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Experimental Study of Using External Confinement Materials on High-and-normal Strength Circular Specimens Concrete Columns

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Abstract— This paper devoted to investigate the behavior of FRP confined concrete columns subjected to axial compressive loading. 28 high-strength concrete specimens were externally encapsulated using CFRP and fiber glass straps and subjected to a concentric load. A different number of CFRP and GFRP wrapped layers are tested, the experimental results show that external confinement can enhance the properties of high strength concrete columns. The improvement in strength for the E-glass fiber-wrapped specimens is not so clear, as is the case with carbon fiber specimens. However, when wrapped, the columns achieved a significant gain in strength and deflection compared to no wrapped concrete columns.
The external wrapped columns show a considerable improvement in load capacity and deflection, more ductile. There is a significant increase in load capacity more than 250% between the three layers carbon wrapped columns and columns with no wrapped fiber.
Location of failure was limited to a small region located at the upper quarter of CFRP wrapped columns. The E-glass fiber has shown that they are the weakest materials for external confinement than carbon fiber. Therefore; the tested wrapped with three E-glass fiber columns showed a slightly increase in ultimate load capacity not more than 118%. There is no clear effect of the steel reinforcement due to concentric loading of columns.
The test database is assembled from several experimental tests being conducted over the past few decades. A new equation is presented to predict the compressive axial strength of FRP confined columns.

Index Terms— *Confinement; High-Strength Concrete; Columns; Carbon fiber; E-glass fiber; Proposed Equation*

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1 Introduction

The retrofitting techniques in reinforced concrete members using FRP as external confinement materials became widely used in last two decades. Although retrofit technology provides a good engineering and economic alternative to address some of the failure of concrete members in damaged buildings, due to their superior mechanical properties; it includes corrosion resistance, impact resistance, excellent durability, furthermore a significant enhancement in ductility particularly in high strength concrete. The wide application has stimulated a number of research studies in many countries including Iraq, particularly in the last few years to understand the structural behavior of external confinement concrete members.

The most important application of composite retrofitting technology is the use of FRP jackets to give a significant external confinement to the concrete columns when the stirrups reinforcement is inadequate. The reduction of the effect of its brittle behavior and the increase of the concrete column to allow the column to attain ultimate load carrying capacity are the most desirable qualities when using the method of external confinement of the columns by FRP in both normal and high-strength concrete. The maximum strength is attaining as a result of the lateral confinement pressure, applied by the external confinement of the concrete columns.

The external confinement greatly reduces the lateral expansion of the column under axial load, improving the column's stiffness. Because of external confinement, the high-strength concrete column is capable of carrying higher loads than when it is not externally confined. Extensive previous literatures have shown that the confinement will increase the ductility as well as the strength of concrete effectively [1, 2, 3]. Several experimental and analytical studies have been conducted in recent years to evaluate the axial load capacity and stress-strain response of concrete confined with CFRP and GFRP laminates (ACI Committee 440 2002). All of the studies mentioned above clearly agreed that the confinement of columns with FRP jackets leads to a significant and noticeable improvement in the ability of the concrete column to the axial strength and load carrying capacity under both static and cyclic loading.

Several previous studies have been proposed several equations for the purpose of calculating external confinement as well as predicting the column's ability to carry axial force as well as describing the strain-strain response in columns wrapped with FRP jackets.A comprehensive review and assessment of existing models have been recently presented by Touhari M. and Mitiche-Kettab R. (2016) [4]. In the current research, a large database was compiled with high accuracy and careful attention from the concrete columns confined with

FRP, circular shape and tested under a concentric load only. This data base was presented through a broad analytical study of relevant research resources containing experimental results, published between 2001-2016. New equations are presented to predict the compressive axial strength of FRP confined columns.

2 Mechanism of Confinement

The lateral confinement pressure provided by a FRP jacket to concrete is naturally passive. In FRP confined concrete cylinders, the concrete core extends laterally and this expansion is restrained by the FRP material when it is subjected to an axial compression load. This pressure produces a circular tension resultant in the envelope [5]. The action of expansion and the reaction of the confinement are represented by a uniform lateral pressure f'l in the interface and the response of FRP material as shown in Fig. 1.

This expansion of the concrete core is confined by the FRP jackets, and thus transforms the concrete core to a 3-D compressive stress condition. The confinement mechanism goes from axial loading to tri-axial loading.

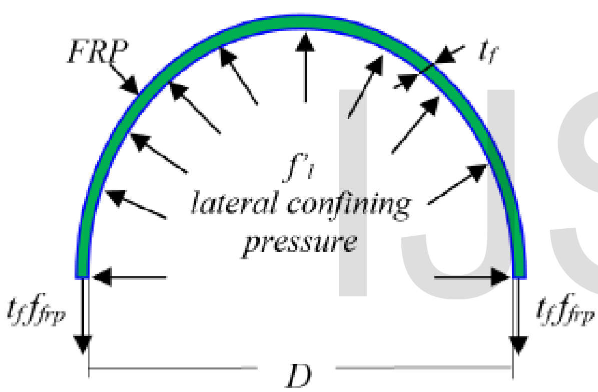

Fig.1: Confinement Mechanism.

The maximum value of the confinement pressure that the FRP can exert is attained when the circumferential strain in the FRP reaches its ultimate strain and the fibers rupture leading to brittle failure of the cylinder. This confining pressure $f'l$ is given by:

$$f'l = \frac{2t_f . f_{frp}}{D} = \frac{2E_{frp} \,.\, \varepsilon_{frp,u} . t_f}{D} = \frac{\sigma_{frp} . f_{frp}}{2} \qquad (1)$$

In these relations, $f\,'l$ presents the lateral confining pressure, E_{frp} is the tensile modulus of FRP composite material, t_f is the thickness of the composite jacket, $\varepsilon_{frp,u}$ is the ultimate circumferential strain in the composite jacket, D is the diameter of the concrete core and σ_{frp} is the FRP volumetric ratio which is given by the following equation for entirely wrapped circular cross section [5]:

$$\sigma_{frp} = \frac{4t_f}{D} \qquad (2)$$

3 Significance of Research

The main purpose of this experimental study is to study the behaviour of high-strength concrete columns under the influence of external confinement by FRP jackets subjected to axial loading, as well as to evaluate the effectiveness of increasing the number of external confinement layers of FRP on concrete columns. In addition, to evaluate the use of CFRP and E-glass fibers on load carrying capacity and study the deflection in wrapped concrete columns.

Finally, to predict the enhancement and advantage of using different number FRP layers on general behavior wrapped columns, and to propose a new equation to predict the compressive axial strength of FRP confined columns.

4 Experimental Program

4.1 Materials

The properties of the materials used in this experimental work are summarized below:

4.1.1 Cement: Ordinary Portland produced by Sinjar manufacture of cement and it's characteristics are listed in Table (1), the test results show that the cement conforms to the ASTM C150 [6].

TABLE 1

CHARACTERISTICS OF THE CEMENT USED THROUGHOUT THIS WORK

Chemical properties	Weight percentage,%	ASTM C150
SiO2	20.4	-
AL2O3	5.54	-
Fe2O3	2.93	-
CaO	64.06	-
MgO	2.95	5.0 max.
SO3	2.06	-
In.SUL.R	0.61	1.5 max.
L.O.I	0.83	3.0 max
Free Lime	0.8	0.66 – 1.02
L.S.F	95.34	
Bugue Composition	Weight percentage,%	
C3S	61.03	
C2S	12.44	
C3A	9.72	
C4AF	8.91	
Physical and mechanical properties		
3DAY	29.7 MPa	15 min.
7DAY	39.5 MPa	23 min.
Autoclave %	0.03	0.8 max.
Blaine	299.6	230 min.
Specific	3.08	-

*The Table above was supplied by Sinjar Manufacture of Cement.

Supplementary cementitious material:

4.1.2 Silica fume

The physical properties of the silica fume used in this study are given in Table 2.

TABLE 2
PHYSICAL PROPERTIES OF SILICA FUME

Physical characteristics	Typical values
Appearance	Grey powder
Specific gravity	2.2
Average particle size	0.1 micron
Bulk density	240 kg/m³
Particle size	0.1µ -0.5µ
Specific surface area	20,000 Kg/m2

4.1.3 Admixtures

Superplasticizers:

According to the ASTM C 494/C 494M [7] a new superplasticizers type "F" high range water reducing was used in this research, with technical data as listed in Table 3.

TABLE 3
PHYSICAL PROPERTIES OF SUPERPLASTICIZER

Structure of the material	Naphthalene Sulphonate based
Color	Brown
Density	(1.15-1.21) Kg/liter
Chloride content %(EN480-10)	<0.1
Alkaline content % (EN480-12)	<10

*The table above was supplied by BASF chemical Company.

4.1.4 Fine aggregate

Locally available river sand complied with BS.882: 1992[8], used in this research. The fineness modulus, specific gravity, on a saturated and surface-dried basis, and water absorption were 3.1, 2.62 and 0.23% respectively.

4.1.5 Coarse aggregate

Locally available river coarse aggregate (natural aggregate) with a nominal maximum aggregate size of 19mm was used. Washed with water and dried in the air. The fineness modulus, specific gravity, on a saturated and surface-dried basis and water absorption were 6.8, 2.7 and 1% respectively. Grading of the coarse aggregate complied with BS 882: 1992 [8].

4.1.6 Water

Water's tap was used in this research for mixing and carrying of with 23ºC ±2ºC.

4.1.7 Carbon fibers

The technical properties of carbon fiber are listed in Table 4.

4.1.8 E-glass fibers

The technical properties of E-glass fiber are listed in Table 5.

TABLE 4
TECHNICAL PROPERTIES OF CFRP [9].

Property:	
Fiber Type	Mid strength carbon fibers.
Fabric Construction	Fiber orientation: 0° (unidirection- Wrap: black carbon fibers (99% of Weft: there heat-set fibers (1% of to-
Fabric length / roll	≥50 m
Fabric width	300 / 600 mm
Fabric Design Thickness	0.131 mm (based on fiber content).
Fiber Density	1.76 g/cm3
Tensile strength:	4300 N/mm2 (nominal).
Tensile E-modulus:	238000 N/mm2 (nominal).
Elongation at break:	1.8% (nominal).

TABLE 5
TECHNICAL PROPERTIES OF GFRP

Properties:	
Thickness mm,	0.17
Specific gravity δ,	2.63
Tensile modulus ε, GPa	82.5
Tensile strength MPa σ, MPa	3450
Tensile elongation %	4.8
Specific modulus E/δ, GPa	32
Specific strength σ/δ, MPa	1320
Longitudinal coefficient of thermal expansion, x10^{-6} m/m.K	5.5

5 TEST PARAMETERS

Twenty eight small-scale circular columns specimens of 300 mm height and 100 mm diameter were tested, a set of three standard cylinders (150x300mm) for each group to predicate concrete compressive strength . Specimens' properties and details are provided in Table 6.

6 CONCRETE AND MIX PROPORTIONS

One concrete mix was prepared with constant water/ (cement+ silica fume) ratios, 10% of silica fume by wt. of cement was added. The curing regime of 21 ±1.5ºC and was adopted.
Table 7, shows mix proportions of high-strength concrete.

6.1 Compressive strength

Compression tests were conducted on 150 × 300 mm cylindrical specimens according to ASTM C 39/C 39M [10] at 28

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days of age. Before starting the cylindrical specimens, were covered with a solid plaster to ensure that the load is fully and uniformly distributed between the test machine and the cylindrical specimens. A servo-hydraulic closed loop testing machine with a 3,000 kN capacity applied a monotonically increasing displacement loading at a constant rate.

confined concrete include concrete strength which can be seen in Fig. (2).In their research Toutanji and Balaguru [3] found that the compressive strength increased by approximately 200% because of the confinement with CFRP and by approximately 100% due to Glass fiber. Fibers oriented in one direction give very high stiffness and strength in that direction.

TABLE 6
SUMMARY OF TEST PARAMETERS

Specimen Code	No. of specimens	f'c Mpa cylinder 150x300mm	Stirrups	$\rho_{min} = 0.12f'c/fy$	ρ	Confinement material
C1P control	2	71.9	----	----	----	----
C2P-1L-CF	2	72.7	----	----	----	One Layer of CFRP
C3P-2L-CF	2	72	----	----	----	Two Layers of CFRP
C4P-3L-CF	2	71.8	----	----	----	Three Layers of CFRP
C5P-1L-EGF	2	70.4	----	----	----	One Layer of E-glass
C6P-2L-EGF	2	70.8	----	----	----	Two Layers of E-glass
C7P-3L-EGF	2	72.3	----	----	----	Three Layers of E-glass
C8R(control)	2	72.27	Ø6@50mm	0.0203	0.0216	----
C9R-1L-CF	2	71.8	Ø6@50mm	0.0203	0.0216	One Layer of CFRP
C10R-2L-CF	2	72.4	Ø6@50mm	0.0203	0.0216	Two Layers of CFRP
C11R-3L-CF	2	71	Ø6@50mm	0.0203	0.0216	Three Layers of CFRP
C12R-1L-EGF	2	70	Ø6@50mm	0.0203	0.0216	One Layer of E-glass
C13R-2L-EGF	2	70.5	Ø6@50mm	0.0203	0.0216	Two Layers of E-glass
C14R-3L-EGF	2	71	Ø6@50mm	0.0203	0.0216	Three Layers of E-glass

TABLE 7
MIX PROPORTIONS OF HIGH-STRENGTH CONCRETE

Mix	Mix proportions
W/(C+S)	0.33
Water (Kg/m³)	217
Cement (Kg/m³)	575
Silica fume (Kg/m³)	57.5
Silica fume % of cement	10
Superplasticizer L/m³	7
Superplasticizer % of cement	1.16
Coarse Aggregate (Kg/m³)	1367
Fine Aggregate (Kg/m³)	467
Design strength MPa	90
Slump (mm)	60

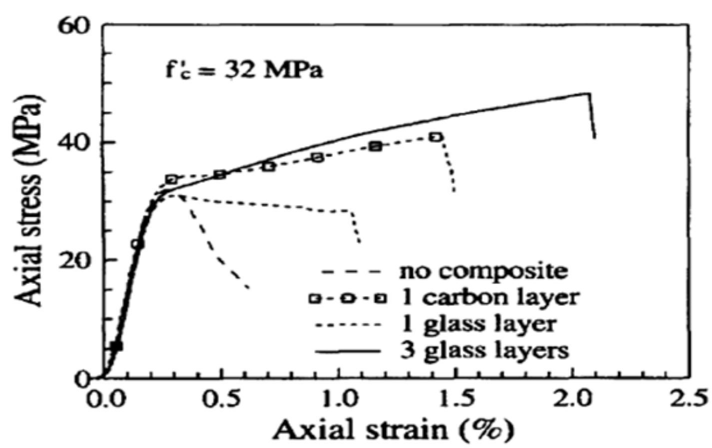


Fig.2: Parameters affecting the effectiveness confinement.

7 EXTERNAL CONFINEMENT WITH FRP

The application of FRP in the construction industry can eliminate some unwanted properties of high-strength concrete, such as the brittle behavior of high-strength concrete.

7.1 FRP wrapping configurations

Parameters that affect the strength and ductility of FRP-

7.2 Wrapping Procedure

After drying, the surface of all specimens intended to be wrapped by FRP sheets was well cleaned by a steel brush to remove any dirt and dust. The surface of the concrete specimens were thoroughly cleaned with a specially designed brush and homogenized and prepared to be covered with the epoxy material. Meanwhile, the FRP layers was cut and prepared according to the required surface area.

The preparation of FRP sheets is followed by painting columns faces with epoxy carefully using soft paint brush. It was made sure that the epoxy was equally and homogenously distributed at a constant thickness over the whole surface of the columns. The process of providing epoxy was followed by pasting FRP sheets on each specimen carefully and according to the variables requirements of each specimen. To ensure a good distribution of epoxy material on the FRP layer, a steel roller was used and to ensure that there were no closed air bubbles. The concrete columns specimens were left for seven days after they were wrapped with FRP according to the instructions of the manufacturer of epoxy material [11].

8 Test Results and Observed Behavior

All the columns showed similar behavior under the concentric loading. Although sounds of snapping of the fibers could be heard near the failure load, the failure of the columns specimens in was characterized by a quite failure except in columns wrapped with two and three CFRP layers. The results from experiment conducted on the twenty eight columns specimens are shown in Table 8. The Table contains the results of ultimate load capacity of wrapped and unwrapped control specimens.

The Tables also contain the percentages of ultimate load for wrapped to that of control specimens, The maximum stress was also calculated in the wrapped concrete columns and three layers of E-glass fiber, the enhancement in ultimate load capacity varied from 9 % to 18 %, on the other hand there is a significant enhancement in ultimate load capacity varied from 45% to 113 % due to use one, two and three layers of carbon fiber.

Therefore, the effect of wrapping concrete columns with CFRP gives more efficiency than the E-glass fiber. No significant enhancement was observed in columns wrapped with single, two and three layers E- glass fiber, against this behavior observed in the wrapped columns with CFRP.

Generally, there is a significant increase in deflection in columns wrapped with CFRP which is indicating more ductility comparing with less number in CFRP layers. It is observed from test results that the response of ultimate load capacity with number of layers in columns wrapped with CFRP slightly linear more than columns wrapped with E-glass fiber as shown in Fig. 3 and Fig. 4.

Table 8
Columns Test Results

Specimens code	NO. of specimens	Pu (kN)	Comp. strength *f'co* MPa	Confined stress of columns *f'cc* (MPa)	*f'cc/f'co*	Lateral confinement pressure *f'l*	Confined Axial stain* 10^{-3}	Maximum axial deflection (mm)
C1P cont.	2	565	71.91	71.91	1	-	10.127	3.038
C5P-1L-CF	2	820	72.7	104.36	1.44	11.266	11.690	3.507
C6P-2L-CF	2	1080	72	137.45	1.91	22.532	12.743	3.823
C7P-3L-CF	2	1460	71.8	185.82	2.59	33.798	14.882	4.464
C2P-1L-EGF	2	570	70.4	75.55	1.07	11.73	9.707	3.26
C3P-2L-EGF	2	620	70.8	78.91	1.12	23.46	10.914	3.274
C4P-3L-EGF	2	630	72.3	80.18	1.11	35.19	10.965	3.586
C8R cont.	2	560	72.27	72.27	1	-	10.468	3.038
C12R-1L-CF	2	750	71.8	95.45	1.33	11.266	12.2	3.660
C13R-2L-CF	2	1050	72.4	133.67	1.85	22.532	13.116	3.934
C14R-3L-CF	2	1380	71	175.64	2.47	33.798	13.733	4.120
C9R-1L-EGF	2	560	70	71.27	1	11.73	10.468	3.14
C10R-2L-EGF	2	610	70.5	77.64	1.10	23.46	13.024	3.907
C11R-3L-EGF	2	660	71	84	1.18	35.19	13.979	4.376

The maximum stress of confined concrete columns was obtained by calculating the load resisted by the concrete divided by the net concrete area. For columns wrapped with one, two

9 Discussion the Experimental Results

From the twenty eight columns of experiments conducted in this study, it can be noted that the Carbon wrapped columns out-performed the E-glass of columns, which were proved by the testing results of the concentrated loaded columns. The testing results indicated that Carbon fibers wrapping is more effective for the external confinement compared to the E-glass. The following discussion has been done:

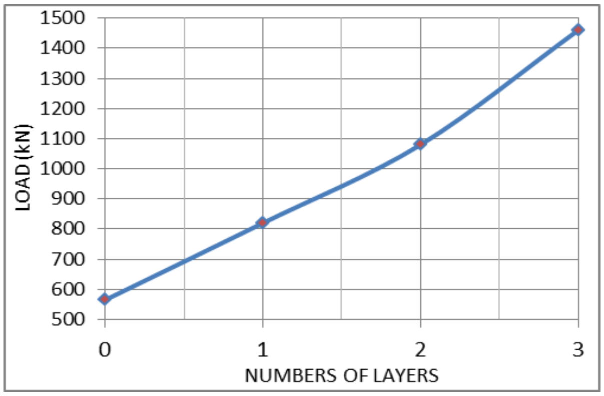


Fig. 3: Relationship between ultimate load and number of layers for columns wrapped with CFRP.

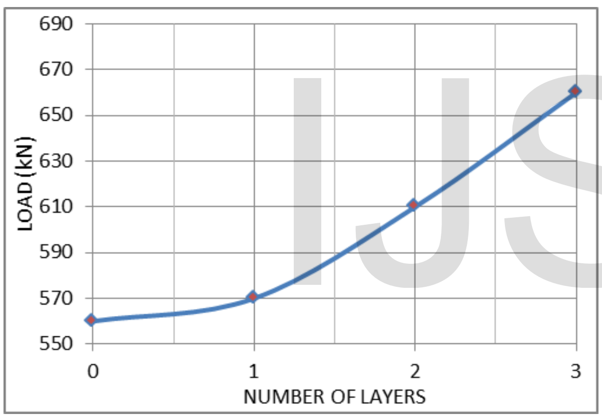


Fig.4: Relationship between ultimate load and number of layers for columns wrapped with GFRP.

9.1 Single layer GFRP wrapped columns: The single-layered E-glass columns achieved no increase in ultimate load over the plain specimens as shown in Fig.6.The excellent character of these columns is that there is very little deflection obtained after reaching the maximum load, failure is normal and the specimens remained confined with FRP almost completely even after the failure.

9.2 Two layers GFRP wrapped columns: The two-layered E-glass columns achieved a slightly increase in ultimate load over the single layer plain and reinforced specimen as shown in Fig6. And the most important aspect about these columns is there was a slightly amount of excess deflection achieved after ultimate load. The failure was quiet and the columns were almost fully confined even after failure.

9.3 Three layers GFRP wrapped columns: The three-layered E-glass column achieved a significant increase in ultimate load over the single and double layers plain and reinforced specimen as shown in Fig6. And the most promising aspect about these columns is that there was a small amount of excess deflection achieved after ultimate load, the failure was still quite. There are no significant effects of steel reinforcement because of the concentrated load.

9.4 Single layer CFRP wrapped columns: The external confinement provided to these columns resulted in a higher ultimate load comparing with no wrapped columns. Failure in these columns are quiet and result in no increase in deflection after reaching the maximum loading state.Fig5 shows the load deflection curves for plain and reinforced columns; there is a significant reduction in ultimate load capacity in reinforced columns. And the most promising aspect about these columns there was a small amount of excess deflection achieved after ultimate load compared with plain columns.

9.5 Two layers CFRP wrapped columns: The test results show that these columns could withstand much higher ultimate load than single layer of CFRP wrapped columns. This reveals that increasing carbon fiber layers could provide significantly greater confining pressure to the high strength concrete columns [12]. In this group the typical failure mechanism was usually marked by sudden failure. The specimens attaining ultimate strength. There is noise in the model during the loading with localized de-bonding fiber and then failure, the concrete is crushed in the final failure. Because of the geometrical configuration adopted, the location of the failure region occurred in the upper quarter of the specimens. And resulted in slight increased deflection after reaching the maximum load as well, Plate 1 shows the failure shape in these columns.

9.6 Three layers CFRP wrapped columns: These specimens achieved significantly better results than the single and double layered specimens both in strength and deflection. In this case the snapping of the carbon fibers could be heard throughout the loading as the concrete tried to expand. It is significance to note that the columns fully damaged in the upper quarter as shown in Plate 2. The typical collapse mechanism of failure was sudden explosive and resulted in significant increase in deflection after reaching the ultimate load as well.

This collapse shape is typical for wrapped columns and it is a direct consequence of the linear elastic behavior shown by the FRP material. It does not necessarily mean loss of ductility of the strengthened element. Fig.5 shows the load deflection curves for plain and reinforced columns wrapped with CFRP.

The comparison among the plain and reinforced columns shows that no significant effect of steel reinforcement. Fig.6 shows the comparison between plain columns wrapped with one, double and three E-glass fibers; it can observe the same general load-deflection behavior except the ultimate load and maximum deflection values.

Plate 1: Two layers CFRP wrapped columns

Plate 2: Three layers CFRP wrapped columns

A significant deflection under a constant load value observed in (one to three)-layers CFRP wrapped reinforced columns comparing with (one to three)-layers CFRP wrapped plain columns, due to the effect of steel reinforcement, as can observe in Fig. 5. Another comparison made between the entire single and double layers GFRP wrapped columns shows increasing more than 9 % of load capacity as shown in Bar chart 1 and (11 to 25) % increasing in deflection as shown in Bar chart 2. There is significant increase in load capacity and maximum deflection about 18% and 40% respectively, between the three layers GFRP wrapped columns and columns with no wrapped fiber as shown in Fig.6, and this also can observed in Bar chart 1 and Bar chart 2 respectively.

The comparison between single layer carbon fiber wrapped columns, double and the three layers carbon fiber wrapped columns which are shown in Fig.5 and bar chart 2 shows that there is significant increase (58 – 67) % in ultimate load capacity and about (7 – 20) % in maximum deflection. Due to the use of three layers of FRP, there is a serious increase in ultimate load carrying capacity of more than 250% in wrapped columns compared to non-wrapped columns, which can observed in Fig.5 and Bar chart 1.

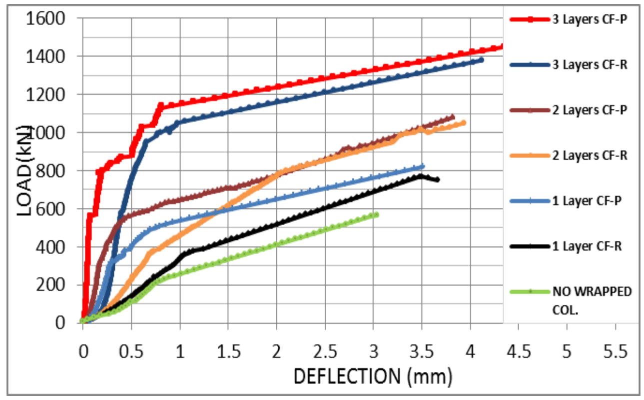


Fig.5 Load-Deflection curves wrapped with CFRP plain and reinforced columns.

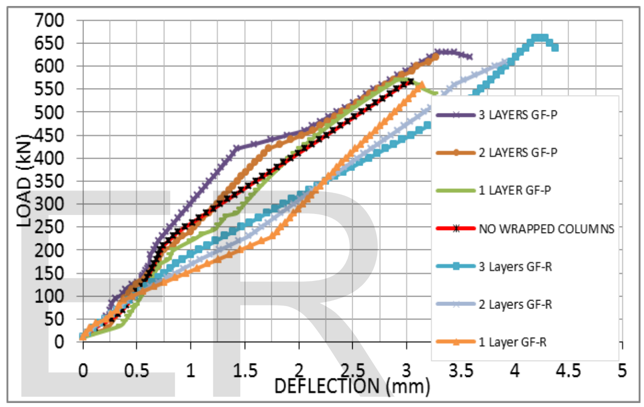
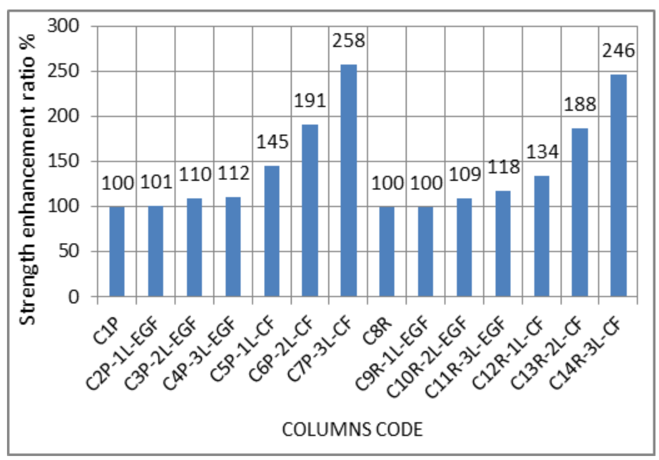
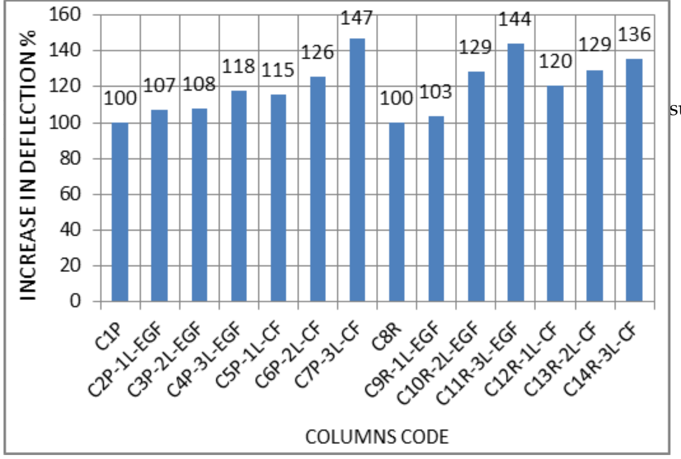


Fig.6 Load-Deflection curves wrapped with E-glass fiber plain and reinforced columns.



Bar chart 1: Columns Code vs Strength enhancement ratio,%



Bar chart 2: Columns Code vs increase in deflection

10 Previous Equations

a. Richart et al. Equation [13]

Various models for confinement of concrete with FRP have been developed. The vast majority of these tests were carried out on specimens of normal concrete columns. A limited number of tests have been reported in the literature on the axial compressive strength and strain of RC specimens confined with FRP, in which the strength at failure for concrete confined by hydrostatic pressure takes the following form:

$$f'cc = f'co + k1 .\, f'l \qquad (3)$$

where:

$f'cc$ = compressive strength of confined concrete

$f'co$ = compressive strength of unconfined concrete

$k1$ = confinement effectiveness coefficient

$f'l$ = lateral confining pressure

Based on their test results, they found values for k1=4.1

b. R. Benzaid et al. Equation [14]

A simple equation was proposed to predict the peak strength of FRP-confined concrete of different unconfined strengths based on regression of test data for the cylinders It can be seen that, strengthening ratio was proportional to the volumetric ratio and the strength of FRP (in terms of effective lateral confining pressure fl,eff and is inversely proportional to unconfined concrete strength. Therefore the relationship may be approximated by a linear function. The trend line of those test data could be closely approximated using the following equation:

$$f'cc/f'co = 1+2.20\ (f\,l,eff)/(f'co) \qquad (4)$$

Where:

$f'cc$ = compressive strength of confined concrete

$f'co$ = compressive strength of unconfined concrete

fl,eff = effective lateral confining pressure

Using a reduction factor η of 0.73 with the replacement of fl,eff by fl into Equation (2) the ultimate axial compressive strength of FRP-confined concrete takes the form:

$$f'cc/f'co = 1+1.6\ (f\,l)/f'co \qquad (5)$$

c. Murugan M et al. Equation [15]

An empirical model for predicting the compressive strength of FRP-confined concrete cylinders 150*300 mm was arrived and takes the following form:

$$f = 1.165fck + k1.k2.t.n \qquad (6)$$

where:

f = Compressive strength of FRP confined cylinders

fck=Characteristics compressive strength of concrete in N/mm^2

$k1$and $k2$ are constants depends on type of FRP material and fiber orientation

Constant, $k1$

Unidirectional GFRP mat, $k1$ = 5.765

Bidirectional GFRP mat, $k1$ = 11.730

Unidirectional CFRP mat, $k1$ = 23.400

Constant, $k2$

Unidirectional GFRP wrapping along the length, $k2$ = 1.000

Unidirectional GFRP wrapping along the circumference, $k2$ = 1.471

Unidirectional CFRP wrapping along the length, $k2$ = 1.000

Unidirectional CFRP wrapping along the circumference, $k2$ = 1.926

t is nominal thickness of FRP layer in mm

n is number of FRP layers.

d. Fardis and Khalil Equation [16]

Fardis and Khalil developed a linear relationship between the ultimate strength and the effective lateral confining stress.

$$f'cc = f'co + 4.1\, f'l \qquad (7)$$

e. Ozbakkaloglu and Jian Equation[17]

Ozbakkaloglu and Jian developed a new model based on over 500 experimental results for CFRP and GFRP confined concrete cylinders:

For CFRP confined concrete cylinders:

$$f'cc/f'co = 1+3.64(f'l,ua)/f'co. \qquad (8)$$

For GFRP confined concrete cylinders:

$$f'cc/f'co = 1+2.64(f'l,ua)/f'co. \qquad (9)$$

Where: $f'l,ua$ is the effective lateral confining stress

f. Pham and Hadi [18] Equation

Pham and Hadi proposed new confinement model for FRP confined normal- and high-strength concrete circular columns

$$f'cc = 0.7f'co + 1.8f'l + 5.7\ t/D + 13 \qquad (10)$$

where: t is the thickness of FRP layer, and D diameter of column.

g. Touhari M. and Mitiche-Kettab R.[4]

developed a new model based on experimental results and database for CFRP and GFRP confined concrete cylinders:

For CFRP confined concrete cylinders:

$$(f'cc)/(f'co) = 1+2.8\ (f'l)/(f'co) \qquad (11)$$

For GFRP confined concrete cylinders:

$$(f'cc)/(f'co) = 1+1.85\ (f'l)/(f'co) \qquad (12)$$

Where: $f'l$ is the effective lateral confining stress

Then, there are a few studies to develop an equation for strength enhancement in confined concrete. All of the above equations assumed that the compressive strength of confined concrete is a function of the unconfined concrete strength and

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the effective lateral confining pressure.

11 Proposed Strength Equations for FRP Confined Circular Concrete Columns

The database used in this paper contains experimental results of confined circular plain and reinforced concrete columns carried out axial load. The test database is collated from several experimental studies being conducted over the past few years [4, 13, 14, 19, 20, 21, 22, 23, 24, 25, 26, and 27]. In order to calculate the compressive strength of FRP confined concrete columns, this study adopted a method proposed by R. Benzaid and H. A. Mesbah [14] to generate a simple-form equation.

11.1. For CFRP confined concrete columns:

Figure 7 shows the relation between actual confinement ratio $f'l/f'co$ and the strengthening ratio $f'cc/f'co$ for the columns specimens of the experimental and database results wrapped with CFRP. It can be seen that, strengthening ratio is proportional to the volumetric ratio and the strength of FRP (in terms of lateral confining pressure $f'l$) and is inversely proportional to unconfined concrete strength. Therefore the relationship may be approximated by a linear function as shown in figure 8. The trend line of these test data can be closely approximated using the following equation:

$$(f'cc)/(f'co)=1.0613+2.0923\,(f'l)/(f'co) \qquad (13)$$

Where:

$f'cc$ = compressive strength of confined concrete
$f'co$ = compressive strength of unconfined concrete
$f'l$ = lateral confining pressure

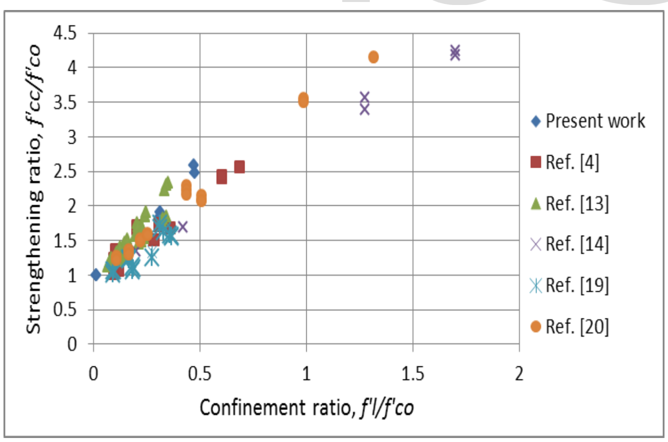

Fig. 7 Strengthening ratio f 'cc/f 'co vs confinement ratio *f 'l/f 'co*

Figs. 7-8 show that Eq. (13) compares excellent with the experimental results and collected test database.

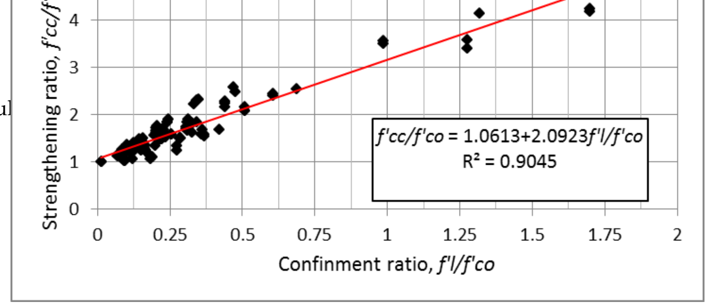

Fig. 8: Relationship between strengthening ratio, *f'cc/f'co* and confinement ratio, *f'l/f'co*

11.2 For GFRP confined concrete columns:

Figure 9 shows the relation between actual confinement ratio f 'l/f 'co and the strengthening ratio $f'cc/f'co$ for the columns specimens of the experimental and database results wrapped with GFRP. It can be seen that, strengthening ratio is proportional to the volumetric ratio and the strength of FRP (in terms of lateral confining pressure $f'l$) and is inversely proportional to unconfined concrete strength.

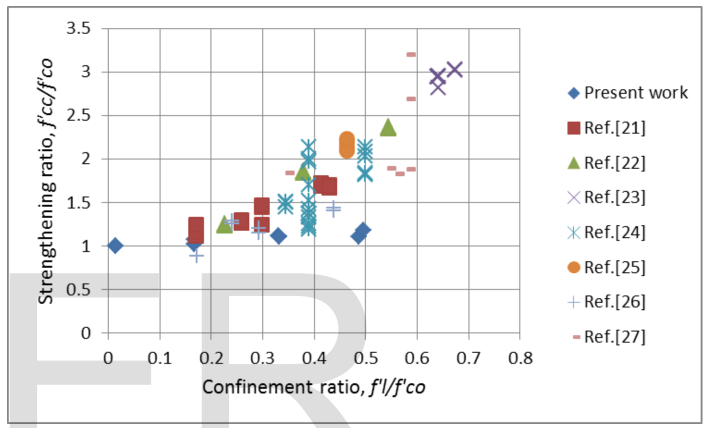

Fig. 9: Strengthening ratio *f 'cc/f 'co* vs confinement ratio *f 'l/f 'co*

Therefore; the relationship may be approximated by a polynomial function (order 2) as shown in figure 10. The trend line of these test data can be closely approximated using the following equation:

$$(f'cc)/(f'co)=5.7693(f'l/f'co)^2-0.9991\,f'l/f'co+1.0843 \qquad (14)$$

Where:

$f'cc$ = compressive strength of confined concrete
$f'co$ = compressive strength of unconfined concrete
$f'l$ = lateral confining pressure

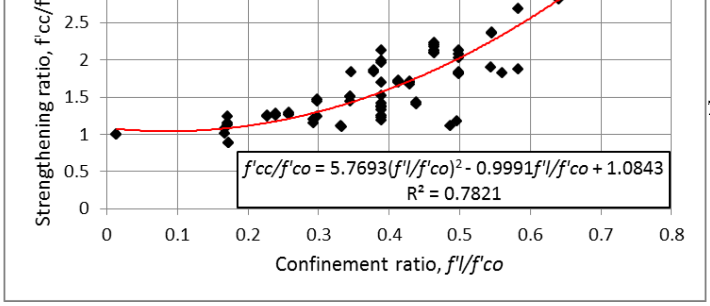

Fig.10: Relationship between strengthening ratio, *f 'cc/f 'co* and confinement ratio, *f 'l/f 'co*

12 Conclusions:

The study presented in this paper tested twenty eight concentrate loaded high strength concrete columns with CFRP and E-glass fiber external confinement. Fourteen of these columns were internally reinforced with typical internal steel reinforcement to justify the use of such practices to retrofit damaged columns in situ. The remaining specimens were made of plain concrete with supplementary layers of external confinement that were to represent the potential of external confinement in strengthening columns structures. A confinement equation was developed for FRP confined normal- and high-strength concrete columns. The predictions of the proposed equation fit the experimental results from the extensive database very well. The findings presented in this paper are summarized as follows:

1. The strength and load carrying capacities of the speci mens wrapped with FRP materials are improved com pared to the unconfined concrete specimens.
2. A simple formula has been suggested to foretell the ulti mate strength of FRP- confined concrete, and acceptable corre lation was acquired between experimental and analytical results.
3. The proposed equation could estimate the compressive strength of confined concrete with unconfined concrete strength ranging between 30 MPa and 185 MPa.
4. Test results proved that the benefits of confinement could be enhanced by applying multiple layers, which can be seen from the results of testing the axial loading columns.
5. The test results also showed that the CFRP provides greatest amount of confinement, and had significantly better results more than 250% in ultimate load capacity.
6. The test results also indicated that the GFRP provides less amount of confinement, and had about 18% in ultimate load capacity.
7. GFRP proved to be the weakest confining material in this work. The ultimate loads capacities achieved by GFRP wrapped specimens were just slightly more than no wrapped columns.
8. Test results also indicated that there is no clear effect of steel reinforcement on load capacity duo to the loading type method.

References

[1] Han C.G., Hwang Y.S., Yang S.G., Gowripalan N., "Performance of spalling resistance of high performance concrete with polypropylene fiber contents and lateral confinement", Cement and Concrete Research, 2005; 35, 1747–1753.
[2] Li J., Hadi M.N.S., "Behaviour of externally confined high-strength concrete columns under eccentric loading", Composite Structures, .(2003); 62, 145–153.
[3] Hadi M.N.S. , Li J., "External reinforcement of high strength concrete columns", Composite Structures, (2004); 65, 279–287.
[4] Touhari M. , Mitiche-Kettab R., " Behaviour of FRP Confined Concrete Cylinders: Experimental Investigation and Strength Model", Periodica Polytechnica Civil Engineering, (2016); 60(4), 647–660.
[5] Khaloo A. , Javid, Y., Tazarv M., " Experimental Study of the Internal and External (FRP) Confinement Effect on Performance of Compressive Concrete Members" Composite Structures, (2006); (2), 672-682.
[6] ASTM C 150,"Standard Specification for Portland Cement," Annual Book of ASTM Standards, American Society for Testing and Materials, 1997.
[7] ASTM Designation : C 494/C 494M – 05a,"Chemical Admixtures for Concrete", 2005 Annual Book of ASTM, standard American Society for Testing of Materials, Philadelphia, Pennsylvania, Section 4, Vol. 04-02, pp. 248-255.
[8] B.S 882:1992 "Specifications for Aggregate from Natural Sources for Concrete".
[9] Product Data Sheet Edition 13/6/2006, Identification no:02 04 01 02 001 0 000025, Sika Wrap® -230 C, "Woven Carbon Fiber Fabric for Structural Strengthening"
[10] ASTM Designation : C 39/C 39M – 05,"Compressive Strength of Cylindrical Concrete Specimens", 2005 Annual Book of ASTM, standard American Society for Testing of Materials, Philadelphia, Pennsylvania, Section 4, Vol. 04-02, pp. 20-24.
[11] Mohammed A. A. , Faiud Y. K., "Parameters Affecting the Behavior of Reinforced Concrete Wrapped with CFRP Sheet" Al-Rafidain Engineering journal, (2012); 20(2) , 1-26
[12] Hadi M. N. S. (2011)." External Reinforcement of Concrete Columns", 11th Underground Coal Operators' Conference, University of Wollongong & the Australasian Institute of Mining and Metallurgy; 121-128.
[13] Richart F. E. , Brandtzaeg A. , Brown R. L. "The Failure of Plain and Spirally Reinforced Concrete in Compression" Engineering Experiment Station, University of Illinois, Urbana, USA. (1926); p. 51.
[14] Benzaid R. , Mesbah H. , Chikh N., "FRP-confined Concrete Cylinders: Axial Compression Experiments and Strength Model", Journal of Reinforced Plastics and Composites, (2010); 29(16).
[15] Murugan M. , Natarajan C. , Muthukkumaran K., "Compressive Behavior of Concrete Cylinders Confined with Glass and Carbon Fiber Reinforced Polymers", International Journal of Structural and Civil Engineering Researches, (2013); 2(2), 69-76.
[16] Fardis MN. , Khalili H., "FRP-encased Concrete as a Structural Material", Magazine of Concrete Research, (1982); 34, 191-202.
[17] Ozbakkaloglu T. , Jian C., " Axial compressive behaviour

of FRP confined concrete: Experimental test database and a new design-oriented model" Composites Part B: Engineering, (2013); 55, 607-634.

[18] Pham T X. , Hadi M., "Confinement model for FRP confined normal- and high strength concrete circular columns", Construction and Building Materials, (2014); 69, 83–90

[19] Lam L. ,Teng J. G. , Cheung C. H. , Xiao Y., "FRP-confined Concrete under Axial Cyclic Compression", Cement Concrete Compos., (2006); 28, 949-958.

[20] Vincent T. , Ozbakkaloglu T., "Influence of concrete strength and confinement method on axial compressive behaviour of FRP confined high- and ultrahigh-strength concrete", Composites Part B: Engineering, (2013); 50, 413-428,

[21] Berthet JF. , Ferrier E. , Hamelin P., "Compressive behavior of concrete externally confined by composite jackets. Part A: experimental study", Construction Building Materials, (2005); 19 (3), 223-32.

[22] Cui C. and Sheikh A., "Experimental study of normal- and high-strength concrete confined with fiber-reinforced polymers", ASCE J Composite Construction, (2010); 14(5), 553-61.

[23] Silva MAG., Rodrigues CC., "Size and relative stiffness effects on compressive failure of concrete columns wrapped with glass FRP", ASCE J Mater Civ Eng, (2006);18(3), 334-42.

[24] Youssef MN. , Feng MQ. , Mosallam AS., "Stress–strain model for concrete confined by FRP composites", Compos B Eng, (2007); 38(5–6), 614–28.

[25] Vincent T. , Ozbakkaloglu T., " Influence of fiber orientation and specimen end condition on axial compressive behavior of FRP-confined concrete", Construction Building Materials, (2013); 47, 814-26.

[26] Jiang T. ,Teng JG., "Analysis-oriented stress–strain models for FRP-confined concrete". ASCE J Eng Struct, (2007); 29(11), 2968-86.

[27] Lin HJ. , Chen CT., "Strength of concrete cylinder confined by composite materials". Journal of Reinforced Plastics and Composites, (2001); 20 (18), 1577-600.