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Materials and Structures

ISSN 1359-5997

Mater Struct
DOI 10.1617/s11527-015-0526-5

ONLINE FIRST

ISSN 1359-5997 CODEN MASTED

Materials and Structures

Matériaux et Constructions

Springer

Springer

Materials and Structures
DOI 10.1617/s11527-015-0526-5

ORIGINAL ARTICLE

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Received: 10 November 2014 / Accepted: 3 January 2015

Abstract The paper investigates FRP confinement of wall-like reinforced concrete columns in a systematic way, by examining a number of parameters not addressed before: the effectiveness of different types of anchors, the role of different cross section aspect ratios (3 and 4), the number of layers, local strengthening at the corners and the reduction of aspect ratio by cross section enlargement. These parameters are combined in an analytical model for the ultimate load in concentrically loaded columns, which is found in good agreement with test results. It is concluded that: properly dimensioned (heavy) anchors nearly double the confining effectiveness of FRP; the use of additional FRP layers near the edges of the cross section increases the confining effectiveness of the jacket by approximately 50 %; and shape enlargement of the cross section with mortar is practically as effective as the use of heavy anchors.

Keywords Concrete · Confinement · Fiber-reinforced polymers · Shape enlargement · Spike anchors · Wall-like columns

List of symbols

A_c	Area of concrete
A_e	Effectively confined area
A_g	Gross section area
A_s	Area of longitudinal steel reinforcement
A_{un}	Unconfined area
D	Diameter of circular column
D^*	Diameter of equivalent circular column
P	Total load
P_c	Load carried by concrete
P_s	Load carried by longitudinal steel
R	Radius at corners of cross section
a_f	Confinement effectiveness factor
b	Small dimension of cross section
h	Large dimension of cross section
f_c	Compressive strength of unconfined concrete
f_{cc}	Compressive strength of confined concrete
f_f	Unidirectional tensile strength of jacket
$f_{f,h}$	Tensile strength of jacket in the hoop direction
f_s	Compressive stress of steel reinforcement
k_R	Factor to account for the effect of radius
k_1	Reduction factor
n	Number of anchors at cross section
s_a	Vertical spacing of anchors
t_f	Thickness of FRP jacket

1 Introduction and background

For approximately three decades, fiber reinforced polymers (FRP) have gained increased popularity as externally applied confining reinforcement of concrete columns, due to their ease of application, excellent

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durability characteristics, high strength and high deformation capacity. Confinement of reinforced concrete (RC) columns with FRP has become a common technique today for increasing the axial load capacity of columns in non-seismic areas as well as for increasing the ductility and for preventing lap-splice failures and delaying rebar buckling of columns under seismic actions. External confinement with FRP materials is typically applied on circular or rectangular columns, wrapped with epoxy-bonded sheets made of unidirectional fibers in the circumferential direction.

The literature on the mechanical behaviour of FRP-confined circular or rectangular concrete elements is vast. Hundreds of investigations have provided substantial test data on the load-deformation response of plain or reinforced concrete specimens (typically small) confined with externally bonded FRP. These data have been quite useful not only in understanding the confining action of FRP jackets, but also in calibrating models for the strength, ultimate strain and constitutive response of concrete wrapped with FRP.

The confining action of FRP jackets results in highest effectiveness on circular columns, where fibers are equally stressed on the entire cross section. Columns with square or rectangular cross sections behave differently: the parts of the cross section near the corners are confined effectively, but other parts remain unconfined. This loss of effectiveness is generally modelled with parabolic areas defined by the corners. FRP jackets in rectangular cross sections are less effective than in a circular one and their effectiveness depends heavily on the aspect ratio of the cross section (ratio of largest to smallest side). Depending on the radius at the corners of the cross section, the effectiveness of FRP jackets reduces significantly as the aspect ratio of the cross section approaches values in the order of 2–3 (e.g. [7]).

In the case of wall-like columns, with aspect ratios of cross sections higher than about 3, both experimental and analytical studies highlight that the effectiveness of FRP jackets is limited. Hosny et al. [8] tested 12 rectangular reinforced concrete columns with cross section of 150 × 450 mm and height equal to 1.5 m. The axially loaded columns were confined using carbon fiber reinforced polymer (CFRP) strips. A key conclusion in this study was that the low effectiveness of CFRP could increase by transforming the shape of the cross section to elliptical or by adding longitudinal steel plates along the wide sides, fixed with anchor bolts. Tan [26] performed compression tests on 52 RC columns with cross section of 115 × 420 mm and height equal to 1.2 or 1.5 m. The jackets comprised CFRP or glass FRP (GFRP) in the circumferential direction, occasionally combined with longitudinal plies near the corners or in the middle of the long sides. In two of the columns the jackets were anchored on the long faces of the columns, but no further information is provided on the type, spacing etc. of the anchors. One last parameter in this investigation was the combination of FRP jackets with or without plaster finishes. This study demonstrated that circumferentially applied FRP has increased effectiveness if combined with longitudinal sheets or anchors. Tanwongsval et al. [27] tested five RC columns with cross section of 115 × 420 mm and height equal to 1.5 m. The columns were strengthened with both circumferentially and longitudinally applied GFRP and were tested in uniaxial compression. The possibility of installing the FRP after enlarging the cross section with two semi-cylindrical parts made of high strength mortar was explored and the effect of strengthening under sustained loading was investigated. Key conclusion in this investigation was that the use of semi-cylindrical attachments in contact with the short faces of the columns was quite effective in increasing the load capacity of columns, by reducing stress concentrations near the corners. Prota et al. [24] performed uniaxial compression tests on nine columns with the geometry as in Tan [26] and Tanwongsval et al. [27]. Parameters under investigation in this study included the use of quadri-directional GFRP and the combination of wrapping with longitudinally applied C-shaped plies around the corners, as a means of delaying buckling of the longitudinal steel rebars. Experimental findings were compared with existing analytical models for FRP confined concrete and it was concluded that reasonably good agreement was found with the model of Lam and Teng [18].

From the literature survey presented above it is clear that confinement of wall-like RC columns with FRP has received very limited attention. Even less attention, if any at all, has been paid to the important aspect of anchoring the FRP along the wide faces. One promising technique to achieve this involves the use of spike anchors, which comprise resin-impregnated fiber rovings. Spike anchors are easy to install and have received the attention of investigators in a few studies related to tensile properties [13, 23], bond aspects [1, 6, 9, 21], flexural strengthening of beams or slabs [3, 22, 25], shear strengthening of beams [11, 14, 17], flexural strengthening of columns Vrettos et al. [29] and shear strengthening of columns [16, 20]. In the field of confinement, spike anchors have been used in columns with L-shaped cross sections [12] and in columns with circular or rectangular sections with aspect ratio equal to 2 [10, 15].

In this paper the authors investigate FRP confinement of wall-like columns in a systematic way. The study examines a number of parameters not addressed before: the effectiveness of different types of anchors, the role of different cross section aspect ratios (3 and 4), the number of layers, local strengthening at the corners and the reduction of cross section aspect ratio by increasing the dimension of the columns' small side. These parameters are combined in an analytical model, which was found in reasonably good agreement with test results.

2 Experimental program

2.1 Test specimens and experimental parameters

A total of 45 identical rectangular reinforced concrete columns were constructed in 15 different designs, that is with three identical specimens per design, as shown in Table 1, and tested in uniaxial compression. A group of seven column designs had a cross section measuring 150 mm by 450 mm, with an aspect ratio of 3, and a second group of eight column designs had a cross section of 150 mm by 600 mm, with an aspect ratio of 4. To facilitate FRP wrapping, the four corners were chamfered to a radius of 20 mm. All columns measured 800 mm in height, so that slenderness effects could be eliminated. Longitudinal reinforcement comprised 6 or 8 12 mm diameter deformed bars in columns with aspect ratio 3 or 4, respectively, with a total area of 679 or 905 mm^2. The longitudinal steel ratio was thus 1 %. Transverse reinforcement consisted of 8 mm diameter stirrups at a spacing of 150 mm. The reinforcement was placed with a clear concrete cover of 15 mm. Details of column geometries and reinforcements are given in Fig. 1.

The columns were designed so that the role of the following seven parameters on the effectiveness of CFRP confinement could be investigated: cross sectional aspect ratio, use of spike anchors, capacity of anchors, number of anchors, number of CFRP layers, cross section modification and local strengthening at the corners. A description of the specimens follows next, supported by Fig. 2 and Table 1.

Columns C3, II3, 1A_lII3, 2A_lII3, 1A_hII3, 1A_hIII3 and MII3 had a cross sectional aspect ratio of 3, as indicated by the last number in their notation.

- Column C3 was tested without jacketing, as control (Fig. 2a).
- Column II3 was confined with two layers of CFRP (Fig. 2b).
- Column 1A_lII3 was confined with two layers of CFRP, combined with light-weight carbon fiber spike anchors placed in the middle of cross sections, at a vertical spacing of 150 mm (Figs. 1c, 2c).
- Column 2A_lII3 was confined with two layers of CFRP, combined with light-weight carbon fiber spike anchors placed in pairs, at a spacing of 150 mm (Fig. 2d).
- Column 1A_hII3 was identical to 1A_lII3, except that the anchors were twice as heavy in comparison to those in 1A_lII3 (Fig. 2e).
- Column 1A_hIII3 was identical to 1A_hII3, except that jacketing was done with three layers of CFRP instead of two (Fig. 2f).
- Column MII3 was confined with two layers of CFRP after reducing the cross sectional aspect ratio by enlarging the cross section through the addition of a 20 mm thick layer of mortar on each long face of the column (Fig. 2g).

Columns C4, II4, 1A_lII4, 2A_lII4, 2A_hII4, 2A_hIII4, 2A_hIIU4 and MII4 had a cross-sectional aspect ratio of 4, as indicated by the last number in their notation.

- Column C4 was tested without jacketing, as control (Fig. 2h).
- Column II4 was confined with two layers of CFRP (Fig. 2i).
- Column 1A_lII4 was confined with two layers of CFRP, combined with light-weight carbon fiber spike anchors placed in the middle of cross sections, at a vertical spacing of 150 mm (Fig. 2j).
- Column 2A_lII4 was confined with two layers of CFRP, combined with light-weight carbon fiber spike anchors placed in pairs, at a spacing of 150 mm (Figs. 1d, 2k).

Table 1 Specimen notation and summary of test results

Notation	Strengthening scheme	Peak force (kN)	Average peak force (kN)	Failure mode	Strength increase (%)	Ultimate strain ε_{cu} (–)	Average ε_{cu} (–)	Increase in ε_{cu} (%)
C3	–	1198.5	1149.4	RB[a] + CC[b]	–	0.0026	0.0030	–
		1125.3				0.0027		
		1124.3				0.0038		
II3	Two layers of CFRP	1548.5	1601.4	JRc[c]	39.3	0.0099	0.0153	410
		1603.2				0.0202		
		1652.4				0.0159		
1A_lII3	Two layers of CFRP, 1 light anchor	1608.8	1556.4	AR[d], JRc	35.4	0.0075	0.0112	273
		1540.3				0.0142		
		1520.2				0.0120		
2A_lII3	Two layers of CFRP, 2 light anchors	1470.5	1477.3	AR, JRc	28.5	0.0141	0.0145	383
		1426.6				0.0150		
		1534.7				0.0145		
1A_hII3	Two layers of CFRP, 1 heavy anchor	1764.3	1809.2	JRc	57.4	0.0105	0.0083	177
		1846.8				0.0057		
		1816.5				0.0086		
1A_hIII3	Three layers of CFRP, 1 heavy anchor	2114.2	2043.8	JRc	77.8	0.0422	0.0305	917
		1881.3				0.0297		
		2135.9				0.0198		
MII3	Section enlargement, two layers of CFRP	1911.6	1830.3	JRc	59.2	0.0143	0.0181	503
		1743.2				0.0215		
		1836.2				0.0185		
C4	–	1403.8	1509.0	RB + CC	–	0.0037	0.0044	–
		1604.4				0.0048		
		1518.9				0.0046		
II4	Two layers of CFRP	1877.7	1907.6	JRc	26.4	0.0105	0.0147	234
		1934.7				0.0126		
		1910.4				0.0209		
1A_lII4	Two layers of CFRP, 1 light anchor	1987.5	1934.4	AR, JRc	28.2	0.0114	0.0119	170
		1899.9				0.0125		
		1915.8				0.0118		
2A_lII4	Two layers of CFRP, 2 light anchors	1901.4	1870.7	AR, JRc	24.0	0.0130	0.0101	130
		1820.5				0.0082		
		1890.3				0.0090		
2A_hII4	Two layers of CFRP, two heavy anchors	2118.8	2191.5	JRc	45.2	0.0103	0.0163	270
		2259.3				0.0065		
		2196.5				0.0081		
2A_hIII4	Three layers of CFRP, two heavy anchors	2708.3	2598.0	JRc	72.2	0.0132	0.0126	186
		2410.0				0.0122		
		2675.6				0.0125		
2A_hIIU4	Two layers of CFRP, two layers of U, two heavy anchors	2457.1	2518.1	JRm[e]	68.0	0.0142	0.0131	198
		2631.8				0.0127		
		2465.3				0.0125		

Table 1 continued

Notation	Strengthening scheme	Peak force (kN)	Average peak force (kN)	Failure mode	Strength increase (%)	Ultimate strain ε_{cu} (–)	Average ε_{cu} (–)	Increase in ε_{cu} (%)
MII4	Section enlargement, two layers of CFRP	2103.5	2102.2	JRc	37.1	0.0131	0.0109	148
		2092.7				0.0085		
		2110.4				0.0110		

[a] Rebar buckling

[b] Concrete crushing

[c] Jacket rupture at corner

[d] Anchor Rupture

[e] Jacket rupture near the middle of the long side

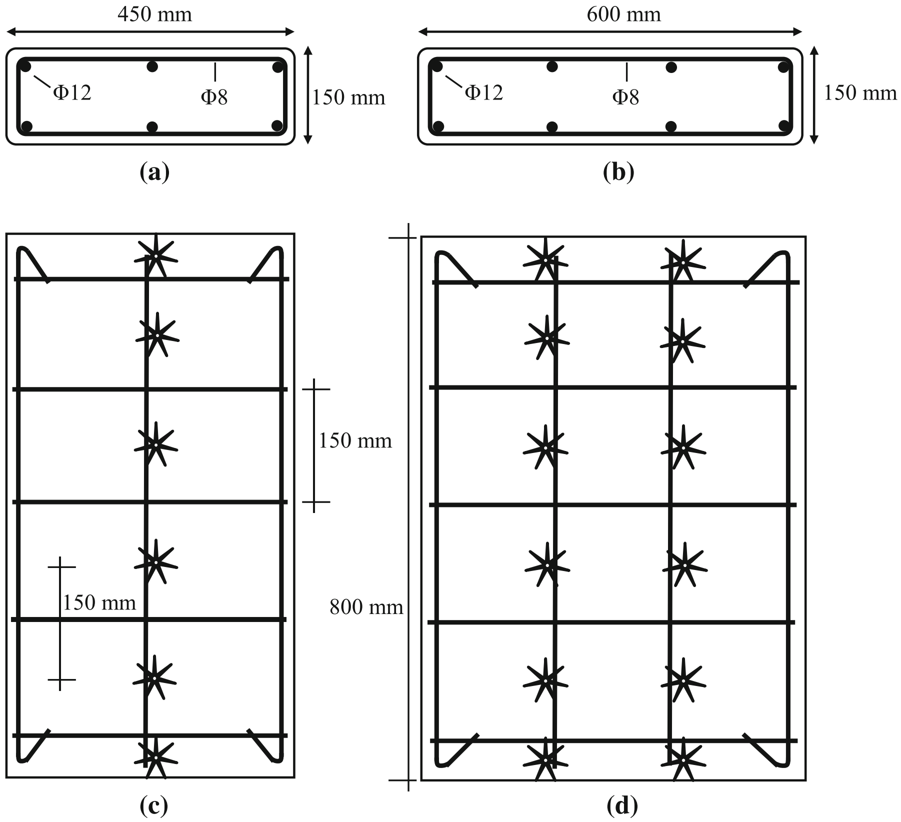


Fig. 1 Column geometry and reinforcement: **a** cross section with aspect ratio 3, **b** cross section with aspect ratio 4, **c** side view of columns with aspect ratio 3, illustrating the locations of spike anchors in specimens with one anchor in the middle of the long side, **d** side view of columns with aspect ratio 4, illustrating the locations of spike anchors in specimens with anchors placed in pairs

- Column $2A_{\mathrm{h}}$II4 was identical to $2A_{\mathrm{l}}$II4, except that the anchors were twice as heavy in comparison to those in $2A_{\mathrm{l}}$II4 (Fig. 2l).
- Column $2A_{\mathrm{h}}$III4 was identical to $2A_{\mathrm{h}}$II4, except that jacketing was done with three layers of CFRP instead of two (Fig. 2m).
- Column $2A_{\mathrm{h}}$IIU4 was identical to $2A_{\mathrm{h}}$II4, except that the jackets at the corners of the cross section were strengthened by inserting another two layers of CFRP in a U-shaped configuration, with fibers as in the outer two layers, that is in the circumferential direction (Fig. 2n).

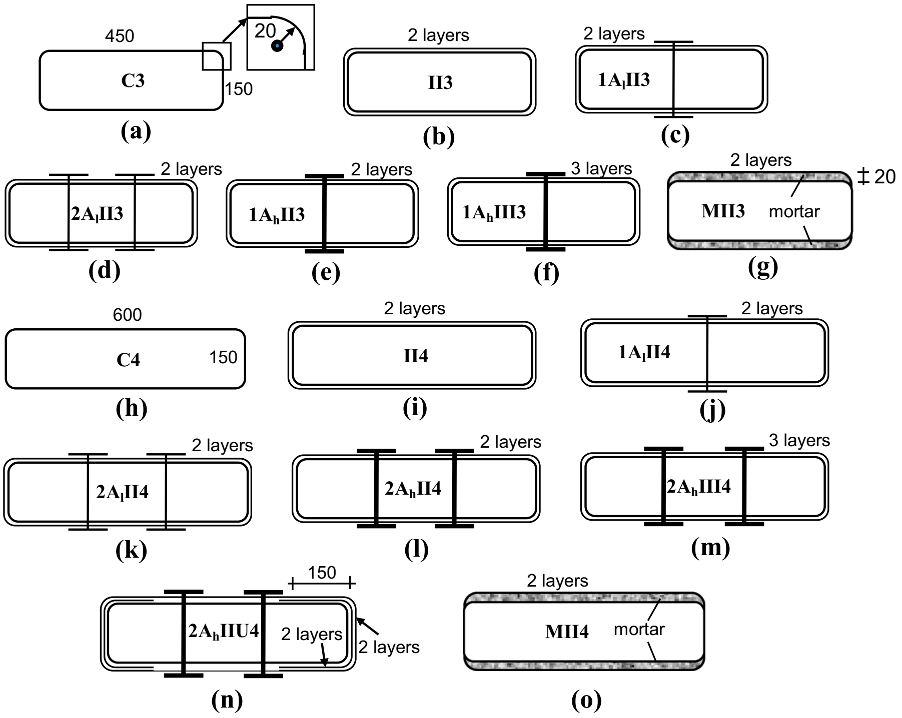


Fig. 2 Configuration of strengthening schemes: **a** C3, **b** II3, **c** $1A_\mathrm{l}$II3, **d** $2A_\mathrm{l}$II3, **e** $1A_\mathrm{h}$II3, **f** $1A_\mathrm{h}$III3, **g** MII3, **h** C4, **i** II4, **j** $1A_\mathrm{l}$II4, **k** $2A_\mathrm{l}$II4, **l** $2A_\mathrm{h}$II4, **m** A_hIII4, **n** $2A_\mathrm{h}$IIU4, **o** MII4 (all dimensions in mm)

- Column MII4 was confined with two layers of CFRP after reducing the cross sectional aspect ratio by enlarging the cross section through the addition of a 20 mm thick layer of mortar on each long face of the column (Fig. 2o).

In the notation of all specimens C denotes a control specimen, II or III denotes the use of two or three CFRP layers, nA_i denotes the use of spike anchors ($n = 1$ or 2 for one or two anchors, $i = \mathrm{l}$ or h for light or heavy anchors), M denotes the use of mortar to enlarge the cross section, U denotes the use of U-shaped CFRP inserts near the corners and the number at the end, 3 or 4, denotes the cross sectional aspect ratio.

2.2 Materials and strengthening procedures

Casting of the columns was made with the same batch of ready-mix concrete in stiff moulds. The average compressive strength at the time of testing of the columns (a few months after casting), measured on 150 × 300 mm cylinders was 18 MPa (average value from six specimens). Strength properties (average values from three specimens) for the steel used for longitudinal and transverse reinforcement were as follows: yield stress 570 MPa, tensile strength 680 MPa. A few days before testing, all specimens were capped with a special self-leveling high-strength mortar.

The carbon fiber sheet used for confinement was a commercial unidirectional fiber product with a weight of 644 g/m^2. The carbon fiber sheet was impregnated with a commercial low viscosity structural adhesive (two-part epoxy resin with a mixing ratio 3:1 by weight) with tensile strength of 72.4 MPa and an elastic modulus of 3.2 GPa (cured 3 days at 60 °C). Values of tensile strength and elastic modulus for one layer of the epoxy-impregnated carbon sheet from manufacturer data sheets were equal to 986 MPa and 95.8 GPa, respectively, corresponding to a nominal thickness equal to 1 mm. These values were confirmed by testing five coupons in uniaxial tension according to [5]. The test results gave an average tensile strength equal to 1,046 MPa and an elastic modulus equal to 93.7 GPa.

Each anchor comprised a tow of fibers of the same type used in the unidirectional sheets. The length of anchors was 350 mm and their weight was 15 and 30 g/m for the light (A_l) and the heavy (A_h) anchors, respectively. Impregnation and bonding of fiber anchors was done using the same epoxy adhesive used for the impregnation of the carbon sheets.

For the columns receiving mortar to enlarge the dimension of the short side, a commercial low-cost cement-based binder suitable for plastering was used, with a binder to water ratio equal to 5:1. The flexural and compressive strength of the mortar was obtained according to [4], as average of six specimens. The compressive and flexural strength at the time of testing the columns were 20 and 6.2 MPa, respectively.

The surfaces of the columns to be strengthened were ground mechanically to remove any laitance. Small cavities were filled with epoxy resin (Fig. 3a). Application of the CFRP took place a few months after concrete casting, by pre-wetting each sheet manually (using a roller brush) with the epoxy adhesive. Each of the (two or three) consecutive layers was bonded on each column so that the starting and finishing edges of the wraps overlapped by 200 mm on the wide face of the column. The extra U-shaped CFRP inserts in column 2A_hIIU4 were placed under the two continuous CFRP layers, starting at a distance of 150 mm from each corner of the cross section (Fig. 2n).

Fiber anchor spikes were formed by impregnating dry fibers with epoxy. Before applying the CFRP layers, 12 mm diameter holes were drilled through the thickness of the columns. To facilitate wrapping with CFRP, the holes were temporarily covered with protruding plastic inserts (Fig. 3a), which were removed prior to application of the anchors. Each fiber anchor was inserted into the holes after applying all layers of the CFRP around the columns, and the protruding fibers were fanned out radially over the last layer, at a distance equal to 100 mm (Fig. 3b). Finally, the anchors were covered with a 200 mm wide strip of CFRP in the central part of each wide face of the column, applied longitudinally, that is with the fibers in vertical orientation (Fig. 3c).

2.3 Experimental results and discussion

Testing was performed approximately 1 month after application of the strengthening system. All columns were tested in uniaxial compression through the application of monotonic loading at a rate of 0.01 mm/s in displacement control, using a 4,000 kN compression testing machine. Loads were measured from a load cell and displacements were obtained using external linear variable differential transducers (LVDT) mounted on the two long sides, at a gauge length of 300 mm, in the middle part of each specimen. From the applied load and average displacement measurements, the stress–strain curves were obtained for each test. Stresses were calculated by dividing the load by the gross section area, taken equal to $150 \times 450 = 67{,}500$ and $150 \times 600 = 90{,}000$ mm^2 for columns with cross sectional aspect ratio equal to 3 and 4, respectively.

All the uniaxial compression stress–strain curves are plotted in Figs. 4 and 5. Average values for peak

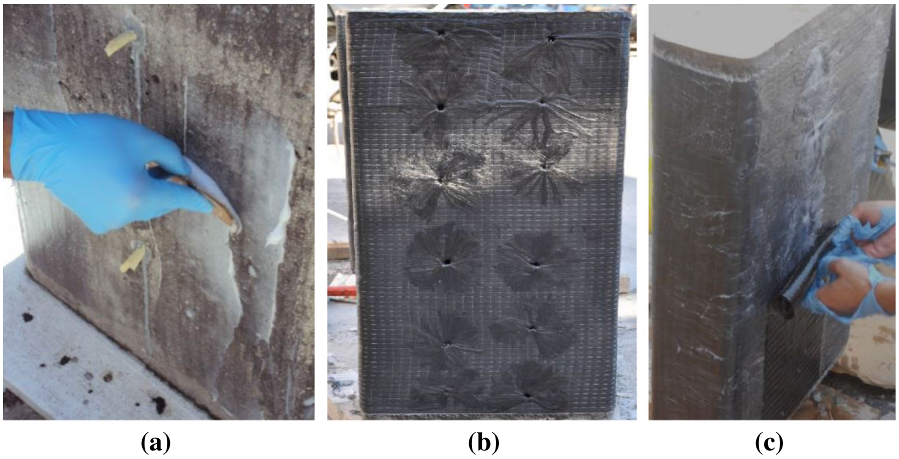

(a) (b) (c)

Fig. 3 Photographs illustrating: **a** filling of cavities with epoxy resin, plastic inserts covering the holes, **b** side view of column with spike anchors placed in pairs, and **c** coverage of anchors with longitudinal CFRP forces, ultimate strains (defined at the point where either the FRP jacket ruptures or the load has dropped by 20 % of the peak value) and the corresponding increase for each jacketing system with respect to values for unconfined columns are given in Table 1.

Failure of the control specimens (C3, C4) was typical of not properly confined reinforced concrete, due to buckling of the longitudinal rebars, which led to crushing of the concrete (Fig. 6a). All the other specimens failed when the FRP jacket ruptured in the circumferential direction at one of the four rounded corners (Fig. 6b), due to stress concentrations. Column 2A_hIIU4, with the two extra layers of CFRP around the corners, was the only one where the jacket ruptured in its straight part, near the middle of the long side (Fig. 6c). In all columns with light anchors (1A_lII3, 2A_lII3, 1A_lII4, 2A_lII4), rupture of the jacket was preceded by gradual rupture of the anchors, implying that at failure the jacket acted as if no anchors were in place (Fig. 6d). This fact explains why the capacity of columns without anchors was similar to that of columns with light anchors. On the contrary, the heavy anchors remained intact (Fig. 6e), thereby increasing the effectiveness of the CFRP jacket all the way to failure.

The results for specimens II3, 1A_lII3 and 2A_lII3 indicate that in columns with aspect ratio equal to 3, two layers of CFRP with no anchors or with the light anchors (which failed prematurely) increased the strength by 30–40 %. As expected, the corresponding increase in columns with aspect ratio equal to 4 (II4, 1A_lII4 and 2A_lII4) was lower, in the order of 25 %. The strength of columns 1A_hII3 and 2A_hII4 was 57.4 and 45.2 % higher than that of C3 and C4, respectively, indicating that the use of heavy anchors nearly doubled the effectiveness of jackets with two layers. Jackets with three CFRP layers combined with (heavy) anchors performed extremely well too, increasing the strength by nearly 80 and 70 %, for columns with aspect ratio 3 (1A_hIII3) and 4(2A_hIII4), respectively. The use of additional CFRP near the edges (column 2A_hIIU4) was also quite effective, by suppressing premature failure of the jacket at the corners; the respective increase in strength was 67 %. Finally, shape enlargement of the cross sections with mortar (columns MII3 and MII4) was practically as effective as the use of (heavy) anchors (1A_hII3 and 2A_hII4). In this case the strength increased by approximately 60 and 40 % in columns with aspect ratio 3 (MII3) and 4 (MII4), respectively, which is comparable to approximately 57 and 45 % corresponding to columns 1A_hII3 and 2A_hII4.

As given by the last column of Table 1, CFRP jacketing increased the axial deformation capacity of all columns substantially. This increase was highest in the cross sections with the lowest aspect ratio.

3 Analytical modelling

The total compressive load carried by each column is calculated by adding the compressive load carried by the concrete, P_c, and the compressive load carried by the steel reinforcement, P_s. In columns with cross sections as those investigated in this study, the confining action due to steel stirrups is negligible. Hence, P_c is calculated by multiplying the total concrete area, A_c, by the strength of concrete confined by FRP, f_{cc}, and the total compressive load becomes:

$$P = P_c + P_s = A_c f_{cc} + A_s f_s \tag{1}$$

where A_s and f_s is the area and compressive stress, respectively, of the longitudinal steel reinforcement.

The compressive strength of concrete confined by FRP in rectangular cross sections with dimensions b and h ($h \geq b$) may be calculated by modifying slightly the widely accepted model of Lam and Teng [18]:

$$\frac{f_{cc}}{f_c} = 1 + 3.3\left(\frac{b}{h}\right)^2 \alpha_f \frac{2t_f}{D^*}\frac{f_{f,h}}{f_c} \tag{2}$$

where f_c compressive strength of unconfined concrete, t_f thickness of jacket, $f_{f,h}$ tensile strength of jacket in the hoop direction, D^* diameter of the equivalent circular column and α_f confinement effectiveness factor, defined as the ratio of effectively confined area A_e to the total area A_g. The model described by Eq. (2) was presented as an extension of the original model of Lam and Teng [19] for circular cross sections with diameter D:

$$\frac{f_{cc}}{f_c} = 1 + 3.3\frac{2t_f}{D}\frac{f_{f,h}}{f_c} \tag{3}$$

Lam and Teng [18] suggested to take $D^* = \sqrt{h^2 + b^2}$, which implies that the equivalent circular cross section circumscribes the rectangular. However, this formulation has the drawback that if $b = h = D$ and the chamfer radius is $D/2$, that is if the

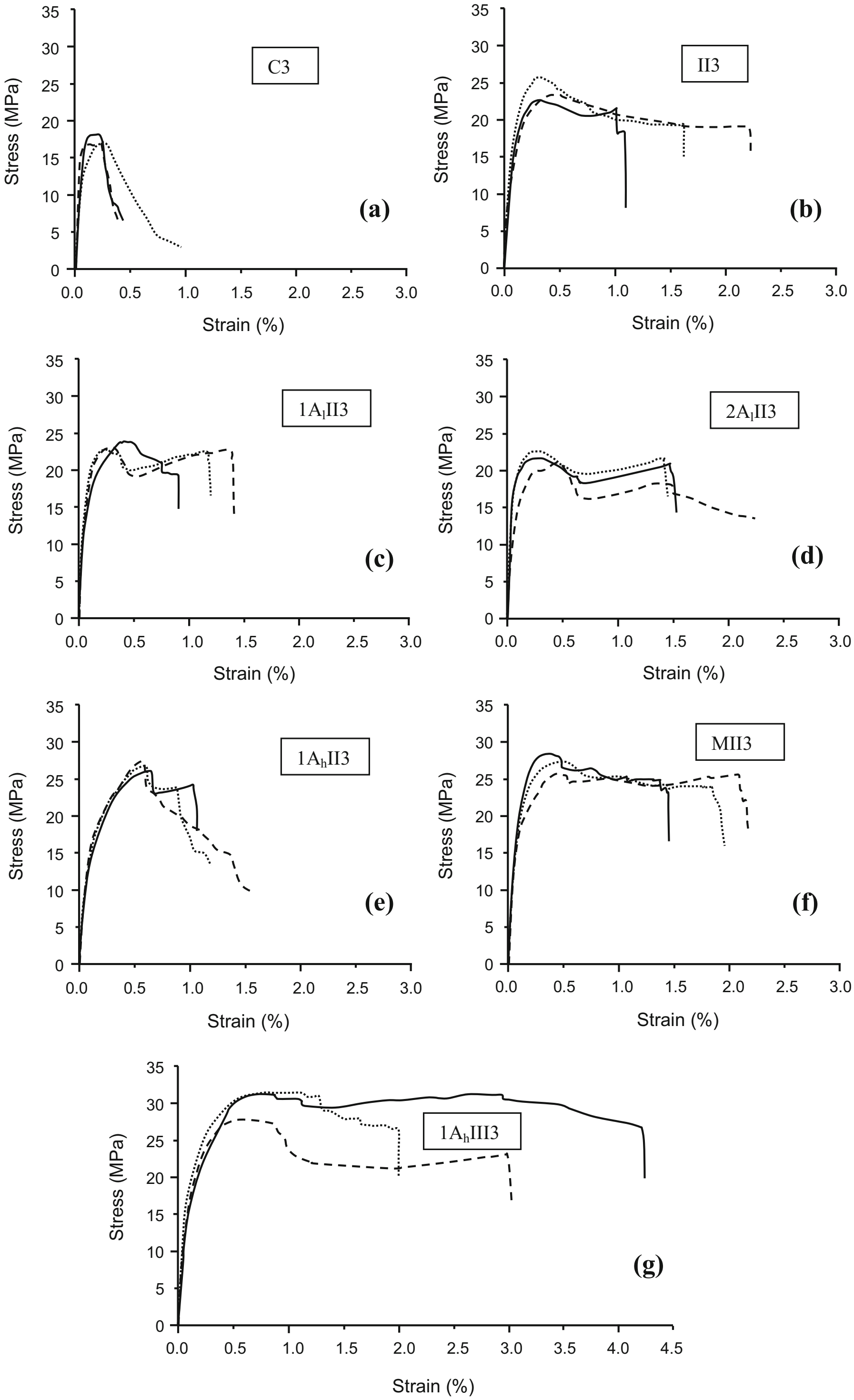
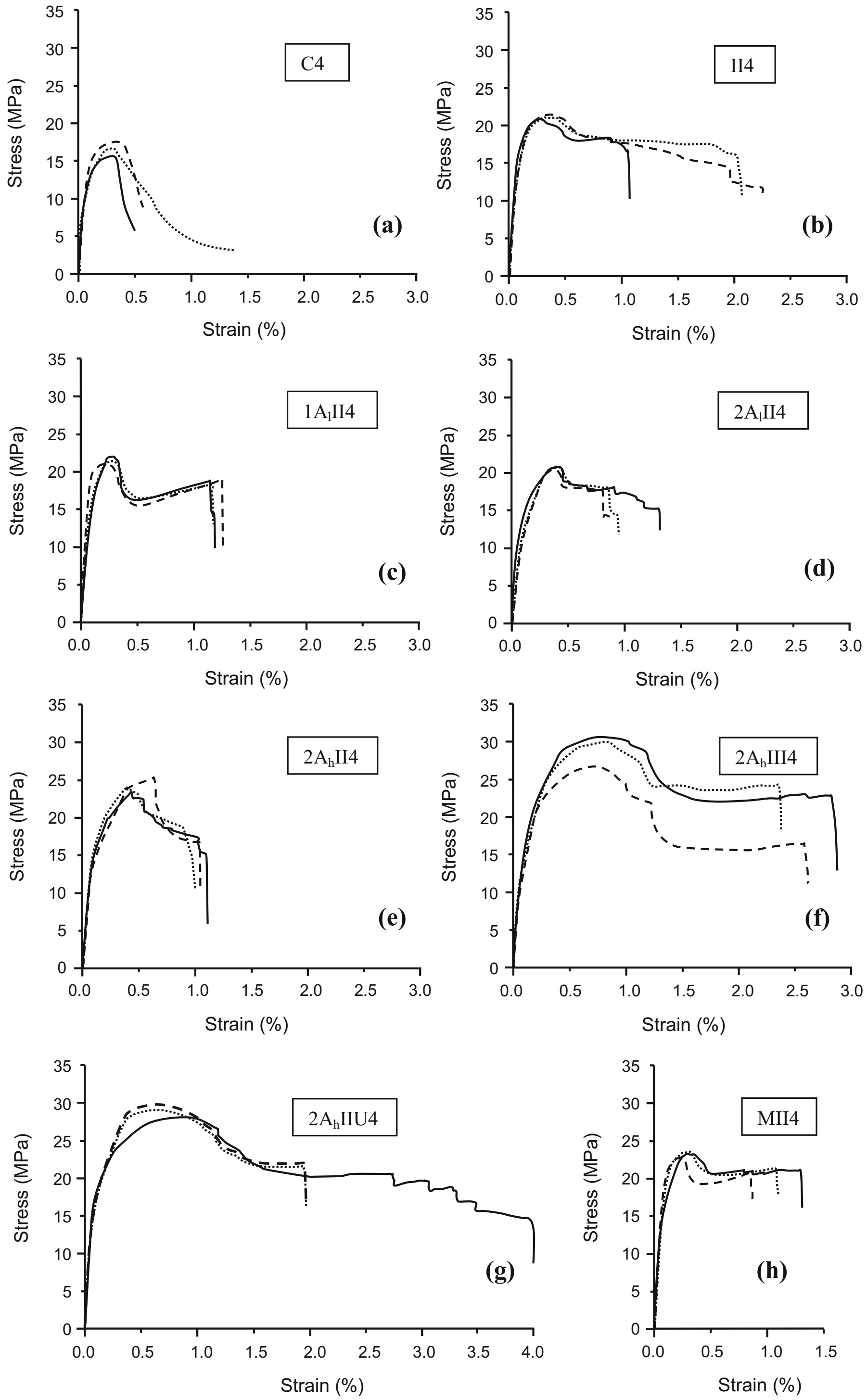


Fig. 4 Axial stress–strain diagrams of columns with cross sectional aspect ratio 3

rectangular section becomes circular with diameter *D*, Eq. (2) does not become identical to Eq. (3), as it should. This obstacle may be overcome by calculating *D** so that the equivalent circular section has the same FRP volumetric ratio as the original rectangular section, which results in the following expression [28]:

Fig. 5 Axial stress–strain diagrams of columns with cross sectional aspect ratio 4



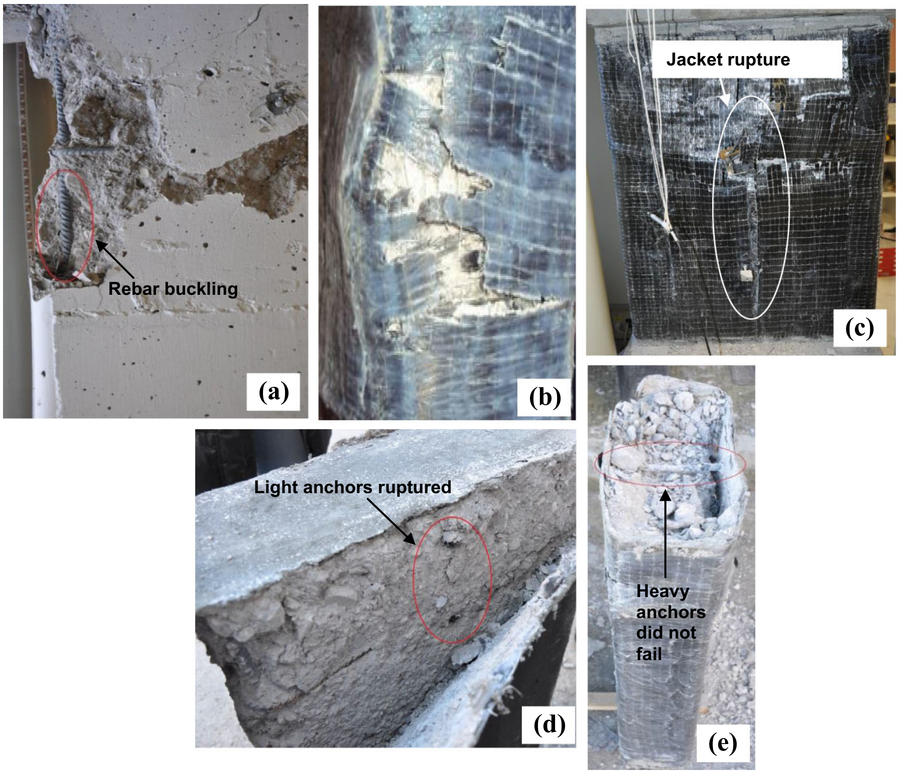


Fig. 6 Typical photographs of failed columns: **a** rebar buckling and concrete crushing in control specimens, **b** jacket rupture at the corner, **c** jacket rupture in the middle of the long side, **d** premature rupture of anchors in columns with light anchors, and **e** no failure of the heavy anchors

$$D^* = \frac{2bh}{b+h} \tag{4}$$

The tensile strength of the jacket in the hoop direction, $f_{\mathrm{f,h}}$, depends on a number of factors including the radius R of the jacket (if the jacket ruptures at rounded corners), the duration of loading, the effect of buckling of the longitudinal steel reinforcement as well as environmental effects (e.g. temperature, humidity) if the jacket is unprotected:

$$f_{f,h} = k_1 k_R f_f \tag{5}$$

where f_{f} unidirectional tensile strength of jacket, obtained from coupon testing, k_{R} factor to account for the effect of radius and k_1 factor (≤ 1) to account for all the other effects. The corner radius reduction factor is taken here equal to [2]:

$$k_{\mathrm{R}} = \begin{cases} \dfrac{R}{60}\left(2 - \dfrac{R}{60}\right) & R \leq 60\ \mathrm{mm} \\ 1 & R \geq 60\ \mathrm{mm} \end{cases} \tag{6}$$

In columns without anchors or with light anchors which fail prematurely, the effectively confined area A_{e} is defined by the parabolas in Fig. 7a. In the presence of heavy anchors, which remain intact at jacket failure, the effectively confined area is modified as shown in Fig. 7b. To account for the use of anchors at vertical spacing equal to s_{a}, each of the points where two parabolas meet at anchor locations (A in Fig. 7b) should be displaced towards the interior of the cross section. This displacement is maximized at cross sections where confinement is minimized, that is at mid-height between anchor locations. Hence, assuming that all points A are displaced along a (vertical) parabola, as it is typically assumed in the case of steel stirrups, the maximum displacement of points A equals $s_{\mathrm{a}}/4$ and the effectively confined area becomes as shown in Fig. 7c. For the general case of n anchors in each cross section, $A_{\mathrm{e}} \approx bh - A_{\mathrm{un}}$, where A_{un} area of unconfined concrete, calculated as follows (Fig. 7c):

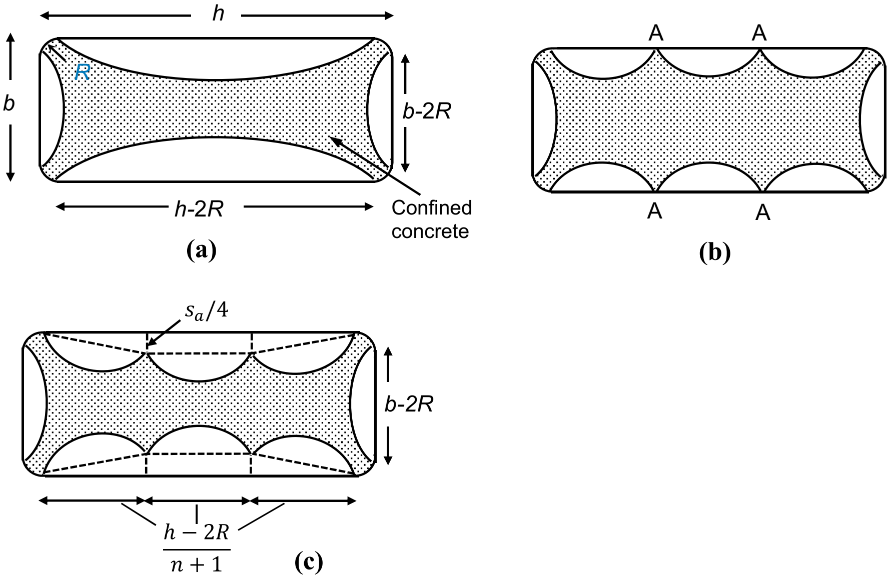


Fig. 7 Effectively confined cross section areas: **a** cross section in columns without anchors or with light anchors, which failed prematurely, **b** columns with heavy anchors, cross section at the location of anchors, and **c** columns with heavy anchors, cross section at mid-height between anchors

$$
\begin{aligned}
A_{\mathrm{un}} &= 2(n+1)\frac{2}{3}\frac{(h-2R)^2}{(n+1)^2 4} + 4\frac{1}{2}\frac{(h-2R)s_{\mathrm{a}}}{(n+1)4} \\
&\quad + 2(n-1)\frac{(h-2R)s_{\mathrm{a}}}{(n+1)4} + 2\frac{2}{3}\frac{(b-2R)^2}{4} \\
&= \frac{(h-2R)(h-2R+1.5ns_{\mathrm{a}}) + (n+1)(b-2R)^2}{3(n+1)}
\end{aligned}
\tag{7}
$$

Finally, the confinement effectiveness factor is given as:

$$
\begin{aligned}
\alpha_{\mathrm{f}} &\approx \frac{\mathrm{A_e}}{bh} \approx \frac{bh - A_{\mathrm{un}}}{bh} \\
&= 1 - \frac{(h-2R)(h-2R+1.5ns_{\mathrm{a}}) + (n+1)(b-2R)^2}{3(n+1)bh}
\end{aligned}
\tag{8}
$$

A point to note here is that the reduction of confinement at mid-height between anchor locations may be neglected, for a number of reasons: (a) these locations may coincide with the locations of steel stirrups (as in this experimental study), the confinement of which, although maximized, is neglected (as done here); (b) the fanned part of the anchors (on top of the jacket) extends beyond the anchor locations, thereby reducing the clear distance between anchors; and (c) anchors may be covered with a vertical strip (as done in this study), which increases the stiffness of the jacket. A convenient way to account for all the above, that is to neglect the reduction of confinement at mid-height between anchor locations, is to apply the analytical model with $s_{\mathrm{a}} = 0$.

The above model was applied to predict failure loads in all columns tested in this study, with: $b = 150$ mm; $h = 450$ mm, $A_{\mathrm{c}} = 66{,}477$ mm^2 and $A_{\mathrm{s}} = 679$ mm^2 for columns with aspect ratio 3; $h = 600$ mm, $A_{\mathrm{c}} = 88{,}751$ mm^2 and $A_{\mathrm{s}} = 905$ mm^2 for columns with aspect ratio 4; $R = 20$ mm; $t_{\mathrm{f}} = 2$ or 3 mm for columns with 2 or 3 CFRP layers, respectively; $f_{\mathrm{c}} = 18$ MPa; $f_{\mathrm{s}} = 570$ MPa (yield stress); $f_{\mathrm{f}} = 1{,}046$ MPa; $k_1 = 1.0$ (short-term monotonic testing, no environmental effects etc.); $n = 0$ for columns without anchors or with light anchors (which failed prematurely); $n = 1$ for columns with one heavy anchor; $n = 2$ for columns with two heavy anchors; and $s_{\mathrm{a}} = 0$ for columns with heavy anchors, for the reasons explained above.

Note that in columns MII3 and MII4, with cross section enlargement, the mortar was taken into account only as a shape modification parameter, affecting α_f, and not as a material contributing to the column strength, due to its much lower elastic

Table 2 Analytical prediction of column strength and comparison with experiments

Column	Experimental peak force P_{exp} (kN)	Analytical peak force P_{an} (kN)	$P_{\mathrm{an}}/P_{\mathrm{exp}}$
C3	1149.4	n.a.	n.a.
II3	1601.4	1611.3	1.01
1A_lII3	1556.4	1611.3	1.04
2A_lII3	1477.3	1611.3	1.09
1A_hII3	1809.2	1715.9	0.95
1A_hIII3	2043.8	1782.0	0.87
MII3	1830.3	1671.0	0.91
C4	1509.0	n.a.	n.a.
II4	1907.6	2113.4	1.11
1A_lII4	1934.4	2113.4	1.09
2A_lII4	1870.7	2113.4	1.13
2A_hII4	2191.5	2214.1	1.01
2A_hIII4	2598.0	2264.4	0.87
2A_hIIU4	2518.1	2294.6	0.91
MII4	2102.2	2117.4	1.01

modulus in comparison with the reinforced concrete part of the columns. It should also be noted that, as the CFRP jacket in column 2A_hIIU4 failed in its straight part with two layers, far from the corners, the above model was applied in this case with no radius reduction, i.e. $k_\mathrm{R} = 1$, and $t_\mathrm{f} = 2$ mm. Finally, the model was not applied in the case of the two control specimens, C3 and C4, as these columns failed due to premature buckling of the longitudinal reinforcement, hence $f_\mathrm{s} < 570$ MPa.

The analytical results for the capacity of all columns tested are summarized in Table 2, along with the ratio of analytical to experimental values. Overall, the agreement between test results and analytical predictions is satisfactory, with the largest differences being from 1 to 13 %, indicating that simple modelling approaches, as described above, give realistic predictions of test results.

4 Conclusions

A total of 45 reinforced concrete columns measuring 150 by 450 mm or 150 by 600 mm in the cross sectional dimension, that is with aspect ratio 3 or 4, were tested to failure to examine the effectiveness of different CFRP jacket solutions with or without anchors as well as with section enlargement. The failure loads were also estimated using a simple analytical approach. From the work carried out herein it is concluded that:

- CFRP jackets without anchors give moderate increase in axial strength, in the order of 40 or 25 % for columns with aspect ratio 3 or 4, respectively.
- Light anchors fail prematurely and the columns behave as if no anchors are used.
- Heavy anchors nearly double the confining effectiveness of CFRP jackets.
- If CFRP jackets are combined with heavy anchors, their effectiveness increases almost linearly with the number of layers. Jackets with three layers increase the strength by nearly 80 or 70 % for columns with aspect ratio 3 or 4, respectively, whereas the corresponding values for two layers are about 55 and 45 %.
- The use of additional CFRP in the circumferential direction near the edges suppresses failure of the jacket near the corners, thereby increasing the confining effectiveness of the jacket by approximately 50 %.
- Shape enlargement of the cross section with mortar is practically as effective as the use of (heavy) anchors.
- The simple analytical approach described in this study gives reasonable predictions of test results.

Despite the large number of parameters examined in the present study, further investigation is needed to study other FRP materials, long-term effects, response under cyclic loading and jacket-steel reinforcement interactions.

Acknowledgments The authors wish to thank the students D. Kakavas, M. Karahaliou, M. Karydi, G. Kontopoulos and G. Skarakis, for their assistance in the experimental program. The research was funded by Fyfe Europe S.A. Special thanks go to M. Karantzikis and C. Kolyvas of Fyfe Europe S.A. for their input in the design of the experimental program.

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