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Abstract

In this work, a new technique for the efficient confinement of reinforced concrete (RC) columns of rectangular cross-section is described and its effectiveness is assessed experimentally. This technique is based on the concept of applying strips of carbon fiber reinforced polymer (CFRP) wet layup sheets with a certain prestress level using a mechanical device. The influence of the cross-section aspect ratio of columns on the axial stress-strain response, strain field in the CFRP and strength increase provided by the different adopted strengthening configurations was investigated. All specimens had a height of 1100 mm, and three cross-sections were considered: 120 mm×120 mm, 240 mm×120 mm and 480 mm×120 mm, representing cross-section aspect ratios (large/small edge) equal to 1, 2 and 4, respectively. Four types of columns were tested: conventional RC columns (reference columns), fully-wrapped columns, partially-wrapped columns, and columns strengthened according to the new technique. All columns were subjected to axial compression loading until failure. The experimental results show that the cross-section aspect ratio has a significant effect on the confinement effectiveness that CFRP strengthened systems can provide to RC columns of rectangular cross-section. The maximum axial strength and axial strain at the peak load of all columns significantly decrease when the cross-section aspect ratio increases. Based on the obtained experimental results, it is shown that the proposed technique is more efficient in terms of increasing the load carrying capacity of rectangular RC columns than CFRP-based conventional strengthening techniques.

Keywords	Confinement, RC columns of rectangular cross-section, CFRP, Prestress application, Axial compressive loading tests, Analytical model
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Universidade do Minho
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To the Editor of the Composites Part B:
Engineering Journal

May 18, 2018

Dear Editor,

I am submitting an original research article entitled "A NEW STRENGTHENING TECHNIQUE FOR INCREASING THE LOAD CARRYING CAPACITY OF RECTANGULAR REINFORCED CONCRETE COLUMNS SUBJECTED TO AXIAL COMPRESSIVE LOADING" for consideration of publication in the Composites Part B: Engineering Journal.

This manuscript describes the development of a new innovative technique based on the concept of applying strips of carbon fiber reinforced polymer (CFRP) wet layup sheets with a certain presstress level using a mechanical device for increasing the load carrying capacity of rectangular reinforced concrete (RC) columns. In this scientific subject, the experimental tests are performed and compared with the conventional strengthening techniques (full and partial confinement techniques). The applicability of the ACI, *fib* Bulletin 14 and CNR-DT 200 guidelines is also assessed for the prediction of the compressive strength of columns confined with FRP systems. It is concluded that the new technique is more efficient in terms of increasing the load carrying capacity of rectangular RC columns than CFRP-based conventional strengthening techniques. Finally, the design guidelines are adapted for estimating the compressive strength of rectangular cross section RC columns strengthened according to the new technique, and good predictive performance was obtained.

This manuscript describes the Authors' original work. It has not been published elsewhere and is not under consideration by another journal. The authors approved the manuscript and agree with this submission. No conflict of interest to declare.

Thank you very much for your consideration of this manuscript.

Yours Sincerely,

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Highlights

- A new technique (SC) for the confinement of RC columns of rectangular cross-section is proposed
- The efficiency of the SC technique was experimentally compared with FRP-based existing ones
- The proposed SC technique was more efficient than the fully- and partially-wrapped techniques
- Guidelines were adapted for predicting the strength of RC columns confined with the SC technique
- Good predictive performance was obtained for the proposed design guideline

A NEW STRENGTHENING TECHNIQUE FOR INCREASING THE LOAD CARRYING CAPACITY OF RECTANGULAR REINFORCED CONCRETE COLUMNS SUBJECTED TO AXIAL COMPRESSIVE LOADING

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Abstract

In this work, a new technique for the efficient confinement of reinforced concrete (RC) columns of rectangular cross-section is described and its effectiveness is assessed experimentally. This technique is based on the concept of applying strips of carbon fiber reinforced polymer (CFRP) wet layup sheets with a certain prestress level using a mechanical device. The influence of the cross-section aspect ratio of columns on the axial stress-strain response, strain field in the CFRP and strength increase provided by the different adopted strengthening configurations was investigated. All specimens had a height of 1100 mm, and three cross-sections were considered: 120×120 mm^2, 240×120 mm^2 and 480×120 mm^2, representing cross-section aspect ratios (large/small edge) equal to 1, 2 and 4, respectively. Four types of columns were tested: conventional RC columns (reference columns), fully-wrapped columns, partially-wrapped columns, and columns strengthened according to the new technique. All columns were subjected to axial compression loading until failure. The experimental results show that the cross-section aspect ratio has a significant effect on the confinement effectiveness that CFRP strengthened systems can provide to RC columns of rectangular cross-section. The maximum axial strength and axial strain at the peak load of all columns significantly decrease when the cross-section aspect ratio increases. Based on the obtained experimental results, it is shown that the proposed technique is more efficient in terms of increasing the load carrying capacity of rectangular RC columns than CFRP-based conventional strengthening techniques.

Keywords: Confinement, RC columns of rectangular cross-section, CFRP, Prestress application, Axial compressive loading tests, Analytical model

1. INTRODUCTION

In recent years, Fiber Reinforced Polymer (FRP) composites have been extensively used for the strengthening and rehabilitation of existing reinforced concrete (RC) structures. There are several reasons for using FRP composites, such as high stiffness, lightweight, non-corrosiveness in harsh environments, and the ease of application [1]. Externally bonded FRP composite jacketing is one of the most common applications of FRP composites for the strengthening of RC columns as it can provide significant confinement to the concrete, mainly in columns of circular cross-section. This technique allows the increase of axial load and deformation capacity, as well as its energy absorption performance [2].

From previous studies, it can be clearly noted that the confinement effectiveness depends on the lateral confining pressure applied to the concrete core. The confinement of FRP-strengthened columns with circular section is more efficient than in columns with non-circular section due to the uniform confining pressure assured by the former type of cross-section [3-8]. However, most of the existing structural columns have a rectangular cross-sectional configuration. Relatively less experimental data exists on RC columns of rectangular cross-section confined with FRP systems, and, hence, the availability of reliable models for the prediction of their response is limited [6, 9-10]. Mirmiran *et al.* [3] studied the confinement of concrete columns of circular and square cross-sections with FRP jackets and found that its effectiveness depends on several parameters such as concrete strength, type of fibers and resins, fiber volume and fiber orientation in the jacket, jacket thickness, shape of cross-section (circular versus square), slenderness ratio of the column (i.e. length-to-diameter/edge ratio) and the interface bond between the core and the jacket. Other research works also found that the corner radius of FRP-confined prismatic concrete columns is an important parameter that influences the confinement effectiveness of FRP strengthening systems [3, 11-15]. This issue is attributed to the stress concentration occurring in the corner zones, which promotes premature tensile rupture of the strengthening systems, particularly if the corner radius is less than a critical value [3, 11-15]. Moreover, the size and aspect ratio of the cross-section (largest edge to smallest edge ratio) can also compromise the effective confinement provided by FRP systems. When this aspect ratio increases, the confinement effectiveness of the columns significantly decreases [16-17]. To improve the efficiency of FRP confined columns, the use of hybrid strengthening techniques has been previously explored. Hadi *et al.* [18] used a technique that converts a square column to a circular section by bonding pieces of segmental circular concrete covers, called the Circularization technique, providing a significant increase of the confinement effectiveness of the column. However, the geometry of these columns can be significantly altered, the intervention can be quite time consuming, and the confinement effectiveness is susceptible to the creep of the segmental circular concrete covers. Rousakis and Tourtouras [19] proposed a strengthening technique for RC columns of square cross-section by using special mechanical devices combined with highly deformable polypropylene fiber ropes, PPFR. The results revealed that the stress-strain relationship of the strengthened columns was highly improved by the proposed technique, having the strengthened RC columns exhibited higher load carrying capacity when compared to columns with conventional wrapping techniques. Nevertheless, the technique requires a high content of wrapping material to ensure proper strengthening conditions for applying the prestress to the PPFR system.

In the present work, a new strengthening technique is proposed for increasing the axial load carrying capacity and deformation performance of RC columns of rectangular cross-section. This strategy, herein denominated by strip constriction (SC) technique, is based on the concept of applying strips of carbon fiber reinforced polymer (CFRP) wet layup sheets with a certain prestress level by means of a mechanical device. The influence of cross-sectional aspect ratio of columns on the confinement behavior was investigated. The performance of the SC technique is compared to the one provided by conventional strengthening techniques based on the full or partial confinement of the columns with CFRP wet layup sheets. In the following sections, the experimental program is detailed, and the relevant results are presented and discussed.

The applicability of ACI [1], *fib* Bulletin 14 [21] and CNR-DT 200 [22] guidelines for the prediction of the compressive strength of columns confined with FRP systems is assessed. Finally, these guidelines are improved in order to be capable of predicting with acceptable accuracy the load carrying capacity of RC columns confined with the new proposed technique.

2. EXPERIMENTAL PROGRAM

2.1 Column prototypes

The experimental program includes a total of 11 prototypes of column to investigate the compressive behavior of rectangular RC columns externally confined by CFRP wet layup sheets (Fig. 1). All specimens have 1100 mm in height, and all strengthened columns have a corner radius of 25 mm to minimize premature failure occurrence in the CFRP due to high tensile stress developments in these zones. Different types of CFRP strengthening techniques and arrangements, and different aspect ratio for the cross-section of the columns, were considered for investigating their influence on the strengthening performance. Four types of RC columns were executed: (1) Without any type of strengthening intervention, considered the reference columns (REF); (2) Fully-wrapped columns (FW); (3) Partially-wrapped columns (PW); (4) Columns strengthened according to the new technique (SC). The cross-sections of the columns investigated in this experimental program were 120×120 mm^2, 240×120 mm^2 and 480×120 mm^2, representing a cross-section aspect ratio (larger/smaller edge, λ=h/b) of, respectively, 1, 2 and 4. All strengthened columns were confined using three layers of CFRP sheet. To prevent failure due to stress concentration in the extremities of the columns in contact with the test equipment, two additional strips of 90 mm width were applied in the zones, resulting in five layers of CFRP sheet.

The strengthening according to the new technique (SC) was performed using a mechanical device detailed in Figs. 1-2. The mechanical device consists of two parts: two D-shaft round (D-shaped) steel bars (with a diameter of 50 mm) with one hole to insert a threaded rod; and a threaded rod with washer and nut. The D-shaped devices are later fastened against the CFRP strips using a washer and nut on the opposite extremity, transmitting the intended prestress level to the CFRP strips, which introduces an initial confinement stress field in the RC column.

The columns are labeled as ”λX-Y”, where λ represents the cross-section aspect ratio (h/b) and therefore X can assume the values of 1, 2 and 4; Y is replaced by REF, FW, PW, SC for representing the reference column, the column fully wrapped, the column partially wrapped and the column strengthened according to the strip constriction technique. For example, λ2-FW is the column with a cross-section aspect ratio of 2, and fully wrapped.

2.2 Material properties

2.2.1 Concrete

Local Portland cement, river sand, and coarse aggregate of 12 mm maximum size were used for producing the concrete of the columns. The average compressive strength of 4 cylindrical concrete specimens of 150 mm diameter at 28 days was 21 MPa (with COV of 2.8%), obtained by performing compression tests according to the BS EN 12390-3:2009 recommendations [20].

2.2.2 Reinforcement

For the reinforcement of the columns, ribbed bars of 6 mm diameter were used as steel hoops, and 10 mm diameter as longitudinal bars. The nominal yield stress of the reinforcement was approximately 550 and 450 MPa for the ribbed bars of 6 and 10 mm, respectively.

2.2.3 CFRP sheets

A high tensile strength carbon fiber fabric, S&P C-sheet 240 was used for wrapping the columns. Two-component S&P epoxy resin 55 was used to impregnate the CFRP sheets. The details of CFRP material properties from the technical data sheet are shown in Table 1.

2.3 Preparation of column prototypes

2.3.1 CFRP Wrapping

For wrapping the columns, the procedure recommended by ACI 440.2R-08 [1] was followed. The corners of the cross-section were grinded up to the desired radius of 25 mm, and the concrete surface to be in contact with the CFRP was lightly sanded to smoothen the surface. Water was used to remove all dust and dirt from the surface, and the columns were then left to dry. When necessary, voids on the surface of columns were filled using cement paste. A two-component epoxy resin was used to bond the CFRP sheets to the surface of the columns. The relevant properties of epoxy resin are also indicated in Table 2. Before placing the CFRP sheets, a thin layer of resin was applied on the surface of the columns. The first layer of CFRP sheet was then placed on the surface of the columns. A plastic roller was used to remove the excess resin and any air voids between the CFRP layer being applied and the substrate. For wrapping subsequent layers, the epoxy resin was applied again on the outer surface of the previous layer, and the next layer of CFRP sheet was placed. On each CFRP layer, an overlap of 50 mm was ensured. The CFRP wrapping system was arranged in order to become symmetric in parallel to the longer edge of the cross-section. After placing the last layer of CFRP, a final coat of epoxy resin was applied, and the plastic roller was used once again in an attempt of removing air voids. Finally, the wrapped columns were left to dry in laboratory environment for approximately one week before testing.

2.3.2 The proposed strip constriction (SC) technique

Before applying the CFRP strips, a transparent plastic-film was applied on the concrete column to reduce the friction between the concrete surface and the CFRP strips. The CFRP strips were then bonded by ensuring an overlapping length of approximately 50 mm at one of the shorter sides of the column's cross-section, and left to dry for approximately one week. In order to transfer the intended prestress to the CFRP strips (approximately 20% of the ultimate strain of the CFRP sheet), the previously presented mechanical system was used. To install the device, firstly, the threaded rod was inserted through a hole previously drilled on the column. Then, the D-shaped steel bars were installed on both sides of the column. Finally, a nut was gradually screwed with a dynamometric wrench. In each turn, the D-shaped steel bars push the CFRP strips into the grooved section, inducing the intended prestress in the CFRP strips. The torque from the wrench and the strain of the CFRP strips were monitored up to the attainment of the target strain in the CFRP strips (0.33%). The above indicated plastic-film applied in the contact zones between CFRP strips and concrete substrate has the purpose of promoting as much as possible a uniform prestress distribution on the column perimeter. The prestress application on the CFRP strips is illustrated in Fig. 3.

2.4 Testing instrumentation

All columns were capped with polyester paste on the bottom and top surface of the columns for promoting uniform axial load transference. Additionally, a plastic film with oil was applied at both ends of the columns, between the surface of the concrete and the testing frame to further reduce the surface friction. Strain gauges (SG) were installed in the strengthened columns, at mid-height, to monitor the strain evolution in different positions. One strain gauge was installed at the center of the shorter edge, while other(s) was(ere) placed along the longer side of the column's cross-section according to the schematic representation in Fig. 4.

Linear voltage displacement transducers (LVDTs) were also installed to record the axial deformation of the columns. Three different distances along the column height were monitored to evaluate the overall behavior of the columns. The selected distances between the lower and upper fixing points were 1060 mm, 600 mm and 200 mm (Fig. 4). The columns were subjected to direct axial compression by means of a closed loop servo-controlled actuator equipped with a load cell of 2000 kN capacity. By reading the LVDTs located symmetrically on the outer sides of the columns, it was verified that an almost pure axial load was assured up to 20% of peak load in the pre- peak stage. Above the deformation corresponding to this load level, parasitic bending moments are introduced due to the non-uniform damage occurring in the cross-section, fundamentally caused by the non-homogeneous material nature of concrete. A representation of the instrumentation of the column prototypes is shown in Fig. 4.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Overall behavior

The summary results obtained from the experimental tests are presented in Table 3. In this table, A_{eff} is the effective column's cross-section (after the treatment for the strengthening process); $P_{\max}$ is the maximum load supported by the column; σ_{cc} is the axial stress at $P_{\max}$ ($\sigma_{cc} = P_{\max} / A_{eff}$); ε_{cc} is the axial strain (measuring stroke of 1060 mm) at $P_{\max}$; $\varepsilon_{f\max}$ is the maximum strain in the CFRP recorded up to the end of the tests; $\Delta F_{\max} = 100 \times \left(P_{\max}^{Str} - P_{\max}^{\mathrm{Ref}} \right) / P_{\max}^{\mathrm{Ref}}$ represents the increase of load carrying capacity provided by the strengthening technique, where $P_{\max}^{Str}$ and $P_{\max}^{\mathrm{Ref}}$ are the maximum load of the strengthened and its corresponding reference column; $\Delta \bar{\varepsilon}_{cc} = 100 \times \left(\varepsilon_{cc}^{Str} - \varepsilon_{cc}^{\mathrm{Ref}} \right) / \varepsilon_{cc}^{\mathrm{Ref}}$ is the increase of axial strain at $P_{\max}$, where ε_{cc}^{Str} and $\varepsilon_{cc}^{\mathrm{Ref}}$ are the axial strain of the strengthened column and its corresponding reference column at $P_{\max}$; and $\Delta F_{\max} / A_{CFRP}$ is the increase of load carrying capacity per quantity of CFRP strengthening material, where A_{CFRP} is the total area of CFRP sheet applied in a strengthened column. It can be seen that the columns strengthened with conventional CFRP techniques (fully and partially wrapped), apart the case of λ1-FW, have provided a modest increase in terms of strength gain ($\Delta F_{\max}$). However, the columns strengthened according to the strip constriction (SC) technique showed a higher strength gain, and the confinement effectiveness seems to increase with the column's cross-section aspect ratio (λ). In fact, while the SC technique provided an increase of $\Delta F_{\max}$ from 25% to 32% with the increase of the cross-section aspect ratio from 2 to 4, the fully and partially wrapped techniques provided a decrease from 23% to 7% and from 13% to 10%, respectively.

3.2 Failure modes

The failure mechanisms of the columns were monitored throughout the experimental tests. It was found that the variation of the cross-section aspect ratios showed no significant effect on the typical failure modes of the columns. The failures of the columns consisted of one or both of the two following types: (1) crushing-splitting of concrete; and (2) rupture of CFRP layers. In the reference columns (λ1-REF, λ2-REF and λ4-REF), failure almost coincided with the attainment of the column's maximum load capacity. The failure occurred suddenly accompanied by an explosive spalling of concrete, followed by the buckling of longitudinal reinforcing bars. The failure regions were very close to the extremities of the columns due to the high stress concentration in these regions. Therefore, despite the one extra steel hoop (at 25 mm from the regular one) applied in these regions in all the tested columns (Fig. 1), it was not possible to avoid this type of failure in the REF columns. In Figs. 5a, 6a and 7a, it can also be noted that the failure took place between the steel hoops. The detachment of the concrete cover has favored the occurrence of buckling of the longitudinal reinforcing bars leading to the collapse of the columns. It can also be mentioned that bar buckling mostly occurred along the shorter side of the column section. Nevertheless, the bar buckling of λ4-REF could be observed in both shorter and longer sides of the column (Fig. 7a).

Regarding the fully-wrapped columns (λ1-FW, λ2-FW and λ4-FW), all columns failed by CFRP rupture as illustrated in Figs. 5b, 6b and 7b. This failure also occurred suddenly, accompanied by an explosive sound at the moment of the CFRP rupture. The rupture of the CFRP layers occurred near the directly loaded zone (upper extremity) of the columns λ2-FW and λ4-FW, while in the λ1-FW column it has occurred at mid-height. Regarding the λ4-FW column, the observed abrupt load decay just after the peak load was caused by the concrete core crushing. The concrete expansibility caused by this crushing process has significantly mobilized the CFRP wrapping mechanism, which was capable of maintaining the load carrying capacity almost constant up to an axial strain of 3‰, when the CFRP failed in tension. When the confinement effectiveness of the fully-wrapped columns was no longer provided by CFRP sheets, the concrete started spalling, followed by the buckling of longitudinal reinforcing bars between the steel hoops. The CFRP tensile rupture was followed by the detachment of the CFRP from the surface of the columns.

The partially-wrapped columns (λ1-PW, λ2-PW and λ4-PW) gradually lost their load carrying capacity with the increase of the axial deformation above the strain at peak load, which was caused by the progressive concrete crushing and buckling of the longitudinal bars at the unwrapped zones. This progressive damage process has ended with the CFRP tensile rupture of the top group of strips in the λ2-PW and λ4-PW columns, followed by the spalling of concrete in the wrapped zones where this failure has occurred (Figs. 6c and 7c). In the λ1-PW column, an intense curvature has occurred in the first unwrapped zone from the top surface of this column, without any occurrence of CFRP tensile rupture (Fig. 5c).

In the columns strengthened according to the new technique (λ2-SC and λ4-SC), failure took place noisily due to the rupture of CFRP strips in the zones contacting the mechanical device (Figs. 6d and 7d). After the CFRP rupture, the load carrying capacity of λ2-SC has gradually decreased by concrete crushing up to the end of the test (Fig. 6d). The λ4-SC column suddenly failed by an explosive crushing of concrete, and the test was stopped by the loading machine control software. It was verified that the concrete core of this column was completely damaged due to the explosive nature of the failure (Fig. 7d). The failure region was localized at the top extremity of the column (the one in direct contact with the hydraulic jack). Moreover, the longitudinal bars have buckled in this localized damage zone.

3.3 Stress-strain response

The stress-strain relationship of the RC tested columns is shown in Figs. 8-9. The axial stress was calculated as the ratio between the applied force and the effective cross-sectional area of the column ($\sigma_c = P/A_{eff}$). The axial strain was determined by dividing the average displacement readings of the LVDTs by the corresponding measuring stroke, having been adopted three values for the measuring stroke (200, 600 and 1060 mm, Fig. 4) for assessing its influence on the column's axial strain. The results presented in Fig.8, corresponding to the λ1-REF column, can be considered representative of the columns of the experimental program. This stress-strain graph demonstrates that, up to peak load, the column's axial strain is almost the same regardless of the measuring stroke considered to convert the displacements recorded in the LVDTs in strains. The strains only become dependent of the measuring stroke when a localized failure starts.

Fig. 9 shows the relationship in terms of axial stress versus axial strain (adopting the measuring stroke of 1060 mm for the determination of the strain values) for all the tested columns.

All reference columns (λ1/2/4-REF) showed a very brittle behavior, as is shown from their stress-strain relationship, since failure was caused by concrete spalling. Regarding the strengthened columns, all of them presented an increase in terms of load carrying capacity and axial deformability, due to the confinement effectiveness provided by the CFRP systems. In the fully-wrapped columns, the one with a cross-section aspect ratio of 1 (λ1-FW) developed a pronounced hardening stage up to the CFRP tensile failure; the column of λ=2 (λ2-FW) presented an almost "pseudo-rigid-plastic behavior", and the column of λ=4 (λ4-FW) experienced a significant drop of load carrying capacity just after the peak load. Therefore, by increasing λ, the confinement performance of the FW group of columns has decreased in terms of compressive strength and deformation capability. The hardening and almost "pseudo-rigid-plastic" stages verified in λ1-FW and λ2-FW, accompanied by a relatively large axial deformability, is a consequence of the effective activation of the confinement pressure provided by the CFRP systems. The level of confinement effectiveness was much lower in the λ4-FW column, as consequence of the smaller stiffness of this CFRP arrangement, allowing a higher concrete expansibility during concrete core crushing, which led to the tensile rupture of the CFRP.

Regarding the partially-wrapped columns (λ1-PW, λ2-PW and λ4-PW), a softening branch was clearly visible on the stress-strain curves after the maximum load had been attained. However, due to the confinement provided by the CFRP strips, the post-peak load carrying capacity of these columns did not suddenly drop. The gradual stress decay in these columns was mainly caused by the damage evolution occurred in the concrete volume in-between the first two sets of CFRP strips from the loading extremity of these columns.

For the columns strengthened according to the proposed technique, λ2-SC developed the highest first peak load. However, due to the pronounced damage evolution of the concrete volume in-between the first two sets of CFRP strips from column's loading extremity (Fig. 6d), its loading carrying capacity has gradually decreased. At about 4.5‰ of axial deformation, the post-peak compressive stress is the same as in the fully wrapped column (λ2-FW). Regarding the series of columns with the highest cross-section aspect ratio (λ=4), the column strengthened with the new technique (λ4-SC) has presented a notable higher performance in terms of the compressive strength and its corresponding axial deformation compared to the other strengthened columns. When compared to the corresponding reference column, the increase in terms of compressive strength provided by the SC technique was approximately 25% and 32% in the columns' group of λ=2.0 and λ=4.0, respectively, while the conventional strengthening techniques only assured an increase ranging from 7% to 23%. However, due to the very brittle rupture occurred in the loading zone of the λ4-FW column, an abrupt load decay has occurred. To avoid this type of premature failure, or at least postpone its occurrence for larger axial deformation, it seems important to increase the confinement stiffness of the column's extremities.

A comparison of the axial stress versus the CFRP strain (ε_f) for the strengthened columns is illustrated in Fig. 10, while Fig. 11 compares the column's axial strain with ε_f (in this last figure the values are only presented up to the peak load of the column). The position of the strain gauge where the ε_f is evaluated is presented in the corresponding figures. For the same level of stress, it can be seen that the CFRP strain in the columns strengthened according to the new technique was higher compared to the CFRP strain in the columns strengthened with the other techniques. In the case of the columns with λ=2 this has only occurred above the axial deformation corresponding to the compressive strength of the reference column (λ2-REF), Fig. 11b. On the other hand, in the columns with λ=4 this phenomenon is visible since the beginning of the tests. These larger values of strain suggest that the confinement effectiveness provided by the CFRP strips was higher when using the new strengthening technique, and the relative confinement effectiveness of the SC technique seems as higher as larger is λ. The maximum CFRP strain values recorded in the strain gauge localized at mid-depth of the strengthened columns ($\varepsilon_{f\max}$) are indicated in Table 3. At the moment of failure of the strengthened columns, $\varepsilon_{f\max}$ was higher in the columns strengthened with the SC technique than with the other two techniques, indicating that the new technique mobilizes more effectively the confinement potential of the CFRP. However, apart the $\varepsilon_{f\max}$ value registered in the λ1-FW (8.34‰), the values of $\varepsilon_{f\max}$ recorded in the other columns were relatively small, which is justified by the occurrence of failure at the top extremity of these columns, preventing the full exploitation of the confinement effectiveness of the adopted strengthening configurations.

3.4 Effect of cross-section aspect ratio on the confinement performance of the adopted strengthening techniques

The axial stress-strain relationship (σ_c-ε_c) for each group of columns with different cross section aspect ratio (λ) is shown in Fig. 12. In all the four groups of columns, the compressive strength and the ultimate axial strain have decreased with the increase of λ. Due to the identical strength class for the concrete of the tested columns, and the equal arrangement for the steel reinforcement and CFRP systems, the initial stiffness of the σ_c-ε_c response was similar in each group of columns. Fig. 12a shows that the amplitude of the axial deformation in the σ_c-ε_c softening stage increases with λ in the REF columns. In the group of columns strengthened with the FW technique (Fig. 12b), the ductility of the σ_c-ε_c response (indicator based on the area under the σ_c-ε_c up to the column's failure) has significantly increased with the decrease of λ. All the columns of the group strengthened by the PW technique (Fig. 12c) have presented a post-peak σ_c-ε_c softening stage. This stage is formed by an initial more abrupt stress-decay branch, where the σ_c/ε_c softening gradient has decreased with the decrease of λ (more ductile behavior), followed by a stage with a more smooth σ_c/ε_c softening gradient, almost equal in all the columns of this group. Finally, the group of columns strengthened with the SC technique (Fig. 12d) clearly demonstrates that the decrease of compressive strength with the increase of λ was much lower than the decrease registered in the other groups of columns, although the deformation capacity and post-peak resistance has decreased significantly with the increase of λ. As already indicated, this fact is justified by the quite different failure modes observed in these two columns.

A comparison of strength gain for all strengthened columns is illustrated in Fig.13. The strength gain was calculated by the ratio between the compressive strength of a strengthened and its corresponding reference column ($\sigma_{cc}^{Str}/\sigma_{cc}^{\mathrm{Ref}}$). It can be observed that when the cross-section aspect ratio increases, the strength gain of the fully-wrapped columns significantly decreases. The strength gain values corresponding to the fully-wrapped columns (FW) were 1.67, 1.23 and 1.07 for the cross-section aspect ratio of 1, 2 and 4, respectively. Regarding the strength gain of the partially-wrapped columns (PW), the observed values were relatively constant, since they have varied between 1.07-1.13 for this strengthening technique. Finally, the new technique (SC) provided an increase of strength gain with the increase of the cross-section aspect ratio, since $\sigma_{cc}^{Str} / \sigma_{cc}^{\mathrm{Ref}}$ was 1.25 and 1.32 for the column of cross-section aspect ratio of 2 and 4, respectively. These results indicate that, despite the smaller content of CFRP applied in the SC technique compared to the FW technique, the SC is more effective for RC of relatively large cross-section aspect ratio.

4. ASSESSMENT THE APPLICABILITY OF EXISTING DESIGN RECOMMENDATIONS

To predict the load carrying capacity of the tested columns, the following three existing models were selected: *fib* Bulletin 14 [21]; CNR-DT 200 [22]; and ACI 440.2R-08 [1]. A summary of the corresponding formulation is provided in Appendix. All these models consider only the confinement contribution from external FRP wrapping (the contribution from steel hoops is not taken into account). The *fib* Bulletin 14 and CNR-DT 200 models adopt a vertical efficiency coefficient to simulate the effective lateral confining pressure of partially FRP-confined columns, which is not the case of ACI 440.2R-08 formulation that was prepared exclusively for full wrapping arrangement. In order to extend the applicability of the ACI formulation for RC columns partially confined with FRP systems, the equation providing the effective lateral confining pressure of partially FRP-confined columns in ACI code is modified by introducing the vertical efficiency coefficient obtained according to CNR-DT 200 recommendations (Eq. A.16).

To apply these models for the prediction of the concrete strength of columns strengthened according to the SC technique, a rectangular cross section is considered as a parallel series of "cells" of almost square section, as schematically shown in Fig. 14. According to the SC technique the number of divisions (n_d) in the larger cross section dimension provided by the mechanical components of this technique should assure "cells" of almost square cross section ($n_d \approx h/b$). Therefore, the compressive strength of a rectangular column strengthened according to the SC technique is the same as the compressive strength of a column of square cross section of $b \approx h/n_d$ edge. At the present stage, the favorable effect in terms of lateral confinement provided by the prestress applied to the CFRP strips in the SC technique is not taken into account, since deeper knowledge on the long term values of this prestress must be known, as well as its spatial distribution, which is an ongoing research.

The analytical results obtained from the adopted guidelines are presented in Table 4. For conventional strengthening techniques with the cross section ratio equal to 1 and 2, the *fib* Bulletin 14 ("Exact approach"), CNR-DT 200 and ACI.2R-08 predict with good accuracy the confined concrete strength values registered experimentally, while the *fib* Bulletin 14 ("Approximate approach") provides quite conservative predictions. It is verified that the modification introduced in the ACI.2R-08 model in order to extend its applicability to partially confinement arrangements seems adequate since it provides a similar level of accuracy in FW and PW columns.

The *fib* Bulletin 14 and CNR-DT 200 models are not prepared for predicting the concrete strength of confined columns of cross-section ratio higher than 3.6, since the coefficient of horizontal efficiency (Eq. A.15) becomes a negative value. However, the applicability of ACI.2R-08 model is not limited by this condition, and the results reported in Table 4 show a satisfactory level of prediction for the columns of λ=4, for both FW and PW.

The results in Table 4 also demonstrate that the approach adopted in Fig. 14 for the SC technique allows all the considered formulations (apart from *fib* Bulletin 14 model with the approximate approach) to predict with good accuracy the compressive strength of the tested columns strengthened with the proposed technique: -17.56% to -5.48% and -7.48% to 3.56% for the columns with cross-section ratio of 2 and 4, respectively.

5. CONCLUSIONS

In this work, a new technique for the confinement of rectangular reinforced concrete (RC) columns is presented and its effectiveness was assessed by performing an experimental program. The effect of the cross-section aspect ratio on the confinement effectiveness provided by different strengthening techniques was investigated. For the cross-section aspect ratio (λ=h/b) of the columns the values of 1, 2 and 4 were adopted, corresponding to column's cross section of 120×120 mm^2, 240×120 mm^2 and 480×120 mm^2, respectively. Four types of columns were tested: 1) reference, without any type of confinement (REF); 2) fully-wrapped (FW); 3) partially wrapped (PW); and 4) columns strengthened according to the proposed technique, designated by strip constriction (SC). The relevant results can be summarized as follows:

(1) All the strengthened columns showed an increase of the load carrying capacity and axial deformation performance compared with their corresponding reference columns.

(2) When compared to the corresponding reference column, the increase in terms of strength gain provided by the FW confinement was approximately 67%, 23% and 7% in the columns of λ=1, λ=2 and λ=4, respectively. Regarding the PW confinement configuration, the strength gain was approximately constant in the tested columns (in between 7% and 13%). The proposed SC technique provided an increase of 25% and 32 % in the columns of λ=2 and λ=4, respectively.

(3) The increase of load carrying capacity per quantity of CFRP strengthening material of the SC technique is higher than the other strengthening techniques, indicating that the SC technique is not only technically efficient, but also cost competitive.

(4) In RC columns of highest cross-section aspect ratio (λ=4), the SC technique has provided a higher increase of compressive strength and axial deformability compared to the other conventional

strengthening techniques. For the column's group of λ=2, the SC technique was the most effective in terms of compressive strength, but the FW technique has provided the highest axial deformation.

(5) The experimental results revealed that for the same level of column's axial stress, the maximum CFRP strain in the SC columns was higher than in the columns strengthened with the other two considered strengthening techniques.

(6) The effect of cross-section aspect ratio plays an important role on the performance of strengthened RC columns. For all strengthened groups of columns with different λ, the compressive strength and ultimate axial strain have decreased with the increase of the cross-section aspect ratio. However, the columns strengthened according to SC technique showed a lower decrease of compressive strength with the increase of λ compared to the other strengthening groups of columns.

(7) The predictive performance of *fib* Bulletin 14 (*Exact and approximate approaches*), CNR-DT 200 and ACI.2R-08 for the estimation of the compressive strength of the investigated strengthening techniques was assessed. Apart from the "*approximate approach*" of *fib* Bulletin 14, which estimated too conservative values, the remaining analytical models have provided satisfactory predictions for the columns with λ=1 and λ=2. The ACI.2R-08 model is, amongst the considered ones, the only one that can predict the compressive strength of confined columns of λ>4, although its applicability was restricted to FW confinement configurations. This formulation was extended to PW configurations with acceptable predictive performance.

(8) By idealizing a rectangular cross section of a column strengthened with the proposed SC technique as a set of parallel square cells, *fib*, *CNR* and *ACI* models were adapted for predicting the compressive strength of SC strengthened columns. The obtained results evidence good predictive performance.

6. ACKNOWLEDGEMENTS

The first author would like to thank Erasmus Mundus Programme and TecMinho to provide financial and scholarship supports. The support from the FCT in the scope of PTDC/ECM-EST/1882/2014 project is also acknowledged. Moreover, the authors would like to thank the collaboration of Casais and CiviTest companies for the collaboration on the preparation of the RC columns, and Clever Reinforcement Company for providing the CFRP sheets and adhesives. Also gratefully acknowledge the technicians of laboratory of the structural division of the Department of Civil Engineering of Minho University.

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Appendix

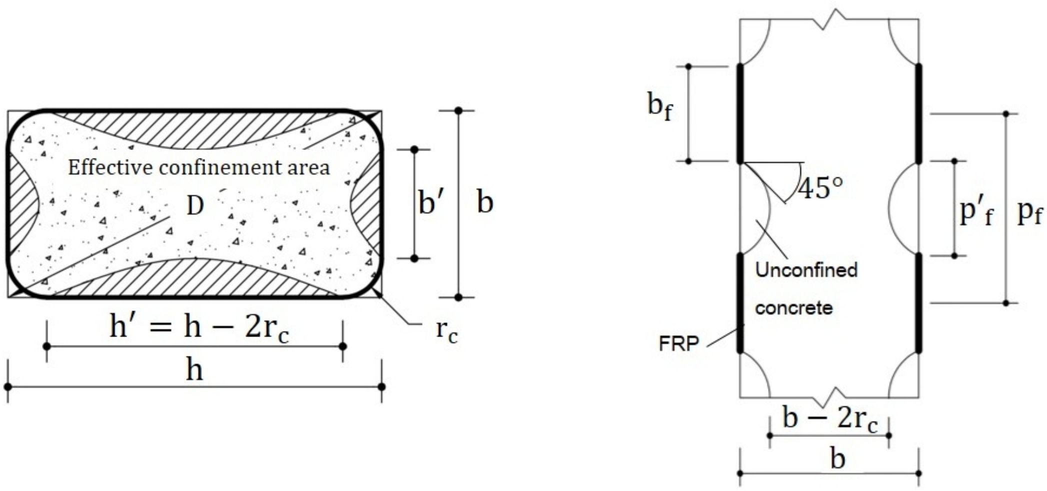


Fig. A.1 Confinement of rectangular sections

The fib bulletin 14-2001 proposal guideline for FRP-confined concrete (fib, 2001) [21]

"Exact predictive equation"

$$f_{cc} = f_{co}\left(2.254\sqrt{1+7.94\frac{f_l}{f_{co}}} - 2\frac{f_l}{f_{co}} - 1.254\right) \tag{A.1}$$

"Approximate predictive equation"

$$f_{cc} = f_{co}\left(0.2+3\sqrt{\bar{f}_l}\right) \tag{A.2}$$

$$\bar{f}_l = \frac{f_l}{f_{co}} \tag{A.3}$$

$$f_l = \frac{\sigma_{lx}h+\sigma_{ly}b}{h+b} \tag{A.4}$$

$$\sigma_{lx} = K_{confx}\varepsilon_{ju}\,;\; K_{confx} = \rho_{jx}k_e E_f\,;\; \rho_{jx} = \frac{2b_f n t_f}{p_f b} \tag{A.5}$$

$$\sigma_{ly} = K_{confy}\varepsilon_{ju}\,;\; K_{confy} = \rho_{jy}k_e E_f\,;\; \rho_{jy} = \frac{2b_f n t_f}{p_f h} \quad \text{(A.6)}$$

$$k_e = k_H k_V \quad \text{(A.7)}$$

$$k_H = 1 - \frac{\left(b-2r_c\right)^2 + \left(h-2r_c\right)^2}{3A_g\left(1-\rho_{sg}\right)} \quad \text{(A.8)}$$

$$k_V = \left(1 - \frac{p'_f}{2b}\right) \quad \text{(A.9)}$$

where f_{cc} is the compressive strength of FRP-confined concrete; f_{co} is the compressive strength of unconfined concrete; f_l is the equivalent lateral confining pressure; σ_{lx} and σ_{ly} are the lateral confining pressure acting perpendicular to core dimensions h and b, respectively; b is the smaller dimension of the column cross section; h is the larger dimension of the column cross section; r_c is the corner radius of the cross section; K_{confx} and K_{confy} are the stiffness of the FRP wrapping in *x* and *y* direction; ε_{ju} is the effective tensile failure strain of the FRP wrapping; E_f is the modulus of the FRP wrapping; ρ_{jx} and ρ_{jy} are the volumetric ratio of transverse confining reinforcement in the *x* and *y* direction, respectively; b_f is the width of FRP strip; n is the number of FRP layers; t_f is the thickness of FRP per one layer; p_f is the center-to-center spacing of FRP strips; A_g is the gross area of the cross section; ρ_{sg} is the longitudinal steel reinforcement ratio; k_e is the confinement effectiveness coefficient; k_H is the coefficient of horizontal efficiency; k_V is the coefficient of vertical efficiency. For RC confined member with continuous FRP wrapping, it is assumed that k_V = 1; and p'_f is the clear spacing between FRP strips

CNR-DT 200/2004 proposal guideline for FRP-confined concrete (CNR-DT 200, 2004) [22]

$$\frac{f_{cc}}{f_{co}} = 1 + 2.6\left(\frac{f_{l,eff}}{f_{co}}\right)^{\frac{2}{3}} \quad \text{(A.10)}$$

$$f_{l,eff} = k_e f_l \quad \text{(A.11)}$$

$$f_l = \frac{1}{2}\rho_f E_f \varepsilon_{fd,rid}\,;\; \rho_f = \frac{2nt_f\left(b+h\right)b_f}{bhp_f} \quad \text{(A.12)}$$

$$\varepsilon_{fd,rid} = \min\left\{\eta_a \varepsilon_{fk} / \gamma_f ; 0.004\right\} \quad \text{(A.13)}$$

$$k_e = k_H k_V k_\alpha \quad \text{(A.14)}$$

$$k_H = 1 - \frac{\left(b - 2r_c\right)^2 + \left(h - 2r_c\right)^2}{3A_g} \qquad \text{(A.15)}$$

$$k_V = \left(1 - \frac{p'_f}{2b}\right) \qquad \text{(A.16)}$$

$$k_\alpha = \frac{1}{1 + \left(\tan \alpha_f\right)^2} \qquad \text{(A.17)}$$

where $f_{l,eff}$ is the effective confinement lateral pressure; ρ_f is the geometric strengthening ratio as a function of section shape and FRP configuration (continuous or discontinuous wrapping); $\varepsilon_{fd,rid}$ is the reduced FRP design strain; η_a is the environmental conversion factor for the external exposure conditions of FRP systems (=0.85); γ_f is the partial factor for FRP material (=1.10); ε_{fk} is the characteristic strain at failure; k_α is the coefficient of fiber orientation; and α_f is the angle of fibers.

ACI 440.2R-08 proposal guideline for FRP-confined concrete (ACI, 2004) [1]

$$f'_{cc} = f_{co} + \psi_f 3.3 k_e f_l \qquad \text{(A.18)}$$

$$f_l = \frac{2E_f n t_f \varepsilon_{fe}}{D} \qquad \text{(A.19)}$$

$$\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu} \qquad \text{(A.20)}$$

$$D = \sqrt{b^2 + h^2} \qquad \text{(A.21)}$$

$$k_e = k_H k_V \qquad \text{(A.22)}$$

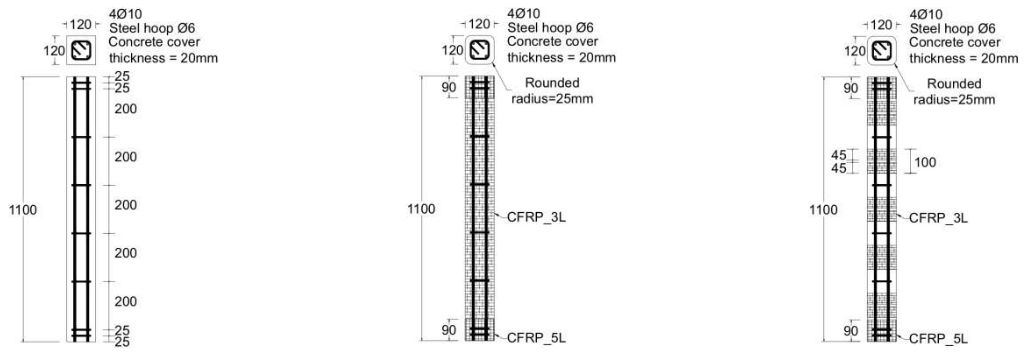
$$k_H = \frac{A_e}{A_c}\left(\frac{b}{h}\right)^2 \qquad \text{(A.23)}$$

$$\frac{A_e}{A_c} = \frac{1 - \dfrac{\left[\left(\dfrac{b}{h}\right)\left(h - 2r_c\right)^2 + \left(\dfrac{h}{b}\right)\left(b - 2r_c\right)^2\right]}{3A_g} - \rho_{sg}}{1 - \rho_{sg}} \qquad \text{(A.24)}$$

where ψ_f is an additional reduction factor based on the committee's judgment (=0.95); ε_{fe} is the effective strain level in the FRP at failure; k_ε is the FRP strain efficiency factor (=0.586); ε_{fu} is the ultimate tensile strain of FRP material; D is the diagonal of rectangular cross section; k_V is the coefficient of vertical efficiency (obtained according to CNR-DT 200 proposal guideline).

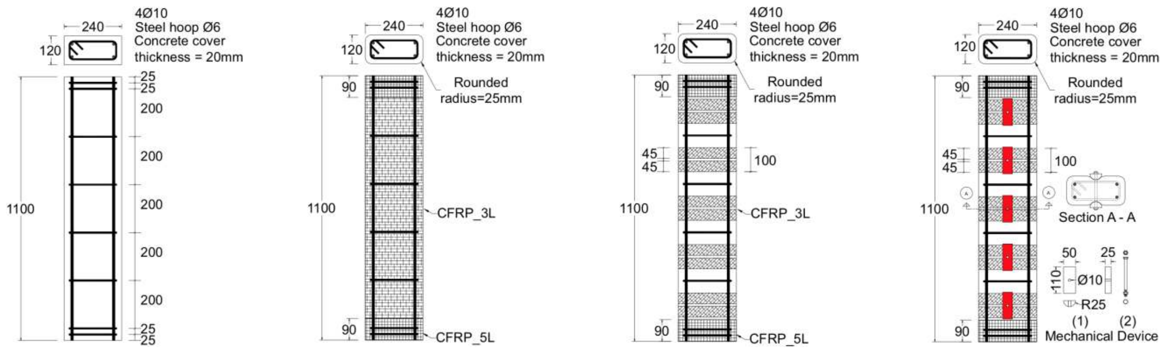
FIGURES

List of Figures:



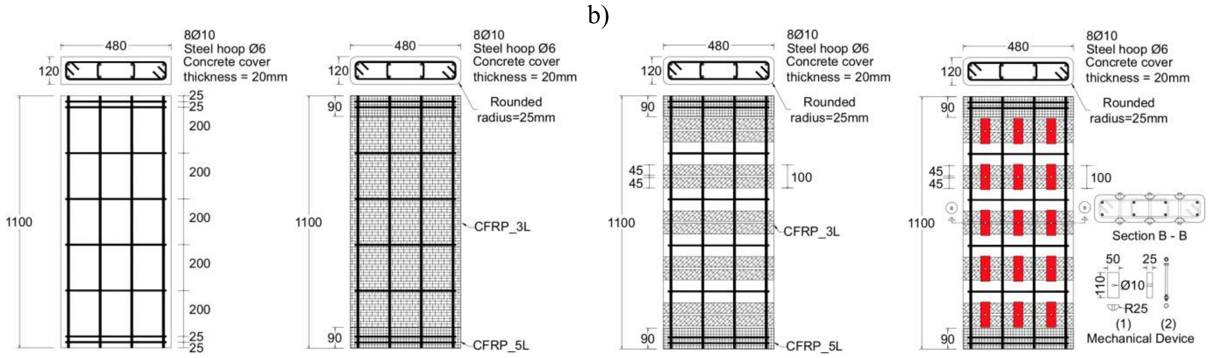
λ1-REF (Reference column) | λ1-FW (Fully-wrapped column) | λ1-PW (Partially-wrapped column)

a)



λ2-REF (Reference column) | λ2-FW (Fully-wrapped column) | λ2-PW (Partially-wrapped column) | λ2-SC (New technique column)

b)



λ4-REF (Reference column) | λ4-FW (Fully-wrapped column) | λ4-PW (Partially-wrapped column) | λ4-SC (New technique column)

c)

Fig. 1 - Geometry, reinforcement, and strengthening configuration for the series of RC columns with cross-sectional aspect ratio of: a) 1; b) 2; and c) 4 (dimension in mm)

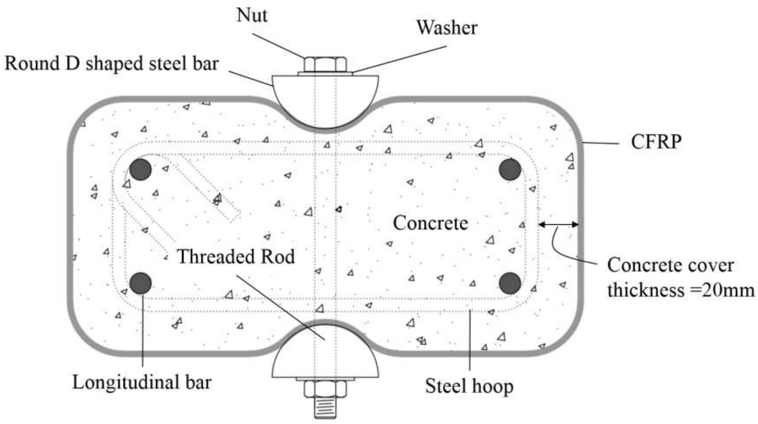


Fig. 2 - Schematic representation of the new proposed technique

Fig. 3 - Representation of the prestress application on the CFRP strips

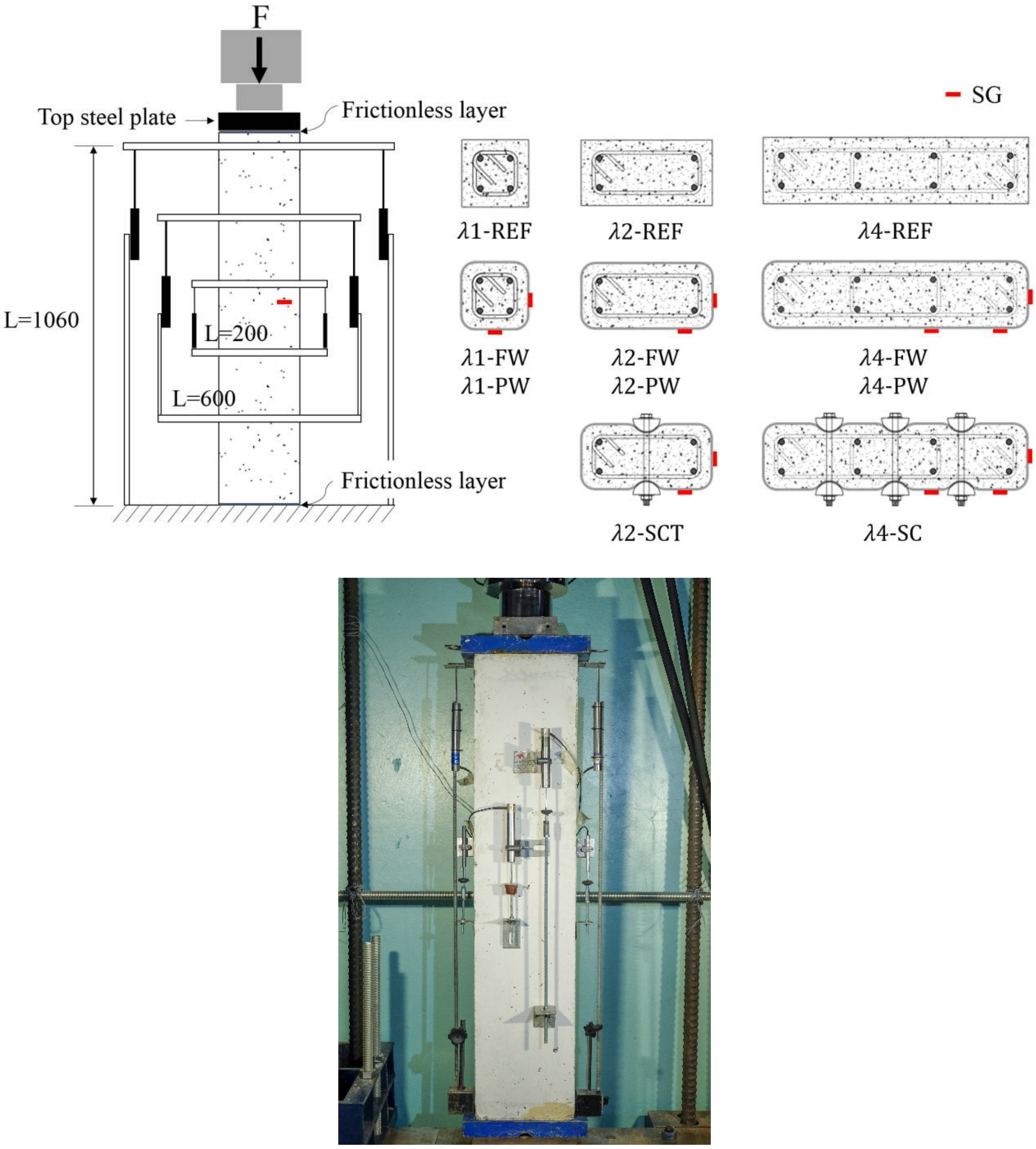


Fig. 4 - Strain gauge positioning (red mark) and test setup (dimensions in mm)

(a) λ1-REF (b) λ1-FW (c) λ1-PW

Fig. 5 - Failure modes of the columns with cross-section aspect ratio (λ) equal to 1

(a) λ2-REF (b) λ2-FW (c) λ2-PW (d) λ2-SC

Fig. 6 - Failure modes of the columns with cross-section aspect ratio (λ) equal to 2

(a) λ4-REF (b) λ4-FW (c) λ4-PW (d) λ4-SC

Fig. 7 - Failure modes of the columns with cross-section aspect ratio (λ) equal to 4

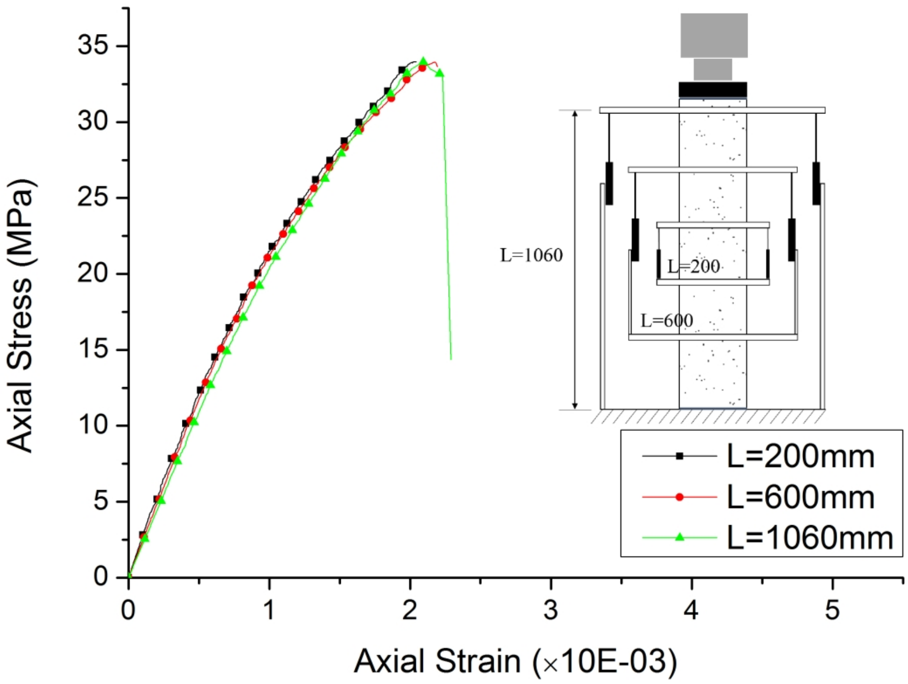
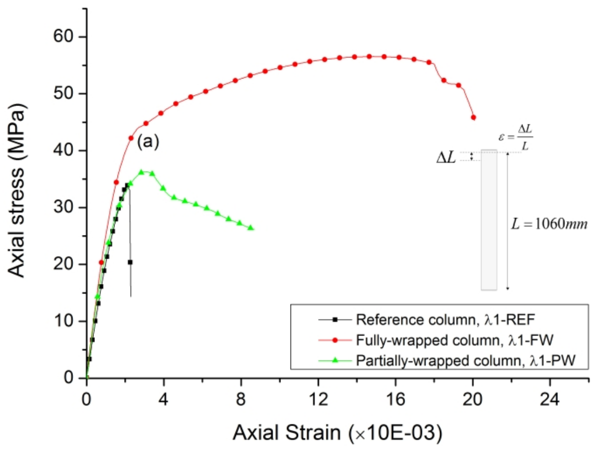
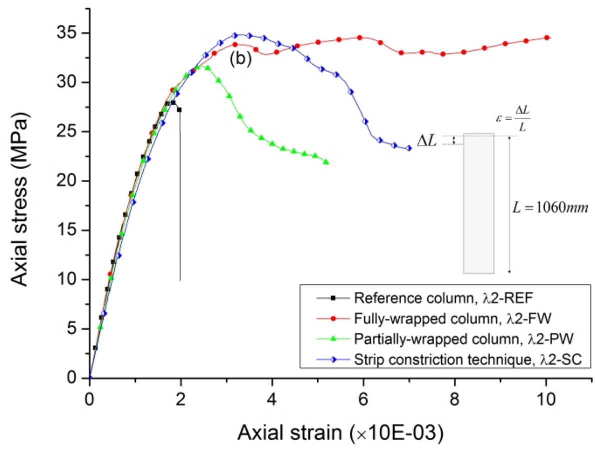


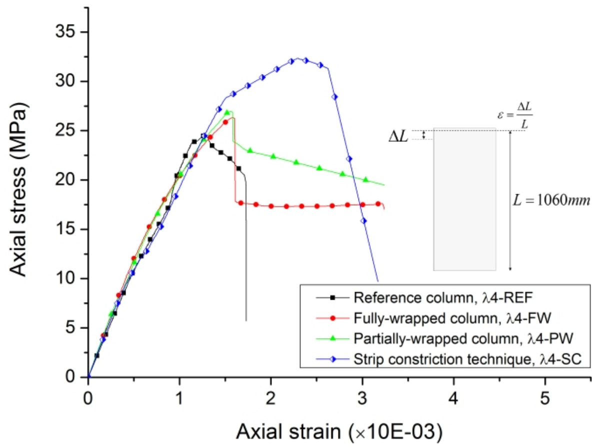
Fig. 8 - Axial stress versus axial strain relationship recorded in the λ1-REF column for the following three measuring strokes: 200, 600 and 1060 mm



(a) λ= 1

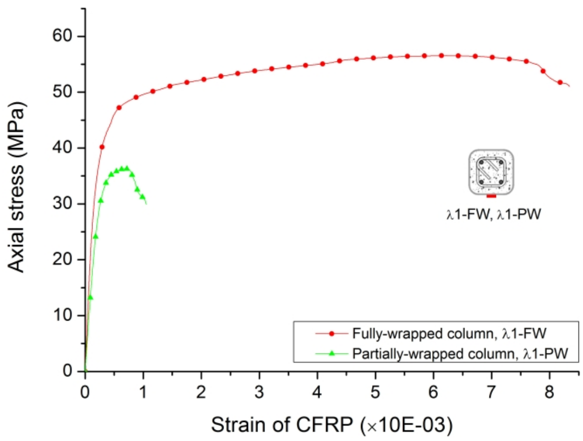


(b) λ= 2

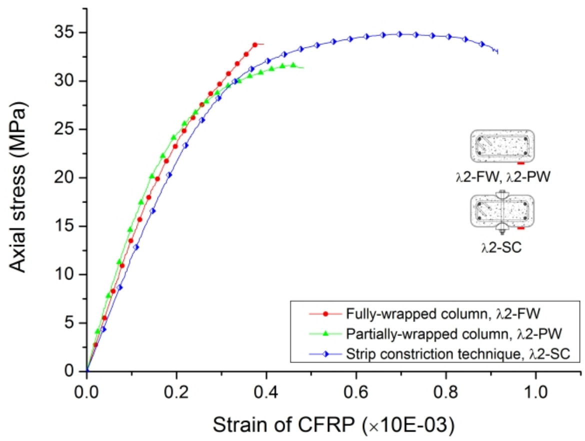


(c) λ= 4

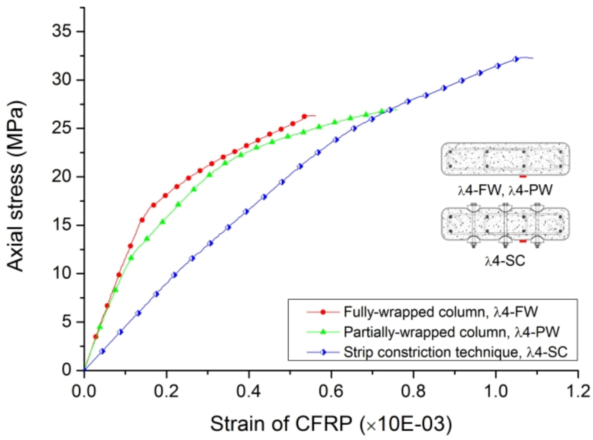
Fig. 9 - Axial stress versus axial strain relationship in the RC columns of cross-section aspect ratio (λ) of: a) 1; b) 2; and c) 4



(a) λ= 1

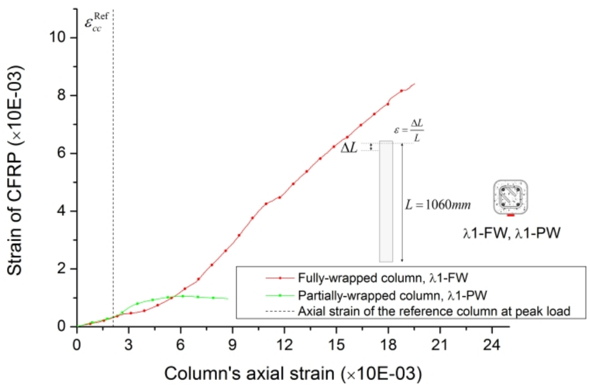


(b) λ= 2

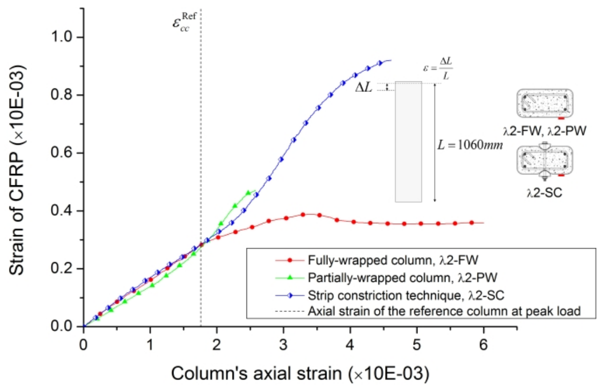


(c) λ= 4

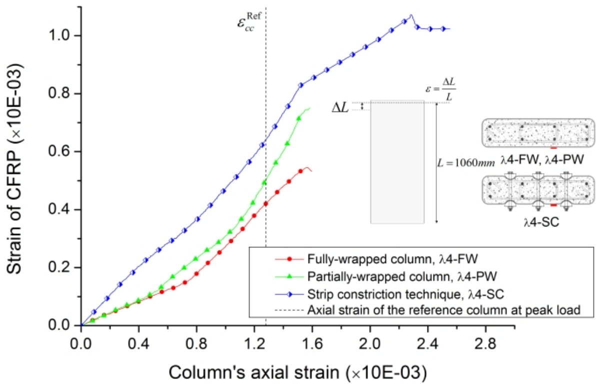
Fig. 10 - Axial stress versus CFRP strain relationship in the RC columns of cross-section aspect ratio (λ) of: a) 1; b) 2; and c) 4



(a) λ= 1

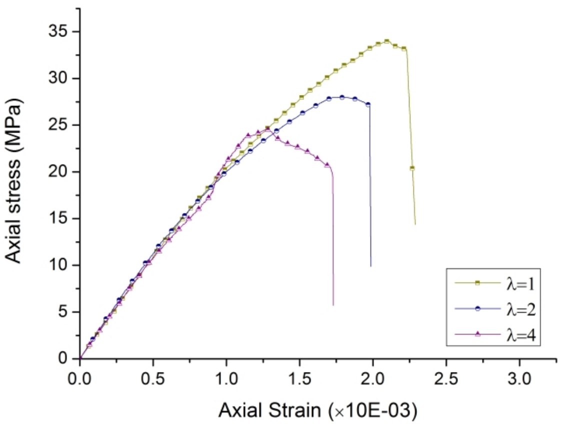


(b) λ= 2

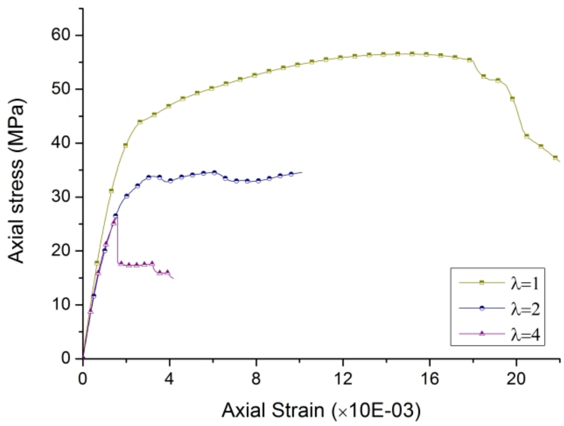


(c) λ= 4

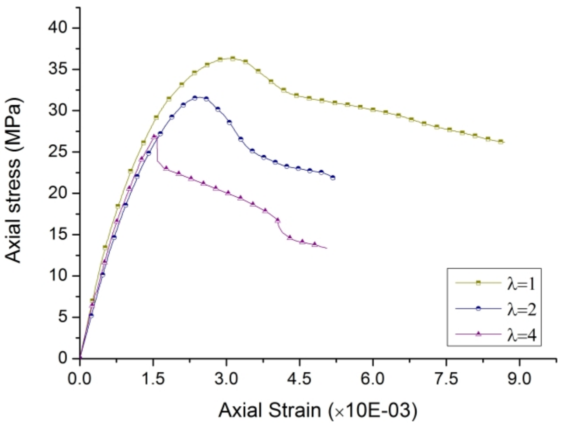
Fig. 11 - Column's axial strain versus CFRP strain relationship in the RC columns of cross-section aspect ratio (λ) of: a) 1; b) 2; and c) 4



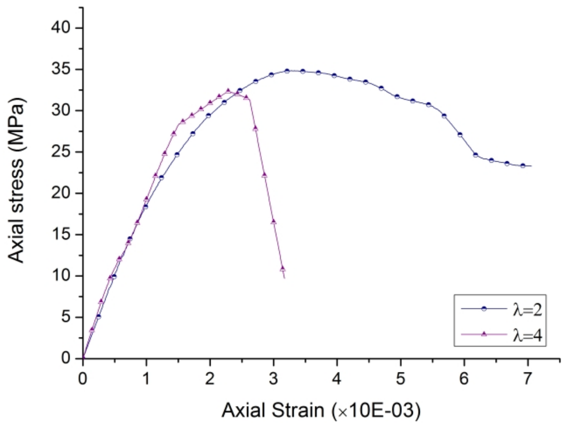
(a) Reference columns (REF)



(b) Fully-wrapped (FW) technique



(c) Partially-wrapped (PW) technique



(d) Strip constriction (SC) technique

Fig. 12 - Axial stress-strain relationship for all types of columns with different cross-section aspect ratio

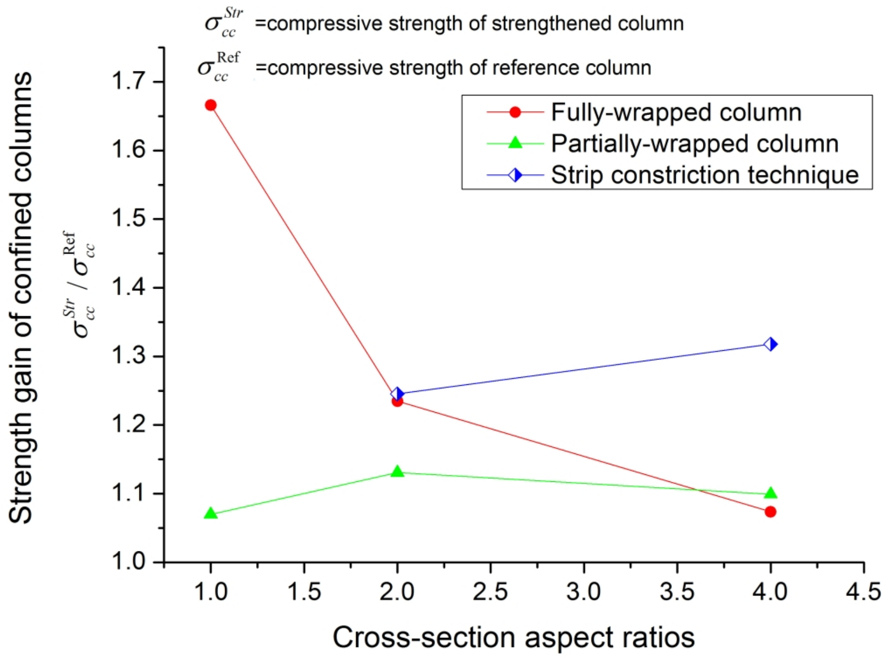


Fig. 13 - Strength gain of the strengthened columns versus cross-section aspect ratios

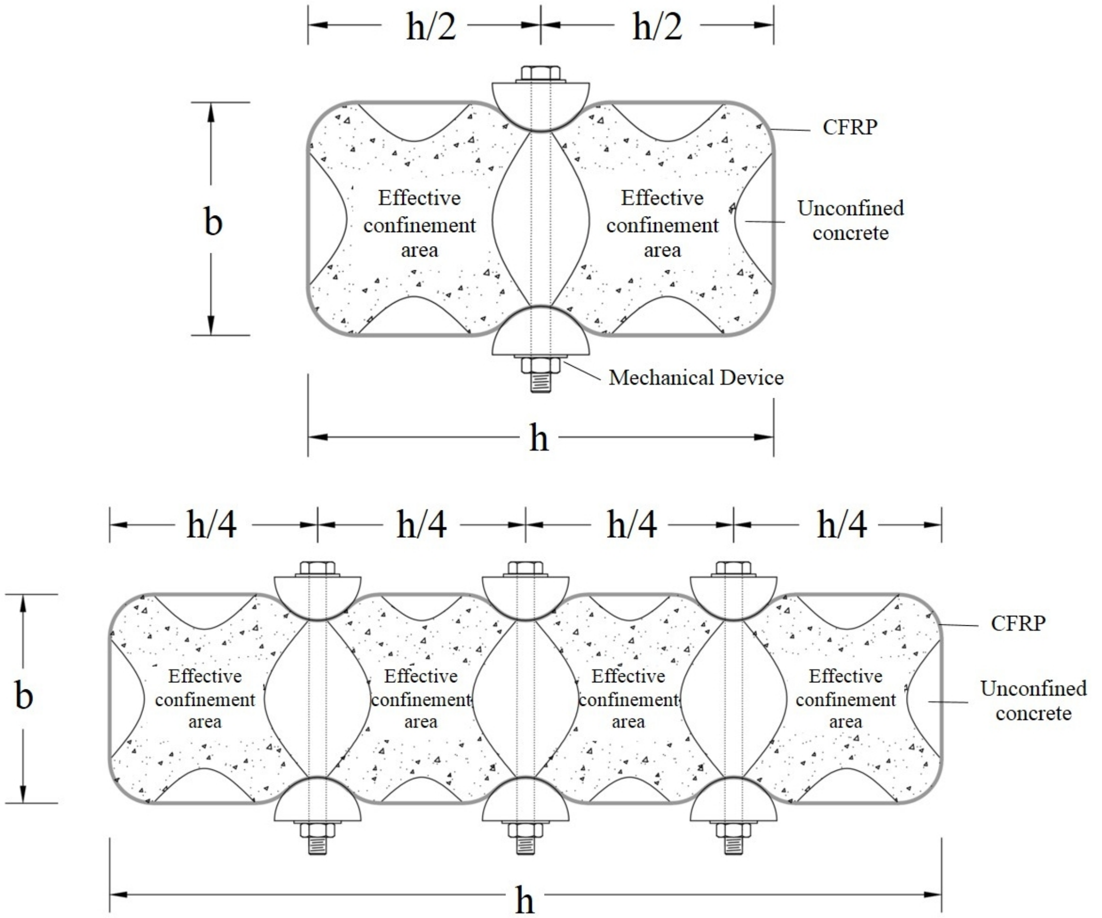


Fig. 14 - Effective confinement area of rectangular sections provided by the proposed (SC) technique

TABLES

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Table 1 - Mechanical properties of CFRP (S&P C-sheet 240)

Property	Value
Tensile strength (MPa)	3800
Tensile modulus (GPa)	240
Elongation at rupture (%)	1.55
Density (g/cm^3)	1.7
Thickness (mm/ply)	0.117

Table 2 - Mechanical properties of epoxy adhesive (S&P Resin 55)

Property	Value
Density (Kg/l)	1.11
Mixing ratio by weight (resin to hardener)	2:1
Tensile strength at 14 days (MPa)	35.8
Elongation at failure at 14 days (%)	2.3
Modulus of elasticity at 14 days(MPa)	2581.8

Table 3 - Summary of experimental results for all columns

Column designation	λ=h/b	A_{eff} (mm²)	$P_{\max}$ (kN)	σ_{cc} (MPa)	ε_{cc} (‰)	$\varepsilon_{f\max}$ (‰)	$\Delta F_{\max}$ (%)	$\Delta\bar{\varepsilon}_{cc}$ (%)	A_{CFRP} (m²)	$\Delta F_{\max} / A_{CFRP}$ (%/m²)
λ1-REF	1	14400.00	488.70	33.94	2.09	-	-	-	-	-
λ1-FW		13863.50	783.85	56.54	14.84	8.34	66.60	610.81	1.78	37.36
λ1-PW		13863.50	503.32	36.31	3.06	1.05	6.98	46.30	1.10	6.37
λ2- REF	2	28800.00	805.45	27.97	1.76	-	-	-	-	-
λ2- FW		28263.50	976.10	34.54	10.04	0.39	23.49	469.45	2.66	8.83
λ2- PW		28263.50	893.68	31.62	2.45	0.48	13.06	38.97	1.64	7.98
λ2-SC		27192.30	947.11	34.83	3.28	0.92	24.54	86.05	1.64	15.00
λ4- REF	4	57600.00	1413.08	24.53	1.28	-	-	-	-	-
λ4- FW		57063.50	1502.92	26.34	1.58	0.56	7.36	24.08	4.42	1.67
λ4- PW		57063.50	1538.95	26.97	1.55	0.76	9.93	21.57	2.72	3.66
λ4- SC		53849.90	1741.45	32.34	2.29	1.09	31.82	79.61	2.72	11.72

Table 4 - Comparison of results obtained from experimental tests and analytical models for RC columns of square and rectangular cross section

Column designation	Experimental result, $f_{cc}^{\exp}$	Analytical models, f_{cc}^{anal}				$\frac{f_{cc}^{anal}-f_{cc}^{\exp}}{f_{cc}^{\exp}}\times 100$			
		fib		CNR-DT 200	ACI	fib		CNR-DT-200	ACI
		Approx.	Exact.			Approx.	Exact.		
	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	(%)	(%)	(%)	(%)
λ1-REF	25.16	-	-	-	-	-	-	-	-
λ1-FW	47.42	32.09	41.11	39.51	42.81	-47.77	-15.34	-20.02	-10.76
λ1-PW	26.71	15.71	25.50	26.68	28.42	-70.04	-4.76	-0.13	6.00
λ2- REF	24.36	-	-	-	-	-	-	-	-
λ2- FW	29.87	25.09	33.83	32.77	24.04	-19.03	11.72	8.86	-24.23
λ2- PW	26.92	12.82	23.61	24.61	22.03	-109.96	-14.01	-9.37	-22.18
λ2-SC	29.98	15.71	25.50	26.68	28.42	-90.82	-17.56	-12.36	-5.48
λ4- REF	21.93	-	-	-	-	-	-	-	-
λ4- FW	23.04	N/A	N/A	N/A	21.38	N/A	N/A	N/A	-7.75
λ4- PW	23.72	N/A	N/A	N/A	21.13	N/A	N/A	N/A	-12.27
λ4- SC	27.41	15.71	25.50	26.68	28.42	-74.46	-7.48	-2.73	3.56

N/A = not available