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Retrofitting of Long RC Columns with CFRP Strips and Steel Plates

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ملخص البحث:

بالرغم من تصميم العناصر الانشائية بطريقة صحيحة الا انه يتطلب عمل صيانة لها و يفضل ان تكون منخفضة التكاليف و ذلك لزيادة العمر الافتراضي للمنشأ. و يتم ذلك من خلال التدعيم الذي يزيد من كفاءة العناصر الانشائية مع الزمن. و الطرق التقليدية الشائعة تم الان استبدالها بمركبات حديثه من البوليمرات المسلحة بألياف الكربون CFRP فهي تستخدم لتقوية أعمدة الخرسانة المسلحة بطريقتين: تعزيز عن طريق اضافتها علي شكل شرائط CFRP في المجاري أو بشكل شرائح CFRP او الجمع بينهما في نهاية المطاف. و يتعرض هذا البحث الي تاثير أساليب التدعيم المذكورة على أعمدة الخرسانة المسلحة الطويله و المعرضة الي انبعاج. يتناول الباحث في هذا البحث الي فاعلية تدعيم الاعمدة الطويلة باستخدام تلك الالياف. وقد تم استخدام سبعة عينات في هذا البرنامج التجريبي. وقد استخدمت نوعين من المواد الداعمة (شرائح من الياف الكربون و ألواح من الصلب)، أيضا تم اختبار طول الالياف الداعمة باستخدام (كامل طول، 3/2 طول التدعيم و3/1 طول التدعيم). وعلاوة على ذلك تم اختبار نوع من عامل الربط باستخدام الربط الايبوكسي والمسامير الصلب بقطر 20 مم. وفقا لنتائج الاختبار باستخدام الياف من الكربون تم ملاحظة ان القدرة تضاعفت عن العمود الغير مدعم. كما اظهرت النتائج ان كلا من الطريقتين المستخدمتين في التدعيم يكون الانهيار نتيجة الانفصال علي سطح الايبوكسي المستخدم.من ناحية أخرى تدعيم العمود باستخدام الواح الصلب المدعمة بالمسامير يحدث لها انهيار عند منطقة المسامير. و اخير اظهرت النتائج ان التدعيم بكامل الطول يؤدي الي نتائج اعلي من التدعيم بطول 3/1 عمود وطول 3/2 عمود .

ABSTRACT

Experimental investigation was carried out to study the efficiency of different retrofitting techniques on enhancing the structural behavior of RC long columns. Seven RC long columns were tested, six of them were strengthened and the last one kept unstrengthened and considered as control specimen. Two types of strengthening materials were used, CFRP strips and steel plates. Also the length of the strengthening material was examined using full length, 2/3 and 1/3 length of the column specimen. Moreover the type of bonding agent was examined using epoxy bonding and steel rivets of 20 mm diameter. According to the test results, CFRP technique with full column length enhanced the column capacity by double value compared with the control column. Columns strengthened by CFRP laminate or steel plates failed due to de-bonding of the epoxy layer. On the other hand, the column strengthened with steel plate and bonded by steel rivets failed by de-bonding between rivets and the column at the weak concrete zone around the rivets. However, the columns strengthened with 1/3 and 2/3 column length with FRP laminate showed lower capacity compared with the full length one.

Keywords: CFRP, Reinforced concrete, long columns, strengthening

1-INTRODUCTION

The design of slender load-bearing members is one of the most asserted trends. The same requirement is then imposed on strengthened structures and members. That is the main reason for replacing strengthening techniques using conventional materials (concrete, steel) with new ones. Progressive composites – fiber reinforced polymers (FRP) – have many advantages such as high strength-to weight and stiffness-to-weight ratios, corrosion resistance, ease of installation, etc.; their disadvantage is their relatively high cost. For static strengthening purposes, unidirectional composites with carbon fibers and epoxy resin are widely used. There are two mainly forms of CFRP used for strengthening. The first one is polymers in strip form which are bonded to the structural member's surface or into the pre-cut grooves in the concrete cover – the well-known near surface mounted reinforcement (NSMR). They transfer tensile forces and perform as added reinforcement with related characteristics. The second one is polymer sheets in a confinement form that can be shaped like stirrups or continuously like a spiral. The confinement effect is based on the well-known fact that the containment of the lateral deformation of concrete increases its strength. The confinement effects can be considered by the increase in the concrete's strength and the modification of the stress-strain model. The confinement of concrete has a major effect on columns; its effect on axially loaded short squared and circular concrete columns was demonstrated in numerous tests, [1]-[5]. The research on long loaded slender concrete columns is still quite limited, and there are few publications on this topic which is why this application is not advanced. Mirmiran, et al. [6] started the research in this field with concrete-filled fiber-reinforced polymer tubes, CFFT, which showed that as the slenderness ratio is increased, the columns' strength rapidly drops . Pan, et al. [7] investigated slender reinforced concrete columns wrapped with FRP; the behavior of these columns differs from that of CFFTs, even though the strengthening effect decreases with an increase in the slenderness ratio and the initial end eccentricity. Confinement with a unidirectional and also a bidirectional CFRP jacket was the subject of Tao's investigation [8]. The ultimate strength measured for the columns strengthened by unidirectional CFRP is quite close to that of un-strengthened ones. A small-scale test was carried out by Fitzwilliam et al. [9] contained columns wrapped with CFRP in a hoop and also in a longitudinal direction. They concluded that for slender columns, wrapping in a hoop direction resulted in only a modest increase in capacity. Longitudinal CFRP wraps improve the behavior of slender concrete columns and allow for the achievement of higher strengths and capacities.

To enable a wider application of strengthening techniques for slender RC columns, it is necessary to engage in more research in this field and try to derive design methods for the strengthening effects of CFRPs. The behavior of RC slender columns strengthened with FRP strips is different from those wrapped with FRP. In contrast to the large available database on short columns strengthened with FRP, publications on slender columns are relatively few. It is, therefore, useful to experimentally study the load carrying capacity and behavior of RC slender columns strengthened with different techniques.

2-Experimental study

2-1 Test Specimens

In order to assess the effectiveness of the CFRP strips and steel plates for strengthening slender RC columns subjected to compression load, four series of specimens were tested. The specimens were consists of 1800 mm long columns, with a cross section of 70 x 100 mm so, the slenderness ratio L/b was 25. Columns were longitudinally reinforced with 4 φ 8 bars. The horizontal reinforcement consisted of 6 mm stirrups spaced at 150 mm. Hinge support was provided at both ends of each column. Fig.1 shows the reinforcement details of the columns. The first series consisted of a non-strengthened column (C1, control one). The second series was composed of concrete columns strengthened with CFRP strips with full, (2/3) and (1/3) column length, C2 to C4. The third series was composed of columns strengthened with steel plates with different lengths 1200 and 1800 mm for C5 to C6, respectively. The four series concern with the bonding techniques for steel plates, C7. The steel plates in C7, with 1800 mm length, were bonded with both epoxy agent and 20 mm diameter steel rivets spaced 150 mm. CFRP strips and steel plates were fixed to the long column sides. Both CFRP laminates and steel plates have the same thickness of 1.2 mm and the same width of 100 mm. Table 1 provides a summary of the details of the specimens used in this program. All the columns were subjected to vertical compression load up to failure loads. The experimental test set-up is shown in Fig. 1. Strains of the concrete, steel and composite reinforcements were monitored during the test. Electrical resistance strain gauges were applied to the steel reinforcement and FRP in opposite faces. All strain gauges were positioned at mid-height of the specimens. The most accurate measurement allowing for descending branch plotting was enabled by linear variable displacement transducers (LVDTs).

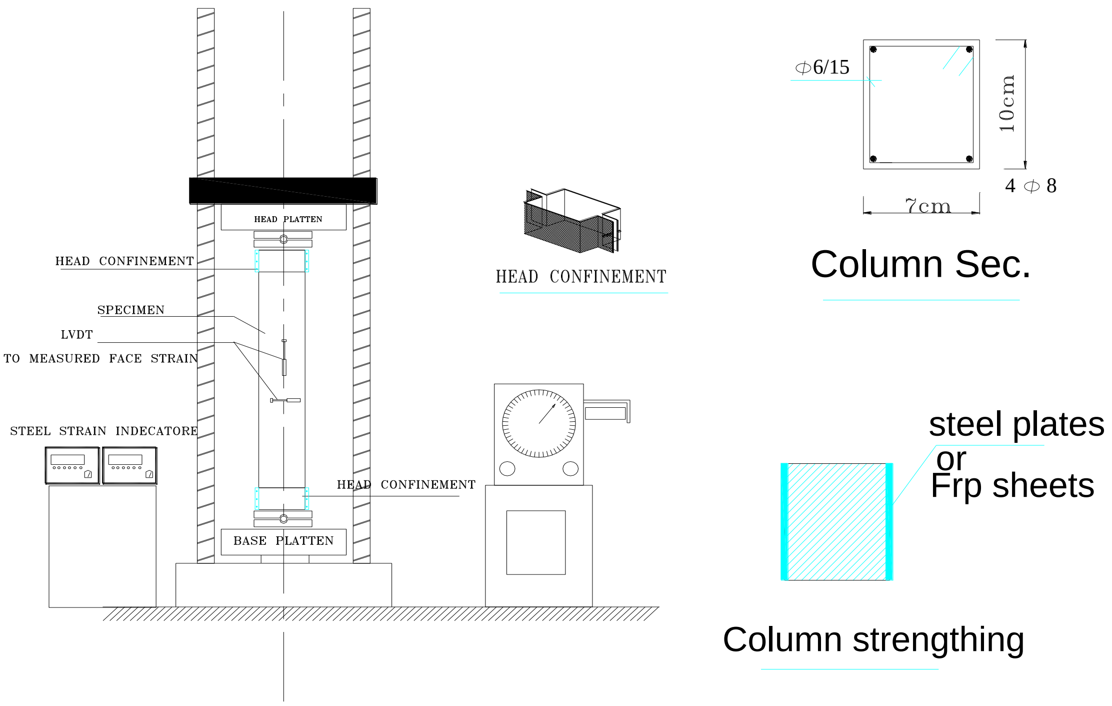

Fig. 1 Schematic of loading arrangement and column section

Table 4 Details of specimens

Specimen	Type of Strengthening	Length of Strengthening	Dimensions of material	Bond tools
C1 Control		None		
C2	externally FRP strip	1800 mm	1800*100*1.2mm	Epoxy adhesive
C3	externally FRP strip	1200 mm	1200*100*1.2mm	Epoxy adhesive
C4	externally FRP strip	600 mm	600*100*1.2mm	Epoxy adhesive
C5	externally steel plate	1800 mm	1800*100*1.2mm	Epoxy adhesive
C6	externally steel plate	1200 mm	1200*100*1.2mm	Epoxy adhesive
C7	externally steel plate	1800 mm	1800*100*1.2mm	Epoxy adhesive + steel rivets

2-2 Material Properties

The concrete mix consisted of fine aggregate, coarse aggregate, cement, and water to get target strength of 30 MPa. The concrete mix used to prepare testing specimens is indicated in Table 2. The average compressive of the concrete from test of six standard RC cubes (150x150x150 mm), i.e. f_{cu} was 32 MPa. The longitudinal steel reinforcement ratio was constant for all columns and equal to 2.85%, with the yield stress of 240 MPa as shown in Table 3.

Table 2 Mix proportions of concrete for one cubic meter

Cement Kg	Crushed dolomite Kg	Sand Kg	Water Liter
400	1384	692	170

Table 3 Details of reinforcing steel bars

Nominal diameter mm	grade	Actual area cm^2	Unit weight Kg/m	Yield strength MPa	Ultimate strength MPa	Elongation %
ϕ 6	24/36	0.279	0.212	291	430	32
ϕ 8	24/36	0.470	0.382	310	480	26

The carbon-fiber strips used were supplied by Sika Egypt under the commercial name (Sikawrap Hex-230C). The thickness of the CFRP strips was 1.2 mm, see Table 4. Two-component epoxy adhesive (Sikadur 330), supplied by the same company, was mixed according to the proportions recommended by the manufacturer to bond the FRP sheets to the target surfaces of the tested columns. Sikadur 31 CF epoxy adhesive was used to fix the externally steel plates for columns C5, C6 and C7.

Table 4 Mechanical properties of CFRP strips

Fiber Type	Guaranteed Ultimate Strength (GPa)	Elastic Modulus (GPa)
Sika wrap Hex-230C	3.5	230

3- TEST RESULTS AND DISCUSSION

3-1 Mode of Failure

The performance and failure mode of all tested specimens was controlled by flexure, as expected due to their design characteristics. This was an important requirement; as the main objective of this study was to evaluate the effectiveness of flexural strengthening of RC slender columns.

3-1-1 Failure mode of control specimens

Fig. 2 presents the main characteristics of the modes of failure for the control un-strengthened rectangular slender columns. Generally, failure was sudden and brittle. There was only one major crack that appeared near mid-height of the specimen near failure. Lateral buckling of specimens was noticeable. The control specimen attained a peak load of about 190 kN, the concrete cover and a part of the core at middle of the column disintegrated and bar buckling initiated after the concrete cover spalled off.

3-1-2 Failure modes for strengthened columns

The strengthening of columns with either CFRP laminates or steel plates affected the modes of failure of these columns. Strengthened specimens typically showed a final ductile flexural failure. Several minor cracks appeared in the early stages of loading on the tension side of the cross section. With only one exception, C6, all strengthened specimens displayed higher flexural resistance compared to the control specimen. Flexural cracking at the column base started at the early stages of loading and the number of cracks increased and propagated with increasing lateral drift. The final failure was accomplished with crushing of the concrete in the compression side as well as buckling of internal reinforcement. This mode of failure is shown in Fig. 2. Contrary to the un-strengthened column, the failure of the strengthened specimens was never attributed to buckling for the internal steel, as a significant portion of the total force in the tension zone was carried by the FRP or steel plates. However, buckling of the longitudinal internal bars always occurred abruptly after failure of the FRP reinforcement.

C1

C2

C3

C4

C5

C6 failed under cap

C7

Fig. 2 Specimens failure pattern

3-2 Specimens Ductility

The modulus of toughness defined as the area under the load-deflection curve is considered in this research to represent the ductility of the tested slender columns. It was always thought that the gain in the ductility of the columns would increase with the addition of horizontal confinement. The area under the load-axial deformation curves for each column was calculated and presented in Table 5. These values can correlate to the ductility of the columns. It is clear from Table 5 that the column C2 which was vertically strapped with FRP performed better than the control reference column by 72.6%. While column C5 with steel plate performed far better than the control reference column by 143.6%.

It was always thought that the gain of columns ductility would increase when using both strengthening techniques (FRP or steel plates). Table 5 represents the percentage of the gain in ductility for different column specimens relative to their control one. It is clear that the two strengthening schemes exhibited noticeable gain in ductility compared to the control specimens. Also, test results show that the gains of ductility compared to the control column was little in case of decreasing FRP and steel plate's lengths. Changing length of FRP from full column length to 2/3 and 1/3 column length reduced the gain of ductility from 72.6 % to 10.39% and 1.4 % respectively. This means that a significant enhancement in ductility is shown when using full length FRP and no enhancement was observed when the length reduced to (1/3) of column height. Using steel plates can increase the overall ductility by 143.6% related to the control column but when using steel rivets the gain of ductility was 8.9%. It could be said that the improvement in ductility of slender columns was much higher for columns with steel plates than those with FRP laminates using epoxy bonding.

Table 5 Specimens ductility

Specimen	Ductility kN.mm	Gain %
C1 Control	1087	0.00
C2	1877	72.6
C3	1200	10.39
C4	1103	1.40
C5	2645	143.6
C6	1320	21.4
C7	1184	8.90

3-3 Effect of Strengthening Length of CFRP and Steel plates

Figs. 3 and 4 show the relation between applied compression load and vertical deformation. It is easily noted that using FRP and steel plates helped in reaching higher ultimate loads for all strengthened specimens using FRP layers and steel plates. Table 6 shows the specimens loading levels. For specimens strengthened with CFRP by full length, 2/3 and 1/3 of column length, the ultimate load increased by 94.73 %, 68.42%

and 10.52 % respectively. For column C5, with steel plates of full column length, the ultimate load increased the by 31.57 %. For column C6, with steel plates with 2/3 of column length, the strength gain was 7.89%.

Table 6 Specimens loading levels

Specimen	Failure Load (kN)	Yield Load (kN)	Cracking Load Level (kN)	Δ_u(mm)
C1, Control	190	190	100	7.60
C2	370	320	200	8.10
C3	320	290	174	2.26
C4	210	170	95	4.80
C5	250	240	132	15.55
C6	205	No yield	84	4.8
C7	222	No yield	89	11.00

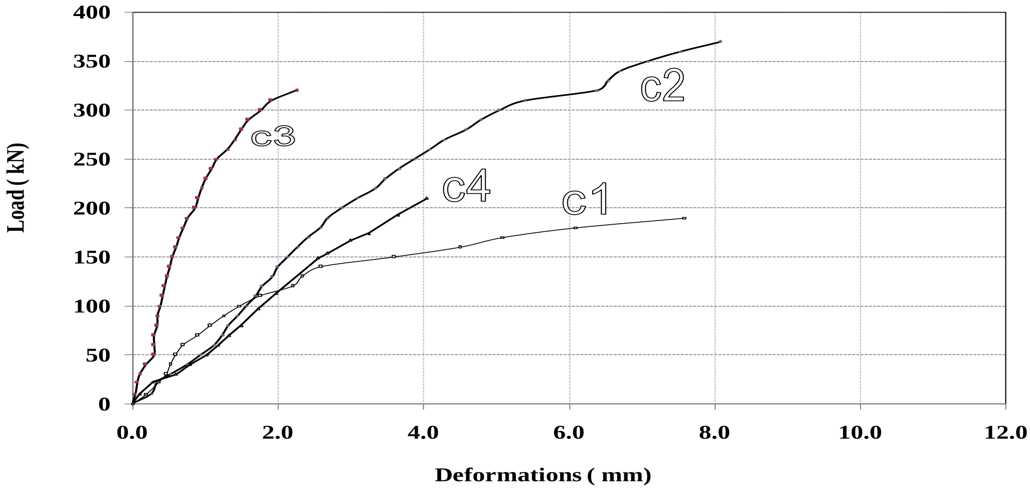

Fig. 3 Effect of FRP strengthening length

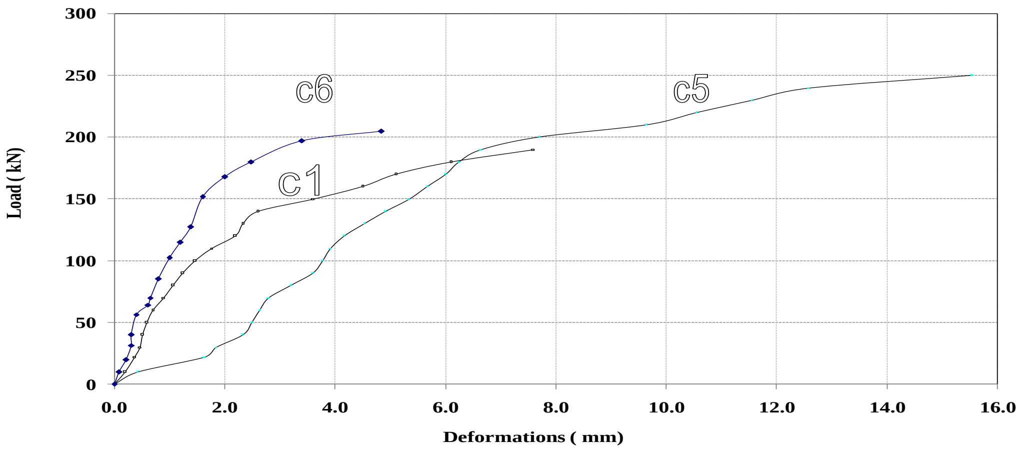

Fig. 4 Effect of steel strengthening length

3-4 Effect of Strengthening Material

Figs. 5, 6 and Table 6 show the ultimate failure load for the different technique of strengthening. When using FRP laminates and steel plates as two separate strengthening methods with full column length the ultimate failure loads increased by 94.7% and 31.5 % for C2 and C5 respectively, Fig 5. The same trend was observed when the strengthening length was reduced to be 2/3 column length. For C3 and C6 the ultimate failure loads were increased by 86.4% and 7.8% respectively as shown in Fig. 6.

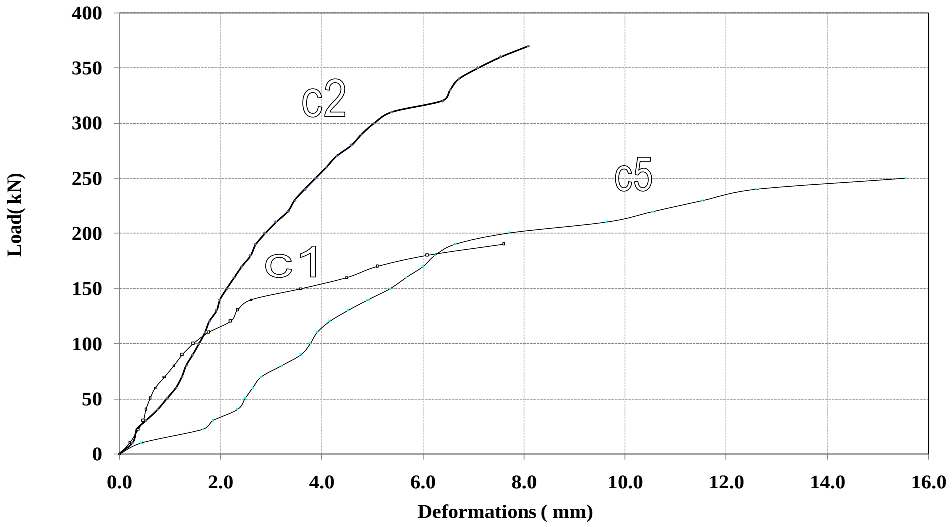

Fig. 5 Effect of strengthening material, FRP and steel plates, with 1800 mm length

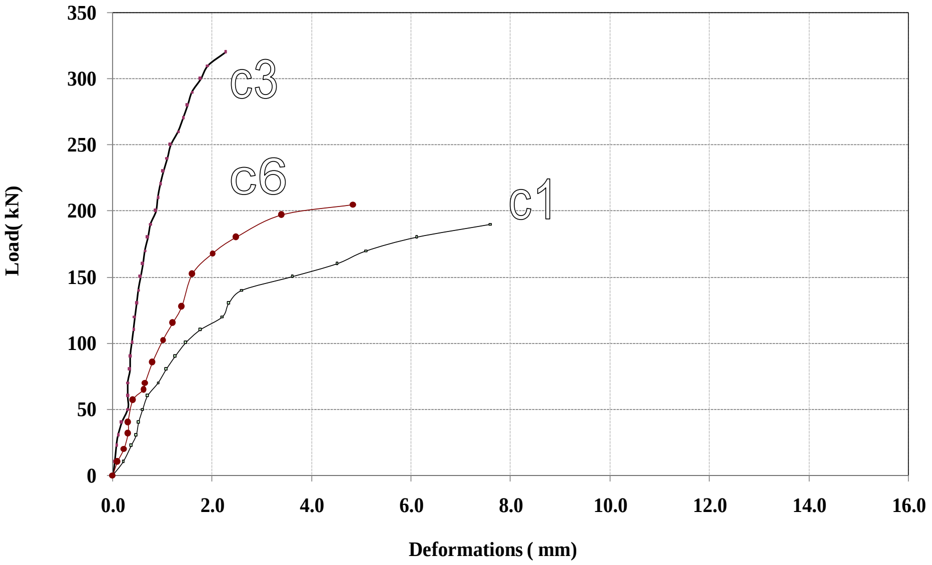

Fig. 6 Effect of strengthening material, FRP and steel plates, with 1200 mm length

3-5 Effect of Steel Plates Bonding Type

Fig. 7 and Table 5 show the effect of using two bonding technique for joining steel plate with concrete surface. Using Epoxy adhesive was the first one and the other one was by using Epoxy adhesive plus 20 mm diameter steel rivets. The test results show no enhancement when using steel rivets in additional to epoxy adhesive and this may be attributed to the weak concrete zones around the rivets. The results may differ for full scale specimens. For C5 and C7 the ultimate failure loads increased by 31.5% and 16.8% respectively.

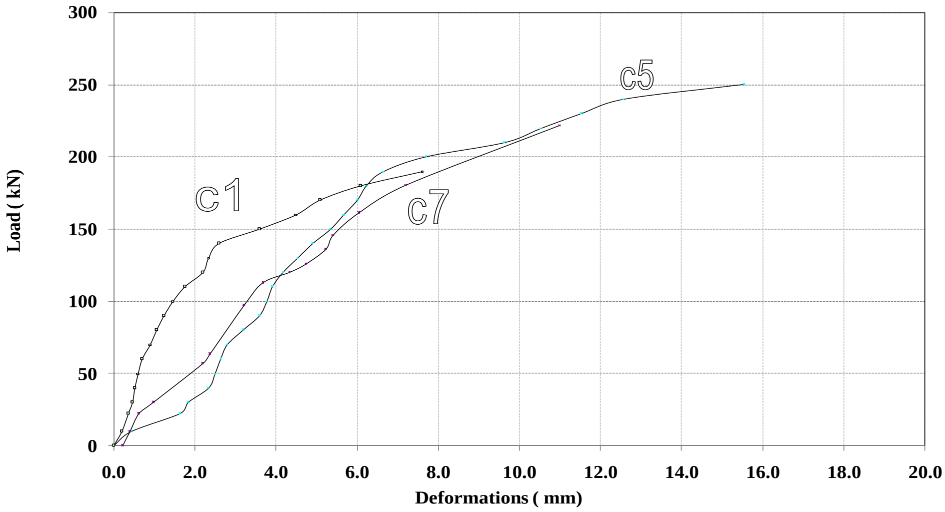

Fig. 7 Effect of steel plates bonding type with 1800 mm strengthening length

3-6 ECP 203-2007 Code Provisions for Design of Slender Columns

According to this code, a braced rectangular column is designed as short column if

$\lambda_b = He/b \leq 15$ (1)

or, $\lambda_i = He/i \leq 50$ (2)

where $H_e = \beta \, .H_{col}$ (3)

where, *He* is the effective column buckling height, *b* is the column dimension perpendicular to the axis of bending, *i* is the radius of gyration of the column cross section (equal to 0.289 times the overall depth of rectangular columns), H_{col} is the unsupported height of the column from the top of floor to the bottom of the floor above and β is the effective length factor which depends on the end conditions of the column and can be determined as given in the code (for a braced frame β≤1.0). If the column slenderness ratio exceeds this limit, the column will buckle prior to reaching its limit state of material failure. The effect of buckling can be taken in design by an additional moment (*Madd*) induced by the deflection of the column's buckled shape at the section being considered and can be calculated as follows:

$M_{add} = P \, . \, \delta$ (4)

Where, *P* is the applied ultimate axial load and δ is the induced deflection due to buckling which can be calculated from the following expression:

$\delta = (\lambda_b)^2 \, b \, /2000$ (5)

The induced deflection δ can be calculated also from the following general form:

$\delta = (\lambda_i)^2\ b/30000$ (6)

where *b* is the column dimension in the direction of buckling. According to this code, for rectangular cross section λb should not be taken more than 30 or $\lambda\ i \leq 100$.

Table 7 Comparison of test results with the predictions of ECP 203-2007

Specimen	Failure Load $P_{ul\text{-}Exp}$ (kN)	$P_{ul\text{-}ECCS}$ (kN)	$P_{ul\text{-}Exp} / P_{ul\text{-}ECP203}$
C1 Control	190	146	1.30
C2	370	332	1.11
C5	250	218	1.14
C7	222	218	1.02

It should be noted that according to the method of ECP 203-2007 the values of δu can be calculated using Eq. 5 or Eq. 6. However, the values calculated using Eq. 5 is more than that of Eq. 6, and hence these values were used in calculating *Pul-ECCS.* A comparison between the recorded experimental ultimate axial load of the strengthened columns (*Pul-exp*) with the predicted values (*Pul-ECCS*) using the design methods of the Egyptian code is given in Table 7. The value of Pu was calculated from the equilibrium between the external forces (with δu as calculated for each method) and the internal forces of the section. It should be noted that, a rectangular stress block of maximum stress equal to (0.85 *fc ')* and the ultimate concrete strain equal to 0.003 was used in calculation of the values of *Pu* . It should be noted that according to ECP 203-2007, columns can be considered as slender if $\lambda i > 50$. The recorded experimental ultimate load (*Pul-exp*) for the tested strengthened slender columns showed to be more than that predicted by the ECCS-2007. The values predicted by the ECP 203-2007 method were generally conservative for the four columns.

4- CONCLUSIONS

The presented experimental program clarified the feasibility of using FRP and steel plate for strengthening of RC slender columns. Results obtained are summarized as follows:

1. It may be concluded that strengthening of RC slender columns using FRP laminates showed better improvement in load capacity at the same value of lateral buckling than columns strengthened by steel plates. By using FRP laminates and steel plates as two separate strengthening methods with full column length the ultimate loads increased by 94.7% and 31.6% respectively.

2. The gain in ductility of slender columns strengthened with steel plates was higher than those strengthened with FRP. For specimens strengthened with FRP system and steel plates, full column length, the gain was 72.6 % and 143.6% respectively.
3. By using steel rivets plus the Epoxy adhesive with the steel plates, the gain of ductility was 8.9% with no enhancement in the column load capacity and this may be attributed to the weak concrete zones around the rivets.
4. Changing length of FRP laminates from full column length to 2/3 and 1/3 column length reduced the gain of ductility from 72.6 % to 10.39% and 1.4 % respectively.
5. Using epoxy adhesive and epoxy adhesive plus steel rivet enhance the ultimate column loads by 31.5% and 16.8% respectively, while the decreasing percentage was 11.2% after using 20 mm steel rivet.

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