Strengthening of Reinforced Concrete Circular Columns by Carbon Fiber Reinforced Polymer Laminates

Dr. Ali Hussein Mohammed Ali Bass

A.Manal Mahmoud Ahmed Mahdi

Abstract:

The wrapping of concrete structures with fiber polymers has been an essential part of concrete technology aimed at the improvement of concrete performance indices during the construction and lifelong usage of the structures. Thus, the use of fiber reinforced polymer (FRP) materials for structural repair and strengthening has continuously increased in recent years, due to several advantages associated with these composites when compared to conventional materials like steel. The role of FRP for strengthening of existing or new reinforced concrete structures is growing at an extremely rapid space owing mainly to the ease and speed of construction, and the possibility of application without disturbing the existing functionality of the structure. This study presents the results of an experimental investigation on the structural behavior of reinforced concrete columns strengthened with unidirectional carbon fiber laminates. Laboratory work has been conducted at the University of Khartoum and includes two parts: the first series of tests focusing on the flexural-compression behavior of un-strengthened circular columns. Then, the second series studied FRP strengthened circular columns under the same loading conditions, investigating the confinement capability of FRP laminates, changes in failure mode and flexural strength enhancements.

The ultimate axial loads of all columns obtained from the experiment are compared with the results from the theoretical analysis. The results obtained from the experiment were approximately higher than the theoretical analysis results by (22.0 – 46.0) %. The contribution of one-layer CFRP laminate to the ultimate load capacity of concentric strengthened columns is higher than reference ones by about (22.0 -28.5) %. On the other hand, the contribution of two-layer CFRP laminate to the ultimate load capacity of concentric strengthened columns is higher than reference ones by about (29.5 - 46.0) %.

Keywords: fiber polymer, concrete columns, strengthening, FRP materials, CFRP laminates, strength, axial load, concentric.

تقوية الأعمدة الخرسانية المسلحة الدائرية بشرائح الألياف الكربونية

د. علي حسين محمد علي – أستاذ مشارك – قسم الهندسة المدينة – كلية الهندسة المدنية – جامعة بحري

أ. منال محمود أحمد مهدي – طالب دكتوراة- كلية الدراسات العليا – جامعة كرري

مُستخلَص:

يعتبر تغليف الهياكل الخرسانية ببوليمرات الألياف جزءاً أساسياً بتكنولوجيا الخرسانة التي تهدف إلى تحسين أداء الخرسانة أثناء التشييد والاستخدام مدى الحياة للمنشآت. وبالتالي فإن استخدام مواد البوليمر المقواة بالألياف لإصلاح وتقوية الهياكل تزايدت بشكل مستمر في السنوات الأخيرة، وذلك بسبب العديد من المزايا المرتبطة بهذه المركبات بالمقارنة مع المواد التقليدية مثل الفولاذ. نجد أن دور مواد البوليمر المقواه بالألياف (FRP) فى تقوية الهياكل الخرسانية المسلحة القائمة أو الجديدة أصبح ينمو بوتيرة سريعة للغاية ويرجع ذلك أساساً إلى سهولة وسرعة البناء، وإمكانية التطبيق دون الإخلال بوظيفة الهيكل الموجود. تعرض هذه الدراسة نتائج التحقيق التجريبي على السلوك الإنشائي للأعمدة الخرسانية المسلحة المقواة بشرائح ألياف الكربون الأحادية. تم إجراء العمل المختبري في جامعة الخرطوم ويتضمن جزئين: السلسلة الأولى من الإختبارات تُركِّز على سلوك الإنثناء والضغط للأعمدة الدائرية غير المقواة. بينما السلسلة الثانية من الإختبارات تدرُس الأعمدة الدائرية المقواة بشرائح مواد البوليمر المقوى بألياف الكربون (FRP) تحت نفس ظروف التحميل، والتحقق من قدرة التحزيم بهذه الشرائح والتغيرات في وضع الفشل وتحسين مقاومة الإنحناء. تمت مقارنة الأحمال المحورية القصوى لجميع الأعمدة التي تم الحصول عليها من التجربة مع نتائج التحليل النظري. وعليه فإن النتائج التي تم الحصول عليها من التجربة كانت أعلى من نتائج التحليل النظري بحوالي (0.22 – 0.64) %. وأعطت مساهمة التحزيم بطبقة واحدة من شرائح البوليمر المقواه بالألياف الكربونية (CFRP) لسعة الحمل الأقصى للأعمدة المقواه المحملة مركزياً زيادة بحوالي (0.22 – 5.82)% مقارنةً بالأعمدة المرجع (غير المقواه). من ناحية أخرى، فإن مساهمة التحزيم بطبقتين من شرائح البوليمر المقواه بالألياف الكربونية (CFRP)

لسعة الحمل الأقصى للأعمدة المقواه المحملة مركزياً أعطت زيادة بحوالي (5.92 – 0.64)% مقارنةً بنفس الأعمدة المرجع.
الكلمات المفتاحية: ألياف البوليمر، أعمدة خرسانية، تقوية، مواد البوليمر المسلحة بالألياف، شرائح البوليمر المقواه بالألياف الكربونية، المقاومة، الحمل المحوري، مركزي.

1. Introduction

Rehabilitation and strengthening of existing concrete structures have come more and more in focus during the last decade. All over the world there are structures intended for living and transportation. The structures are of varying quality and function, but they are all ageing and deteriorating over time. Of the structures needed in 20 years from now about (85-90) % of these are already built. Some of these structures will need to be replaced since they are in such bad condition. However, it is not only the deterioration processes that make upgrading necessary, errors can have been made during the design or construction phase so that the structure needs to be strengthened before it can be used [1].

The use of fiber reinforced polymers (FRP) jackets as an external reinforcement mean to strengthen existing RC columns has emerged in recent years with very promising results, among others. Several studies on the performance of FRP wrapped columns have been conducted, using 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 performance of columns of circular cross-section. The data available for column of square and rectangular cross-sections increased over recent years, but are still limited. This field remains in its developmental stages and more testing and analysis are needed to explore its capabilities, limitations, and design applicability [2,3].

Over the last decade there has been significant growth in the use of fiber reinforced polymer (FRP) composite materials as construction materials in structural engineering, these materials have proven themselves to be valuable for use in the construction of new buildings and bridges and for the upgrading of existing buildings and bridges. Now, at the beginning of the twenty-first century, the structural engineering community is about to enter a stage in which structural design with FRP composites is poised to become very popular as routines design with classical structural materials such as masonry, wood, steel, and concrete. This popularity has arisen due to the need to maintain and upgrade essential infrastructure in all parts of the world, combined with the well-known advantages of FRP, such as good corrosion resistance and ease for site handling due to their light weight. The continuous reduction in the material cost of FRP composites has also contributed to their popularity. Reinforced concrete (RC) Columns with carbon fiber-reinforced polymer CFRP composites offer an attractive solution to enhance the strengthening of columns and to increase the load carrying capacity of them [4].

2. Research Methodology and Experimental Work

The strengthening by confinement of RC columns by means of externally bonded FRP laminates is a well-established technique for strengthening and retrofitting purposes. Seen widely in mosques like Kuwait holly mosque, bridges as in the great rehabilitation works in Khartoum State Shambat bridge concrete piers and girders and widely overseas in the larger transportation stations and halls that are permanently affected by seismic actions [5].

In this research the case is strengthening of cylindrical RC column where as many researches contributes in this case. The study shall reach out results of the contribution of CFRP confinement for 200 mm diameters column specimens aiming at investigating permanent mathematic relationship between the laminates pressure and the attained concrete compressive strength without the contribution of the reinforcing steel rebars.

The design of FRP strengthening is performed on the well-established principles of mechanics. Most major codes like ACI, Euro code, Japanese code, etc. give guidelines for the design of FRP system for wrapping of concrete columns to increase their capacity. Various institutes recommend the use of FRP Composites for strengthening of concrete structures [6]. The study confirms and applies mainly the ACI 440.2R-17 [7] for the design, calculations, and application of CFRP plies for strengthening of two concrete grades considered as RC circular columns samples.

2.1. Experimental works

This investigation presents a pilot research that includes laboratory testing of full-scale circular RC columns externally confined with CFRP laminates and subjected to pure axial load. Specimens that are representative of full according to American concrete institute ACI 318-19 [8] for gravity loads only.

Tests were conducted to investigate how the external confinement affects axial resistance capacity and deformation of RC column. Moreover, the contribution of the CFRP confinement laminate pressure in strength of two concrete grades to sustain additional axial load was investigated.

- **Characteristics of Materials and Specimen Details**

In this section the properties of concrete ingredients namely; aggregate, Ordinary Portland cement, and water were determined according to the American Specifications ACI 318-19. Mixing was carried out at the laboratory of the Building and Road Research Institute (BRRI) – University of Khartoum. Thus, two mixes proportions for 30 MPa and 40 MPa concretes were designed by absolute volume method. Moreover, the properties of CFRP laminate and bonding materials were discussed.

Unidirectional CFRP composites (Woven carbon fiber fabric) with the following typical properties according to the manufacture specifications were used; as described in Table 1.

Table 1. Specifications of CFRP Laminate Used [Authors].

Description	Thickness	Properties
Woven carbon fiber fabric for structural strengthening is a unidirectional woven carbon fiber fabric for the dry or wet application process. 	0.43±0.05mm	• Tensile strength = 3000 MPa • Tensile modulus = 210×10^3 MPa • Elongation = 1.5% • Width =300 mm • Thickness = 0.43±0.05 mm • Weight = 200±6 g/m^2

Figure 1 shows dimensions used for the columns; 1,300 mm height and 200 mm diameter. Circular columns were reinforced by two types of steel reinforcements with six T12 mm, f_y = 460 MPa as longitudinal rebars located at the perimeter. Lateral reinforcement was provided by a T8 mm with a 100 mm pitch.

Eighteen (18) circular columns were tested under pure axial load and were divided into three categories depending on the strengthening techniques, as illustrated in Table 2, and are categorized as follows:

(1) Control or Reference columns of concrete grades 30 and 40 MPa.

(2) RC Columns of grades 30 and 40 MPa strengthened by bonding one-layer of CFRP laminates.

(3) RC Columns of grades 30 and 40 Mpa strengthened by bonding two layers of CFRP laminates.

Table 2. Description of RC specimens' categories for compression test [Authors].

Specimens	Diameter (mm)	Height (mm)	Longitudinal steel bars	**Compressive strength** at 28 days $f'c$ (MPa)		Number of layers
Reference columns						
$C_{1,0}$, $C_{1,0*}^{\#}$	200	1300	6 Ø 12	30	40	0
$C_{2,0}$, $C_{2,0*}$	200	1300	6 Ø 12	30	40	0
$C_{3,0}$, $C_{3,0*}$	200	1300	6 Ø 12	30	40	0
RC Columns strengthened by One-layer CFRP						
$C_{1,1}$, $C_{1,1*}$	200	1300	6 Ø 12	30	40	1
$C_{2,1}$, $C_{2,1*}$	200	1300	6 Ø 12	30	40	1
$C_{3,1}$, $C_{3,1*}$	200	1300	6 Ø 12	30	40	1
RC Columns strengthened by Two layers CFRP						
$C_{1,2}$, $C_{1,2*}$	200	1300	6 Ø 12	30	40	2
$C_{2,2}$, $C_{2,2*}$	200	1300	6 Ø 12	30	40	2
$C_{3,2}$, $C_{3,2*}$	200	1300	6 Ø 12	30	40	2

Note: # denotes; first number represent sample number, second number represent numbers of CFRP plies.

* denotes specimens with C40 concrete grade.

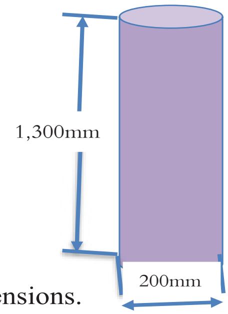

Figure 1. Casting of Model Columns and Dimensions.

2.2. Test Procedures

An overview of the complete experimental program is included and in the following sections, the preparation of the test models and detailed descriptions of all the test set-ups is presented. All wrapped models were strengthened with one ply and two plies of carbon fiber laminate and tested after 28 days of curing. The layers of fibers were applied one at a time, with each layer overlapping itself to provide for development of the full tensile strength of the laminate. The overlapping length was 100 mm [7, 9].

The columns were axially loaded using a displacement control compression apparatus in the laboratory, as shown in Figure 2. All columns were loaded under a monotonic uni-axial compression load up to failure. The compressive load was applied at a rate corresponding to 0.24 MPa/s until failure.

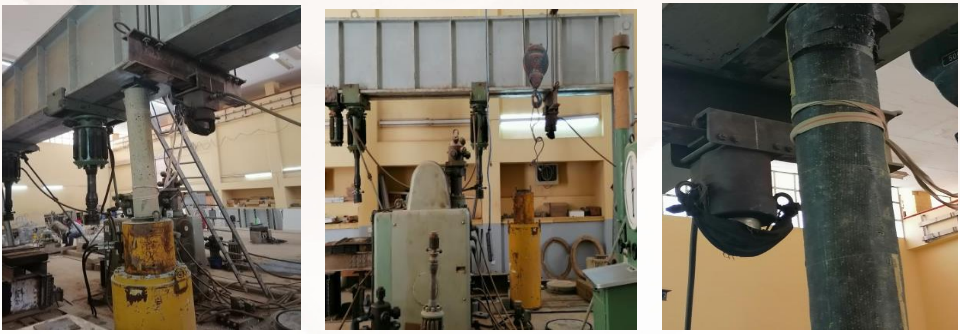

Figure 2. Instrumentation and Columns test setup**.**

2.3. Compression test results and Mode of failures

The compression test results for columns with C40 and C30 are illustrated in Table 3. Then, the mode of failure for each specimen was also observed, as shown in Figure

Table 3. Model Columns laboratory compression test results [Authors].

Columns Label	**Failure Load** (Tons)	**Columns Label**	**Failure Load** (Tons)	**Percentage** of load increase (%) *	**Percentage** of load increase (%)	**Mode of failure**
Reference Columns						
$C_{1,0*}$	127.75	$C_{1,0}$	95.60	0	0	Crushing of concrete
$C_{2,0*}$	127.75	$C_{2,0}$	95.60	0	0	"
$C_{3,0*}$	127.75	$C_{3,0}$	100.27	0	4.9	"
Average	**127.75**		**97.156**	0	1.6	"
Columns strengthened with one-layer CFRP						
$C_{1,1*}$	161.52	$C_{1,1}$	117.986	26.43	23.42	Tearing & separation of CFRP
$C_{2,1*}$	163.83	$C_{2,1}$	117.986	28.24	23.42	"
$C_{3,1*}$	170.94	$C_{3,1}$	119.430	33.81	19.11	"
Average	**165.43**		**118.467**	**29.495**	**21.98**	
Columns strengthened with two layers CFRP						

Columns Label	Failure Load (Tons)	Columns Label	Failure Load (Tons)	Percentage of load increase (%) *	Percentage of load increase (%)	Mode of failure
$C_{1,2*}$	183.40	$C_{1,2}$	123.27	43.562	28.94	Tearing & separation of CFRP
$C_{2,2*}$	186.51	$C_{2,2}$	123.27	45.996	28.94	"
$C_{3,2*}$	189.62	$C_{3,2}$	127.95	48.431	27.61	"
Average	**186.51**		**124.83**	**45.996**	**28.50**	

Note: * denotes percentage of load increase for C40 specimens.

The RC reference columns normally fail under compression failure because the axially loaded stress exceeds allowable stress. After failure, crushing and end splitting observed in the upper surface of columns.

Figure 3. Mode of failures for tested columns.

3. Presentation of Results and Discussion

Columns are elements of special importance for the static system of many buildings. Strengthening's out of carbon fiber laminate (CFRP-sheets) keep the basic component size to a large extent. However, the reinforcement effect here is only achieved by the confinement of the core concrete of the column. The typical collapse mechanism of the models usually marked by sudden failure. Approaching ultimate strength, noise associated with localized debonding, fiber failure, and crushing of concrete was observed.

Table 3 summarizes the laboratory compressive load and its percentage increase for the tested columns. Thus, by considering the average values; 29.50 % and 45.99% additional axial load capacity by confinement of C40 column specimen by one layer and two layers of CFRP, respectively. Therefore, adding another layer for strengthening contributes by 16.49%, so 55.15% of increased strength is achieved by application of single layer and this result shall be compared with C30 concrete column as a matter of further realization. Obviously, the additional strength percentage is 21.98% for C30 RC column which is less than that attained when the strengthening is added for C40 specimen, as illustrated in Figures 4 and 5.

3.1. Theoretical Calculations

Theoretical analysis taking into account confining pressure due to FRP composite is available. However, findings and equations developed by ACI Committee 440 will be used as the analytical framework for circular columns. Engineering and scientific terms used in calculations are given in Table (4).

Table 4. Engineering and scientific terms used in this study from ACI 440.2R-17 [7].

Symbols	Definition
A_g	Gross area of concrete section, mm^2
A_c	Cross-sectional area of concrete in compression member, mm^2
A_{st}	Total area of longitudinal reinforcement, mm^2
D	Diameter of compression member for circular cross sections, mm
C_E	Environmental reduction factor
f'_c	Specified compressive strength of concrete, MPa

Symbols	Definition
f_y	Specified yield stress of non-prestressed steel reinforcement, MPa
f_f	Stress in FRP reinforcement, MPa
f'_{cc}	Maximum compressive strength of confined concrete, MPa
f_l	Maximum confinement pressure due to FRP jacket, MPa
Φ	Reduction factor for required strength
ε_f	Strain in FRP reinforcement mm/mm
ε_{fu}	Design rupture strain of FRP reinforcement mm/mm
ε'_c	Compressive strain in unconfined concrete mm/mm corresponding to f'_c
ε_{cc}	Ultimate axial compressive strain of confined concrete corresponding to 0.85 f'_{cc} mm/mm
ε_{fu}	Design rupture strain of FRP mm/mm
ε_{fe}	Effective strain in FRP attained at failure
K_a	Shape factor = 1 for circular cross-sections
K_b	Shape factor = 1 for circular cross-sections
ψ_f	Strength reduction factor for fully wrapped section = 0.95 in the calculations
n	Number of plies of FRP for confinement

According to ACI 318 [8] for circular short column design, the ultimate design load capacity is calculated as follow:

$$\phi Pn = 0.85\phi[0.85\times f'_c\,(A_g - A_{st}) + f_y\,A_{st}] \qquad \text{Eq. (1)}$$

Factors "0.7, 0.8, and 0.85" are reduction for concrete strength in design from laboratory test result. The reduction is due to expected voids in concrete, and the last multiplication factor is reduction of

15% due to insufficient curing of concrete in side compared with that in laboratory as done.

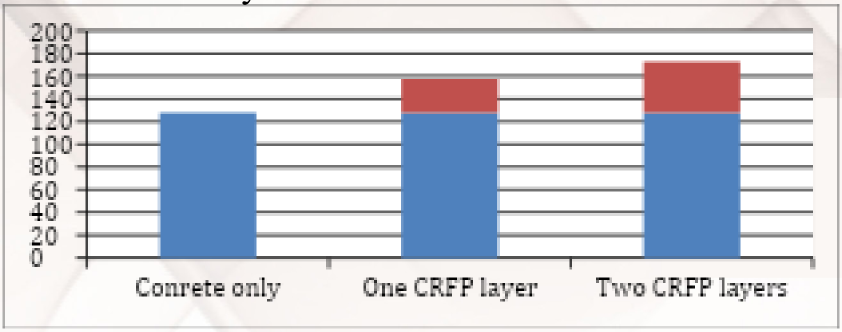

Figure 4. Contribution of CFRP laminates for strengthening of C40 RC column.

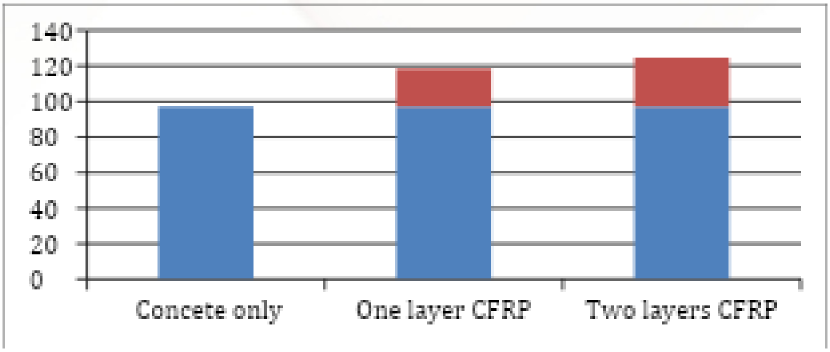

Figure 5. Contribution of CFRP laminates for strengthening of C30 RC column.

- For calculation of the design ultimate load using CFRP confinement, the following steps are considered:

Step [1]: According to the design code (ACI440.2R-17) [10], the numbers of plies of CFRP to be used for retrofitting the RC column depending on the given CFRP properties factorized using Equation (2).

From Table (9.4), this column is to be used in internal building and the reduction factor of exposure to inner environment to be used $C_E = 0.95$, therefore;

$f_{fu} = C_E \times f_f$, ……………………………………………….. Eq. (2)

Therefore; $f_{fu} = 0.95 \times 3000 = 2{,}850$ MPa

And, $\varepsilon_{fu} = C_E \times f_{f,}$ ……………………..………….... Eq. (3)

Thus, $\varepsilon_{fu} = 0.95 \times 0.015$ mm/mm = 0.0143 mm/mm.

Step [2]: To determine the maximum compressive strength of confined concrete ($f›_{cc}$) Mpa, as shown in Equation (4). Corresponding to f'c, where this value expresses the working compressive strength of confined concrete without steel reinforcement.

$f›_{cc}$= …………………….… Eq. (4)

The maximum confinement pressure due to CFRP jacket (f_l) is given by Equation (5);

f_l = ………………………………………………. Eq. (5)

And the minimum confinement ratio is given by Equation (6);

Minimum confinement ratio = $f_l / f›_c$ ……..……..……...… Eq. (6)

K_a is shape factor, and for circular column $K_a = 1$ according to confirmed fact in clause (12.1.1) ACI 440 .2R-17.

Step [3]: To verify that the ultimate axial strain of the confined concrete < 0.01, Eq. (12.1j) from ACI 440.2R can be used as expressed in Equation (7);

$\varepsilon_{ccu} = \dot{\varepsilon}_c (1.50 + 12K_b\, f_l / f›_c\, (\varepsilon_{fe} / \dot{\varepsilon}_c)^{0.45}$ ………………….... Eq. (7)

For each of the average 4 model columns as the results shall comply with the elastic theory so the concrete shall not disintegrate or highly damage according to Spoelstra & Manli (1999) [10].

With reference to ACI440.1R-17 Eq. (12.1i);

$\varepsilon_{fe} = K_\varepsilon\, \varepsilon_{fu}$ ………………………………………. Eq. (8)

Where;

K_ε ≡ is an efficiency factor based to Lam and Ten (2003 a, b) [11,12], confirmed ACI 440.2R-17 factor to be 0.55 for medium and big sizes cross-sectional concrete columns where $f_l / f›_c > 0.08$.

Also, by taking $K_\varepsilon = 0.55$ and $\varepsilon_{fu} = C_a\, \varepsilon_f$.

Step [4]: To determine the number of plies (n), Equation (9) can be used;

$n = f_l D / (2E_f\, t_f\, \varepsilon_{fe})$ …………………………………... Eq. (9)

According to Lam and Teng;

$f'_{cc} = f'c + \psi_f 3.3 Ka\, f_l$ .... Eq. (10)
where; ψ_f ≡ Additional reduction factor for the laminate pressure equals to 0.95 for sharp fully wrapped sections, and 0.85 for flexure.

Therefore, Table 5 summarizes the output results from the above-mentioned equations for the tested columns.

Table 5. The required service load and number of plies due to strengthening [Authors].

Test specimen	Failure load P_{nav} (kN)	Service load P_{nreq} (ϕP_n) (kN)	f'_c (MPa)	f_{fu} (MPa)	f'_{cc}/f'_c	f_l/f'_c	Number of plies (n)
C_{10}*	1277.5	830.38	40	–	0.000	0.000	–
C_{11}*	1654.3	1,075.81	40	3,000	1.564	0.220	0.97 ≈ 1
C_{12}*	1855.1	1,205.82	40	″	1.802	0.243	1.32 > 1
C_{20}*	971.56	631.51	30	–	0.000	0.000	–
C_{21}*	1184.7	770.06	30	3,000	1.380	0.115	0.50 < 1
C_{22}*	1248.3	811.40	30	″	1.477	0.144	0.61 < 1

Note: * first number corresponding to group of same grades, and the second number corresponding the numbers of plies of CFRP table represents average values of the categorized test models.

The tensile strength of CFRP laminate f_{fu} = 3000 MPa.

Then to reach a relationship from strengthening results the (f'_{cc}/f'_c) values versus (f_l/f'_c) values are plotted in histogram as shown in Figure (6).

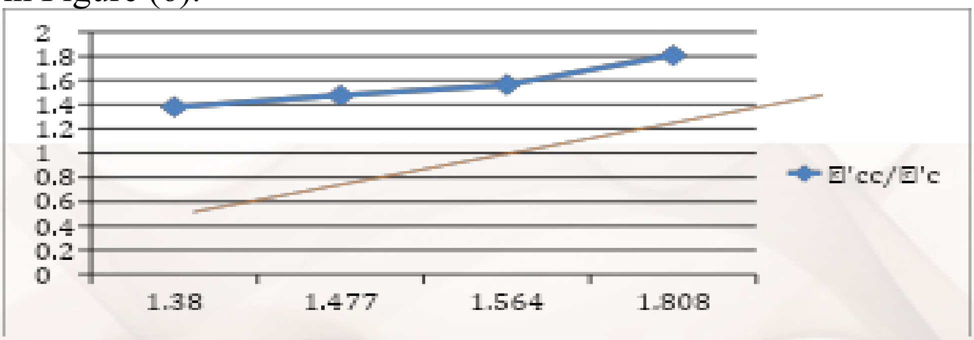

Figure 6. Values (f'_{cc}/f'_c) versus (f_l/f'_c) relationship.

3.2. Discussion of Results

- For C40 concrete column, a single ply laminate of CFRP significant result visualized that the stresses transferred to the full system and that means reinforced concrete was still elastic till the whole system fully occupied by the load stresses and the confinement pressure equals to 6.8 MPa which is almost 11% of the total strength due to the system without the steel reinforcement where the compressive strain is 0.0099 mm/mm.
- The confinement pressure due to the application of two plies CFRP, the system compressive strain i.e. 0.0107 mm/mm, thus the strain is likely as same as the system with two plies and the crushing stress can be accommodated by the single layer that the crushing of the column happened before the second layer has full confinement pressure that may has effective contribution in the strengthening mode visualizing that only 13.5% added strength achieved.
- For the second case, using C40 concrete grade no need for double laminate of CFRP, and only the design of higher size column may be enough or otherwise additional reinforcement may be required since the section is still under reinforcement. Higher grade concrete may satisfy beneficial results from doubly confinement.
- For C30 concrete column, the concrete section continued elastic with 0.0012 mm/mm strain so the single ply has effective full confinement pressure. Therefore, the confinement so far beneficial, confinement pressure 8.3% related to the whole working system this is clearly observed in Figure (5) and the contribution of the laminate pressure is very low. This fact also complies with doubly confined grade C30 column where the model failed before the second layer of CFRP has its full efficiency in carrying the transferred load stress.
- With reference to K. OLIVOVÁ, J. BILČIK, (Slovac Journal

of Civil Engineering 2008) [13], they reached a fact that 10% was addition strength attained in the column capacity confined by CFRP when the vertical crushing load is 250 kN. And for the column loaded by a vertical load 650 kN, 9% additional strength was attained. And they observed that the failure mode of the unconfined column was similar to that when confined and this marked that the rupture happened after the concrete was completely crushed.

- K. OLIVOVÁ, J. BILČIK [14] concluded that, the premature deboning occurred in the externally bonded reinforcement technique was avoided in the majority of strengthening column since some laminates of the CFRP reaches the tensile strain values close to the ultimate rupture strain of the CFRP.
- Riad Benzaid and Habib- Abdelhak Misbah [15], they plotted a relationship shows the correlation between the confinement ratio to the strengthening ratio. This appears in a trend line producing a formula functioning this relationship in circular column as; $(f'_{cc} / f'c) = 1.1184+2.1872\ (f_l / f'_c)$.

Riad Benzaid and Habib- Abdelhak Misbah concluded some significant results as;

1- The failure of CFRP wrapped specimens occurred in a sudden an explosive way, and for cylindrical specimens, the fibre rupture started mainly in their central zone. Experiments for purpose of this research also realized the first fact that the occurrence of the explosion while failure, but the rupture started in top compression zone and this attributed to the lower compressive strain of the whole system that the stress transmission to the whole fibre not completed.

2- The efficiency of the CFRP is confinement is higher for circular than for square section, actually this research interested in circular section depending upon former experiment outcomes and practically we've reached significant considerable results by strengthening circular section using CFRP. The same fact proved by Fathi Abdelrabeh et al. [26] in their research paper Strengthening of Reinforced Concrete Long Circular column using CFRP.

3- Increasing numbers of CFRP laminates produce an increase in the compressive strength of the confined column, this is also satisfied by this research, but for C30 only single ply was satisfactory effective.

- Authors, T.C. Triatafillon*. Et al. (2022) [16] reached that; If CFRP jackets are combined with heavy anchors, their effectiveness increases almost linearly with the numbers of layers. Thus, this fact is observed in Figure (4) for C40 single and double layers.
- In this research for concrete C40 the confinement of single laminate added 11% and 13.5% effective compressive strength to the column confined by single and double laminate, respectively. Where for concrete C30 the additional compressive strength is 6.3% and 9.72% for single and doubly confinement, respectively.

4. Conclusion and Recommendations

4.1. Conclusion

The main conclusions, that can be drawn based on the experimental and analytical studies carried out under this investigation, are the following:

1- Carbon fiber reinforced polymer CRFP is used widely for strengthening concrete structures members for flexural and axially compressive members or members subject to both.

2- Strengthening of columns with externally bonded laminates can only result in substantial enhancement of the load carrying capacity if;

- The structural element in its non-strengthened state is under reinforced.

- The load on the structural element during strengthening is low.
- The structural element has a reserve in vertical and longitudinal load capacity.
- The laminates can be bonded effectively on a sound concrete surface.

3- For strengthening existing structures evaluation after complete assessment shall be done to verify that the whole structure is still elastic after time period of operation and this shall be realized for all member components by test and measurements. The evaluation processes check cracks width, crack depths, strains, and the deflection if any comparing the results with the design and the design Code requirement for the structure, and then if possible, releases the structure from some loads if its members are incapable to sustain more loads, otherwise evaluate the extra load needed for the new utility and purpose this extra load shall be reason for strengthening.

4- In this research the required load to be carried by the system is that factored load attained at failure of the columns in both two grades due to compression test.

5- The mixes design nevertheless are experimental trials subject to variable conditions but strengths of concrete cylindrical specimens through the tests gave actually the pre-determined grades, and therefor guide to reliable results compatible with all data and equations used in tests and analyses.

6- The results of RC circular column using CFRP predicted distinguished results in high compressive load capacity added to the concrete characteristic strength.

7-The effects of concrete compressive strengths on structural behaviour were investigated by comparing the results from beams which were manufactured from two different strength concretes [f'_c = 25.85 MPa and 47.61 MPa]; both types were plate bonded. The results showed that strengthening the high-performance concrete increased the serviceability limit, the yield load and the maximum load carried in comparison to the lower strength beams.

8- No difficulties raised when confining and bonding the circular specimen.

9- Grade 40 concrete which is more elastic so shortly the elastic zone transferred shortly to the laminates allowed the laminate to have effective contribution in additional load carrying capacity of the column.

10- A linear co- relationship seen when plotting the system combined strength- concrete strength ratio to the confine pressure-concrete strength ratio.

11- A constant percentage load capacity marked when different grades of concrete are chosen for CFRP strengthening system as explained while analyzing the test results and seen clearly grade 40 is 75% more than grade 30 concrete, the single confinement results shows also 75% additional load capacity of the specimen added to grade C40 more parallel increment.

12- The rounded sections perform good results more better than rectangular and square sections where these sections need edges reshaping which is difficult processes or for the newly constructed elements sections which shall be strengthened by CFRP require difficult constructions of formworks which may not be familiar in the construction market, specially some curved surfaces element are required, not even the construction, but in the other hand the calculation need some data related to the shape factors K_a, K_b.

13- It is important for a practical use of FRP Composites for strengthening columns to round the edges as far as possible so as to increase the effectiveness of the confinement.

4.2. Recommendations

From the work presented in this research, the following recommendations can be drawn:

1-Test results have demonstrated that composite laminate bonding generates significant improvements in ultimate capacity of reinforced concrete members and that the stiffness of a member is increased.

2- In strengthening applications, the external CFRP laminate should fail in tension after yielding the internal steel reinforcement but before failure of the concrete in the compressive zone, since this would ensure a more ductile failure mode.

3- More structures like halls, mosques, car sheds, require biggest columns for supporting wide roofing's for new design or preexisting structures and may need long length column support, CFRP is an effective solution where shall produce high strength loading capacity with slender smart and architecture.

4- Scientifics and researching institutions missing the main research equipment's and laboratories and only undergraduate teaching and training laboratories are available and even there are some universities missing the main laboratory equipment. The government through the authorized part shall give an additional regards and interest in this quarter.

5- CFRP is cheapest material and easy to manufactured there for the government shall encourage this aspects and others according building research feedback.

6- Hand bonding and confinement is difficult process wise and may not give an effective confinement especially when more than one ply is needed, so machines for folding and fixation are targitly necessary.

7- A pulling test devise to test the effective adhesion of the bonding materials shall be maintained and available for any strengthening process using epoxies resin material. After crushing test to assure that the CFRP is well fixed to the skin, a pulling test shall be conducted and thereafter the results of effective numbers of plies (n), confinement pressure $\int_l$, $\int_{cc}$, all shall be reliable results and the failure load as well.

8- The testing instrument shall be accompanied with some other correlating digital measuring and graphical systems to perform the other related data correspondent with deformation or gradually deforming load and this will give very good indications and the characteristics of elements and fix good facts and logics that might fix the relationship between test results and the theorem.

9-Traing and culture of this technology shall be widely expanded within the engineers and technicians, in field labors as well. And while visiting some laboratories it is clearly observed that lab environment room temperature, excitation, test conditions are completely ignoring the research recommends giving more attention to lab environment and testing conditions.

10- many experts when asked by some customers for evaluating an existing building for purposes of widening or adding other stories, the expert satisfied only by calculating the preserved or residual strength of the building members ignoring that, due to operation of the building in long term in use some strains may happen and some energy of the building may be lost, theoretically the strength properties may remain to mention the new circumstances but there may be other unseen factors may reduce this residual strength. And therefore, the research recommends for every re-evaluated building a suggestion for confinement by even single CFRP shall be fixed and calculated, this will add even new effective strain to the members of the building.

11- In Sudan there are some structures strengthened using CRFP like Khartoum Shambat Bridge and Burri (Armed Forced Bridge) and the reinforcing done for bridges piers and box and the I girders, but after that application no care was done or a follow up to assure effectiveness and the validation of such treatment. The research encouraging authorities in charge to follow up.

12- Prestressing of CFRP laminates may be necessary for economic and structural requirements.

13- As the construction industry begins to apply FRP composites in the field of strengthening and repair, the need for educating civil engineering students with background on the subject has become more evident. Therefore, according to questionnaire results, it is very important to incorporate some strengthening topics in civil engineering courses in Sudan, especially for graduate studies.

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