AXIAL TESTING OF CONCRETE COLUMNS CONFINED WITH CARBON FRP: EFFECT OF FIBER ORIENTATION

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Abstract

Tests were conducted to demonstrate the concrete confinement capability of FRP laminates consisting of carbon fibers with different fiber orientations including ±45-degree direction and different concrete cross section (circular and rectangular). The performance of the ±45-degree FRP laminates is compared to that of unidirectional FRP laminates of different manufacturers and amounts of materials. Results indicate that the ultimate capacity of ±45-degree FRP laminate strengthened rectangular columns is slightly lower than that of columns strengthened with fibers in the hoop direction. However, the ±45-degree columns exhibit a higher ductility probably due to the enlargement of the failure zone as allowed by the given fiber orientation. The larger failure zone ensures better energy dissipation with more material participating in the stress redistribution. Numerical analysis supports the laboratory findings. Suggestions for implementation in design guidelines for concrete confinement using FRP laminates with different fiber orientations are made.

Introduction

Reinforced concrete columns need to be laterally confined in order to ensure large deformation under load and provide adequate resistance capacity. In the case of a seismic event, energy dissipation allowed by a well-confined concrete core can often save human lives. On the contrary, a poorly confined concrete column behaves in a brittle manner leading to sudden and catastrophic failures.

Steel jacketing provided by hoops or ties exerts a constant confining pressure as soon as the steel has yielded. When a perfectly elastic material such as FRP is used, the confining pressure on concrete keeps increasing as the load and volumetric expansion increases. This new behavior has to be understood and a different approach to the theory has to be taken.

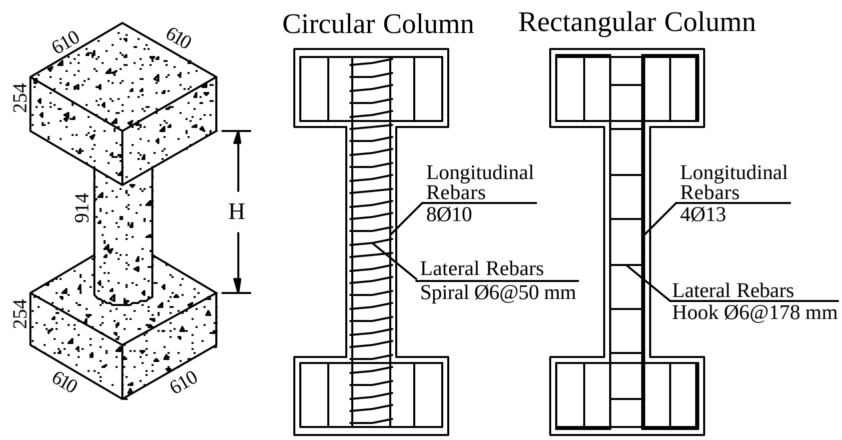
Piers and columns upgraded by using externally bonded FRP laminates has been proven to be a reliable technique to enhance flexural and shear capacity, and improve ductility as well as increase ultimate load carrying capacity[1-5].

Theoretical models taking into account confining pressure due to either steel or FRP are available[6-10]. However, in this paper, findings and equations developed by ACI Committee 440[11] will be used as the analytical framework for both rectangular and circular columns.

Five circular columns and three rectangular columns were tested under pure axial load. Two of them were control specimens without FRP used as a benchmark. One rectangular column was wrapped using the ±45-degree CFRP (Carbon FRP) laminates (DB450-C) and one using a unidirectional CFRP laminate (CF-130). Three circular columns were tested using the ±45-degree laminate, and three unidirectional CFRP laminates, CF-130, L200-C, and L300-C.

Specimen Details

Figure 1a shows dimensions used for the columns. The enlargement at the two ends of each specimen provides good load transfer, ensures failure to happen in the column zone of the specimen, and simulates the restraint of the horizontal members of a real structure.



a)Column Dimensions b) Steel Reinforcement Details

Figure 1. Dimensions (mm) and Steel Reinforcement Details

Rectangular columns were reinforced with four ϕ13 Grade 60 (414 MPa) steel longitudinal rebars located at each corner. Lateral reinforcement was provided by ϕ6 closed ties spaced 178 mm on center. Circular columns were reinforced with eight ϕ10 Grade 60 (414 MPa) steel longitudinal rebars. Lateral reinforcement was provided by a ϕ6 spiral with a 50 mm pitch (Figure 1b). Table 1 shows concrete cross section dimensions and steel reinforcing detail.

Table 1. Column Cross-Sections and Reinforcement Detail

Column	Cross-Section [mm]	Height H [mm]	Enlargement [mm]	Longitudinal Reinforcement	Lateral Reinforcement
Rectangular	178x178	914	610x610x254	4ϕ13	ϕ6@178 mm
Circular	200	914	610x610x254	8ϕ10	ϕ6@50 mm

Table 2 summarizes the properties of concrete, steel, and FRP, respectively: $f`_c$ is the compressive concrete strength obtained as an average value of three cylinders; f_y is the yield strength of the steel reinforcement from three coupons; t_f is the thickness of the FRP ply considering fibers only; f_{fu}^*, E_f, and ε_{fu}^* are the guaranteed tensile strength, modulus of elasticity, and ultimate tensile elongation of the FRP related to the fiber content only and measured in the hoop direction (90-degree, see also Figure 2a), as reported by the manufacturer.

In the same table, the term control represents the unwrapped specimen used as a benchmark, CF-130 is the specimen wrapped with a unidirectional carbon FRP with fibers in the hoop direction (90-degree), used as comparison, DB450-C is the column wrapped with the ±45-degree carbon FRP, L200-C and L300-C are the two specimens wrapped with unidirectional (90-degree) carbon FRP having different fiber content.

Table 2. Material Properties

Column	Concrete	Longitudinal Steel	Lateral Steel	FRP			
[-]	$f`_c$ [MPa]	f_y [MPa]	f_y [MPa]	t_f [mm]	f_{fu}^* [MPa]	E_f [GPa]	ε_{fu}^* [%]
Circular							
Control	19.6	360	632	---	---	---	---
CF-130	23.8	360	632	0.165	3800	227	1.67
DB450-C	25.5	393	517	0.270	1689	125.6	1.9
L200-C	25.5	393	517	0.122	4140	230	1.7
L300-C	25.5	393	517	0.175	4090	230	1.7
Rectangular							
Control	35.4	400	427	---	---	---	---
CF-130	19.6	400	427	0.165	3800	227	1.67
DB450-C	19.8	400	427	0.270	1689	125.6	1.9

All columns were wrapped following standard procedure indicated below:

1. Surface Preparation: The surface of the structure was cleaned and prepared for installation through the use of sand blasting.
2. Primer Application: A coat of Primer is applied to the concrete surface. The primer prepares the surface of the concrete for the application of the CFRP sheets.
3. Putty Application: A very thin coat of Putty is smoothed over the surface to fill in any small voids, cracks or uneven surfaces.
4. First Hand of saturant Application: A layer of saturant is applied next. This precedes the installation of the first layer of CFRP.
5. FRP Sheets Application: The first layer of FRP sheets is then applied. The sheets are rolled into the saturant to insure good adhesion.
6. Second Hand of saturant Application: A second application is necessary to ensure good penetration of the saturant around the fibers.

All wrapped specimens were strengthened with one ply of carbon fiber laminate and tested after one week of curing. Corners for non-circular cross section specimens received a 13 mm chamfer. Corner rounding is a well-accepted procedure that is normally used when retrofitting rectangular reinforced concrete columns to avoid stress concentration where FRP laminates are bent. The layers of fibers were applied one at a time, with each layer overlapping itself to provide for development of the full tensile strength of the laminate. The overlapping length was 100 mm. No overlap was provided between adjacent sheets in the vertical direction.

Test Setup

Strain gages were applied to longitudinal and lateral steel to record axial and circumferential strain. Strain gages were also placed on the external FRP reinforcement. A sketch showing the position of the gages for the columns wrapped with the ±45-degree carbon FRP is given in Figure 2. Three LVDT's (Linear Variable Differential Transducers) were also used to record lateral displacement of the column (Figure 2b).

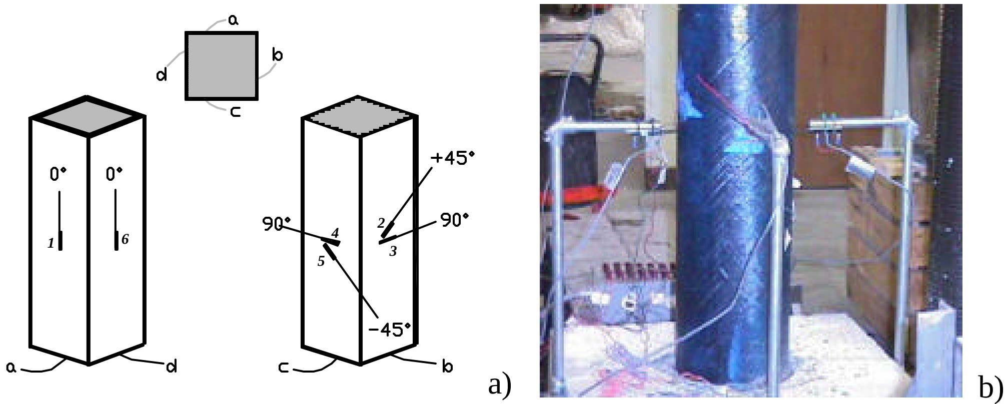


Figure 2. Strain Gages Positions and Test Setup

Experimental Results

The typical collapse mechanism of the specimens was usually marked by sudden failure. Approaching ultimate strength, noise associated with localized debonding, fiber failure, and crushing of concrete was detected. Because of the geometrical configuration adopted, the location of the failure region occurred in the middle height of the specimen.

Table 3 summarizes the area of the concrete *(A_c)*, the area of the longitudinal and lateral steel *(A_s, A_{st})*, the maximum axial capacity *(P)*, the maximum axial and lateral (circumferential) strain *(e_y, e_x)* measured in the steel reinforcement for the control specimens and along the fibers for the strengthened specimens, and the normalized load *(P_N)* defined as:

$$P_N = \frac{P}{(A_c - A_s)\, f'_c + A_s f_y}$$

where A_c and $f`_c$ represent area and cylinder compressive strength of the concrete, and A_s and f_y area and yield strength of the steel, respectively.

Table 3. Test Results

Column [-]	A_c [mm^2]	A_s [mm^2]	A_{st} [mm^2/mm]	Load P [kN]	ε_y [%]	ε_x [%]	Normalized Load P_N [-]
Circular							
Control	31,416	628	0.57	928	2.06	0.47	1.125
CF-130	31,416	628	0.57	1356	0.19	0.49	1.338
DB450-C	31,416	628	0.57	1236	1.50	0.85	1.662
L200-C	31,416	628	0.57	1543	0.89	0.88	1.501
L300-C	31,416	628	0.57	1542	0.83	0.48	1.490
Rectangular							
Control	31,684	531	0.16	1120	0.32	0.09	0.819
CF-130	31,684	531	0.16	943	0.63	0.54	1.196
DB450-C	31,684	531	0.16	720	0.68	0.17	0.883

A comparison between unwrapped and wrapped with DB450-C rectangular and circular columns is given in Figure 3. Rectangular specimens show a smaller axial load capacity and ductility due to the stress concentration at the corners that decreases the efficiency of the cross section.

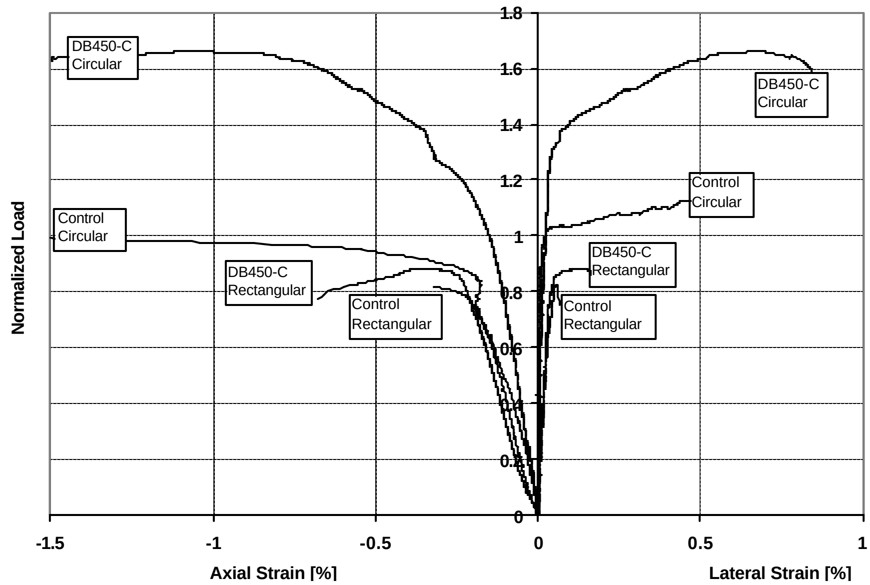


Figure 3. Comparison between Circular and Rectangular Columns

Circular Columns

Explosive failures of each column strengthened with unidirectional carbon type L200-C and L300-C, and CF-130 were observed. This failure mode is typical for wrapped columns and it is a direct consequence of the linear elastic behavior shown by the FRP material. It does not necessarily mean loss of ductility of the strengthened element.

A gentler and less sudden failure was observed for the specimen wrapped with the ±45-degree carbon fiber laminate. The ultimate limit state was progressively reached, and warnings of imminent collapse were given by formation of "bubbles" in the laminate surface located at mid-height of the column as shown in Figure 4.

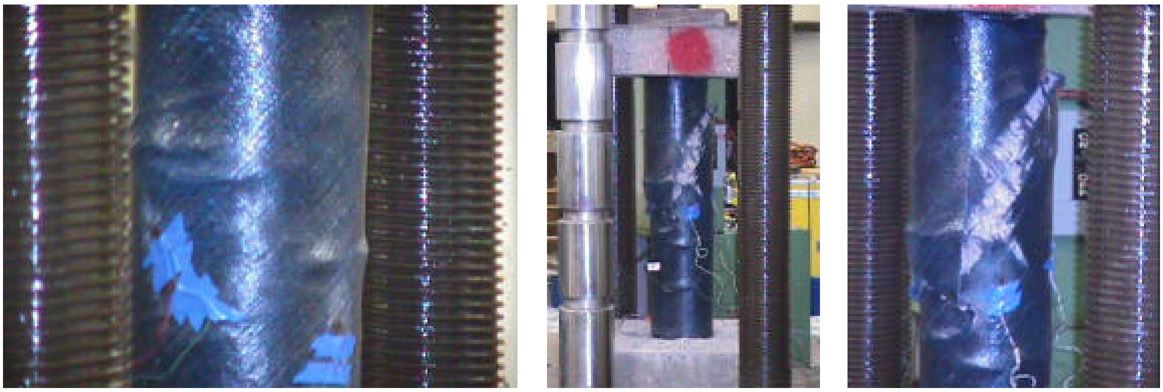


Figure 4. Bubbles on DB450-C Laminate Prior and After Failure

Increase in strength has been observed for all the columns tested with respect to the control specimen. Compared with L200-C and L300-C, DB450-C was found to provide better ductility, and be more effective regarding the maximum load capacity (Figure 5).

The more ductile behavior exhibited by the specimen wrapped using the ±45-degree laminate is probably due to the enlargement of the failure zone associated with a better stress redistribution, compared to the very limited damaged area displayed by specimens strengthened with unidirectional FRP (Figure 6).

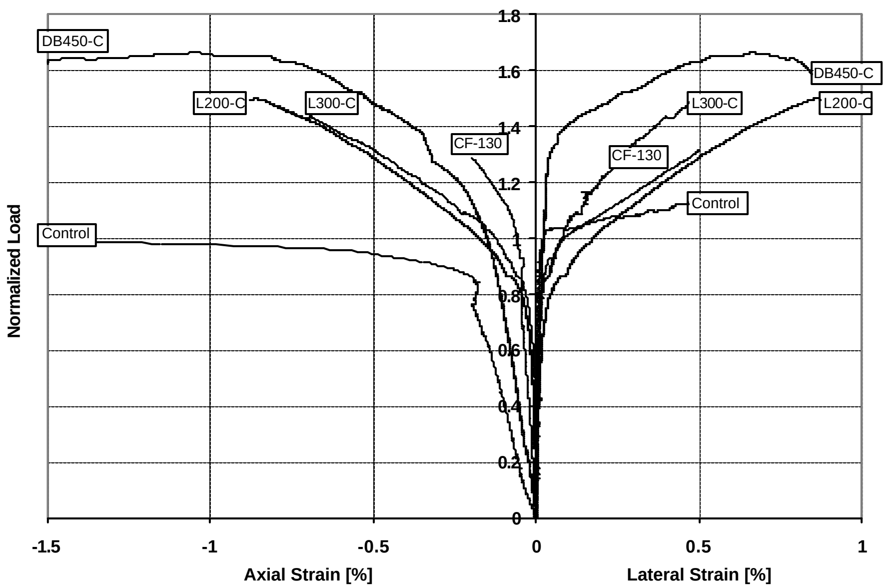


Figure 5. Normalized Load-Strain Envelopes for Circular Columns

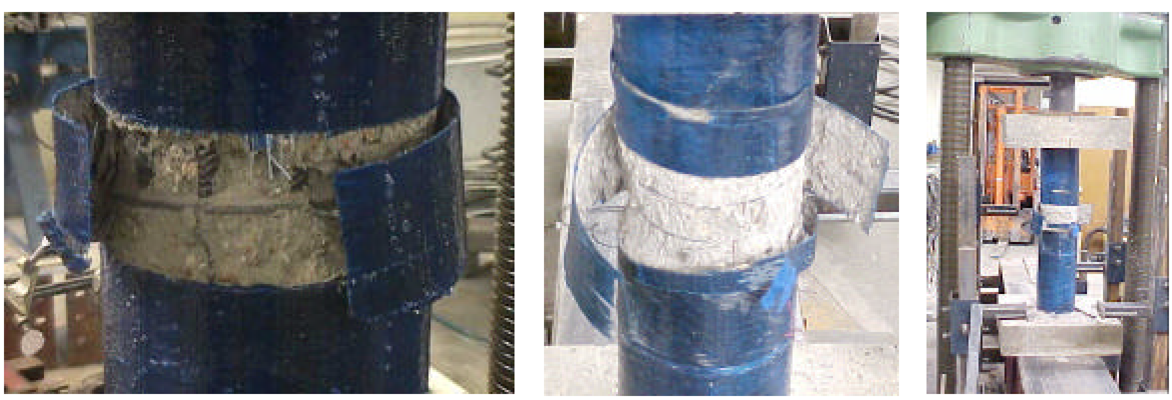


Figure 6. Failure of Unidirectional FRP laminates

Rectangular Columns

The same failure observed for the circular column wrapped with DB450-C was recorded for the rectangular ones strengthened with the identical ±45-degree carbon FRP. A diagram showing normalized axial load versus axial and lateral strain is given in Figure 7 for all rectangular specimens tested.

For rectangular columns the ±45-degree laminate was found to be less effective with respect to the specimen strengthened with the unidirectional FRP. This different behavior compared to that shown by circular specimens is probably due to the high-localized stress concentration reached in the corners, and it probably depends from the shape of the concrete confined region in which the compressive stresses go from the center of the member through the four corners of the cross section. Hence, having fibers running in the hoop direction rather than in the ±45-degree direction provides better stiffness leading to an increase of the overall load capacity.

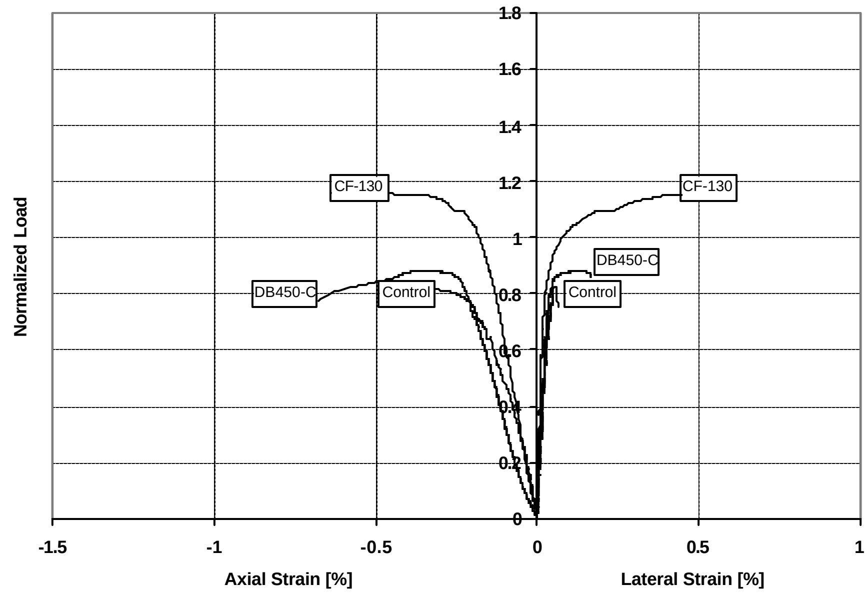


Figure 7. Normalized Load-Strain Envelopes for Rectangular Columns

When the concrete core is not well confined as in the case of the rectangular cross section having fiber running in the ±45-degree direction there is no appreciable increase of strength.

Theoretical Analysis

A numerical analysis following the procedure reported by ACI Committee 440[11] has been conducted and results are here presented and discussed. For brevity, and because it is representative of the entire experimental campaign, only a comparison between experimental and theoretical results regarding the rectangular specimen wrapped with CF-130 carbon fiber laminate is presented.

The axial compressive strength of a non-slender member confined with an FRP jacket is calculated using the conventional expressions of ACI 318[13] substituting for f'_c the factored confined concrete strength $y_f f'_{cc}$ written as:

$$f'_{cc} = f'_c \left[2.25 \sqrt{1 + 7.9 \frac{f_l}{f'_c}} - 2 \frac{f_l}{f'_c} - 1.25 \right]$$

where y_f is a recommended additional reduction factor taken equal to 0.95, and f_l represents the confining pressure provided by the FRP jacket and expressed by:

$$f_l = \frac{k_a r_f e_{fe} E_f}{2}$$

where r_f is the FRP reinforcement ratio, e_{fe} is the effective FRP strain limited to $e_{fe}=0.004<0.75e_{fu}$ whenever the member is subjected to combined compression and shear, and k_a is an efficiency reduction factor that can be taken as equal to 1.0 for circular sections and it is expressed as follows for rectangular sections:

$$k_a = 1 - \frac{(b-2r)^2 + (h-2r)^2}{3bh(1-r_g)}$$

where *b, h,* and *r* represent width, thickness, and radius of the edges of the section, and r_g is the ratio of the longitudinal area of steel reinforcement to the cross-sectional area of the compression member.

Based on these equations a numerical stress-strain diagram can be plotted and compared to the experimental behavior obtained in the test as shown in Figure 8.

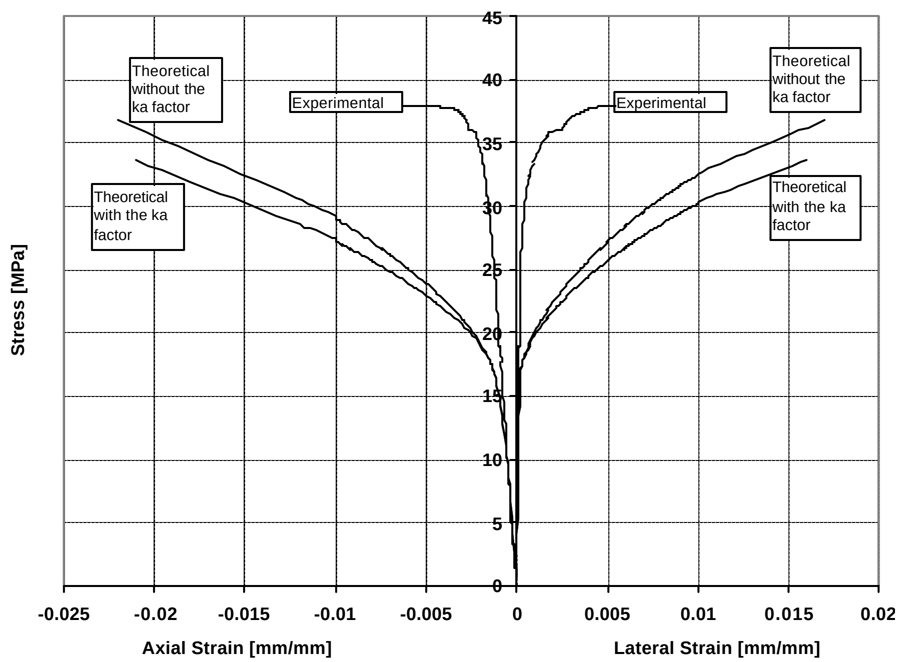


Figure 8. Numerical and Experimental Stress-Strain Diagrams

Maximum strain theoretically allowed to FRP laminate (0.0167, Table 2) is practically achieved only locally and corresponds to FRP rupture, while surrounding fibers are subjected to a lower strain value. If the strain gage had been located closer to the failed fibers, the experimental curve would have had a better resemblance to the theoretical one.

Note that without any additional reduction factor for the shape of the cross section *($k_a=1$)*, the maximum theoretical stress match as the experimental one. In conclusion, the representation adopted by ACI Committee 440 for the confined concrete behavior can be considered conservative, and in good agreement with the experimental investigation results.

In Figure 9 is shown a theoretical P-M diagram sketched starting from the equations that describe the behavior of the concrete confined by FRP. Concrete compressive strength has been taken equal to 19.6 MPa, and steel yield strength equal to 400 MPa (Table 2). The maximum axial load recorded during the test was 943 kN (Table 3). According to ACI 318[13] procedures, nominal axial load capacity of the member can be expressed as:

$$\phi P_n = 0.80\phi(0.85(A_c - A_s)\, f'_c + A_s f_y)$$

being ϕ, for non-spiral reinforcement member subjected to axial compression, taken equal to 0.7. Hence, by multiplying $P=943$ kN for 0.8 and 0.7 one gets $\phi P_n=528$ kN, a slightly larger value than 500 kN achieved with the numerical computation (Figure 9).

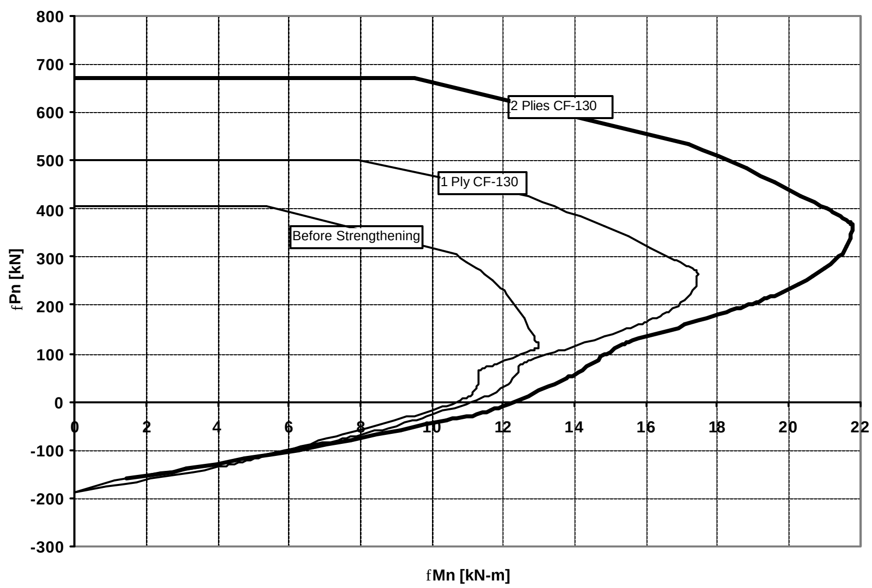


Figure 9. P-M Diagram Before and After Strengthening

The after-strengthening curves are obtained by using one and two plies of CF-130 carbon fiber laminate externally bonded to the concrete surface. The area between the curves represents the increase in load/moment capacity achieved using FRP jacket.

Conclusions

Five circular columns and three rectangular columns were tested in pure compression. Control specimens and columns strengthened with CF-130 carbon fiber laminates were previously reported in the literature[12]. In this experimental program, one circular column was wrapped with the ±45-degree carbon FRP (DB450-C), two others were strengthened with unidirectional carbon FRP laminates (L200-C, and L300-C), and one rectangular column was also wrapped with the DB450-C.

FRP rupture was the typical failure mode observed in all cases. Location of failure was limited to a small region located at the mid-height of the specimen for the two columns wrapped with the unidirectional FRP laminates. On the contrary, when using DB450-C laminates, failure was observed to be spread over a much larger region, leading to a more ductile behavior of the strengthened element.

The ±45-degree CFRP laminate can effectively be used to enhance column's ductility performance. An increase in ductility is not so evident for rectangular columns, where the effective concrete core confinement is reduced due to the geometry of the cross section. When the main goal is enhancing the load capacity, a unidirectional FRP laminate may be more effective.

An analysis carried out to compare experimental results with design guidelines for confined concrete model adopted by ACI was confirmed experimentally.

Future research is needed to validate the confined concrete model proposed in the ACI Committee 440 document including tests on columns subjected to combined axial load and bending moment.

Acknowledgements

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