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Received on:16/03/2017
Accepted on:17/08/2017

Influence of Spirals on the Behavior of Short RC Columns Strengthened by External CFRP

Abstract- *An experimental study was carried out to investigate the behavior of normal strength reinforced concrete (RC) circular short columns strengthened by carbon fiber reinforced polymer (CFRP) sheets. Three series comprising total of (15) specimens were loaded to failure under axial concentric compression load. Strengthening was varied by changing CFRP strips number, spacing and wrapping methods. The finding of this research can be summarized as follows; for the columns without CFRP, the influence of the spiral pitch was significant: compared with 100 mm spiral pitch, dropping the spacing to 65 mm and 30 mm increased the load carrying capacity by 25% and 43% respectively. The columns with less internal confinement (lesser amount of spirals) were strengthened more significantly by the CFRP than the ones with greater amount of internal spirals. As an example of the varying effectiveness of the fully wrapped CFRP, the column with spiral pitch at 100 mm was strengthened by 74% with the CFRP. In contrast, the ones with 30 mm spiral pitch only increased in strength with CFRP by 51%. Compared with the control specimen (no CFRP), the same amount of CFRP when used as spiral strips led to more strengthening than using CFRP as hoop strip-the former led to nearly 8% more strengthening than the latter in the case of 100 mm internal spiral pitch. In the case of 65 mm the internal spiral pitch, the difference (between the hoops &spiral CFRP strengthening)is close to 10.5%. The difference between the two methods of strengthening in the heavily spiral columns (30 mm spiral pitch) is more significant.*

Keywords*-Carbon Fiber Reinforced Polymer, Load Carrying Capacity, Reinforced Concrete, Volumetric Ratio, Spiral columns.*

How to cite this article :K. F. Sarsam, R. I. Khalel and M.A. Hadi, "Influence of Spirals on the Behavior of Short RC Columns Strengthened by External CFRP" *Engineering and Technology Journal,* Vol. 36, Part A, No. 2, pp. ٢٢٣-٢٣٣, 2018.

1. Introduction

The columns are among the most important elements of a structure, given that their rupture can lead to the destruction of the whole building. There are a number of different types of reinforcement for existing concrete, including normal or high resistance concrete with supplementary reinforcement, the coating of existing columns with steel plates, applying additional steel fiber for concrete and, more recently, jacketing with a mantle of carbon fiber reinforced polymer (CFRP) [1]. The latter strengthening presents innumerable advantages, like the rapid and easy application of jacketing, enhanced fire resistance, and it does not increase the transversal section of the columns[2], also the substantial applications of CFRP strengthening technology is to enhance the load carrying capacity of RC columns throughout the provision of confining CFRP wrap. The column wrapping technique is especially effective for circular columns because the strength and ductility of concrete in a circular section can be basically increased through lateral confinement [3]. .
Although the high cost of the CFRPs, compared to the cost of the other strengthening materials, can be considered the main limitation for its use, when the whole costs during the lifespan of the structure are taken in consideration, the durability offered by the strengthened polymers can turn them in a very competitive option, through offering a great benefit-cost ratio [2]. Considering the need of a better understanding of the structural behavior of the strengthened columns, the present study provides an experimental work for the short columns of reinforced concrete (RC) strengthened with CFRP, with the primary objectives of determining the effect of the spiral pitch on the load carrying capacity of short RC columns represented as a volumetric ratio of transverse reinforcement and the effect of the external CFRP on the load carrying capacity of short RC columns.

2. Experimental Work

Through the design of the experimental program, the variables included in this study are focused mainly on the internal spiral pitch, CFRP strips number, spacing and wrapping methods. Detailed description of each variable is presented

https://doi.org/10.30684/etj.36.2A.15
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3. Specimens Description

A total of 15 RC specimens were designed with a circular section of 150 mm diameter and overall height of 600 mm. A concrete cover of 15 mm was provided in all confined specimens and between the ends of the longitudinal bars and the top and bottom surface of the column specimens to prevent direct loading on the bars.

The specimens were divided into three groups depending on the pitch of the spiral reinforcement; each five specimens were reinforced with six longitudinal steel bars of 6mm diameter and lateral spiral reinforcement of 4 mm diameter with 100, 65 and 30 mm spiral pitch respectively. Figure 1 shows the geometry of the spiral column specimens.

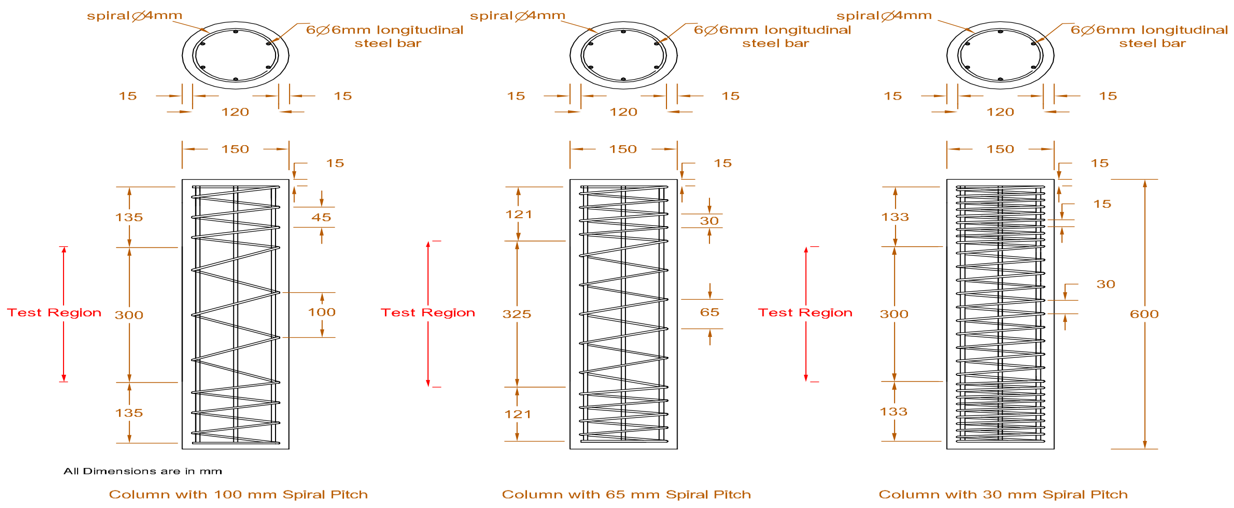

Figure 1: The geometry of the spiral column specimens

4. Specimen's Identification and Strengthening Schemes

In each specimens group (five columns), the first column specimen (Type A) is a control one. The second column specimen(Type B) is strengthened by 25mm width CFRP strip with hoop spacing of 115 mm c/c (CFRP ratio= 25%). The third column specimen(Type C) is strengthened by 25 mm width with CFRP strip as spiral with pitch of 160 mm (CFRP ratio= 25%), It is worth mentioning that the CFRP strip was wrapped helically in the opposite direction to the direction of the interval spiral reinforcement. The fourth column specimen(Type D) is strengthened by 25 mm width CFRP strip with hoop spacing of 58 mm c/c (CFRP ratio =50%) and the fifth column specimen(Type E) is strengthened with Full CFRP wrap (CFRP ratio=100%). see Figure2.

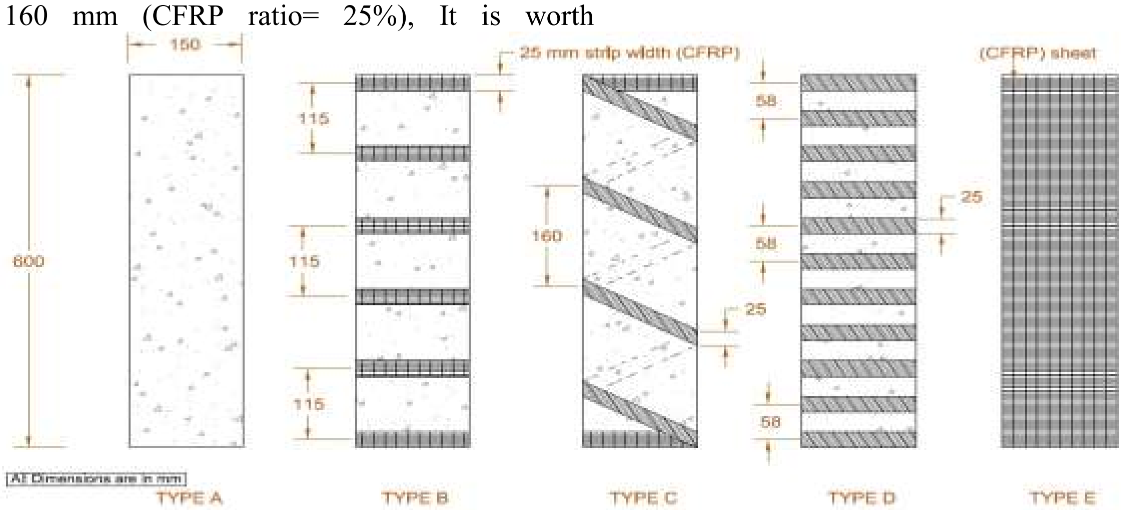

Figure 2: Types of CFRP confinement.

Column specimens are identified with a series of letters and numbers, which refer to the spiral columns by letter S. The numbers (100, 65 and 30) represent the lateral spiral pitch, while the letters (A, B, C, D and E) refer to the type of column's classification according to the external confinement by CFRP as in Figure 2. Figure 3 shows the key for the column specimens.

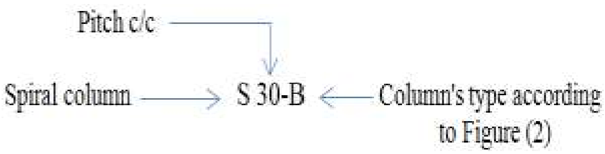

Figure 3: Column specimen's key.

5. Construction Materials

I. Cement

The cement used in this research is (Type I) ordinary Portland cement; it is producted in Iraq with trade mark (AL-Mass). The chemical and the physical analysis properties are in agreement with the Iraqi specification No.5/1984 [4].

II. Fine Aggregate

AL-Ukhaider natural sand with maximum size of 4.75mm was used as fine aggregate through this work. The specific gravity, sulfate content, fineness modulus and absorption of fine aggregate are within the requirement of Iraqi specification No.45.1984 [5].

III. Coarse Aggregate

Natural crushed gravel with maximum size of 10mm is used throughout this work. The aggregate was washed, stored in air to dry the surface, and then used in saturated surface dry condition. The grading of the coarse aggregate is within the requirement of the Iraqi specification No.45/1984[5].

IV. Water

Tap Water was used for mixing and curing the concrete.

V. Reinforcing Steel Bars

For all column specimens, two sizes of deformed steel bars are used. Bar size 6 mm diameter for longitudinal reinforcement with 513 MPa yield stress and bar size 4 mm with 717 MPa yield stress for the transverse reinforcement.

VI. Carbon Fiber Reinforced Polymers (CFRP)

SikaWrap®-300C Woven carbon fiber fabric is applied for strengthening or repairing system of reinforced concrete structures. Fiber type, mid strength carbon fiber. The roll of carbon fiber was 50cm width and 50 m length as reported by the manufacturer .This system was supplied by (sika Switzerland). Table 1 shows the product description of the (CFRP) from SikaWrap®-300C.

VII. Bonding Materials

Sikadur®-330 is recommended by SikaWrap®-300C Woven carbon fiber fabric manufacturer to bond CFRP to the concrete. Table (2) presents the product description for the Sikadur®-330

Table 1: The product description for SikaWrap®-300C Woven carbon fiber fabric*

Areal weight	**300g/m^2 ± 15 g/m^2**
Fabric design thickness	0.166 mm
Tensile E-modulus	230 000 N/mm^2
Tensile strength	3900 N/mm^2
Elongation at break	1.5% (nominal)

*Provided by the manufacturer.

Table 2: The product description for the sikadur®-330.*

Appearance /colours	**Part A:white, Part B:grey Parts A+B mixed=light grey**
Mixing ratio	Parts A : part B = 4 : 1 by weight
Density	1.30 kg/l + 0.1 kg/l (parts A+B mixed)
Tensile strength	30 N/mm^2 (7 days at +23°C)
Tensile E – modulus	Flexural: 3800 N/mm^2 (7 days at +23°C) Tensile: 4500 N/mm^2 (7 days at +23°C)
Elongation at break	0.9% (7 days at +23°C)

*Provided by the manufacturer.

6. Trial Mixed of Concrete

Several trial mixes are designed to reach the cylinder strength of (30MPa). Trial mix No. (4) was adopted for this study. Table 3 represents details for trial concrete mixes

Table 3: Details for the trial concrete mixes.

Trial No.	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)	W/C ratio	Mix ratio by weight	Compressive strength(MPa) 28 Day
1	330	780	922	205	0.61	(1:2.35:2.7)	17
2	350	710	1025	190	0.54	(1:2:2.9)	25
3	370	685	1020	190	0.51	(1:1.8:2.7)	27.3
4	400	740	1000	192	0.48	(1:1.85:2.5)	31

7. Concrete Mixes

The concrete is mixed by applying a horizontal rotary mixer with a capacity of ($0.1m^3$). The dry components of cement, sand and gravel are mixed for 4 to 5 minutes, then the water is add to the mixture in quarters then leaving all components to mix for 2 to 3 minutes.

8. Specimens Molds

The columns used PVC tubes cut to match the column height. The base of the mold is constructed from plywood, a way that prevents water from leaking through.

9. Casting and Curing

Totally three batches of concrete were used to cast the columns. Each batch was used to cast five columns with six cylinders (100×200) mm [6], to calculate the compressive strength of concrete at age of 7 and 28 days respectively. In addition, six cubes (100× 100 × 100) mm [7], to calculate the compressive strength of concrete at age of 7 and 28 days for comparison with cylinder compressive strength. Three cylinders (100×200) mm [8] were used for splitting tensile strength test. Three prisms (100×100×400) mm [9] were used for flexural strength tests (modulus of rupture). In this study, the column specimens were cast vertically and vibrated with two stages, by using the electrical vibrator to consolidate the concrete and to remove the air bubbles. After 24 hours, specimens are stripped from the molds and cured in water tanks for 28 days.

10. Preparation for Column Specimens

The column specimens were taken out of the curing tanks and left to dry for one day. The surface of the specimens was ground by using the grinder machine to remove any loose and weak particles. After that, the specimens were washed again and left to dry for one or two days.

11. Installation of CFRP

After drying the column specimen's surface, the installation procedure was started, by planning the locations of the CFRP strips to insure that the spacing is distributed along the column according to the design. An epoxy resin, prepared by mixing one part type B (hardener) and a four parts type A (resin) by weight, is mixed well by the mixer machine to insure getting homogenous epoxy light grey color as recommend by the manufacturer. (1mm) thickness of epoxy resin applied to the concrete surface, while at the same time the carbon fiber sheets were fully saturated with that epoxy. Then the CFRP sheet installed to that concrete surface and pressed with a roll in the direction of the CFRP fibers to remove the entrapped air, the CFRP then coated with another layer of epoxy resin. According to the recommendation of the manufacturer, the overlapping is around 100mm of CFRP is sufficient to provide full strength of CFRP and to prevent de-bonding failure during the test. Finally after 7-days at laboratory temperature، the column specimens will be ready for test.

12. RC Column Specimens Test

A 2500 kN capacity compression testing machine (AVERY) (located at structural laboratory of the department of the university of technology) is used to apply monotonically compression load to the column specimens. A total of two dial gauges and 8 demec points, 4 in each opposite face were used for each specimen, the column gross axial shortening was measured by using dial gauge located at the bottom surface of the testing machine which rises through the testing process, while the other gauges is located at the mid height of the column specimens to measure the lateral displacement. Two demec points were stuck at the mid height along the column (vertical axis) to measure the longitudinal compressive strains at two opposite directions of column, two other demec points mounted at the mid height along the column cross section (horizontal axis) to measure the lateral strains at two opposite directions of the column. Both ends of column specimens were confined by steel collars 50 mm high and 10 mm thick. All the column specimens were tested under constant loading at average rate of 20 kN/sec. From the beginning of test up to failure. For each increment of loading the dial gauge readings, longitudinal strain and lateral strain were recorded until column failure as shown in Figure 4.

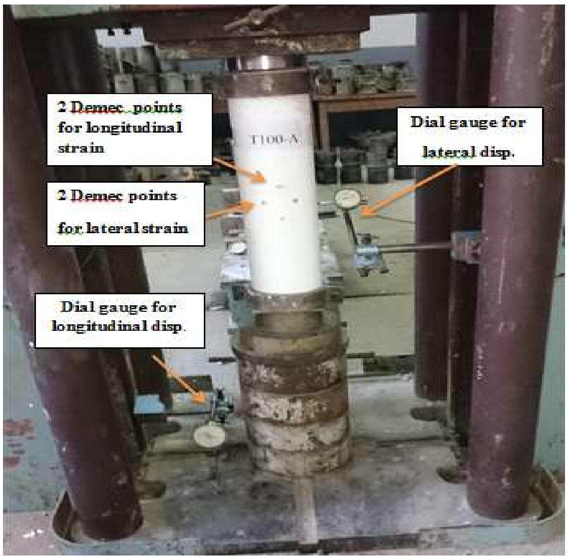

Figure 4: Locations of dial gauges and demec points for the column specimen

13. Control Specimens

The control specimens were cast from the same concrete batch used for casting the columns. The control specimens were tested immediately after the columns test. Table 4 represents the mechanical properties for the control specimens.

14. Experimental Axial Load Capacity for the Tested RC Spiral Column Specimens

From the experimental results, it can be seen that the strengthening of RC columns by CFRP strips is significantly effective in increasing the ultimate load capacity. The increases were (24, 45 and74)% for 100 mm spiral pitch strengthened with CFRP ratios of (25,50and100)%, respectively. The corresponding values of increase for 65mm and 30mm spiral pitch were (19,37and 64)% and (10,23and51)% respectively, for the same CFRP ratios. The columns with less internal confinement (lesser amount of spiral) were strengthened more significantly by the CFRP than the ones with greater amount of internal spirals. Figure 5 represents the experimental ultimate load capacity for the spiral columns.

Table 4: Mechanical properties for the control specimens

Control specimens	Compressive strength f'_c (MPa)	Compressive strength f_{cu}(MPa)	f'_c/f_{cu}	Splitting tensile strength f'_{sp}(MPa)	Modulus of rupture f_r (MPa)
S30	30.21	36.57	0.826	3.1	4.2
S65	29.95	36.39	0.823	2.8	4
S100	30.18	36.85	0.819	3	4.1

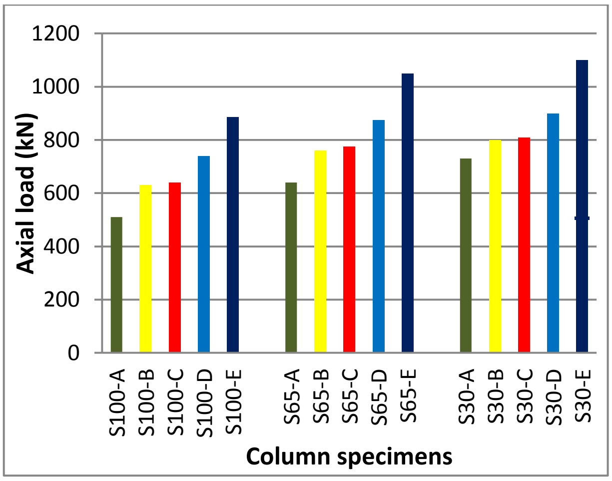

Figure 5: Ultimate load capacity for the Spiral column specimens

15. Failure Mode

All specimens were tested until failure. The reference columns showed linear behavior initially, the first crack was initiated through the mid height at about 57% of its ultimate load. With further loading, the cracks were increased at the center location along its length. Finally the concrete cover swelled followed by outward buckling for the longitudinal steel bar and rupture for one or two steel spirals. As shown in Figure 6.

For the columns confined with CFRP strips, the first crack was at the mid height for unbounded concrete surface between the CFRP strips. At higher loading the cracks developed, further. Finally, the columns failed by rupture of CFRP strip followed by crushing of concrete and buckling for one or more longitudinal steel bar. It was an explosive failure. For the heavy spiral (S30), ruptures were noticed of internal spiral steel without buckling of longitudinal steel bar Figures 7 to 9 show the failure patterns for columns types B, C, D for the three series. The strengthening schemes used in this work were very successful with no CFRP debonding with any tested column specimen.

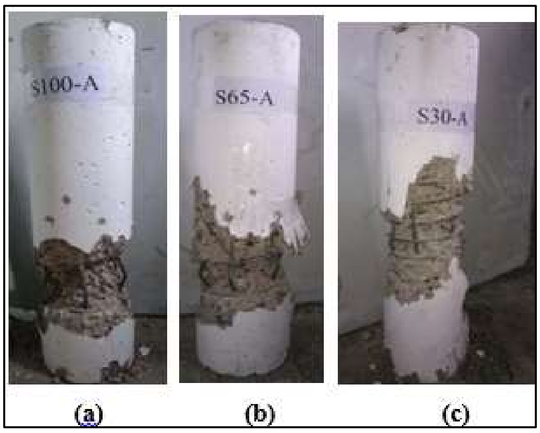

Figure 6: Failure modes for control columns

(a) (b) (c)

Figure 7: Failure modes for columns type (B)

(a) (b) (c)

Figure 8: Failure modes for columns type (C)

(a) (b) (c)

Figure 9: Failure modes for columns type (D)

Columns with fully wrapped CFRP exhibited no cracking. Figure (10) shows the failure made of columns type (E). Because of Poisson effects of confinement، failure occurred with cracking sound of CFRP-rupture happening at column mid height.

(a) (b) (c)

Figure 10: Failure modes for columns type (E)

16. Effect of Load-Strain Behavior of Spiral Column Specimens

Figure 11: shows that for unconfined CFRP columns the influence of the pitch was more significant: compared with 100 mm pitch, dropping the pitch to 65 mm and 30 mm, led to significant carrying capacity. The load carrying capacity for the columns increased with the increasing of the internal confinement (more amounts of spirals).

Figure (12 to 14) show the effect of CFRP confinement for spiral columns; compared with the unconfined column the increase in strengthening by the CFRP was more significant in raising load carrying capacity of the column specimens. For the same internal confinement, the load carrying capacity for the columns increased with the increasing of the external confinement (CFRP ratios).

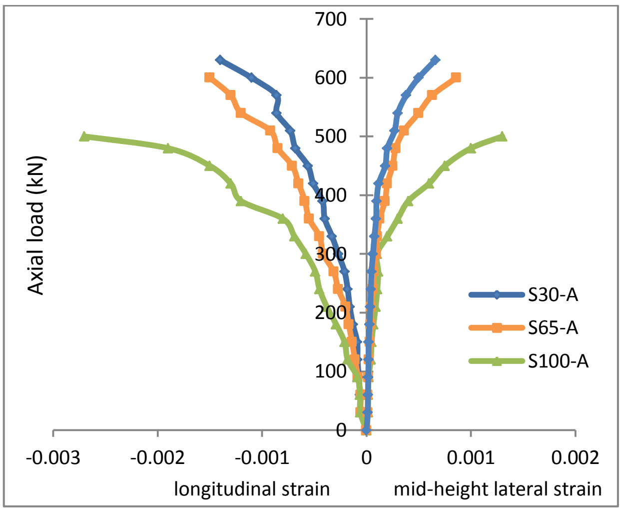

Figure 11: Load- strain curves for unconfined CFRP spiral columns

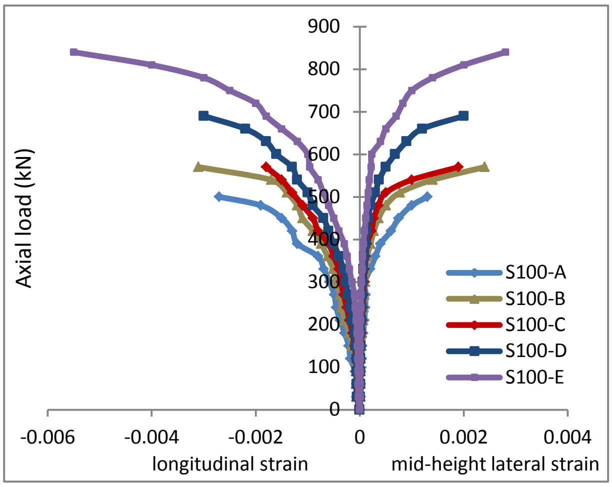

Figure 12: Load- strain curves for confined CFRP spiral columns-S100

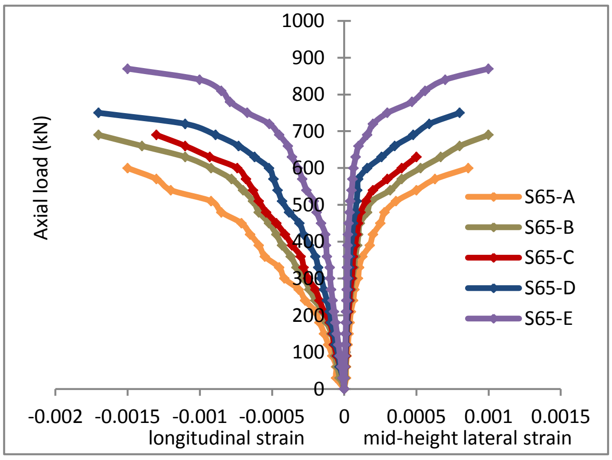

Figure 13: Load- strain curves for confined CFRP spiral columns-S65

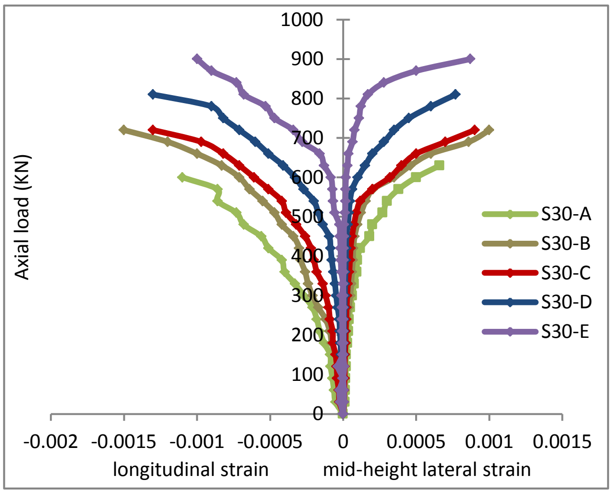

Figure 14: Load- strain curves for confined CFRP spiral columns-S30

17. Effect of Load-Displacement Behavior of Spiral Column Specimens

Figure 15 shows effectly of load-longitudinal displacement behavior of unconfined columns (no CFRP) on load carrying capacity. It can be seen that there is a significant difference between the unconfined columns, the column with close pitch produce improvement in decreasing the longitudinal displacement and this led to increase the load carrying capacity. On the other hand there is a reduction of lateral displacement with increasing internal confinement as shown in Figure 16. For Figure 15 column type (S30-A) show increasing in the longitudinal displacement more than (S65-A) for the axial load between (0-300) KN, may that belong to the calibration of the dial-gauge or others.

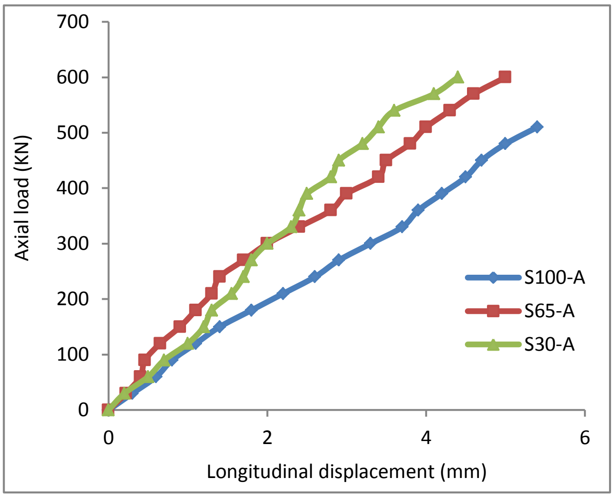

Figure 15: Load- longitudinal displacement curves for unconfined spiral columns

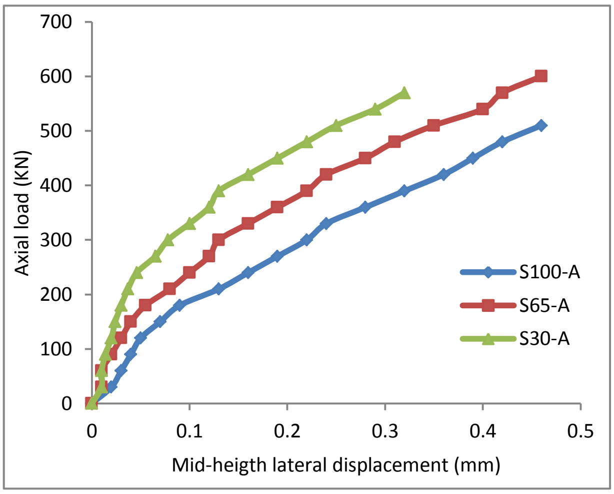

Figure 16: Load- lateral displacement curves for unconfined spiral columns

Figures 17 to 19) show the effect of load-longitudinal displacement of columns with (100, 65 and 30mm internal spiral pitch) externally confined with CFRP on load carrying capacity. Compared with the control specimens (no CFRP), there is a significant effectiveness between the columns. There is an improvement in reducing the longitudinal displacement with the increase of the CFRP confinement. Thus, the lateral displacement will decrease too which in turn increases the load carrying capacity as shown in Figures (20 to 22). For the same internal confinement, increasing the external confinement (CFRP ratios) will increase the strength of concrete, thus the longitudinal and lateral displacement will decrease too.

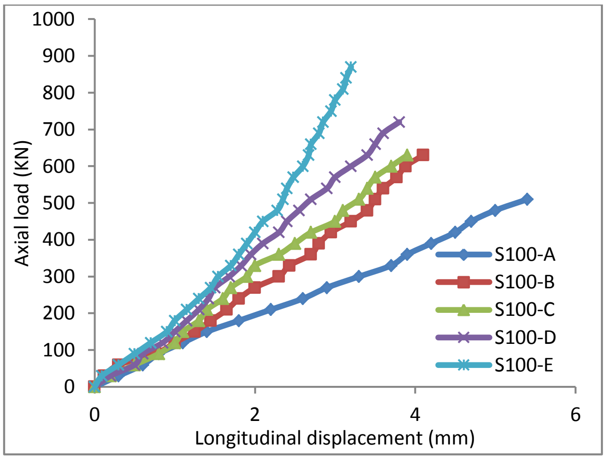

Figure 17: Load- longitudinal displacement curves for confined spiral columns with internal spiral pitch 100 mm.

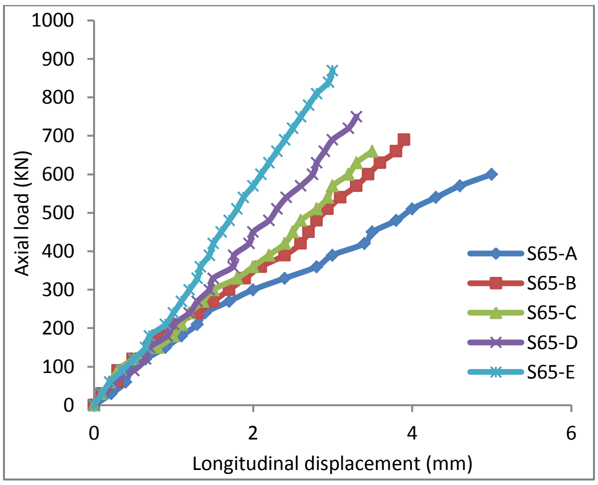

Figure 18: Load- longitudinal displacement curves for confined spiral columns with internal spiral pitch 65 mm.

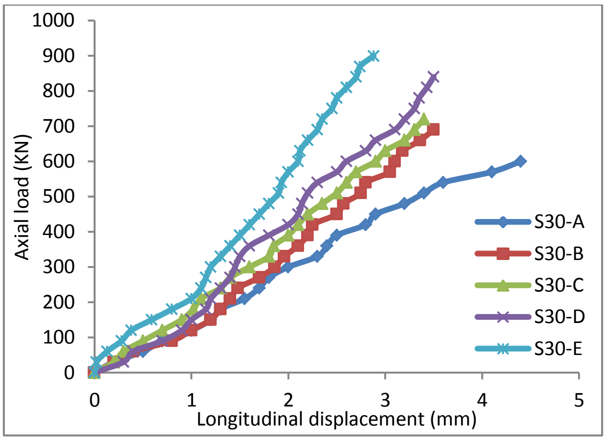

Figure 19: Load- longitudinal displacement curves for confined spiral columns with internal spiral pitch 30 mm.

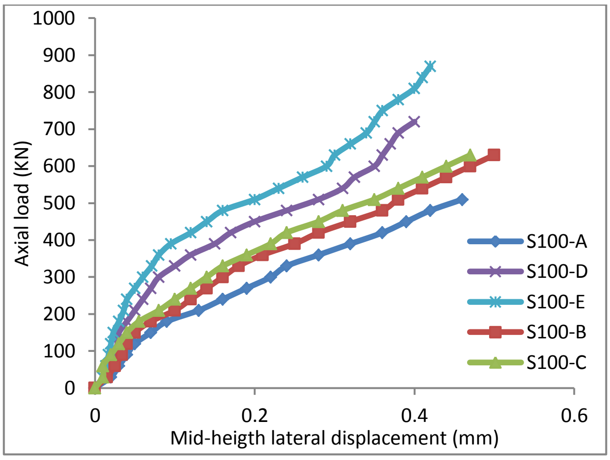

Figure 20: Load- lateral displacement curves for confined spiral columns with internal spiral pitch 100 mm.

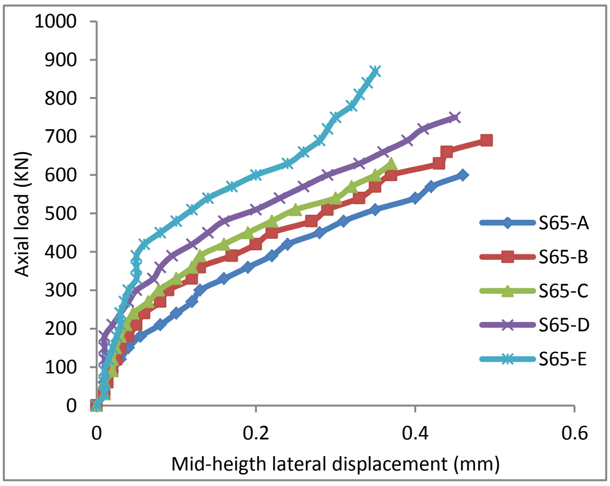

Figure 21: Load- lateral displacement curves for confined spiral columns with internal spiral pitch 65 mm.

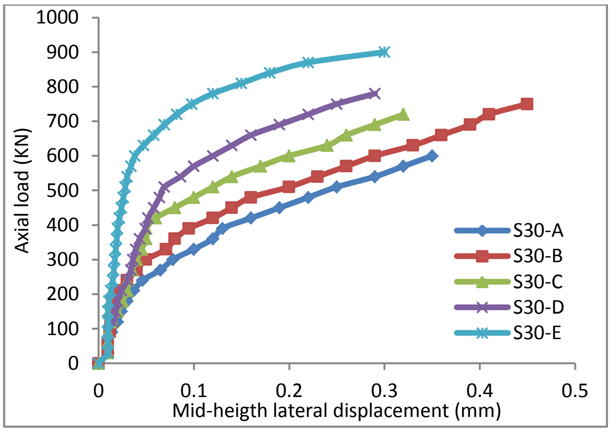

Figure 22: Load- lateral displacement curves for confined spiral columns with internal spiral pitch 30 mm.

18. Load Capacity

I. Ultimate load capacity for unconfined RC spiral column

To predict the ultimate axial compressive load for column the American Concrete Institute (ACI 318M-14) [10] has suggested the following equation for the spiral column (neglecting the reduction factors):

$$P_o = 0.85 f'_c (A_g - A_{st}) + f_y A_{st} \quad (1)$$

Where P_o is the maximum axial load, f'_c is the cylinder compressive strength of concrete, A_g is the gross cross sectional area of RC column, A_{st} is the total area of the longitudinal reinforcement, f_y is the yield stress of longitudinal reinforcement.

II. Ultimate load capacity for strengthened RC spiral column

For a column confined with CFRP under concentric loading, the ultimate load capacity can be calculated according to American Concrete Institute (ACI Committee 440.2R-08) [11] for nonprestressed member with spiral reinforcement apply the following equation neglecting reduction factor (0.85Ø).

$$P_o = 0.85 f'_{cc} (A_g - A_{st}) + f_y A_{st} \quad (2)$$

The maximum confined concrete compressive strength f'_{cc} is calculated applying equation (3) (Lam and Teng 2003a,b) [12&13] using the inclusion of additional reduction factor Ψf=0.95.

$$f'_{cc} = f'_c + \Psi_f 3.3 K_a f_l \quad (3)$$

f'_c is the unconfined cylinder compressive strength of concrete, Ka is the efficiency of the geometry of the section(K_a =1 for circular section), f_l is the maximum lateral confinement pressure is calculated by Equation(4)(International Federation for Structural Concrete) [14]

$$f_l = \frac{1}{2} K_e \, p_j \, E_j \, \varepsilon_{ju} \quad (4)$$

$$p_j = 4\, t/D \quad (5)$$

p_j is the volumetric ratio of the CFRP jacket, E_j is the modulus of CFRP jacket, ε_{ju} is the effective failure strain of the CFRP wrapping; t is CFRP jacket thickness and D is the diameter of CFRP jacket. For fully wrapped columns ke=1, use equation (6) [14] to find ke for partial wrapping, for partial wrapping with fiber orientation use ke by applying equation (7) [14].

$$K_e = \left[1 - \frac{s'}{2D}\right]^2 \quad (6)$$

$$K_e = \left[1 + \left(\frac{P}{\pi D}\right)^2\right]^{-1} \quad (7)$$

Where s' is the clear spacing between the CFRP strips, P is the pitch for CFRP spiral. Table (5) shows the experimental values of the axial compressive strength compared with the calculated values according to references 8 and 9. According to the ACI 318M-14 code [10] limits, the maximum spiral pitch is 75mm. It can be seen that the experimental values of the ultimate load capacity were greater than the calculated ones with 30 mm spiral pitch (within the code limits). When the spiral pitch increased to 65 mm the difference between the experimental and calculated values was reduced. While the calculated values were greater than the tested results (unsafe results) with increasing spiral pitch to 100mm (greater than S_{max} of the code). Therefore, the ACI 318M-14 code[10] provisions for the spiral pitch of the unconfined spiral columns can be applied for RC spiral columns confined with CFRP strips.

Table 5: The experimental and calculated values of axial compressive strength for RC spiral columns

Column Designation	Tested unconfined concrete compressive strength f'_c (MPa)	Calculated confined concrete compressive strength f'_{cc} (MPa)	Experimental values of the axial compressive strength (kN)	Calculated values of the axial compressive strength (kN)
S100-A	30.18	----	510	536
S100-B	30.18	43.44	630	733.42
S100-C	30.18	41.97	640	711.55
S100-D	30.18	51.62	740	855
S100-E	30.18	57.24	885	938.7
S65-A	29.95	----	640	532.74
S65-B	29.95	43.21	760	730
S65-C	29.95	41.74	775	708.13
S65-D	29.95	51.39	875	851.68
S65-E	29.95	57	1050	935.13
S30-A	30.21	----	730	536.61
S30-B	30.21	43.47	800	733.86
S30-C	30.21	42	810	712
S30-D	30.21	51.65	900	855.55
S30-E	30.21	57.27	1100	939.15

19. Conclusions

1- For the columns without CFRP, the influence of the spiral pitch was significant: compared with 100 mm spiral pitch, dropping the spacing to 65 mm and 30 mm increased the load carrying capacity by 25% and 43% respectively.

2-Using the CFRP strips to strengthen RC columns is significantly effective in increasing the ultimate load capacity. The increases were (24,45 and74)% for 100mm spiral pitch strengthened with CFRP ratios of (25,50and100)%, respectively. The corresponding values of increase for 30mm spiral pitch were (10,23and 51)% for the same CFRP ratios.

3- The columns with less internal confinement (lesser amount of spiral) were strengthened more significantly by the CFRP than the ones with greater amount of internal spirals.

4- Compared with the control specimen (no CFRP), the same amount of CFRP when used as spiral strips led to more strengthening than using CFRP as hoop strip-the former led to nearly 8% more strengthening than the latter in the case of 100 mm internal spiral pitch. In the case of 65 mm internal spiral pitch, the difference (between the hoops &spiral CFRP strengthening) is close to 10.5%. The difference between the two methods of strengthening in the heavily spiral columns (30 mm spiral pitch) is more significant.

5-The experimental values of the ultimate load capacity were greater than the calculated ones, when the internal spiral pitch was 30mm(within the limits of the ACI code[10]). When the spiral pitch increased to 65mm, the difference between the experimental and calculated values was reduced. However unsafe results were gained (experimental/calculated values< 1.0) with increasing the spiral pitch to 100 mm (greater than S_{max} of the code).

6-For the same load, the increase in strengthening of spiral columns externally confined with CFRP led to a decrease of longitudinal strain, mid-height lateral strain, longitudinal displacement and lateral displacement of the columns.

7- The strengthening schemes used in this work were very successful with no CFRP debonding with any tested column specimen.

8-Failure of the RC column under axial compressive load starts by rupture of CFRP strip followed by crushing of concrete at mid height of column and spalling of concrete cover. For column specimens with low transverse reinforcement ratio, the failure is accompanied with buckling of the longitudinal reinforcement between the spiral pitch. While, for the high transverse reinforcement ratio, the failure is accompanied with rupture for the internal spiral followed by bucking for the longitudinal reinforcement.

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