MINISTRY OF EDUCATION
TECHNICAL UNIVERSITY OF CIVIL ENGINEERING OF BUCHAREST
DOCTORAL SCHOOL

ADVANCED PROCEDURES ON STRENGTHENING SQUARE CONCRETE COLUMNS WITH CFRP COMPOSITES IN DIFFERENT CONFIGURATIONS

SUMMARY

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1. INTRODUCTION

1.1 General

Columns behaviour and performance are extremely important for the buildings and structures safety. [1]

Nowadays, it is widely noticed that there is require for strengthening and/or retrofitting of concrete structures and the most common elements are beams and columns. The damage of the Reinforced Concrete (RC) structures occur due to various situations like: age, mechanical actions, over loading, seismic actions, alter in the facility use, or modifications of code requirements. Confinement of concrete columns is an effective method used to improve the columns axial compression capacity and ductility. [2]

Initially, the old strengthening/retrofitting technique of structural columns was executed by using of steel or concrete jackets grouted to the concrete core, but at toward the start of the 1990s they were exchanged by Fibre Reinforced Polymer (FRP) jacketing technique. The implementation of FRP materials such as Carbon Fiber Reinforced Polymer (CFRP) for columns strengthening/retrofitting acquired popularity in the last few years, not only for its ease of application and flexible, but mostly for its fundamental properties as a material, such as: high strength to weight ratio, and corrosion resistance. [2]

CFRP confinement is carried out by wrapping the fibers mainly in the hoop direction to the column longitudinal axis achieving passive confinement, once the concrete core starts dilating due to internal cracks, the CFRP jacket is activated.

1.2 Problem definition

So far, the most of all buildings the columns cross-sections are square and rectangular columns. Therefore, special attention need to be given to their strengthening and rehabilitation to maintain the safety of buildings infrastructure, especially, for rectangular / square sections with section depth ≥ 300mm because the recent studies have proved that the compression behavior of FRP-confined columns is significantly affected when the size of a rectangular / square cross-section increased [66]. This work is directed to the strengthening techniques applied to non-slender low strength square concrete columns with cross-section of (300 x 300mm) subjected to pure compression loading.

1.3 Aim and scope

The main objective of this study is to investigate experimentally and analytically the effects of CFRP strengthening in different configurations on the strength and the load carrying capacity of low strength concrete square columns with section (300 x 300mm) subjected to axial loading by jacketing of CFRP sheets and with/without CFRP strips in addition to that the CFRP anchors spike were combined to increase the effective confined area of square sections because in the previous researches the CFRP confinement pressure consecrates on the square concrete corners and not on the entire parameter. The main intent of this research are as the following below:

1) To investigate the efficiency of CFRP strengthening of low strength square concrete columns;

2) To investigate the effect of the number of CFRP layers on the ultimate load capacity of confined square concrete columns;

3) To investigate the effect of using full and partial confinement on the same and different specimen.

4) To evaluate the effect of combining the CFRP anchor spike system with CFRP jacket in strengthening square columns.

5) To evaluate the experimental results with the theoretical predictions models of (ACI 440-17, FIB-90-19, CNR-DT 200-13 and models presented by authors)

6) A parametric finite element study have been conducted to evaluate and compared with the experimental results.

2. LITERATUR2E REVIEW

2.1 The use of FRP strengthening materials

2.1.1 Externally bonded FRP reinforcement (EBR)

One of the present’s state-of- art tacks is the use of FRP materials, which are presently viewed by structural engineers as new and considerably promising materials in the construction industriousness. Composite materials for strengthening of civil engineering structures are available generally in the form of: [6]

- Thin unidirectional strips (thickness in the order of about 1 mm); and
- Flexible sheets or fabrics, made of fibres in one or at least two different directions, respectively.

Fig. 2-1 shows the compression between the typical stress-strain diagrams of steel and unidirectional FRP composites under short-term monotonic loading.

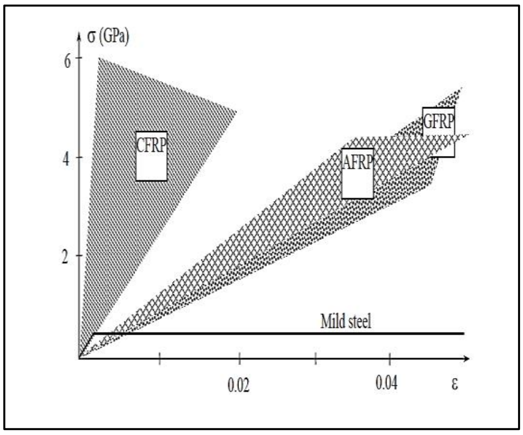


Fig. 2-1: Uniaxial tension stress-strain diagrams for different unidirectional FRPs and steel. CFRP = Carbon FRP, AFRP = Aramid FRP, GFRP = Glass FRP. [6]

To ensure the total structural integrity of the strengthened member it is important that proper FRP EBR systems should be used, correct design and proper execution. The condition of the concrete member before strengthening may need repair techniques before the applying of the FRP EBR system.

2.1.2 Advantages and disadvantages of FRPs

In general, FRP materials when compared to steel are characterized by: [6]

- Excellent corrosion resistance;
- Low weight (1/4 to 1/5 of steel);
- Stiffness tailored to the design requirements;
- Satisfactory chemical resistance;
- Unlimited availability in geometry and dimensions;
- Large deformation capacity; and
- Excellent fatigue strength and creep/relaxation performance.

However, composites can suffer from certain disadvantages, such as:

- Brittle behavior, i.e. linear elasticity to failure without any significant yielding (no yielding plateau) or plastic deformation;
- High cost of raw materials;
- Incompatible thermal expansion coefficients with concrete; and
- Exposure to high temperatures causes premature bond degradation.

2.2. Use of FRP anchors to strengthen concrete columns

Anchor spikes are known as FRP anchors or fiber anchors. Basically are consist of fibers strand with one end bonded in the composite matrix and the other end inserted in the concrete body. They can be fabricated to overcome several geometric complexities because they can be seamlessly integrated with the matrix of the FRP being anchored. Another advantage to anchor spikes is that the spikes can be fabricated from the same FRP materials as the externally bonded fabric, which facilitates construction and eliminates potential corrosion hazards from dissimilar materials. [47]

2.3 FRP-confined axially compressed concrete

2.3.1 Behavior of confined concrete

It is widely approved that confined concrete has higher compressive strength and strain than unconfined concrete. In fact, when the concrete specimens subjected to axial compression loading the confinement prevents the concrete expansion, resulting to higher load capacity. [8]

Therefore, until the developing of longitudinal cracks in concrete the stresses in the composite are small. As illustrated in Fig. 2-2, the typical stress-strain curves of concrete well confined by FRP composites are consist of three zones (elastic, transition and plastic zone).

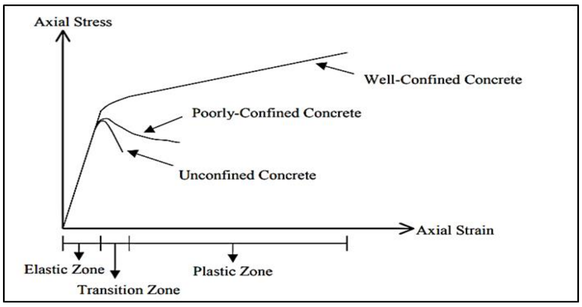


Fig. 2-2: Typical stress-strain curves for concrete confined by FRP. [9]

At the initial stage of loading the slope of the confined concrete curve is very similar to the unconfined concrete because the concrete afford less expansion under small level of loading and that does not activate the pressure in the FRP jacket. [9]

Once the peak strength of the unconfined concrete has been reached, the plastic zone develops immediately. In this level of loading, the concrete starts to expand fastly and resulting in activating the FRP jacket. In the plastic zone, a little increase in stress resulting in a considerable increase in lateral expansion (comparing to the elastic one). [9]

2.3.2 Various research findings

External confinement of concrete columns with Fiber Reinforced Polymer (FRP) was one of the attractive tasks in civil engineering covered through experimental and theoretical studies.

M. Reza Esfahani and M. Reza Kianoush (2005) presented the results of a study on the axial compressive strength of columns strengthened with FRP wrap. The experimental part included testing of three similar circular reinforced concrete columns (805 with D=203mm) strengthened with FRP wrap and three similar square columns (180 x 180 x 805mm), two with sharp corners, and the other with rounded corners. All specimens have the same steel reinforcement. [14]

The authors concluded that the FRP wrap can increase the axial strength and ductility of circular columns significantly. The application of FRP wrap may not increase the axial strength of square columns. However, if the corners of the square columns are rounded appropriately, the axial strength and ductility of columns increase considerably. [14]

M. Razavi, A. Mohd, Y. Ahmad and K. Koushfar (2013) an experimental test conducted to examine the effect of confinement efficiency on the behavior of circular and square concrete prisms confined with GFRP and CFRP composites and subjected to pure compression loading up to failure. The results proved that the prisms confined with CFRP composites achieved higher compressive strength than the prisms confined with GFRP composites. The investigators observed that the prisms with circular sections achieved higher strength than all prisms with square sections. [20]

Sushil S., Urmil V. and Himat S. (2013) presented a results of experimental test carried out on square reinforced concrete columns having various rounded corners and confined with GFRP composites subjected to compression loading up to failure. The experimental investigation of this study proved that the confined columns with rounded corners behaved better results than the control columns in term of upgrading the ultimate strength. Additionally, the confined columns with rounded corners equal to 25-mm had higher strength than the other confined ones with rounded corners equal to 5-mm. [22]

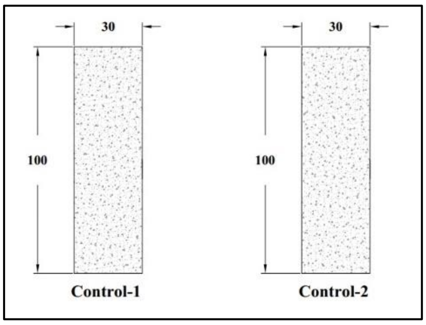
C. S. Lewangamage, C. K. Rankoth and M. T. R. Jayasinghe (2017) conducted experimental study on square reinforced and unreinforced concrete columns confined fully and partially with CFRP sheets/strips. The volumetric ratio of CFRP strips was kept constant to study the effect of the jacket arrangement pattern. The results showed that all fully and partially confined columns had considerable increase in strength and ductility. In addition, it has been observed that the strength and ductility increments would vary depending on the strips location. [26]

Xian Li et al (2017) [51] in this study the investigators had examined the effect of the cross-sectional aspect ratio and the internal steel reinforcement on the confinement efficiency offered by a combination of FRP wraps with FRP anchors for rectangular RC columns. The test results indicate that CFRP wraps enhanced the compressive strength of CFRP-confined rectangular RC columns even with a large aspect ratio of 2.25; however, the strength enhancement levels decreased with an increase in aspect ratio. CFRP anchors were effective in restraining concrete from bulging out and thus improved the confinement effectiveness of the CFRP wraps.

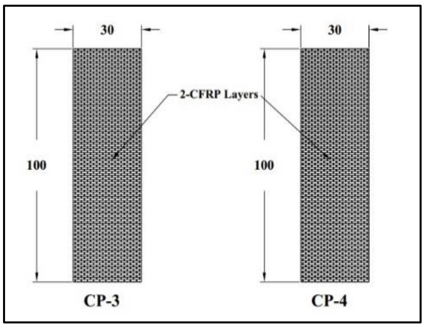
3. EXPERIMENTAL PROGRAM

3.1 Specimens details

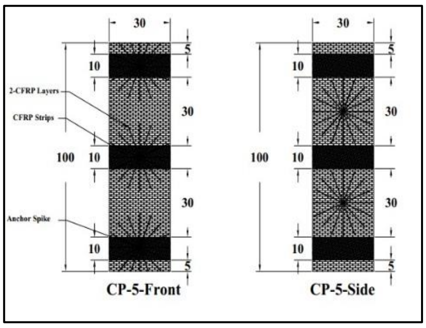
A total number of 8 (30 x 30 x 100) cm concrete prismatic columns with a corner radius of 3cm (recommend rounding them off to a radius of at least 2 cm in compliance with CNR-DT 200 R1/2013) [52] were tested with various CFRP arrangements. The experimental program was conducted in the laboratory of the Technical University of Civil Engineering of Bucharest. The specimens details are shown in Fig.3-1 (a – f).



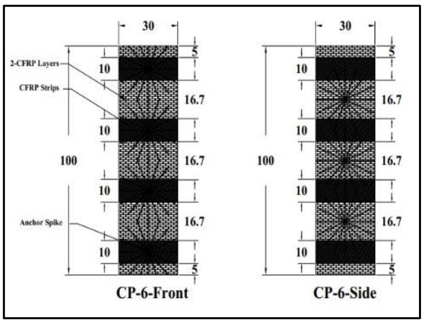
a) Two control specimens CP-Cnt 1 and CP-Cnt 2.



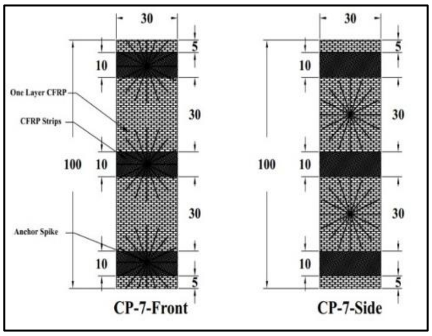
b) Two specimens CP-3 and CP-4 strengthened with 2 CFRP layers.



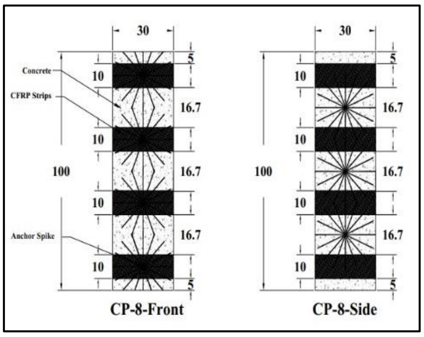
c) Specimen CP-5 strengthened with 2 CFRP layers, 3 CFRP strips and 10 CFRP anchors.



d) Specimen CP-6 strengthened with 2 CFRP layers, 4 CFRP strips and 14 CFRP anchors.



e) Specimen CP-7 strengthened with 1 CFRP layers, 3 CFRP strips and 10 CFRP anchors.



f) Specimen CP-8 strengthened with 4 CFRP strips and 14 CFRP anchors.

Fig. 3-1: Details of tested specimens.

Note: all dimensions of the tested columns in the figures are in centimetre.

3.2 Concrete materials

3.2.1 Cement

Ordinary Portland cement type CEM II B-LL 32,2 R was used in the present work.

3.2.2 Aggregates

The fine and coarse aggregates size were ranging from (0/4mm – 8/16mm) used throughout this work provided by AGREMIX company (local company)

3.2.3 Plastiproof type A (admixture)

PLASTIPROOF is a liquid admixture acting as a waterproofing agent and concrete plasticizer (ASTM C-494: Type A) [55].

3.2.4 Water

Ordinary tap water was used for mixing purposes.

3.3 Materials proportion

Mixes proportion by weight were used throughout the present work to get a vibrated concrete strength of approximately (low strength concrete with average of 28 days cube compressive strength of approximately C16/20), the weight of materials for concrete are illustrated by Table (3-1).

Table 3-1: Concrete mix proportions.

Class	Cement	Cement dosage (kg/m^3)	Water (L)	Admixture Plastiproof 0.5% (L)	Agreggates (kg)	0-4 (kg)	4-8 (kg)	8-16 (kg)
C 16/20	CEM II B-LL 32,5 R	280	188.33	1.26	1890	794	378	718

3.4 Testing of fresh concrete

Fresh concrete properties can be examined based on slump test which is a standard workability test for concrete in accordance with EN 12350-2:2009 [56], the slump-height of the compacted concrete was measured and it was 13.5mm in accordance with EN 12350-2:2009 [56].

3.5 Mechanical properties of hardened concrete

3.5.1 Compressive Strength

For each batch, the strength of concrete was determined by testing six standard cubes after 28 days. The compression tests were performed using the universal testing machine. Table 3-2 illustrate the average compressive strength values of concrete cubes at 28 days for each batch.

Table 3-2: Concrete compressive strength of cubes.

Batch No.	Specimen ID	$f_{c,\ cube}$ *(MPa)*
1	CP-Cnt 1	22.5
	CP-3	
2	CP-Cnt 2	24.5
	CP-4	
3	CP-5	24.2
	CP-6	
4	CP-7	23.6
	CP-8	

3.6 CFRP materials properties

3.6.1 CFRP sheets/strips

MapeWrap C UNI-AX 240 high tensile strength carbon fiber fabric was used for jacketing / strips. The nominal thickness of the CFRP materials was of 0.133 mm. The mechanical properties of CFRP flexible sheets were taken from manufacturing specifications and as presented in in Table 3-3.

Table 3-3: Technical properties of MapeWrap C UNI-AX 240.

CFRP sheet type	Tensile strength (MPa)	Modulus of elasticity (MPa)	Elongation at failure (%):	Equivalent thickness of dry fabric (mm)
MapeWrap C UNI-AX 240	4,830	252,000	2	0.133

3.6.2 MapeWrap C FIOCCO 8mm (anchor spike)

MapeWrap C FIOCCO 8mm was used as CFRP anchors. Technical properties of the CFRP (MapeWrap C FIOCCO) were taken from manufacturing specifications and presented in Table 3-4.

Table 3-4: Technical properties of the CFRP (MapeWrap C FIOCCO).

CFRP anchor spike connectors	Tensile strength (MPa)	Modulus of elasticity (MPa)	Carbon cord diameter (mm)
MapeWrap C FIOCCO	4,830	230.000	8

3.7 Jacketing of CFRP composites and anchors spike installation

Fig. 3-2 (a-d) illustrates the steps of wrapping the CFRP sheets.

a) Cleaning the concrete surface.

b) Applying two coats of MapeWrap Primer 1.

c) Applying epoxy resin MapeWrap 31

d) Wrapping CFRP sheets with the fibers oriented in the hoop direction

Fig. 3-2: Steps of wrapping the CFRP sheets.

Fig.3-3 illustrates the steps of installing the MapeWrap C FIOCCO connectors.

a) Wrapping CFRP strips.

b) Wrapping CFRP strips

c) Drilling holes for the anchors.

d) Insert MapeWrap FIOCCO cord in each hole.

e) Inject Mapefix VE SF 300 fastener to fill the holes.

f) Apply a coat of MapeWrap 31 on the substrate then splay all the fibers

Fig. 3-3: The steps of the CFRP anchors installation.

3.8 Load measurements

The experimental test was carried out using a universal testing machine with maximum capacity of 3000 KN, available in the laboratory of the Technical University of Civil Engineering of Bucharest. The machine is shown in Fig. 3-4.

Fig. 3-4: Universal testing machine used to test concrete columns.

3.9 Axial strain measurements

Axial strains were measured using mechanical dial gauge, the readings were taking from front and back side as shown in Fig. 3-5.

Fig. 3-5: Axial strain measurement.

3.10 Testing procedure

All specimens were subjected to a monotonic axial compression load up to failure using an Electro-hydraulic universal testing machine with a vertical load capacity of 3000 KN. Axial load were recorded in every 200 KN increment of load in the first 1000KN and every 100KN from 1100KN up to the failure load. The load was applied gradually. At each load increment, readings were recorded manually. Axial strains were recorded for every increment of load up to about $0.75P_u$, because of using mechanical dial gauge for strain readings with expected of explosive failure of tested columns made the test hazardous and complex.

4. TEST RESULTS

4.1 Test observations and failure modes

4.1.1 Unconfined columns

The performance and the final failure mode of the unconfined columns (CP-Cnt1 and CP-Cnt2) under axial load was as expected. At the early stages of loading a linear elastic behavior of the concrete can be assumed, with increasing the applied axial load, micro cracking of concrete core will start to generate and propagate. Consequently, a diminishing of the concrete stiffness occurs micro cracks join each other leading gradually to visible longitudinal cracks parallel to load direction. For these two columns, failure happened suddenly due to longitudinal cracks with direction of loading followed by crushing of the concrete.

For column (CP-Cnt1) the first crack noticed at 1500KN of loading and failed at 1830KN, while for (CP-Cnt2) the first crack noticed at 1550KN of loading and failed at 1920KN. Fig. 4-1 illustrate the failure mode of the unconfined columns.

a) Concrete column (CP-Cnt1)

b) Concrete column (CP-Cnt2)

Fig. 4-1: Failure mode of the unconfined columns.

4.1.2 Confined columns

The final failure shapes of the strengthened concrete specimens can be seen in Fig.4-2 from (a – f). The strengthened columns behaved very similar to that of unconfined concrete during the initial steps of applied loading because in the elastic zone the concrete offers little expansion under small level of loads and thus does not activate the jacket to produce confinement pressure.

With increasing the axial load increments, the propagation of micro cracking of concrete core resulting the lateral expansion of concrete which activate the CFRP jacket and the stresses start transfer from the expanded concrete to the CFRP jacket. During increasing the applied load up to 85% of the failure load, clicking sounds could be heard (first crack of CFRP), indicating the straining of the CFRP system and the cracking of the epoxy resin which indicates that the resin has yielded, leaving only the carbon fibers to take the hoop tension. All the tested strengthened concrete columns failed by the rupture of the carbon fibers sheet/strip near to the mid-point of the specimen height and / or within the column edges. Additionally, the failure of each strengthened column happened suddenly with an explosion sound with crushed concrete. The sudden and explosion failure signifies the release of exceptional value of energy due to the confining pressure provided by the confinement of CFRP system.

For column CP-3 the first crack of CFRP was recorded at 1925KN of loading and failed at 2250KN, while for the column CP-4 the first crack of CFRP was noticed at 2250KN and failed at 2350KN.For the column CP-5 the first crack of CFRP was recorded at 1950KN of loading and failed at 2150KN, while column CP-6 the first crack of CFRP was noticed at 2007KN and failed at 2190KN.For the column CP-7 the first crack of CFRP was recorded at 1850KN of loading and failed at 2200KN, while for column CP-8 the first crack of CFRP was noticed at 1720KN and failed at 2070KN.

Fig. 4-2 a: Failure mode of the strengthened column (CP-3).

Fig. 4-2 b: Failure mode of the strengthened column (CP-4).

Fig. 4-2 c: Failure mode of the strengthened column (CP-5).

Fig. 4-2 d: Failure mode of the strengthened column (CP-6).

Fig. 4-3 e: Failure mode of the strengthened column (CP-7).

Fig. 4-3 f: Failure mode of the strengthened column (CP-8).

Fig. 4-2: Failure mode of the tested strengthen columns.

4.2 Load carrying capacity and compressive strength

Table 4-1 indicates the results in terms of upgrading in the ultimate axial compressive strength and load carrying capacity with respect to control specimens. The maximum increase in compressive and load carrying capacity achieved in CP-3 and CP-4 (both columns confined with 2 layers of CFRP) with respect to control were 23% and 22% respectively, while the minimum increase achieved in CP-8 (partial confined with 4 CFRP strips and 14 CFRP anchors) was 10%, whereas those achieved CP-5 (confined with 2 layers of CFRP, 3 CFRP strips and 10 CFRP anchors) , CP-6 (confined with 2 layers of CFRP, 4 CFRP strips and 14 CFRP anchors) and CP7(confined with 1 layer of CFRP, 3 CFRP strips and 10 CFRP anchors) were 14%, 16%, 17% and respectively.

Table 4-1: Experimental Results.

Specimen ID*	$f_{c,\ cube}$ MPa	$f_{c,\ cyl}$ = 0.8 $f_{c,\ cube}$ MPa**	CFRP Strengthening Details	$P_{u,\ exp}$ (KN)		$\frac{P_{u,exp,cc}}{P_{u,exp,co}}$	$f_{c,\ exp} = \frac{P_{u,exp}}{A_c\ (300x300)mm}$ MPa
CP-Cnt 1	22.5	18	-	1830	Av. (1875)	-	20.33
CP-Cnt 2	24.54	19.6	-	1920		-	21.33
CP-3	22.5	18	2 CFRP ply	2250***		1.23	25
CP-4	24.5	19.6	2 CFRP ply	2350***		1.22	26.11
CP-5	24.2	19.3	2 CFRP ply+3 CFRP strip+10 CFRP anchors	2150***		1.14	23.88
CP-6	24.2	19.3	2 CFRP ply+4 CFRP strip+14 CFRP anchors	2190***		1.16	24.33
CP-7	23.6	18.8	1 CFRP ply+3 CFRP strip+10 CFRP anchors	2200***		1.17	24.44
CP-8	23.6	18.8	4 CFRP strip+14 CFRP anchors	2070***		1.10	23

*: The cross sectional area of all tested columns are 300 x 300mm.

**: Equivalent cylinder compressive strength $f_{c,\ cyl} = 0.8\ f_{c,\ cube}$, EN-206:2013 [57]

*** : The ultimate load carrying capacity of CP-3 compared with CP-Cnt 1 because they are from the same concrete batch and same compressive strength. The same happened for CP-4 compared with CP-Cnt 2. While for CP-5, CP-6, CP-7 and CP-8 were compared with average strength values of the CP-Cnt 1 and CP-Cnt 2.

Fig. 4-3 to Fig. 4-9 shows the axial load – axial deformation carves of unconfined and confined specimens respectively.

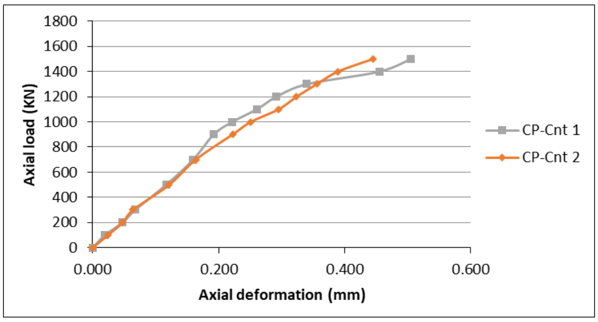


Fig. 4-3: Load – axial deformation for tested columns (CP-Cnt 1 and CP-Cnt 2).

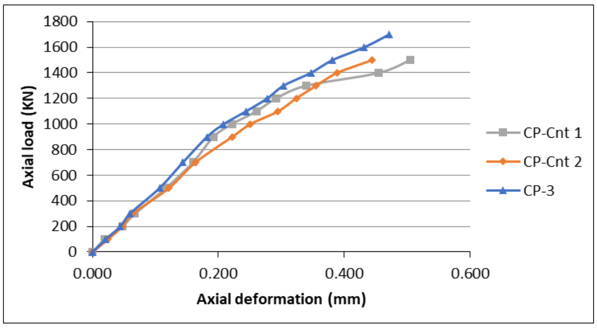


Fig. 4-4: Load – axial deformation for tested columns (CP-Cnt 1, CP-Cnt 2 and CP-3).

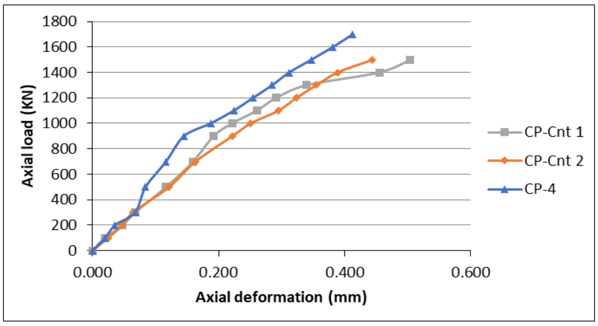


Fig. 4-5: Load – axial deformation for tested columns (CP-Cnt 1, CP-Cnt 2 and CP-4).

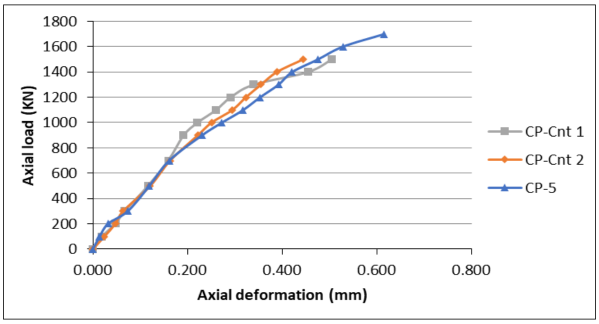


Fig. 4-6: Load – axial deformation for tested columns (CP-Cnt 1, CP-Cnt 2 and CP-5).

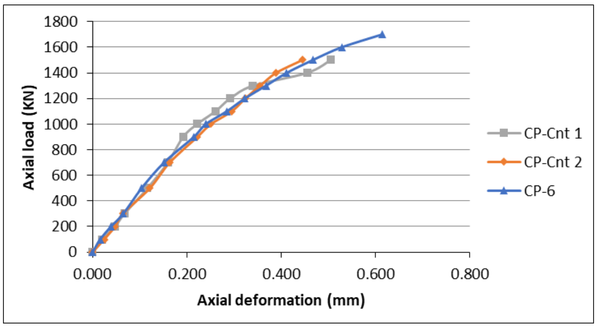


Fig. 4-7: Load – axial deformation for tested columns (CP-Cnt 1, CP-Cnt 2 and CP-6).

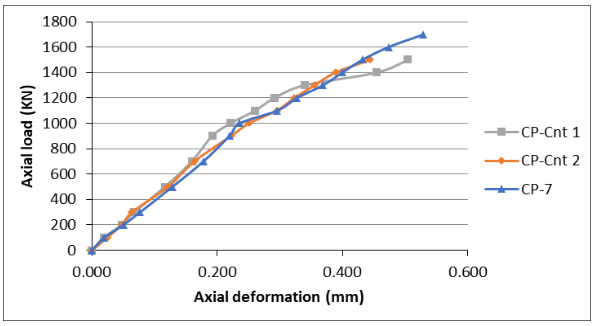


Fig. 4-8: Load – axial deformation for tested columns (CP-Cnt 1, CP-Cnt 2 and CP-7).

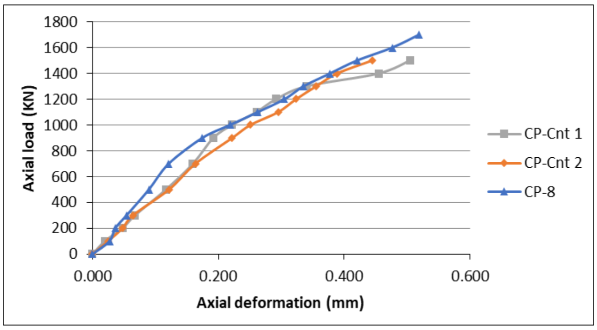


Fig. 4-9: Load – axial deformation for tested columns (CP-Cnt 1, CP-Cnt 2 and CP-8).

Note: All figures contain the recorded values up to about 0.75P_u because of using mechanical dial gauge the axial deformation readings were recorded for about 75% of ultimate axial load (failure load).

From the curves, it can be noticed that the strengthened specimens behaved very similar to that of the unstrengthen ones in the initial load stages because in the elastic zone the concrete offers little expansion under small level of loads and thus does not activate the jacket to produce confinement pressure to the concrete core, with increasing the applied load level the micro cracks start to propagate in the concrete core which make the concrete to expand laterally resulting in activate the CFRP jacket and the plastic behavior of the carve zone starts.

5. THEORATICAL PREDICTION OF LOAD CARRYING CAPACITY OF CONCRETE COLUMNS

5.1 General

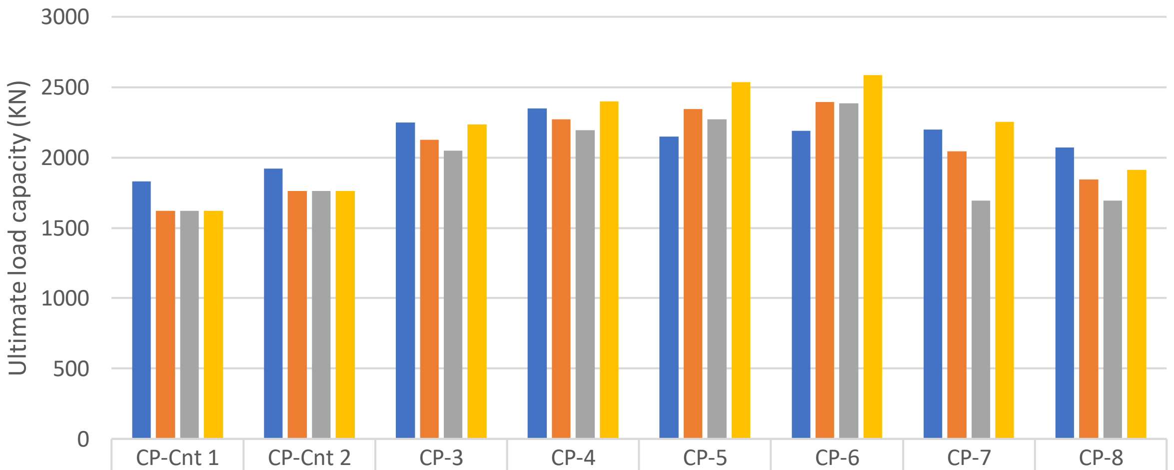
In this part of the study a calculations of the ultimate compressive strength and ultimate load carrying capacity of the tested concrete columns were presented by the theoretical predictions of models reported by the following codes and researchers:

1. ACI 440.2R-2017; [59]
2. FIB Bulletin-90-2019; [60]
3. CNR-DT 200 R1-2013; [52]
4. Lam and Teng model 2003b; [62]
5. Ouyang and Liu model 2007; [63]
6. Wang et al model 2016; and [66]
7. T. C. Triantafillou et al model (2015). [70]

Table 5-1 and Fig. 5-1 shows a comparison between the experimental results from this study and the theoretical predictions by three codes ACI 400.2R-17, FIB Bulletin-90-19 and CNR-DT 200 R1-13. While, Table 5-2 and Fig. 5 -2 show a comparison between the experimental results from this study and the theoretical predictions by four models presented by the above mentioned authors.

Table 5-1: Comparison between the experimental and theoretical predictions by Codes.

Specimen ID	$P_{u,exp}$ (KN)	$P_{u,ACI}$ (KN)	$P_{u,exp}/P_{u,ACI}$	$P_{u,FIB}$ (KN)	$P_{u,exp}/P_{u,FIB}$	$P_{u,CNR}$ (KN)	$P_{u,exp}/P_{u,CNR}$
CP-Cnt 1	1830	1620	1.13	1620	1.13	1620	1.13
CP-Cnt 2	1920	1764	1.08	1764	1.08	1764	1.08
CP-3	2250	2127.6	1.05	2047.5	1.09	2235.4	1.006
CP-4	2350	2272	1.03	2194	1.07	2397.1	0.98
CP-5	2150	2344.5	0.91	2271.6	0.94	2537.1	0.84
CP-6	2190	2394.9	0.91	2385	0.91	2585.5	0.84
CP-7	2200	2045.7	1.07	1692	1.30	2252.3	0.97
CP-8	2070	1842	1.12	1692	1.22	1909.8	1.08



	CP-Cnt 1	CP-Cnt 2	CP-3	CP-4	CP-5	CP-6	CP-7	CP-8
Exp	1830	1920	2250	2350	2150	2190	2200	2070
ACI	1620	1764	2127.6	2272	2344.5	2394.9	2045.7	1842
FIB	1620	1764	2047.5	2194	2271.6	2385	1692	1692
CNR	1620	1764	2235.4	2397.1	2537.1	2585.5	2252.3	1909.8

Fig. 5-1: Comparison between the experimental and theoretical predictions by Codes.

Table 5-2: Comparison between the experimental and theoretical predictions by authors.

Specimen ID	$P_{u,\,exp}$ ***(KN)***	$P_{u,Lam\ and\ Teng}$ ***(KN)***	$P_{u,\,exp} / P_{u,\,Lam\ and\ Teng}$	$P_{u,\,Ouyang\ and\ Liu}$ ***(KN)***	$P_{u,\,exp} / P_{u,\,Ouyang\ and\ Liu}$	$P_{u,\,Wang\ et\ al}$ ***(KN)***	$P_{u,\,exp} / P_{u,\,Wang\ et\ al}$	$P_{u,\,Triantafillou\ et\ al}$ ***(KN)***	$P_{u,\,exp} / P_{u,\,Triantafillou\ et\ al}$
CP-Cnt 1	1830	1620	1.3	1620	1.3	1620	1.3	1620	1.3
CP-Cnt 2	1920	1764	1.08	1764	1.08	1764	1.08	1764	1.08
CP-3	2250	2249	1.00	1599.3	1.40	1947.6	1.15	2393.1	0.94
CP-4	2350	2393	0.98	1681.2	1.39	2091.6	1.12	2464.2	0.95
CP-5	2150	2366	0.90	1666.8	1.29	2064.6	1.04	2654.1	0.81
CP-6	2190	2366	0.92	1666.8	1.31	2064.6	1.06	2654.1	0.82
CP-7	2200	2006	1.09	1329	1.65	1855.8	1.18	2150.1	1.02
CP-8	2070	NA	NA	NA	NA	NA	NA	NA	NA

Note: NA, means that the strengthening technique of CP-8 was not applicable to the theoretical prediction models presented by the researchers.

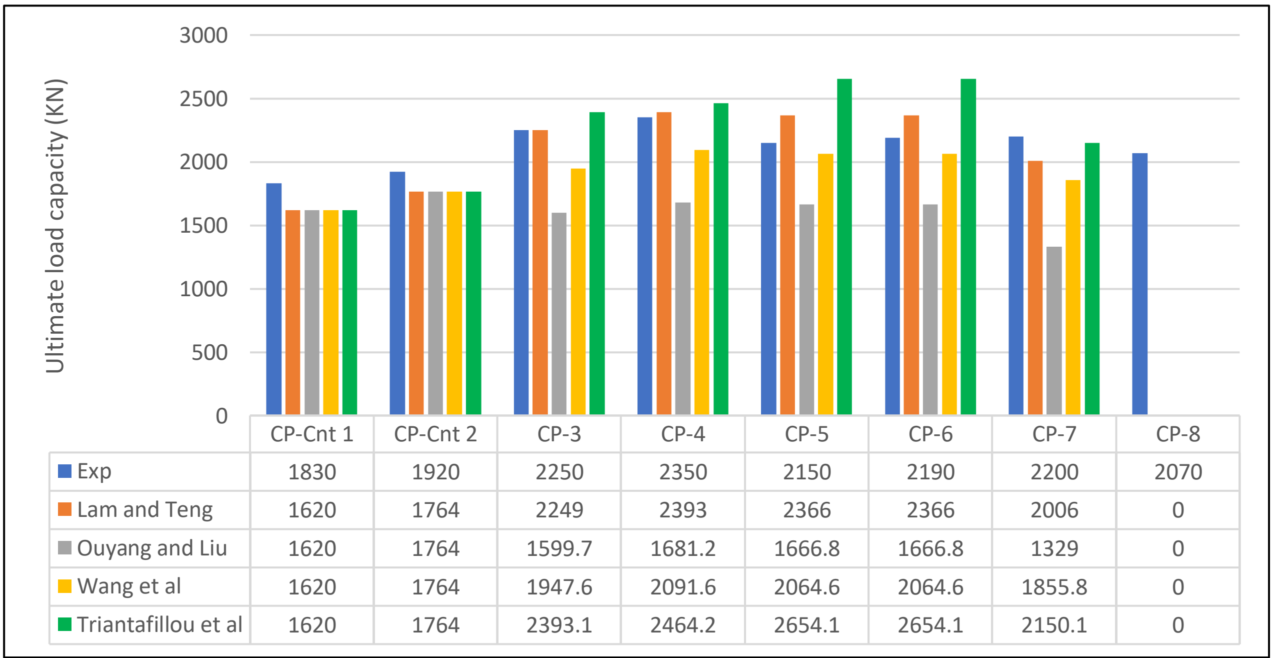


Fig 5-2: Comparison between the experimental and theoretical predictions by authors.

6. FINITE ELEMENT MODELING AND APPLICATIONS

6.1 General

In this part of the study, a three dimensional non-linear finite element formulation model has been presented using ANSYS-16.1 (software computer program) to analyse low strength concrete columns in square section strengthen by CFRP composites in different configurations.

A comparison has been made between the results obtained from the Finite Element Analysis (FEA) and the experimental data.

Parametric Study has been carried out to study the impact of the most important parameters such as: compressive strength of concrete, thickness of the CFRP layers and the presence of steel reinforcement on the performance of the modelled columns subjected to compression load.

6.2 Verification of the tested square concrete columns strengthened with CFRP

The tested column specimens have been analyzed by the FEA. A total of four columns were selected from the experimental test of this study to be modelled by FEA. All columns had the same cross section dimension 300×300 and 1000 mm in height.

6.3 Results of the numerical analysis (ultimate load capacity)

The ultimate loads of the modeled columns were specified by the state that the columns no longer can support extra load as indicated by the convergence failure of ANSYS program in failing to find a solution. Table 6-1 shows the ultimate load of modeled columns got from the software computer program (ANSYS 16.1) with experimental test results.

Table 6-1: Experimental and numerical (ANSYS) of ultimate load capacities.

Column ID	Ultimate Load kN		$P_{u,Exp} / P_{u,Ansys}$
	$P_{u,Exp}$	$P_{u,Ansys}$	
CP-Cnt 1	1830	1680	1.09
CP3	2250	2193	1.02
CP-5	2150	2260	0.95
CP-7	2200	2111	1.04

The axial load-axial deformation curves of columns CP-Cnt 1, CP-3 , CP-5 and CP-7, acquired from the numerical analysis along with the experimental curves are presented and compared in Fig. 6-1. These figures reveal good agreement between the experimental and finite element axial load-axial deformation results. In addtition, complete curves have been obtained from ANSYS while the curves from the experimenal were up to 75% of the P_u because of using mechanical dail gage in reading the axial deformation during the test. Fig. 6-2 shows the nodal stress in the y direction at failure load of the modeled columns.

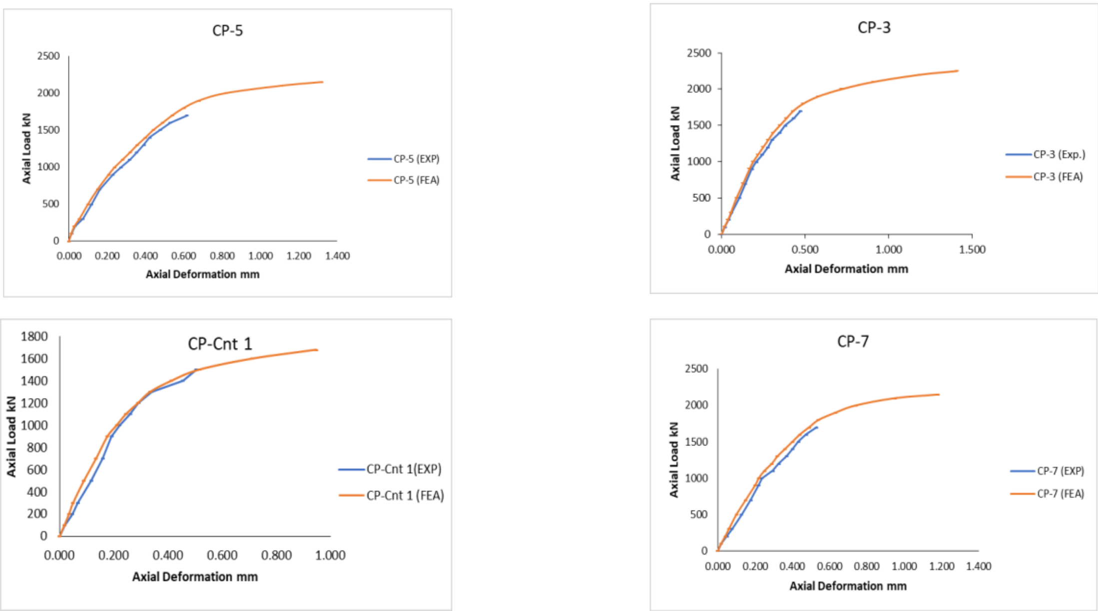
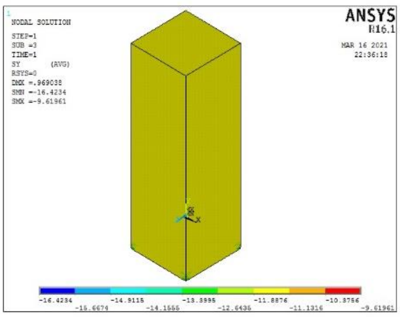
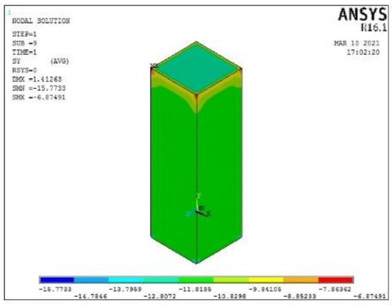


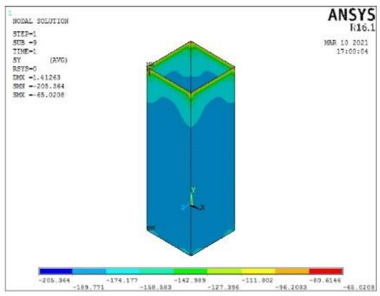
Fig. 6-1: The axial load-axial deformation curves of columns CP-Cnt 1, CP-3, CP-5 and CP-7 for both analytical and experimental



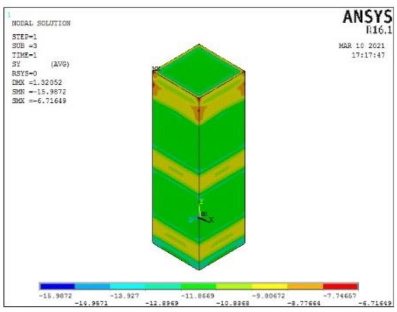
Stresses of concrete of CP-Cnt 1



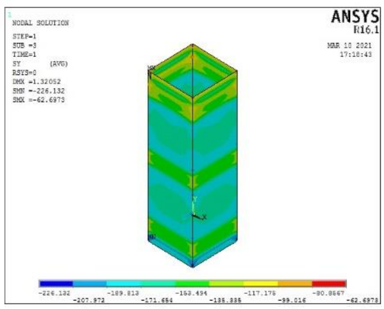
Stresses of concrete of CP-3



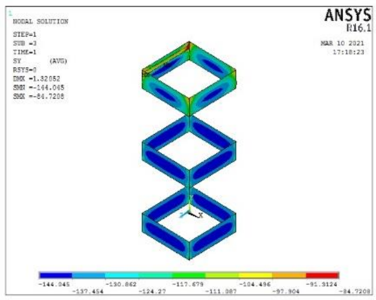
Stresses of CFRP jacket of CP-3



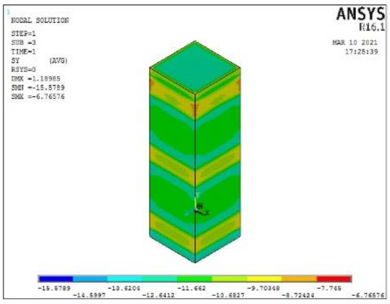
Stresses of concrete of CP-5



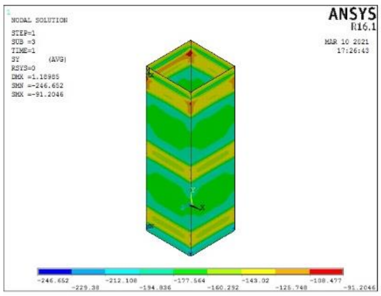
Stresses of CFRP jacket of CP-5



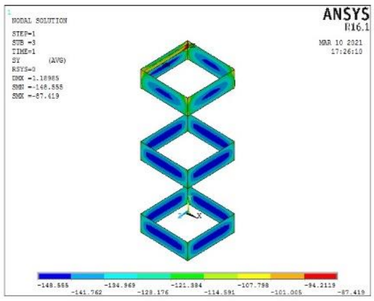
Stresses of CFRP strips of CP-5



Stresses of concrete of CP-7



Stresses of CFRP jacket of CP-7



Stresses of CFRP strips of CP-7

Fig. 6-2: The nodal stress in the y direction at failure load of columns.

6.4 Parametric study

The evaluation on the effect of the foremost imprtant parameters to the behaviour of square concrete columns that could not be performed during the experimental test were performed by using the numerical finite element ANSYS. In the parametric study three parameters were employed to evaluate their effect on the ultimate load of the modeled columns. The parameters were included in this parametric study are:

6.4.1 Effect of number of CFRP Layers

In order to study the effect of number of CFRP layers used for columns CP-3 and CP-5, the columns have been numerically analyized using different numbers of CFRP layers (full layers). The selected numbers of layers were 3 and 4. The comparison between the numerical ultimate loads obtained from different amounts of CFRP layers (3 and 4 layers) of the tested columns are listed in Table 6-2 and 6-3 respectively. It is obvious that the ultimate load increases as the number of CFRP layers increases. When the amount of CFRP layes incresed from 2 to 3 layers, the ultimate load increased by about 5% for both CP-3 and CP-5 respectively as listed inTable 6-2, while when the amount of CFRP layes incresed from 2 to 4 layers, the ultimate load increased by about 10% for both CP-3 and CP-5 respectively as listed in Table 6-3.

Table 6-2: Numerical results of ultimate load with 2 and 3 CFRP layers.

Specimen ID	f_c (MPa)	FEA Strengthening (No of CFRP Layers)	$P_{u, Ansys}$ (kN)	FEA Strengthening (No of CFRP layers)	$P_{u, Ansys}$ (kN)	Ratio of $P_{u,Ansys}$
CP-Cnt 1	18	-	1680	-	-	-
CP-3	18	2 CFRP ply	2193	3	2305	1.05
CP-5	19.3	2 CFRP ply+3 CFRP strip+10 CFRP anchors	2260	3	2375	1.05

Table 6-3: Numerical results of ultimate load with 2 and 4 CFRP layers.

Specimen ID	f_c (MPa)	FEA Strengthening (No of CFRP layers)	$P_{u, Ansys}$ (kN)	FEA Strengthening (No of CFRP Layers)	$P_{u, Ansys}$ (kN)	Ratio of $P_{u,Ansys}$
CP-Cnt 1	18	-	1830	-	-	-
CP-3	18	2 CFRP ply	2193	4	2413	1.10
CP-5	19.3	2 CFRP ply+3 CFRP strip+10 CFRP anchors	2260	4	2475	1.10

6.4.2 Effect of concrete compressive strength

In this numerical analysis study the selected values of the compressive strength of concrete (f_c) were 42 and 60 MPa for columns CP-3, CP-5 and CP-7. The numerical ultimate loads obtained from different values of concrete compressive strength of the tested columns together with the experimental values are listed in Table 6-4. It can be noted from the table that the compressive strength of concrete has a signifcant effect on ultimate load. When the compressive strength of columns CP-3, CP-5 and CP-7 increased to 42 MPa, the ultimate load capacities increased by 228%, 211% and 232% respectively. When the compressive strength of columns CP-3, CP-5 and CP-7 increased to 60 MPa, the ultimate load capacities increased by 311%, 286% and 327% respectively. This effect was expected because the column is compression member and essentially depends on the compressive strength of concrete as more as in this study the applied loads were pure compression (concentric load).

Table 6-4: Numerical results of ultimate load with different compressive strength.

Column ID	f_c (MPa) (Exp)	$P_{u,Ansys}$ (kN)	f_c (MPa) (ANSYS)	$P_{u,Ansys}$ (kN)	Ratio of $P_{u,Ansys}$	f_c (MPa) (ANSYS)	$P_{u,Ansys}$ (kN)	Ratio of $P_{u,Ansys}$
CP-Cnt 1	18	1680	-	-	-	-	-	-
CP3	18	2193	42	5004	2.28	60	6840	3.11
CP-5	19.3	2260	42	4770	2.11	60	6470	2.86
CP-7	18.8	2111	42	4914	2.32	60	6903	3.27

6.4.3 Presence of steel reinforcement

In order to evaluate the effect of the presence of steel reinforcement on the ultimate load capacity of the tested square concrete columns confined with CFRP, assuming that the columns (CP- Cnt 1, CP-3, CP-5 and CP-7) having a steel reinforcing detailes (4 - Ø16 for main reinforcement and 7 Ø 10 for stirrups)

The numerical results obtained from the finite element software ANSYS revealed that the reinforcement steel didn't have any clear affect on the ultimate load capacty of the confined columns, the reason of that could be because the columns were subjected to axial compression load and it have been aporved previously that the concrete take the most action in compression than the longintudinal steel, in addtion to that the columns specimens have CFRP confinement which enhanced in the confinement instead of steel stirrups, while the unconfined column CP-Cnt1 gained the higher increase in the ultimate load capacity by 13% due to the presence of steel reinforcement, which dosn't have external CFRP. Table 6-5 shows the ultimate load capacities of the modeled columns with and without steel reinforcement.

Table 6-5: Ultimate load capacities of the modeled columns with and without steel reinforcement.

Column ID	Ultimate Load		Ratio of $P_{u,Ansys}$
	Without reinforcing steel	With reinforcing steel	
	$P_{u,Ansys}$ (kN)	$P_{u,Ansys}$ (kN)	
CP-Cnt 1	1680	1900	1.13
CP3	2193	2315	1.05
CP-5	2260	2230	0.98
CP-7	2111	2290	1.08

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The following conclusions are drawn from the experimental and analytical phases of this work:

7.1.1 Experimental phase:

1. The experimental results clearly approved that CFRP composite wrapping in different confinement procedures can enhance the ultimate load capacity and ultimate compressive strength of concrete columns under axial load.
2. Lateral deformation of concrete due to the axial loading can be resisted by wrapping the CFRP composites in the hoop direction which enhancing the concrete ultimate compressive strength.
3. The testing results showed unexpected values of the ultimate load capacity for CP-5 and CP-6 (confined with two-CFRP layers and CFRP strips combined with CFRP anchors) which were less than CP-3 and CP-4 (confined with 2 CFRP layers) and even less than CP-7 (confined with one-layer of CFRP with CFRP strips combined with CFRP strips). These unexpected values regarding to the ultimate capacities could happened because of the alternative arrangement of the anchors (not in the same position in each side). But

on the other hand the anchorage system improved based on the final failure mode of these confined columns where the failure didn't happen in the anchors zones, which was an aim of the research. In order to achieve a more effective confinement, the FRP strips be constrained on all sides through the use of anchors, thereby creating shorter distances which are confined between anchors.

4. The number of layers of CFRP materials is the major parameter, having a significant influence on the behavior of specimens. The test results from preliminary testing proved that the benefit of confinement could be enhanced by increasing the stiffness of external confinement by applying multiple layers. When the specimen was wrapped with one layer of CFRP (CP-7) the ultimate compressive strength and the ultimate axial load capacity increased with respect to the average values control specimens were 17%, while when the specimen was wrapped with two layers of CFRP (CP-3) the compressive strength and axial load capacity were increased with respect to control by 23%. This mean when the double quantity of fiber (100%) resulting in increase of extra 6%.
5. The test results of CP-7 also showed better economic technique option in terms of strength. In other words the using of one-CFRP layer (full confinement) and CFRP strips (partial confinement) combined with CFRP anchors resulting in increase in both axial load capacity and ultimate compressive strength with respect to control by 17%.
6. From the results both axial load capacity and ultimate compressive strength with respect to control increased 10% by using partial confinement (4CFRP strips) combined with CFRP anchors (CP-8), which can be considered as an acceptable strengthening technique in term of strength.
7. The final failure modes of all confined columns occurred suddenly with an explosive sound. The sudden and explosive failure refers the release of exceptional amount of energy due to the confining pressure provided by the CFRP composites strengthening.

7.1.2 Analytical and numerical phases:

1. All of the used models predict the strength values less than the experimental values of the unconfined columns and some of the confined columns.
2. The three models presented by ACI, FIB and CNR codes calculate the CFRP contribution of full and partial confinement.
3. The three models by Lam and Teng, Ouyang and Liu and Wang et al account the CFRP contribution of full confinement only, so it was able to calculate the strength for the tested columns having full confinement only (CP-3, CP-4, CP-5, CP-6 and CP-7), while the model presented by Triantafillou designed to calculate CFRP contribution of the full confinement combined with CFRP anchors.

4. The predicted values of CP-3 obtained from ACI, FIB and CNR showed good agreement with experimental values by 5%, 9% and 0.06% respectively less than the experimental values. The same was for CP-4 by 3% and 7% less than the experimental for ACI and FIB respectively and by 2% higher than the experimental with CNR, while the experimental values for both columns CP-3 and CP-4 showed good agreement with the model of Lam and Teng with values of 0% with the experimental value for CP-3 and 2% higher than the experimental values for CP-4. In addition the model of Triantafillou showed good agreement with experimental values of CP-3 and CP-4 by 6% and 5% respectively higher than the experimental values.
5. The predicted values of CP-5 and CP-6 obtained from ACI and FIB models showed good agreement with values between (6%-9%) higher than the experimental values, while the values obtained from CNR were not good in agreement with experimental values by 16% higher than the experimental values. In addition the predicted values of CP-5 and CP-6 obtained from the model of Lam and Teng showed good agreement with experimental values by 10% and 8% respectively higher than the experimental as well as the model of Wang showed good agreement with experimental values by 4% and 6% respectively less than the experimental values, while the model of Ouyang and Liu was conservative with about 30% less than the experimental values.
6. The predicted values of CP-7 obtained from ACI and CNR showed good agreement with experimental values by 7% less than the experimental value for ACI and 3% higher than the experimental value for CNR, while the value of FIB model was conservative by 30% less than the experimental value. In addition the predicted values obtained from both Lam and Teng model and Triantafillou model showed good agreement with experimental values by 9% and 2% respectively less than the experimental values, while the value obtained from Ouyang and Liu was conservative by 65% less than the experimental value.
7. For column CP-8, only the predicted value of CNR showed good agreement with experimental value by 8% less than the experimental value, while the models designed by the researchers were not applicable for CP-8 because they all designed for full confinement and CP-8 was partially confined.
8. The numerical FEA ANSYS results showed that external strengthening with CFRP composites are very effective in upgrading the ultimate load capacity of the square concrete columns with large dimensions (300 x 300 x 1000 mm).
9. The results also showed good agreement between the ANSYS and the experimental test results.

10. The analytical FEA results from the parametric study showed that when the CFRP layers increased from 2 to 3 and from 2 to 4 layers the ultimate load of column specimen CP-3 increased by 5% and 10% respectively. Also, when the CFRP layers increased from 2 to 3 and from 2 to 4 layers the ultimate load of column specimen CP-5 increased by 5% and 10% respectively.
11. The numerical FEA results proved that the compressive strength showed significant effect on the upgrade of the ultimate load, when the compressive strength of the modeled columns increased to 42MPa and to 60 MPa, the ultimate load of column specimen CP-3, CP-5 and CP-7 increased to about 200% and to about 300% respectively. This effect was expected because the column is a compression member and is essentially depends on the compressive strength of concrete as more as in this study the applied loads were pure compression (concentric load).
12. The numerical FEA results showed that the presence of steel reinforcing didn't have clear effect on the ultimate load of the confined columns. The reason of that could be because the columns were subjected to axial compression load and it has been approved previously that the concrete take the most action in compression than the longitudinal steel, in addition to that the columns specimens have external CFRP confinement which enhanced in the confinement instead of steel stirrups, while the unconfined column CP-Cnt 1 gained the higher increase in the ultimate load capacity by 13% due to the presence of steel reinforcement, which did not have external CFRP.

7.3 Future work

1. Study the effect of CFRP strengthening techniques used in this study but without anchorage system on the behaviour of square concrete subjected to axial loading.
2. Investigate the behaviour of square concrete columns with bigger cross section > 300mm with same CFRP strengthening techniques used in this study but with anchors to be in the same position at each side and subjected to axial compression load.
3. Investigate the behaviour of square/rectangular concrete columns confined by CFRP strips with change the locations of the strips to evaluate the effect of strips location on the ultimate strength when subjected to axial compression load.
4. Investigate the effect of the anchorage system used for square/rectangular concrete columns when the confined columns exposed to fire.
5. Use rectangular cross section to study the effect of side aspect ratio h/b on the behaviour of concrete columns when confined with same strengthening techniques used in this study.

6. Use Ultra High Performance Concrete (UHPC) to investigate the compressive behaviour of square concrete columns confined with the same strengthening techniques used in this study.

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