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Influence of ties on the behavior of short reinforced concrete columns strengthened by external CFRP

Kaiss Sarsam [1,*], *Raid* Khalel [1], and *Mohammed* Hadi [1]

[1]Building and Construction Engineering Department, University of Technology, Baghdad, Iraq

Abstract. An experimental study was carried out to investigate the behavior of normal strength reinforce concret (RC) circular short column strengthned with "carbon fiber reinforced polymer (CFRP) sheets". Three series comprising totally of (15) specimens loaded until failure under concentric compresion load. Strengthening was varied by changing the number of CFRP strips, spacing and wrapping methods. The findings of this research can be summarized as follows: for the columns without CFRP, the influence of the tie spacing was significant: compared with 130 mm tie spacing, dropping the spacing to 100 mm and 70 mm increased the load carrying capacity by 18% and 26%, respectively. The columns with less internal confinement (lesser amount of ties) were strengthened more significantly by the CFRP than the ones with greater amount of internal ties. As an example of the varying effectiveness of the fully wrapped CFRP, the column with ties at 130 mm was strengthened by 90% with the CFRP. In contrast, the ones with 70 mm spaced ties only increased in strength with CFRP by 66%. Compared with the control specimen (no CFRP), the same amount of CFRP when used as hoop strips led to more strengthening than using CFRP as a spiral strip- the former led to nearly 9% more strengthening than the latter in the case of 130 mm spaced internal steel ties. In the case of 100 mm internal steel ties, the difference (between the hoops & spiral CFRP strengthening) is close to 4%. In contrast, there is no difference between the two methods of strengthening in the heavily tied columns (70 mm tied spacing).

1 Introduction

Strengthening of RC structures using CFRP has become a popular technology over the last few years. One of the substantial applications of CFRP-strengthening technology is to enhance the load carrying capacity of RC columns throughout the provision of confining CFRP wraps. 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 [1]. The objectives considered in this study are: (1) the effect of the ties on the load carrying capacity of short RC columns represented as a volumetric ratio of transverse reinforcement; (2) the effect of the external CFRP on the load carrying capacity of short RC columns.

2 Experimental work

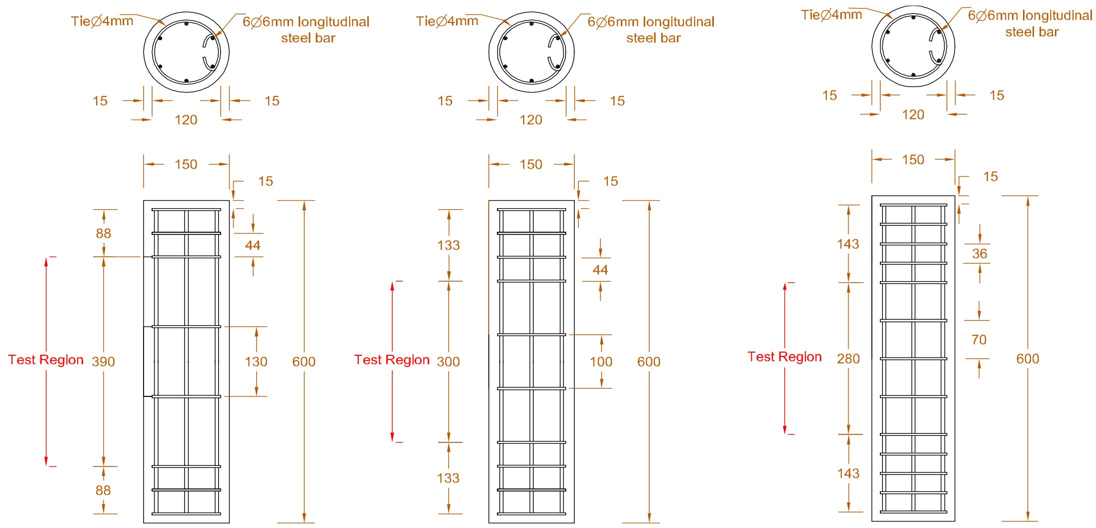
Through the design of the experimental program, the variables included in this study are focused mainly on the internal tie spacing, CFRP strips number, spacing and wrapping methods. Detailed description of each variable is presented below.

2.1 Specimen's description

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

The column specimens were divided into three groups depending on the spacing of the ties reinforcement, each five specimens were reinforced with (6) longitudinal bars with diameter of (6)mm and of (4) mm diameter for the lateral ties reinforcement with 130, 100 and 70 mm tie spacing respectively. Fig (1) shows the geometry of the Tied column specimens.

* Corresponding author: kaisssarsam@yahoo.com



(All dimensions in mm)

(a) 130mm tie spacing column

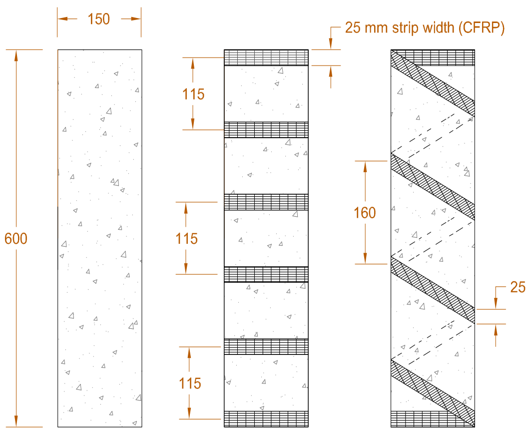
(b) 100mm tie spacing column

(c) 70mm tie spacing column

Fig .1. The geometry of the tied column specimens.

2.2 Specimen's identification and strengthening schemes

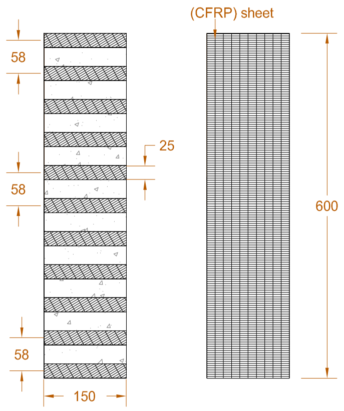
Strengthening schemes were chosen accurately based on the practiced needs and the field condition. In each specimen group (five columns), the first column specimen (type A) is control column. The second column specimen (type B) is strengthened by 25 mm width CFRP strips
with hoop spacing of 115 mm c/c (CFRP ratio= 25%), the third column specimen (type C) is strengthened by 25 mm width CFRP strip as spiral with pitch of 160 mm (CFRP ratio= 25%), the fourth column specimen (type D) is strengthened by 25 mm width CFRP strips 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%), as shown in Fig (2).



(a) Type A

(b) Type B

(c) Type C



(All dimensions in mm)

(d) Type D

(e) Type E

Fig .2. Types of CFRP confinement.

Column specimens are identified with a series of letters and numbers, which refer to the tied columns by letter T. The numbers (70, 100 and 130) represent the lateral ties spacing. 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 Fig.2, Fig. 3. shows the key for the column specimens.

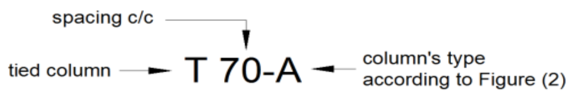


Fig .3. Column specimen's key.

2.3 Construction Materials

2.3.1 Cement

The used cement in this research is (Type I) ordinary Portland cement; Iraqi made with trade mark (Al-Mass). The physical and the chemical analysis properties are in agreement with the Iraqi specification No.5/1984 [2].

2.3.2 Fine aggrgate

Al Ukhader natural sand, maximum size 4.75mm was used as fine aggregate through-out this research work. The specific gravity, fineness modulus, sulfate content and absorption of fine aggregate are within the requirements of Iraqi specification No.45/1984 [3].

2.3.3 Coarse aggrgate

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 as saturated surface dry condition. The grading of the coarse aggregate is as per the Iraqi specification No.45/1984[3].

2.3.4 Water

Water supplied by the network system (Tap Water) was used for mixing and curing the concrete.

2.3.5 Reinforcing steel bars

A 6mm diameter deformed bars were used for longitudinal reinforcement with 513 MPa yield strength and 4 mm diameter deformed bars with 717 MPa yield strength were used for the transverse reinforcement.

2.3.6 Carbon fiber reinforced polymer (CFRP)

Sika-Wrap®-300C woven carbon fiber fabrics (mid strength type fiber) was applied as strengthening agent in this work. The roll of carbon fiber is 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 Sika-Wrap®-300C.

Table1. The product description for the Sika-Wrap®-300C woven carbon fibre 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)

2.3.7 Bonding materials

Sikadur®-330 was used as 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 2. The product description for the Sikadur®-330.

Appearance /colors	Part A:white Part B:grey Parts A+B mixed=light grey
Mixing ratio	Part 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)

2.4 Trial Mixes of Concrete

Several trial mixes were made aiming at cylinder strength of (30MPa). Trial mix No (4) was adopted for this study. Table 3 represents details for trial concrete mixes.

Table3. 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	0.62	(1:2.36:2.79)	17
2	350	710	1025	190	0.54	(1:2:2.93)	25
3	370	685	1020	190	0.51	(1:1.85:2.76)	27.3
4	400	740	1000	192	0.48	(1:1.85:2.5)	31

2.5 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 added to the mixture in quarters and mixed for 2 to 3 minutes.

2.6 Specimen's molds

PVC tubes are cut to match the column height. The base of the mold is constructed from plywood, to prevent water from leaking through.

2.7 Casting and curing

In total, three batches of concrete were used to cast the columns. Each batch was used to cast five columns with six cylinders (100 ×200) mm [4] to determine the compressive strength of concrete at age of 7 days and age of 28 days, respectively. And six cubes (100 ×100 ×100) mm [5], were used to calculate the compressive strength of concrete at age of 7 days and 28 days for comparison with the cylinder compressive strength. Three cylinders (100×200) mm [6], were used for splitting tensile strength test. Three prisms (100 ×100 ×400) mm[7], were used for flexural strength test(modulus of rupture). In this study the column specimens were cast vertically and vibrated with two stages, by using the electric table vibrator to consolidate the concrete and to remove the air bubbles.
After 24 hours, control specimens are stripped from the molds and cured in water tanks for 28 days as long with the columns.

2.8 Preparation for column specimens

The column specimens were taken out of the curing tanks and left to dry for one day. All the specimen's surfaces were grinded by applying the grinder machine in order to eliminate all weak and losses particles. Later the specimens were wash again and left to dry for one or two days.

2.9 Installation of CFRP

After drying the column specimen's surface, the installation procedure initially started, by planning the locations of the CFRP strips to ensure that the spacing is distributed along the column according to the design with the CFRP being cut as required. An epoxy resin is prepared by mixing one part type B (hardener) and four parts type A (resin) by weight. A mixing machine is used to obtain a homogeneous light grey color. 1mm thickness of epoxy resin is applied to the concrete surface, while at the same time the carbon fiber sheets were fully saturated with that resin. Then the CFRP sheet is installed to that concrete surface and pressed with a roll in the direction of the CFRP fibers to eliminate the entrapped air, another layer of epoxy was used to coat the CFRP. According to the recommendation of the manufacturer, the overlapping of 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 testing.

2.10 RC Column specimens test

A 2500 kN capacity compression testing machine (AVERY) located at structural laboratory of the department 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. By using a dial gauge located at the bottom surface of the testing machine to measure the column gross axial shortening. Another gauge is located at the mid height of the column specimens to measure the lateral displacement. Two demec points were stuck in the mid-height of the column to measure the longitudinal compresive strains from two opposite direction of the columns. To measure the lateral strains at two opposite directions of the column, two other demec points are mounted at the mid-height through the column cross section (horizontal axis). Both ends of column specimens were confined by steel collars 50 mm height and 10 mm thick as shown in Fig.4.

All the column specimens were tested under constant loading at an average rate of 20 kN/sec. from the beginning of test up to failure. For each increment of loading dial gauge readings were recorded and longitudinal strain and lateral strain were recorded until the failure of column.

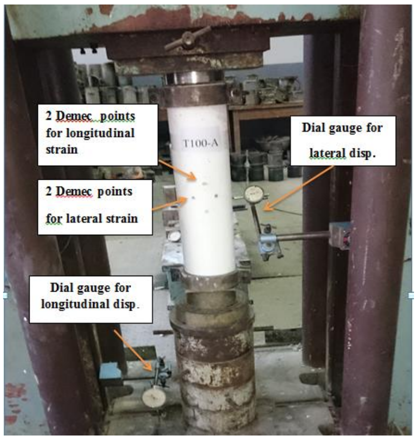


Fig. 4. Locations of dial gauges and demec points for the column specimen.

2.11 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 shows the test results for the compressive strength of concrete cylinders and cubes and for three concrete batches.

Table 4. Mechanical properties for the column specimens

Batch No.	column specimen	f'_c (MPa)	f_{cu} (MPa)	f'_c/f_{cu}	Splitting tensile strength f'_{sp}(MPa)	Calculated splitting tensile strength according to ACI-Code (MPa) *	Modulus of rupture f_r (MPa)	Calculated modulus of rupture according to ACI-Code (MPa)**
1	T70	30.05	36.42	0.825	2.8	3.07	3.9	3.4
2	T100	30.12	36.25	0.831	2.9	3.07	4	3.4
3	T130	29.89	36.32	0.823	2.7	3.06	3.8	3.39

* $0.56\sqrt{f'_c}$
** $0.62\sqrt{f'_c}$

3 Test results and discussion

3.1 Experimental Axial Load Capacity for the Tested RC Column Specimens.

Table 5 represents the experimental ultimate load capacity for the tied columns.

Table 5. The experimental ultimate load capacity for tied column specimens.

Column designation	Capacity of tested columns (kN)	Column designation	Capacity of tested columns (kN)	Column designation	Capacity of tested columns (kN)
T130-A	495	T100-A	585	T70-A	625
T130-B	620	T100-B	730	T70-B	745
T130-C	610	T100-C	720	T70-C	745
T130-D	735	T100-D	855	T70-D	869
T130-E	940	T100-E	1025	T70-E	1040

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 (25, 48 and 90) % for 130 mm ties spacing strengthened with CFRP ratios of (25, 50 and 100) %, respectively. The corresponding values of increase for 100 mm and 70 mm ties spacing were (25, 46 and 75)% and (19, 39 and 66) % respectively, for the same CFRP ratios.

3.2 Failure mode

All specimens were tested until failure. The reference columns showed linear behavior initially, the first crack initiated through the mid height (Test Region) at the respective 55% of its ultimate load. After further loading, the cracks were increased in numbers and width. Finally, the columns failed at mid height by crushing and spalling of the concrete accompanied by local buckling for longitudinal steel bars as shown in Fig 5.

(a) (b) (c)

Fig 5. Failure modes for control columns

(a) (b) (c)
Fig 6. Failure modes for columns type (B)

(a) (b) (c)

Fig 7. Failure modes for columns type (C)

(a) (b) (c)

Fig 8. Failure modes for columns type (D)

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 fiber followed by crushing of concrete and buckling for one or more longitudinal steel bar. It was an explosive failure. Figs. (6 to 8) show the failure patterns due to the rupture of CFRP strips accompanied by local buckling between the steel ties.

Columns with fully wrapped CFRP exhibited no visible cracking. Fig. 9 shows the failure mode 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)

Fig 9. Failure modes for columns type (E)

3.3 Load-strain behavior of column specimens

Fig.10. shows that for unconfined CFRP columns the influence of the tie spacing was significant: compared with 130 mm tie spacing, dropping the spacing to 100 mm and 70 mm, the effect of the internal confinement was clear-with the load carrying capacity rising with confinement.

Figs. (11 to 13). show the effect of CFRP confinement for tied 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.

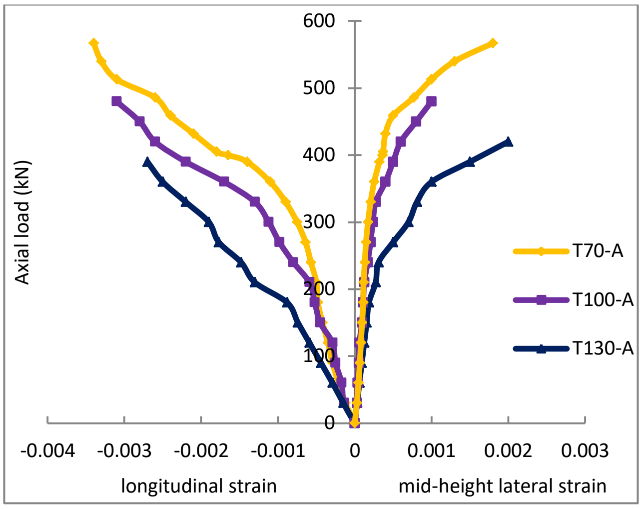


Fig 10. Load- strain curves for unconfined CFRP tied columns.

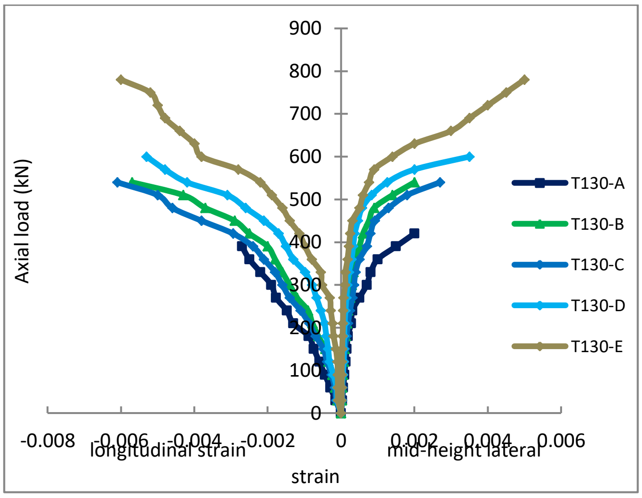


Fig.11. Load- strain curves for confined CFRP tied columns- T130.

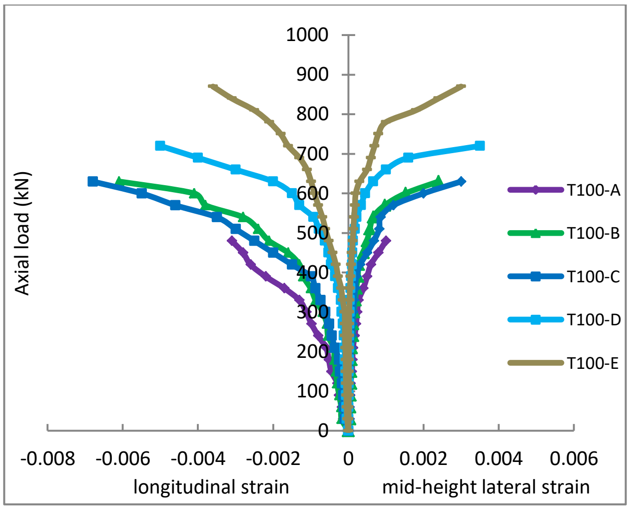


Fig.12. Load- strain curves for confined CFRP tied columns- T100

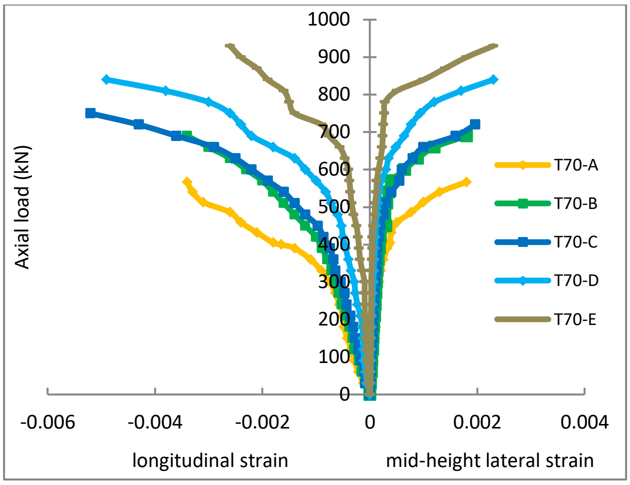


Fig.13. Load- strain curves for confined CFRP tied columns- T70.

3.4 Load-displacement behavior of column specimens

Fig.14. illustrates the load-longitudinal displacement behavior of unconfined columns (no CFRP) on load carrying capacity. There is a significant difference between these un-confined columns. The column with less internal confinement (lesser amount of ties) shows larger longitudinal displacement than the other columns. This in turn affects the decrease of load carrying capacity of that column. On the other hand there is a reduction of lateral displacement with increase of the internal confinement (increased number of ties) as shown in Fig.15.

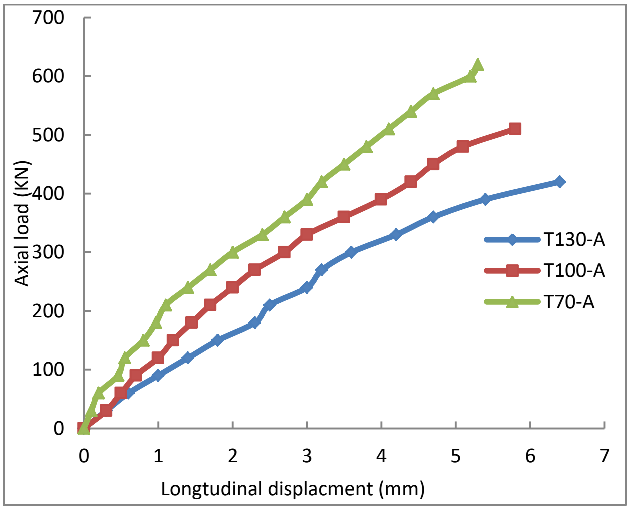


Fig.14. Load- longitudinal displacement curves for un-confined tied column.

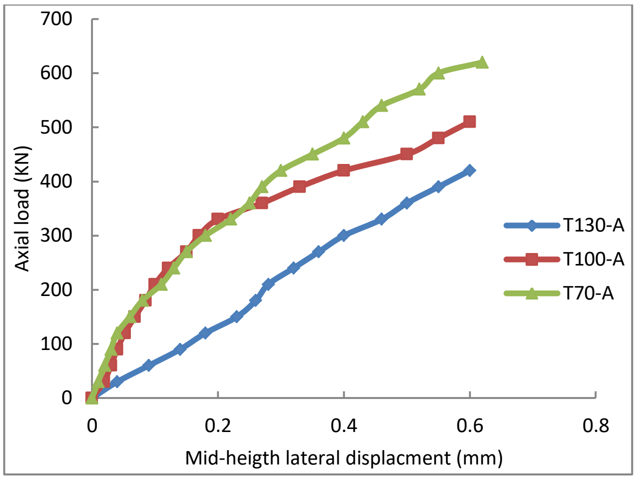


Fig.15. Load-lateral displacement curves for un-confined tied column.

Figs. (16 to 18) show the load- longitudinal displacement of columns externally confined with CFRP. Compared with the control specimens (no CFRP). There is an improvement in reducing the longitudinal displacement with the increase of the CFRP confinement. Thus, the lateral displacement will decrease too. This in turn increases the load carrying capacity as shown in Figs. (19 to 21).

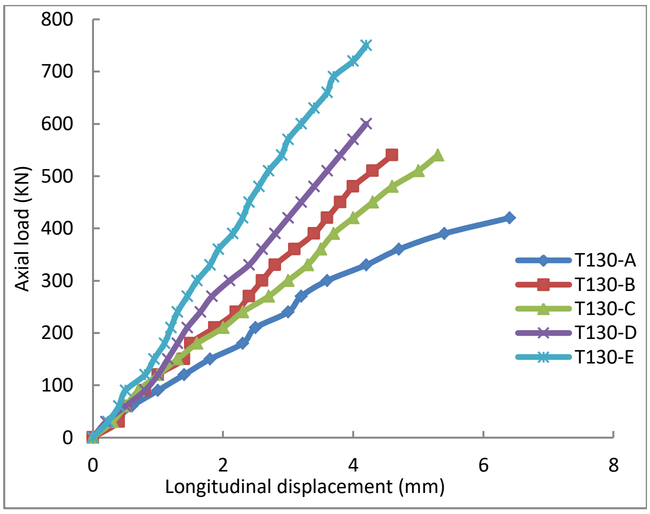


Fig.16. Load-longitudinal displacement curves for CFRP confined tied columns with internal tie spacing 130 mm.

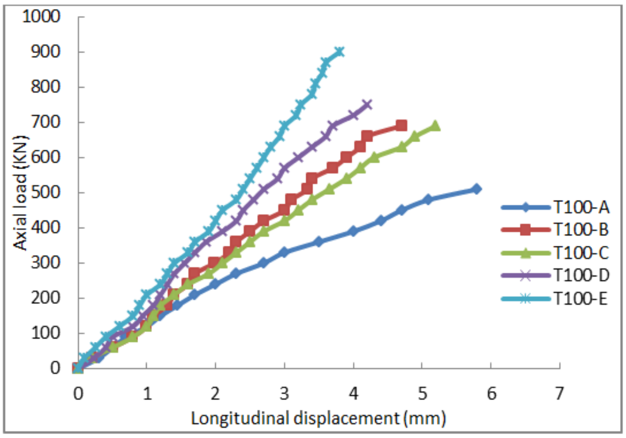


Fig.17. Load- longitudinal displacement curves for CFRP confined tied columns with internal tie spacing 100 mm.

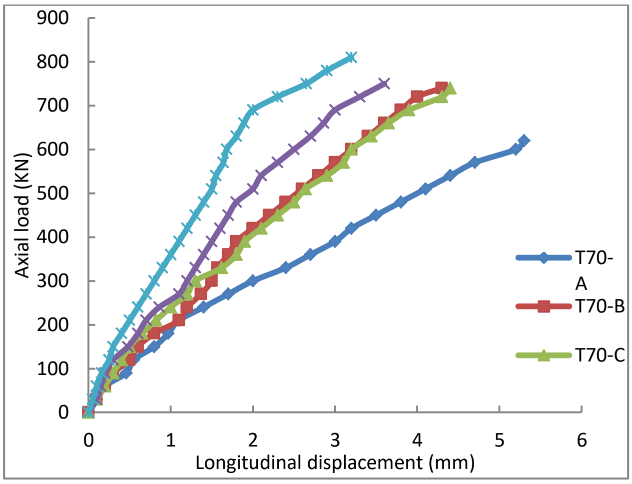


Fig.18. Load-longitudinal displacement curves for CFRP confined tied columns with internal tie spacing 70 mm.

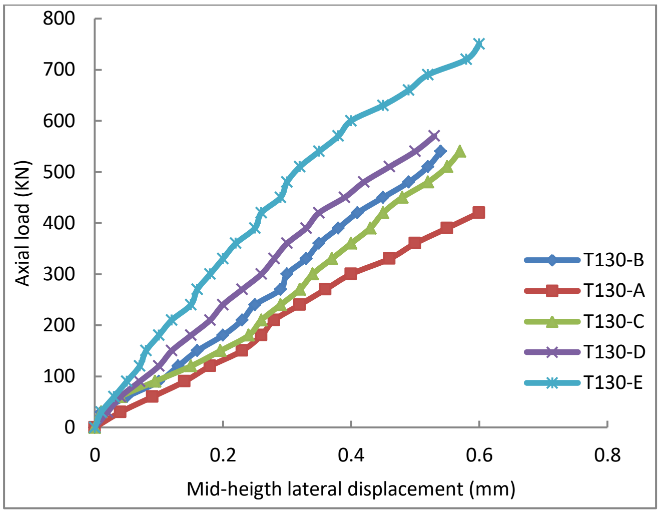


Fig.19. Load-lateral displacement curves for CFRP confined tied columns with internal tie spacing 130 mm.

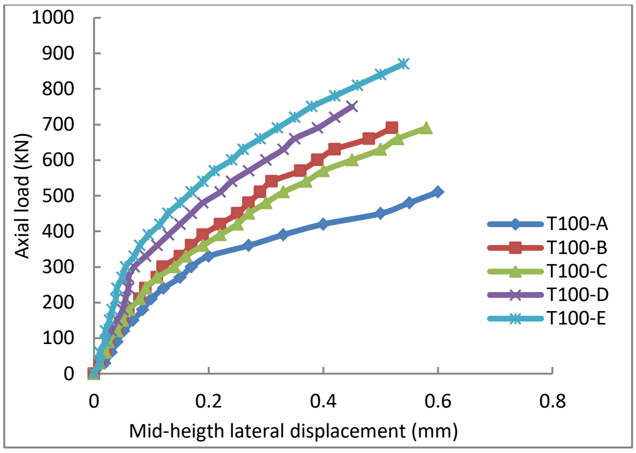


Fig.20. Load-lateral displacement curves for CFRP confined tied columns with internal tie spacing 100 mm.

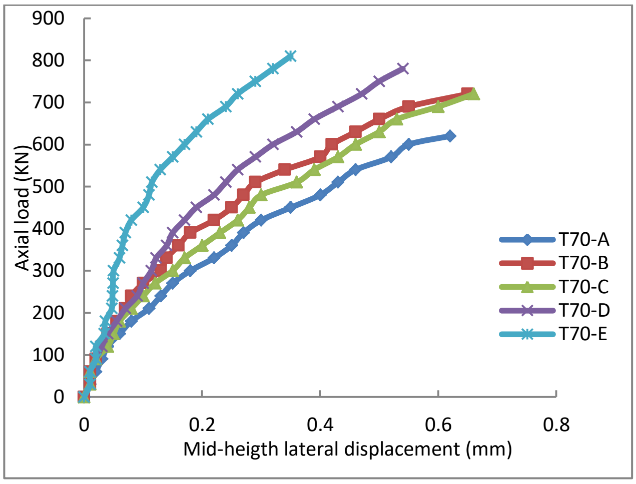


Fig.21. Load-lateral displacement curves for CFRP confined tied columns with internal tie spacing 70 mm.

3.5 Load capacity

3.5.1 Ultimate load capacity for unconfined RC tied columns

To predict the ultimate axial compressive load for column the American Concrete Institute (ACI 318M-14) [8] has suggested the following equation for the tied column (neglecting the reduction factors):

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

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.

3.5.2 Ultimate load capacity for strengthened RC tied columns

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) [9] for nonpre-stressed members with tie reinforcement by applying the following equation neglecting reduction factor (0.8Ø).

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

The maximum confined concrete compressive strength f'_{cc} is calculated by applying equation (3) (Lam and Teng 2003a,b) [10&11] using the inclusion of additional reductions factor Ψf=0.95.

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

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) [1]

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

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

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 K_e =1, use equation (6) [1] to find K_e for partial wrapping, for partial wrapping with fiber orientation use K_e by applying equation (7) [1].

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

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

Where s' is the clear spacing between the CFRP strips, P is the pitch for CFRP spiral. Table (6) shows the experimental values of the axial compressive strength compared with the calculated values according to references 8 and 9.

Table 6. The experimental and calculated values of axial compressive strength for RC tied 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)	P_{exp} $/P_{cal}$
T130-A	29.89	-----	495	527.40	0.94
T130-B	29.89	43.15	620	729.10	0.85
T130-C	29.89	41.69	610	707.45	0.86
T130-D	29.89	51.33	735	850.78	0.86
T130-E	29.89	56.95	940	934.38	1.01
T100-A	30.12	----	585	534.97	1.09
T100-B	30.12	43.36	730	732.22	1.00
T100-C	30.12	41.91	720	710.88	1.01
T100-D	30.12	51.54	855	853.91	1.00
T100-E	30.12	57.18	1025	937.81	1.09
T70-A	30.05	-----	625	534.23	1.17
T70-B	30.05	43.31	745	731.48	1.02
T70-C	30.05	41.84	745	709.83	1.05
T70-D	30.05	51.49	869	853.16	1.02
T70-E	30.05	57.11	1040	936.76	1.11

According to the ACI 318M-14 code [8] limits, the maximum ties spacing is 96 mm. It can be seen that the experimental values of the ultimate load capacity were greater than the calculated ones with 70 mm ties spacing (within the ACI code limits). When the ties spacing increased to 100 mm (close to maximum spacing value of the code), the difference between the experimental and calculated values was decreased. While the calculated values were greater than the tested results (unsafe results) with increasing the ties spacing to 130 mm (greater than S_{max} of the code). Therefore, the ACI 318M-14 code [8] provisions for the ties spacing of the unconfined ties columns can be applied for RC tied columns confined with CFRP strips.

4 Conclusions

1-For the columns without CFRP, the influence of the tie spacing was significant: compared with 130 mm tie spacing, dropping the spacing to 100 mm and 70 mm increased the load carrying capacity by 18% and 26%, respectively.

2-Using the CFRP strips to strengthen RC columns are significantly effective in increasing the ultimate load capacity. The increases were (25, 48 and 90) % for 130 mm spaced internal steel ties strengthened with CFRP ratios of (25, 50 and 100) %, respectively. The corresponding values of increase for 70 mm spaced internal steel ties were (19, 39 and 66) % for the same CFRP ratios.

3-The columns with less internal confinement (lesser amount of ties) were strengthened more significantly by the CFRP than the ones with greater amount of internal ties. As an example of the varying effectiveness of the fully wrapped CFRP, the column with ties at 130 mm was strengthened by 90% with the CFRP. In contrast, the ones with 70 mm spaced ties was only increased in strength with CFRP by 66%.

4-Compared with the control specimen (no CFRP), the same amount of CFRP when used as hoop strips led to more strengthening than using CFRP as a spiral strip-the former led to nearly 9% more strengthening than the latter in the case of 130 mm spaced internal steel ties. In the case of 100 mm internal steel ties, the difference (between the hoops & spiral CFRP strengthening) is close to 4%. In contrast, there is no difference between the two methods of strengthening in the heavily tied columns (70 mm tied spacing).

5- The experimental values of the ultimate load capacity were greater than the calculated ones, when the internal steel tie spacing was 70mm (within the limits of the ACI code [8]). When the ties spacing increased to 100 mm (close to maximum spacing according to the code limits), the difference between the experimental and calculated values decreased. However, unsafe results were obtained (experimental/calculated values < 1.0) with increasing the ties spacing to 130 mm (greater than S_{max} of the code).

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

7-Failure of the RC column specimens under axial compressive load starts by rupture of fiber followed by crushing of concrete at mid height of the 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 transverse ties. While, for the high transverse reinforcement ratio, the failure is accompanied with buckling of the longitudinal reinforcement and rupture for internal ties.

8-The strengthening schemes used in this study were very successful with no CFRP debonding with any tested specimen.

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