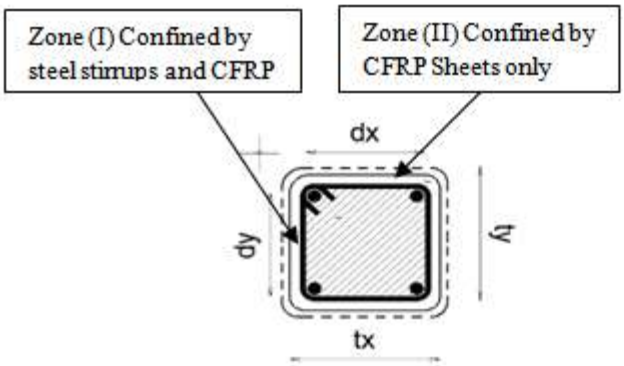

Fig.9: Pressure Zones ofLateral Confining Square Columns

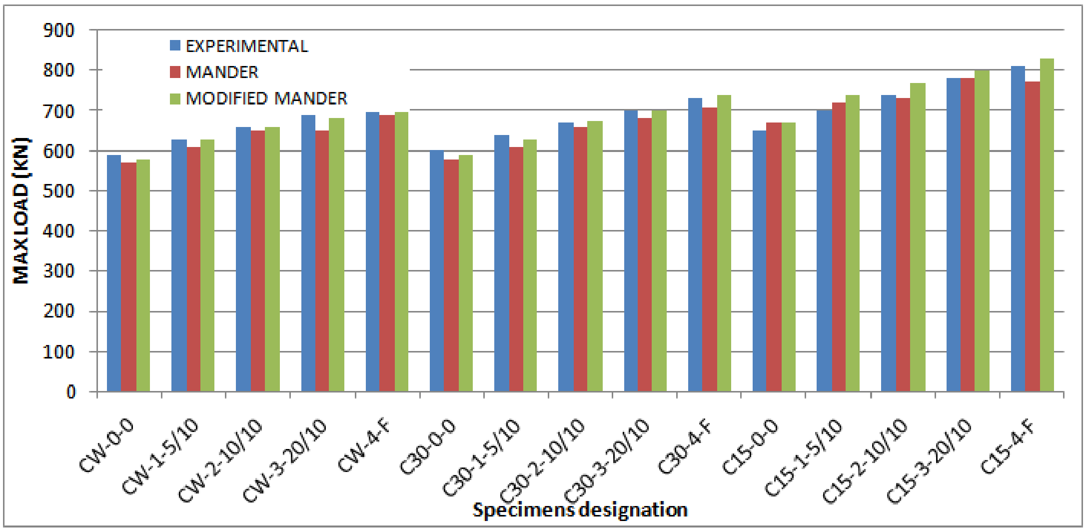

Fig.10: Comparison between Predicted and Measured Maximum Load of the Tested

Fig.10 shows a comparison between the predicted and measured maximum loads of the tested specimens It can be seen that there is good agreement between the measured and predicted failure loads, Fig 16 shows a typical load· longitudinal strain relationship for column strengthened by CFRP In general, the first part of the curve is the same for the two models (model presented by Mander and that modified by equations 7 & 8. The relationship between the load and the longitudinal strain of the first part is linear until a load level equal to 75% of the maximum load, followed by a nonlinear behavior until failure. After the maximum load is achieved, the predicted longitudinal strain using the modified model is in better agreement with the experimental values than that presented by Mander.

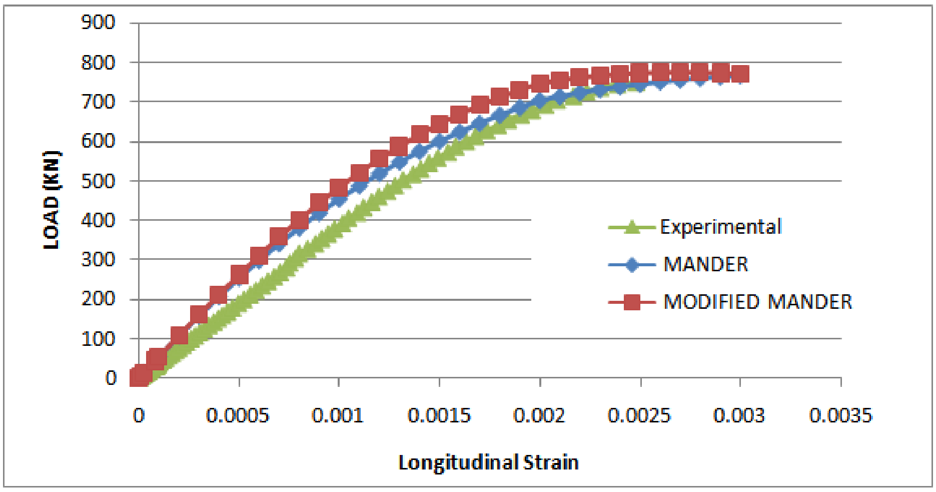

Fig.11: Load –Strain relationship for specimenG3-C15-2-10/10

Factor of equation:

We suggested adding a reduction factor to design equations for partial wrapping for circular columns at **ECP** (Egyptian code practice for FRP) to modify results so this equations can be used to design partial wrapping for square columns and apply this factor with equations in our experimental program and experimental program for others such:

1) Kabashi N.* at Department of Civil Engineering, University of Prishtina,(12)Kosova.2014
2) Krasniqi C. , Nushi V.at Department of Civil Engineering, University of Prishtina, Austria.2014(13)

to make sure that the factor is correct and apply in other researches to help them to design and know:

1) The failure load of their specimens before test its in laboratory
2) Efficiency of wrapping fiber on tier column at stirrups

a) $K_e=(1-((s-b_f)/2d))^2$ b) $Mf=(4*b_f*n*t_f)/(s*d)$

c) $F_l=K_e*((M_f*E_f*\varepsilon_{fe})/(2*\gamma_f)$

d) $F_{cc}=\{(2.55(1+\frac{\sqrt{9.875*Fl}}{Fcu}))\}-(2.5*(F_l/F_{cu})-1.25$

And;

We suggest adding a reduction factor from our experimental results named it (Z=0.763) to the equation

e) $F_{cc}=\underline{z}*[\{(2.55(1+\frac{\sqrt{9.875*Fl}}{Fcu}))\}-(2.5*(F_l/F_{cu})-1.25]$

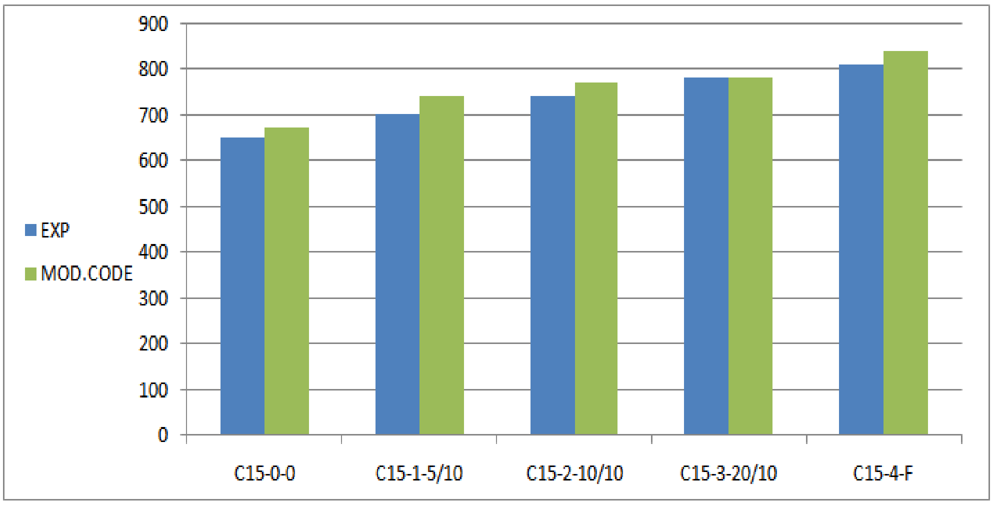

Fig.12: Comparison between Predicted and Measured Maximum Load of the Tested columns for our results

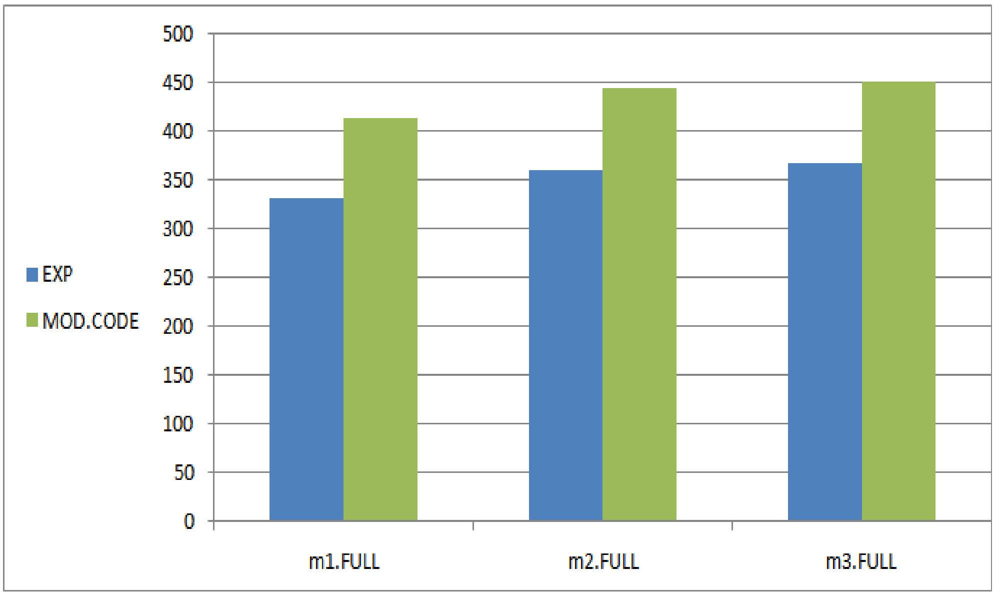

Fig.13: Comparison between Predicted and Measured Maximum Load of the Tested columns for Kabashi N.(12)

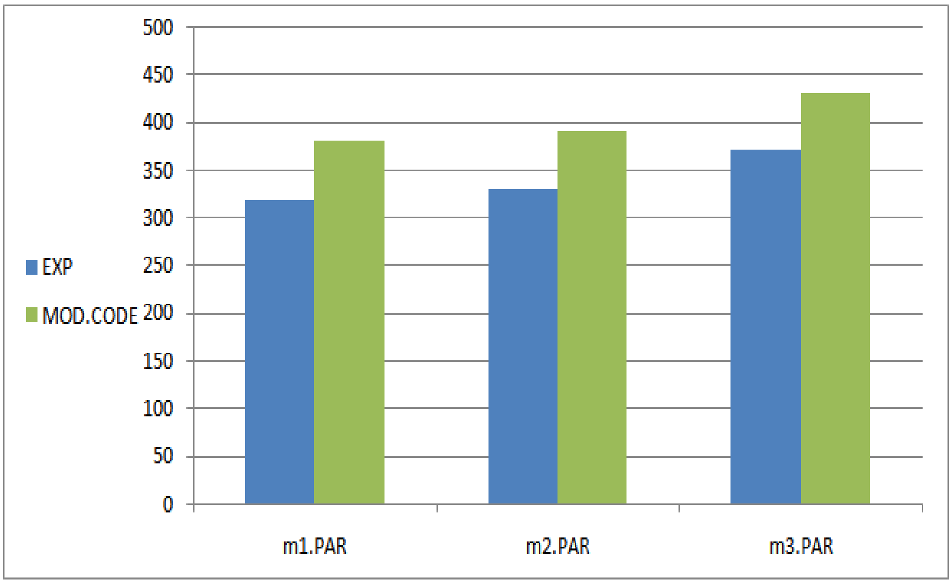

Fig.14: Comparison between Predicted and Measured Maximum Load of the Tested Columns KrasniqiC. ,Nushi V (13)

The Suggested Equation:

We suggest an equation to explain the relationship between percentage of increase load and percentage of CFRP by stirrups wrapping and apply equation in other researches such:

$Y= -0.1479X^2 + 0.4037X$

3) Kabashi N.* at Department of Civil Engineering, University of Prishtina,(12)Kosova.2014
4) Krasniqi C. , Nushi V.at Department of Civil Engineering, University of Prishtina, Auctria.2014(13)
5) Ahmed Fawzy, Department of Civil Engineering, Cairo University.2009(14)

And;

This equation gives acceptable results comparing with experimental results. Fig.15 explains the curve between other researches results

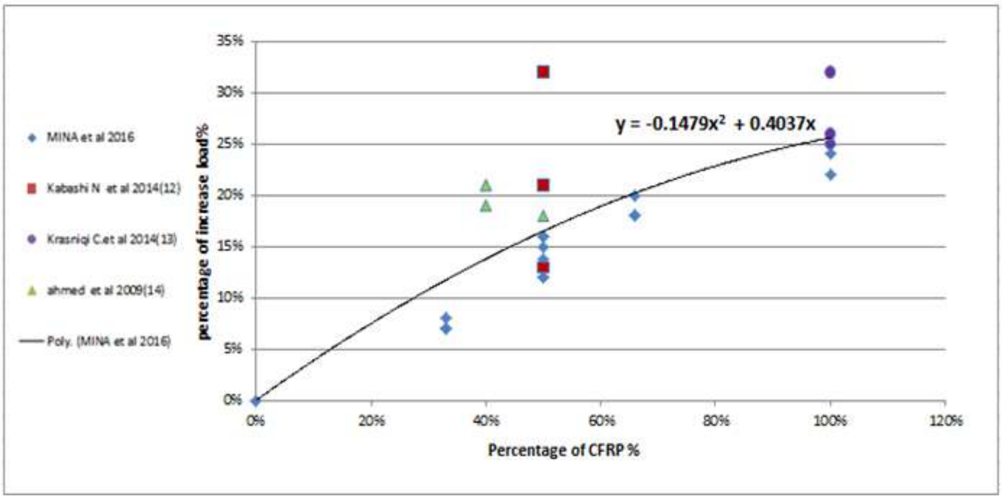

Fig:15: Relation between percentage of CFRP and Percentage of increasing in load

The Theoretical Study:

The suggested equation was applied for square columns with cross section 15*15cm and to proof its validity an analytical model was done using Mander model for the cross sections (25*25, 35*35, 45*45, 55*55) and found that the efficiency of CFRP in other areas of square column stop of its validity and proof the efficiency of CFRP decreased whenever column section increased as shown in Fig 16 , Fig 17

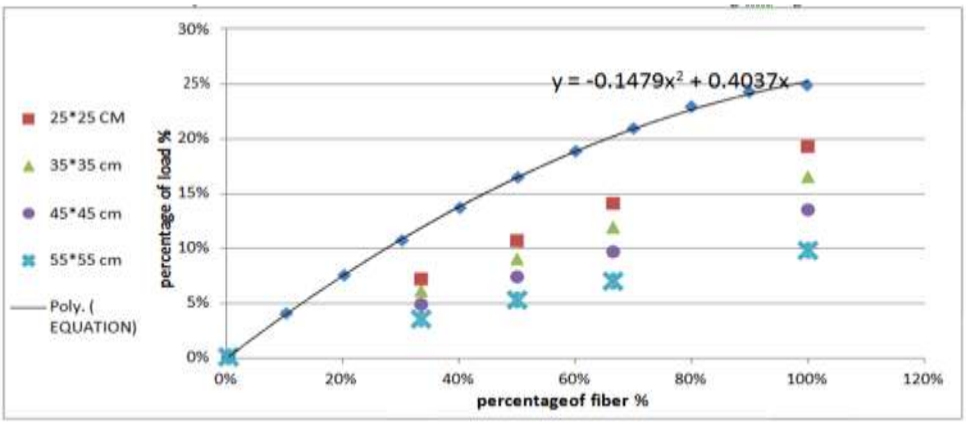

Fig 16: Relation between and percentage of load

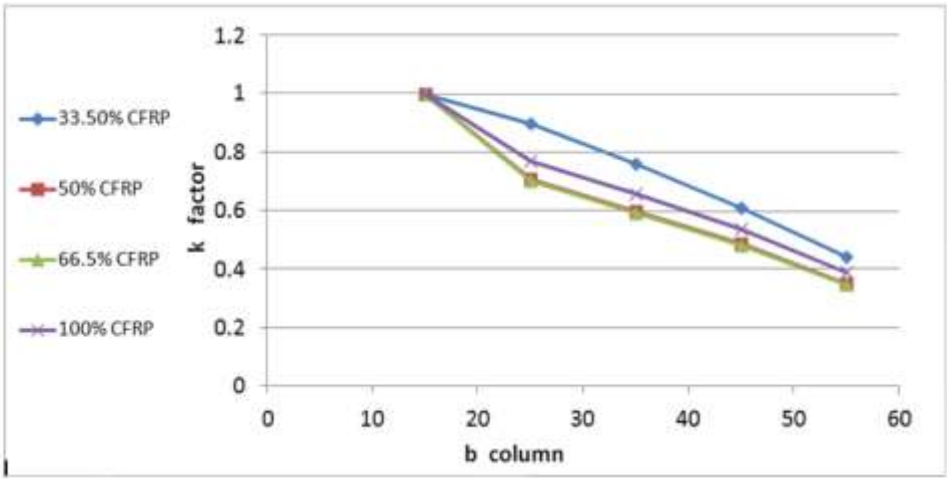

Fig 17: Relation between breadth of column and K factor

The reduction factor (K)
This factor added to suggested equation to it in calculate capacity of columns with different cross sections of square columns 25*25 ,35*35 ,45*45 ,55*55 cm with different percentage of CFRP as shown in Fig 18.

As following:

CFRP%	Factor for different areas (K)				
	15*15	25*25	35*35	45*45	55*55
33.5 %	1	0.9	0.76	0.61	0.44
50 %	1	0.71	0.6	0.49	0.36
66.5 %	1	0.705	0.59	0.48	0.35
100 %	1	0.772	0.66	0.54	0.39

So the equation will be :$\mathbf{P=\underline{K}(-0.1479C^2+0.4037C)}$

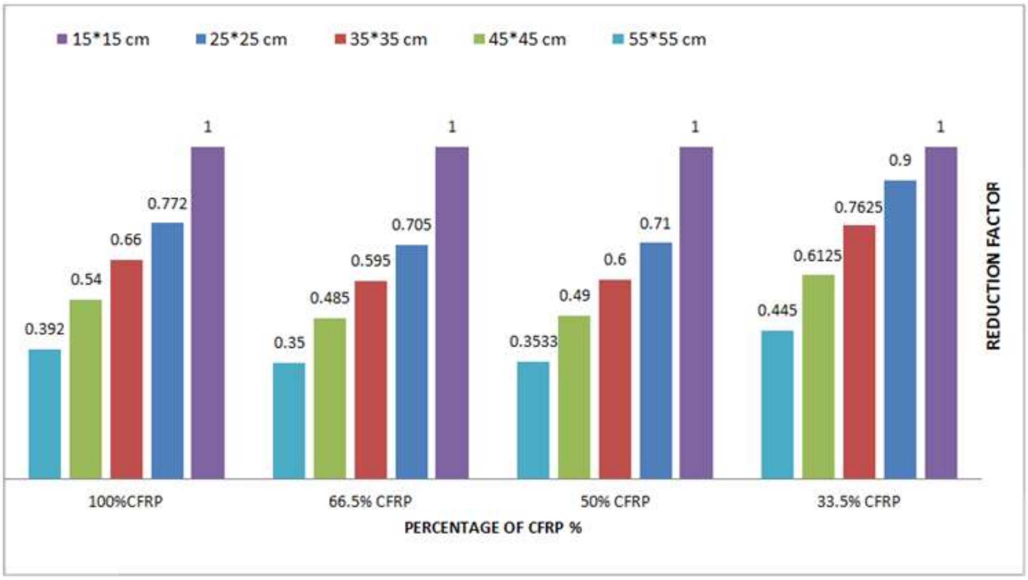

Fig 18: Bar Chart of Factor K

III. CONCLUSIONS

The present paper shows that CFRP sheets can be successfully used for increasing the axial carrying capacity of square columns. It can be drawn that:

1. For the studied square columns, the axial carrying capacity can be increased up to 25% respectively, depending on the strengthening scheme.
2. Increasing the CFRP ratio by increasing the width of CFRP sheets is more effective.
3. The spacing of stirrups in columns that more than column width reduce its capacity but using CFRP can cover the capacity shortage.
4. Column without stirrups needs 50% of CFRP wrapping to regain its capacity. This is economic scheme more than two scheme of wrapping 66%, 100%.
5. Column with spacing of stirrups more than column width needs 33.5% wrapping to regain this capacity and other scheme of 50% is very useful.
6. The width of CFRP strips (W) prefer to equal or more than spacing of CFRP strips (S) to qualified the required capacity.
7. Increasing the CFRP ratio increases the efficiency of stirrups because the failure happens on high load where stirrups reached to maximum strain.
8. Using CFRP sheets only for strengthening of square concrete columns is an effective method to increase the ultimate carrying capacity and Ductility of columns where the specimens more strengthened were more ductile.

9. The suggested reduction factor added to design equations for partial wrapping for circular columns gave good agreement with experimental results for square columns.
10. The proposed analytical model gave good agreement with the experimental results.

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