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R/C Structures Strengthened With CFRP Part II: Analysis of Shear Models

Estruturas de Concreto Reforçadas com PRFC Parte II: Análise dos Modelos de Cisalhamento

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Abstract

This paper corresponds to the second part of a work intended to evaluate the design models of reinforced concrete structures strengthened with Carbon Fiber Reinforced Polymers (CFRP). The shear models analyzed correspond to the guidelines ACI 440 and fib-14, as well as more recent formulations, available in the literature. Such models were applied to eight "T" beams strengthened to shear with CFRP composites strips. Different types of carbon fiber composites (sheets and laminates), from different manufacturers, available in the Brazilian market, were applied. The analyses indicate that anchorage mechanism helps increasing load capacity and ductility and that none of the tested analytical models were capable of reproducing satisfactorily the observed behavior of the tested beams.

Keywords: *carbon fiber reinforced polymers, shear strengthening, experimental tests, analytical models.*

Resumo

Este artigo corresponde à segunda parte de trabalho visando à avaliação de modelos de projeto de estruturas de concreto armado reforçadas com Polímeros Reforçados com Fibras de Carbono (PRFC). São avaliados modelos de cisalhamento correspondentes às recomendações ACI-440 e fib-14, além de outros modelos mais recentes, disponíveis na literatura. Esses modelos foram aplicados na análise de oito vigas "T" reforçadas ao cisalhamento com tiras de PRFC. Diferentes tipos de compósitos de fibras de carbono (tecidos e laminados) disponíveis no mercado brasileiro, de diferentes fabricantes, foram aplicados neste estudo. Os resultados obtidos indicam um ganho de capacidade resistente e ductilidade das vigas reforçadas, a partir do mecanismo de ancoragem usado nas tiras de PRFC, e que nenhum dos modelos analíticos testados foi capaz de reproduzir satisfatoriamente o comportamento estrutural observado nos experimentos.

Palavras-chave: *polímeros reforçados com fibras de carbono, reforço ao cisalhamento, ensaios experimentais, modelos analíticos.*

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1. Introduction

Reinforced concrete has been established, from the decade of 1950, as the most used structural material in the world. Innumerable researches on concrete technology, constructive techniques and analytical and computational tools capable to provide efficient projects are dedicated to this material. As a result more slender and optimized structures, from the safety and economical points of view, have been produced. However, these structures are more vulnerable to the deterioration processes (Cánovas [1]).

In the recent years, research in reinforced concrete has drawn attention on the knowledge of the application techniques concerning its repair and strengthening. According to Figueiras; Juvandes [2], the growing degradation of building structures, bridges and viaducts is due mainly to aging processes, deficiencies in design and construction procedures, lack of maintenance and accidental causes (e.g., .earthquakes .)

The incorporation of new materials to the reinforced concrete, as for instance composite materials, can improve the performance of structural elements. Those materials have already been used thousands of years ago: Egyptians used to mix straw to the clay to improve structural performance of bricks and, seven thousand years ago, boats were built by using tar to glue pieces of juncus.

In addition, the development of new polymeric materials, such as CFRP-Carbon Fiber Reinforced Polymer, GFRP-Glass Fiber Reinforced Polymer and AFRP-Aramid Fiber Reinforced Polymer has allowed a great flexibility for the strengthening techniques in reinforced concrete structures. Strengthening with polymers aims at increasing stiffness, tensile, compression, fatigue and impact strength (Meier [3]).

The CFRP composites are the most indicated for strengthening of reinforced concrete structures since they present characteristics that best fit to this structural type. Optimum mechanical performance when compared with other fibers can be highlighted: high tensile strength, high Young´s modulus in comparison with steel, high strength to fatigue and alkaline resistance (Toutanji; Gómez [4]).

In general the composite materials are more durable than the traditional materials. Furthermore, since they are of easy handling and do not require heavy and expensive frameworks, they can be used in adverse operational conditions.

Although fibers and resins used in the composite systems are relatively expensive when compared with the traditional strengthening materials (concrete and steel), labor and equipment costs for FRP systems installation are always less expensive (Figueiras; Juvandes [2]).

The objective of the this work is to investigate, from experimental laboratory results, the ability of predicting the structural behavior of reinforced concrete beams strengthened to shear with carbon fiber reinforced polymers (CFRP). This work complements another publication entitled "R/C Structures Strengthened with CFRP Part I: Analysis of Flexural Models" (Gamino; Bittencourt; Sousa [5]. More details on this work are presented in Gamino [6].

2. Analytical Investigation

2.1 Shear Strengthening with CFRP: International Design Codes

2.1.1 ACI-440 [7]

The contribution in shear of fiber reinforced composites is given by:

$$V_f = \frac{A_{fv} f_{fe} (\sin\alpha + \cos\alpha) d_f}{s_f} \qquad (1)$$

where:
α = inclination angle of FRP;
s_f = FRP strip spacing;
d_f = depth to center of gravity of FRP;
A_{fv} = total FRP area given by:

$$A_{fv} = 2\ n\ t_f\ w_f \qquad (2)$$

where:
n = total number of FRP strip;
w_f = width of FRP strip;
t_f = FRP thickness;
The effective stress in FRP is:

$$f_{fe} = \varepsilon_{fe}\ E_f \qquad (3)$$

where E_f is the FRP Young´s modulus and ε_{fe} is the effective strain: with:

$$\varepsilon_{fe} = k_v\ \varepsilon_{fu} \leq 0{,}004 \qquad (4)$$

ε_{fu} = ultimate deformation in FRP;
k_v = strain reduction factor in FRP;
This factor depends on the strengthening scheme:

$$k_v = \frac{k_1\ k_2\ L_e}{468\ \varepsilon_{fu}} \leq 0{,}75\ \text{(U-wraps)} \qquad (5)$$

$$k_v = \frac{k_1\ k_2\ L_e}{1190\ \varepsilon_{fu}} \leq 0{,}75\ \text{(two sides only)} \qquad (6)$$

where:

L_e = effective length of the FRP strip given by;

$$L_e = \frac{2500}{(n\ t_f\ E_f)^{0,58}} \quad \text{(U-wraps)} \tag{7}$$

$$L_e = \frac{23,30}{(n\ t_f\ E_f)^{0,58}} \quad \text{(two sides only)} \tag{8}$$

The remaining factors can be obtained from:

$$k_1 = \left(\frac{f_c}{4000}\right)^{\frac{2}{3}} \quad \text{(U-wraps)} \tag{9}$$

$$k_1 = \left(\frac{f_c}{27}\right)^{\frac{2}{3}} \quad \text{(two sides only)} \tag{10}$$

$$k_2 = \begin{cases} \dfrac{d_f - L_e}{d_f} & \text{(U-wraps)} \\ \dfrac{d_f - 2\,L_e}{d_f} & \text{(two sides only)} \end{cases} \tag{11}$$

2.1.2 fib-14 [8]

The contribution in shear of fiber reinforced composites is given by:

$$V_{fd} = 0{,}9\ \varepsilon_{fd,e}\ E_{fu}\ \rho_f\ b_w\ d\ (\cot\theta + \cot\alpha)\sin\alpha \tag{12}$$

where:

α = inclination angle of FRP;

θ = shear crack angle;

ρ_f = FRP ratio computed by:

$$\frac{2\ t_f\ \sin\alpha}{b_w} \quad \text{(continuous sheet)} \tag{13}$$

$$\frac{2\ t_f}{b_w}\ \frac{b_f}{s_f} \quad \text{(wraps)} \tag{14}$$

The effective strain can be computed by:

$$\varepsilon_{f,e} = 0{,}67\left(\frac{f_{cm}^{\frac{2}{3}}}{E_{fu}\ \rho_f}\right)^{0,30} \varepsilon_{fu} \quad \text{(full section only)} \tag{15}$$

$$\varepsilon_{f,e} = 0{,}65\left(\frac{f_{cm}^{\frac{2}{3}}}{E_{fu}\ \rho_f}\right)^{0,56} \varepsilon_{fu} \quad \text{(U-wraps)} \tag{16}$$

2.2 *Shear Strengthening with CFRP: Other Models*

2.2.1 Khalifa et al. [9]

The contribution in shear of fiber reinforced composites is the same expression from the ACI design code but the effective strain is given by:

$$f_{fe} = R\ f_{fu} \tag{17}$$

The reduction factor R is the smallest value from the three equations:

$$R \le \begin{cases} 0{,}50 \\ 0{,}5622\,(\rho_f\ E_f)^2 - 1{,}2188\,(\rho_f\ E_f) + 0{,}778 \\ \dfrac{0.0042\ (f_c)^{2/3}\ w_{fe}}{(E_f\ t_f)^{0,58}\ \varepsilon_{fu}\ d_f} \end{cases} \tag{18}$$

where:

W_{fe} = effective width of the FRP;

ρ_f = FRP geometric ratio obtained by:

$$\rho_f = 2\ t_f / b_w \tag{19}$$

The effective width is:

$$w_{fe} = d_f - L_e \quad \text{(U-wraps)} \tag{20}$$

$$w_{fe} = d_f - 2\,L_e \quad \text{(two sides only)} \tag{21}$$

Finally the effective length can be obtained by:

$$L_e = e^{6{,}134 - 0{,}58 \ln(t_f\,E_f)} \tag{22}$$

2.2.2 Chen; Teng [10]

The contribution in shear of fiber reinforced composites is given by:

$$V_f = 2\,f_{fe}\,t_f\,w_f\,\frac{h_{fe}\,(\cot\theta + \cot\beta)\sin\beta}{s_f} \tag{23}$$

where:

β = inclination angle of FRP;

The effective stress is:

$$f_{fe} = D_f\,\sigma_{f,max} \tag{24}$$

where:

D_f = distribution factor of the FRP;

$\sigma_{f,max}$ = maximum tensile stress in the FRP;

The equations for the determination of maximum tensile stress are:

$$\sigma_{f,max} = \min\begin{cases} f_{fu} \\ 0{,}427\,\beta_L\,\beta_w\sqrt{\dfrac{E_f\sqrt{f_c}}{t_f}}\ ;\ \beta_L = \begin{cases} 1 & \text{se}\ \ \lambda \geq 1 \\ \sin\dfrac{\pi\lambda}{2} & \text{se}\ \ \lambda < 1 \end{cases}\ ;\ \lambda = \dfrac{L_{max}}{L_e} \end{cases} \tag{25}$$

The maximum anchorage length is given by:

$$L_{max} = \frac{h_{fe}}{\sin\beta}\ \ (\text{U-wraps}) \tag{26}$$

$$L_{max} = \frac{h_{fe}}{2\sin\beta}\ \ (\text{two sides only}) \tag{27}$$

The other factor can be obtained by:

$$L_e = \sqrt{\frac{E_f\,t_f}{\sqrt{f_c'}}}\ ,\ \beta_w = \sqrt{\frac{2 - w_f/s_f\sin\beta}{1 + w_f/s_f\sin\beta}} \tag{28}$$

The distribution factor of the FRP is:

$$D_f = \begin{cases} \dfrac{2}{\pi\lambda}\,\dfrac{1-\cos(\pi\lambda/2)}{\sin(\pi\lambda/2)} & \text{if } \lambda \leq 1 \\ 1 - \dfrac{\pi - 2}{\pi\lambda} & \text{if } \ \lambda > 1 \end{cases} \tag{29}$$

2.2.3 Nollet; Chaallal; Perraton [11]

The contribution in shear of fiber reinforced composites is given by:

$$V_f = \frac{A_f\,f_{fu}\,d_f\,(\sin\alpha + \cos\alpha)}{s_f} \tag{30}$$

The maximum shear stress in adhesive layer is:

$$\tau_{ult} = \frac{5{,}4}{1 + k_1\,\text{tg}\,33^o} \tag{31}$$

The factor k_1 can be obtained by:

$$k_1 = t_f\left(\frac{k_n}{4\,E_f\,I_f}\right)^{0{,}25} \tag{32}$$

The factor k_n can be obtained by:

$$k_n = \frac{E_a\,b_a}{t_a} \tag{33}$$

The average shear stress in adhesive layer is:

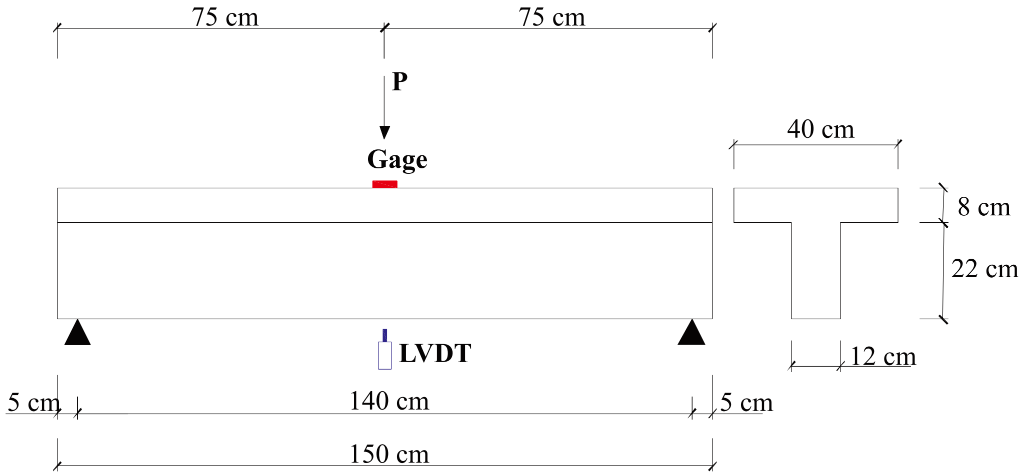
$$\tau_{ave} = \frac{\tau_{ult}}{2} \tag{34}$$

The contribution in shear of composite fabrics is given by:

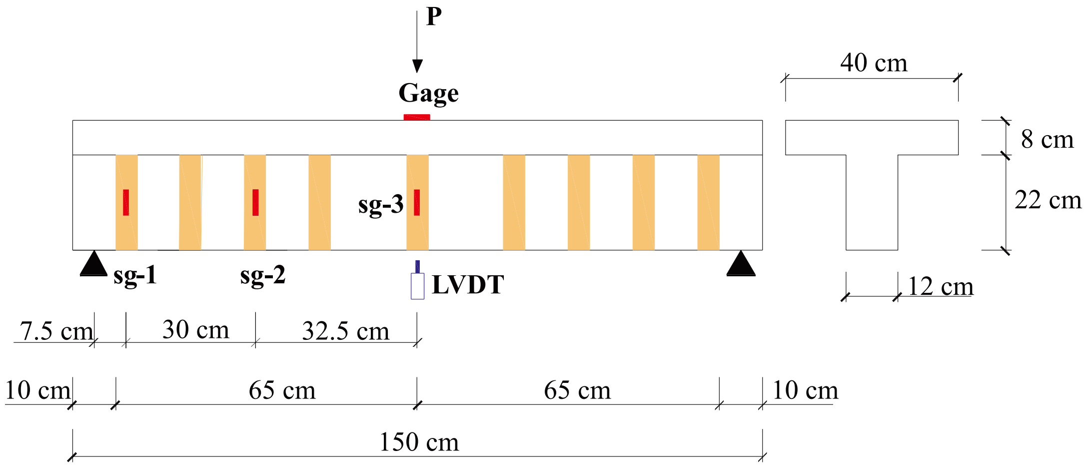
$$V_f = \frac{A_f\,f_{fu}\,d_f\,(\sin\alpha + \cos\alpha)}{s_f} \tag{35}$$

The final contribution in shear of FRP will be the smaller V_f value obtained between Equation (30) and Equation (35).

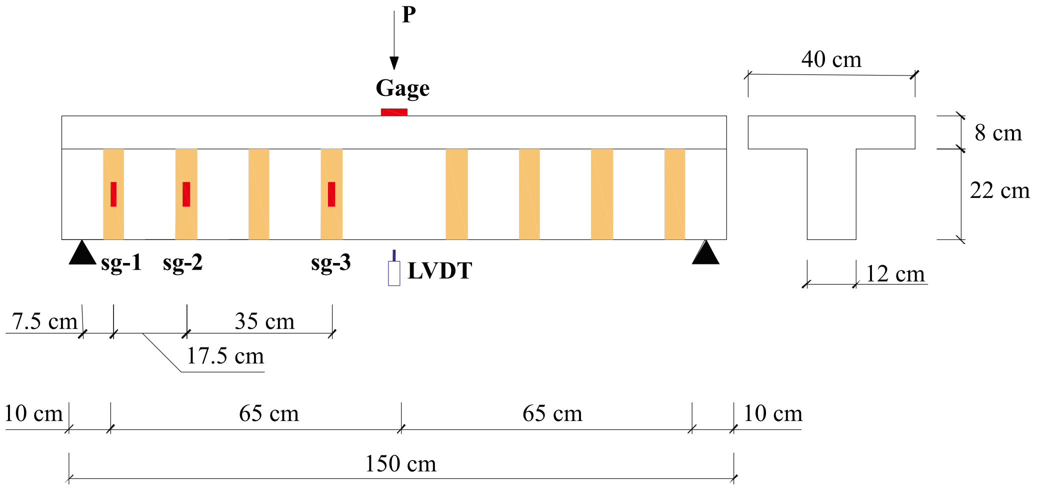
Figure 1 – Test setup of "T" beams strengthened to shear with CFRP



a)Control beams not strengthened with CFRP (Beams RTC1 and RTC2)



b)Beams strengthened to shear with sf equal to 15cm



c)Beams strengthened to shear with sf equal to 17.5cm

2.2.4 Täljsten [12]

A simple form for the determination of V_f is giving by:

$$V_f = 2\,t_f\,\varepsilon_f\,E_f\,0{,}9\,d\,(\cot\beta + \cot\alpha)\,\sin^2\alpha\,\cos^2\theta \tag{36}$$

where:

β = angle between beam axis and a perpendicular line to the FRP orientation;

3. Experimental Procedure

The experimental program included eight “T” beams strengthened to shear with carbon fiber reinforced polymer (CFRP) with s_f equal to 15 cm (Figure 1-b) and s_f equal to 17.5 mm (Figure 1-c).

The midspan displacements were evaluated using a LVDT; deformations in concrete, reinforcement steel bars and CFRP composites were evaluated using electric strain-gages (KYOWA KFG-5-120-C1-11). The beams RTC1 and RTC2, without CFRP (Figure 1-a), were used as reference for “T” beams strengthened to shear. The remaining beams were strengthened with one CFRP layer.

The beams VTC1 and VTC3 were strengthened with U-wraps (CFRP fabric) without anchorage, VTC2 and VTC4 with U-wraps (CFRP fabric) with anchorage (Figure 2) and VTC5 with two sides only (CFRP sheet) without anchorage.

The strain-gages distribution in the reinforcement steel bars (bottom steel or stirrups) for the “T” beams can be observed in Figure 3. The data acquisition system ADS 2000 of the Lynx [13] was used together with the programs AqDados [14] and AqDAnalysis [15], responsible for control and configuration of the equipment, data reading, writing, visualization and processing.

3.1 Materials

Details of the beams tested in the experimental procedure is illustrated in Table 1, concrete/reinforcement steel materials properties are presented in Table 2, CFRP and epoxy adhesive properties are indicate respectively in Table 3 e 4.

The characterization tests of CFRP were evaluated in agreement with ASTM D3039-95 [16] and epoxy adhesive in agreement with ASTM D638-96 [17].

Figure 2 – Anchorage mechanism used in beams VTC2 and VTC4

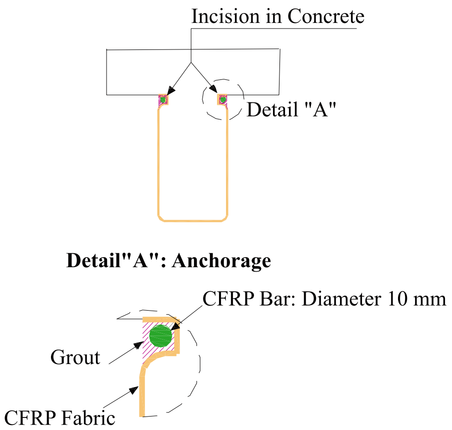


Figure 3 – Positions of *strain-gages* in stirrups rebars of “T” beams

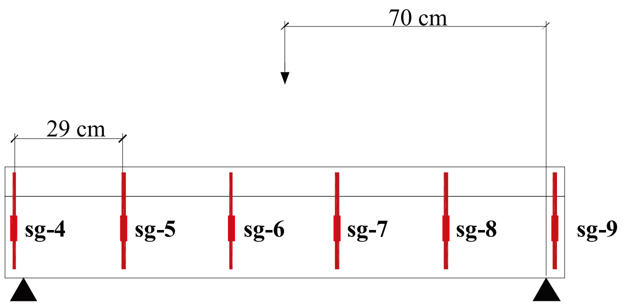


Table 1 – Detail of the beams tested in experimental setup

Beam	A_s	Stirrups (cm)	CFRP Strength Scheme	CFRP Type	w_f (mm)	s_f (mm)
RTC1	2 n° 6	n°1 c/ 29	---	---	---	---
RTC2	2 n° 6	n°1 c/ 29	---	---	---	---
VTC1	2 n° 6	n°1 c/ 29	shear	CFRP2	50	150
VTC2	2 n° 6	n°1 c/ 29	shear	CFRP3	60	150
VTC3	2 n° 6	n°1 c/ 29	shear	CFRP4	50	175
VTC4	2 n° 6	n°1 c/ 29	shear	CFRP4	50	175
VTC5	2 n° 6	n°1 c/ 29	shear	CFRP5	50	150

CFRP2 with Triepox adhesive, CFRP3 with MBrace Saturant adhesive and CFRP4 with Nitobond CF 55 adhesive and CFRP5 with Sikadur 30 adhesive.

Figure 4 – Rupture mechanisms found in tested beams

Shear – VTC1

Debonding – VTC3

Rupture of CFRP – VTC4

Shear crack – VTC5

Table 2 – Concrete and rebars mechanical properties used in tested beams

Rebars

Bar Size	Diameter (mm)	Area (mm^2)	f_y (MPa)	f_u (MPa)	E_s (GPa)
nº 6	20	314	555	734	198
nº 3	10	78,5	525	756	199
nº 2	6,3	31,2	640	800	180
nº 1	5,0	19,6	517	764	188

Concrete

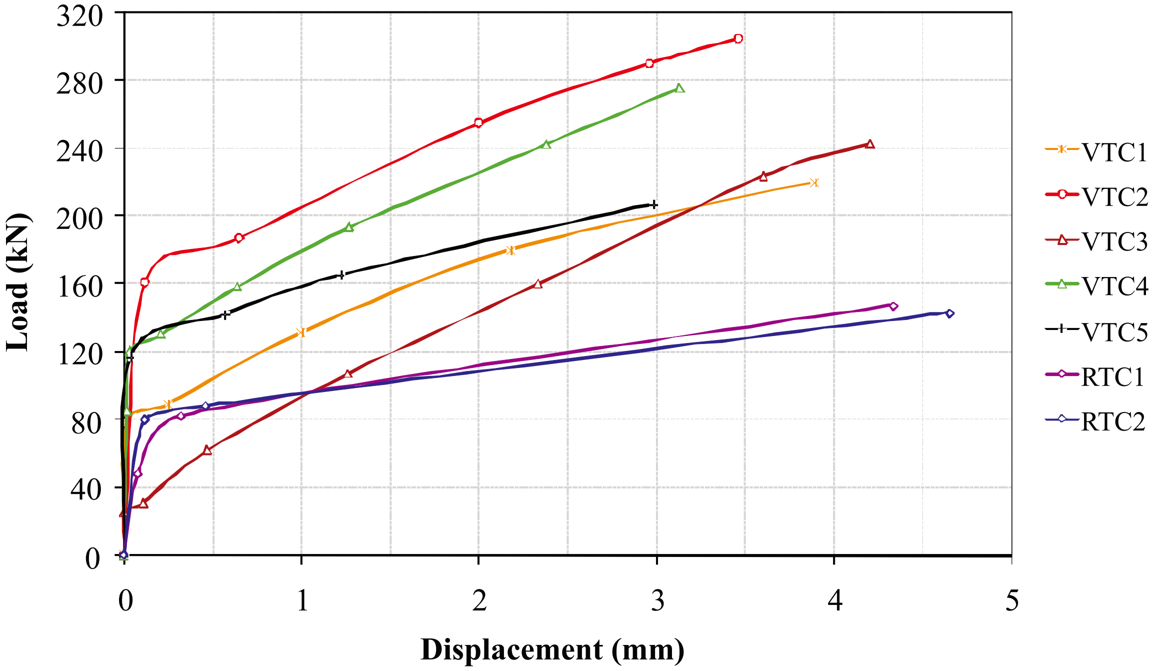
Beam	f_c (MPa)	f_t (MPa)
RTC1	59	5.3
RTC2	60	5.3
VTC1	60	5.4
VTC2	59	5.3
VTC3	60	5.2
VTC4	57	5.5
VTC5	55	5.1

4. Experimental Results and Discussion

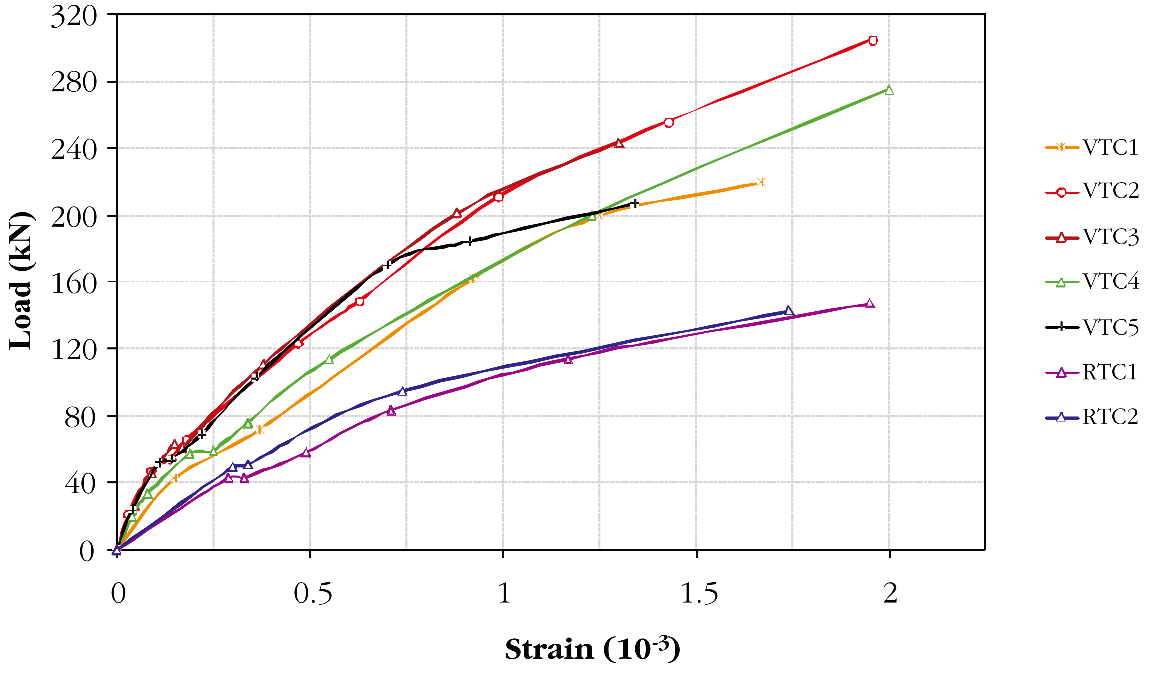
The results obtained from the experimental tests are summarized in Table 5 (reference beams) and Table 6 (strengthened beams with CFRP wraps).

Based on the experimental results of the "T" beams strengthened to shear using CFRP composites, the following observations can be drawn: the smaller strengthened ratio has been obtained for VTC5 (CFRP sheet without anchorage, see Figure 5-a) and the largest ratio has been obtained for beams with anchorage mechanism (see Figure 2), VTC2 (110.3%) and VTC4 (89.6%) – in these beams the failure mode found was rupture of CFRP; the stirrup strains were larger in VTC5 and VTC1, as shown in Figure 6-a – in these beams the observed rupture was the shear mode; the behavior of the beams strengthened without anchorage was more fragile in comparison to the reference beams (RTC1 and RTC2, see Figure 5-b); on the other hand, for the beams

Figure 5 – Structural responses (load capacity and ductility) of the "T" beams strengthened to shear with CFRP



a)Load-displacement curves

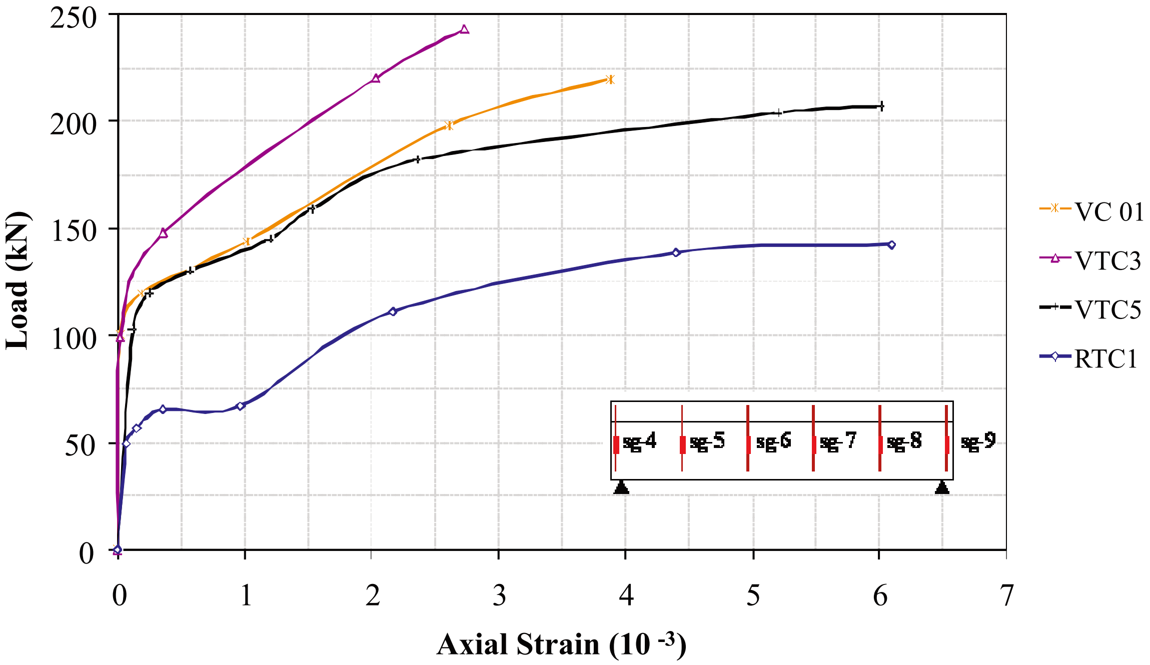


a)Load-strain curves in concrete compression region strengthened with anchorage the observed behavior was more ductile in comparison to the reference beams.

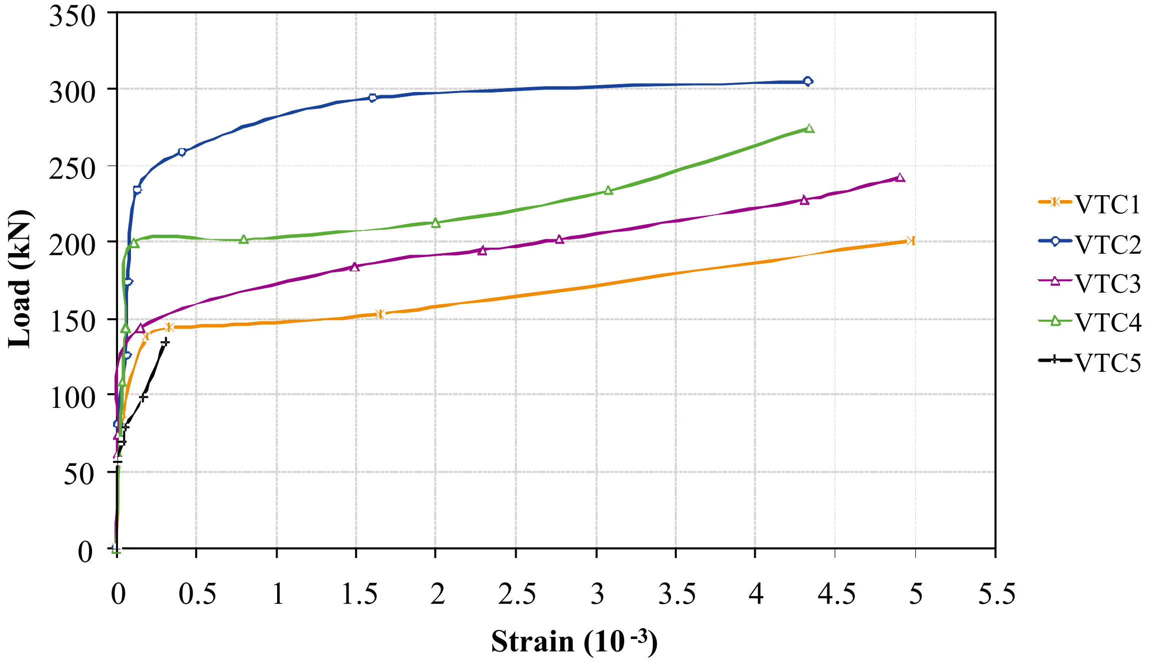
Similar results regarding load capacity and ductility can be obtained using an anchorage system more viable economically, replacing the CFRP bar by a rebar of conventional steel CA-50, and using a cement based instead of a polymeric based grout.

Figure 7 presents the strain evolutions in the CFRP wraps for the beam VTC3. Observe that the strains in CFRP wraps intercepting the critical shear crack are slightly higher than the strains in the wraps out of the crack nucleation zone. In Figure 7 one can observe that the CFRP strip with the strain gage sg-2 was the one intercepting the critical crack, debonding from the substract earlier than the remaining strips. These results served as a comparative basis for computational simulations performed by the authors (Gamino; Sousa; Bittencourt [18]).

Figure 6 –Strain evolution in rebars and CFRP



a)Load-strain curves in stirrups rebars (strain-gage sg-4)



b)Load-strain curves in CFRP (strain-gage sg-2)

Table 3 – CFRP mechanical properties

Type	Thickness (mm)	E_f (GPa)	f_{fu} (MPa)	ε_{fu} (‰)
CFRP1^{i}	0.13	230	3500	15.00
CFRP2^{ii}	0.11	221	2728	12.44
CFRP3^{iii}	0.165	218	2730	12.40
CFRP4^{iv}	0.11	235	3550	15.00
CFRP5^{v}	1.4	310	1250	4.0

^{i}Sika Wrap Hex, ^{ii}TEI 300, ^{iii}MBrace, ^{iv}Fosfiber C and ^{v}Sika Carbodur H514.

Table 4 – Epoxy adhesive mechanical properties

Type	f_{pu} (MPa)
Triepox	58.9
MBrace Saturant	55.8
Nitobond CF 55	62.2
Sikadur 30	28.4

5. Comparison of Predictions and Experimental Results

The comparison of the theoretical results using the analytical models described in this paper and the experimental results are shown in Table 7 and 8. These results are illustrated in Figure 8.

Some safeguards are required at this point: the mechanical properties of the CFRP strips used in the calculation were obtained from characterization tests (average values); the experimental values of "V_f" were obtained from the shear capacity increase quota of the CFRP strengthened beams; Khalifa *et al.* [9], Chen; Teng [10] e Täljsten [12] models are applicable only to beams strengthened to shear in "U" or in two sides; the computed values of "V_f" for beams VTC2 and VTC4 were performed under the assumption that the strengthening wraps the whole section in order to simulate the anchorage system in the junction slab/web adopted in this work.

From the comparison between experimental and analytical results the following observations can be drawn:

a) for the beam VC 01 strengthened with CFRP fabric the V_f value found with the Nollet; Chaallal; Perraton [11] model is closer to the experimental result;

b) for the beams strengthened with CFRP with anchorage mechanism (VTC2 and VTC4), the theoretical values predicted by ACI-

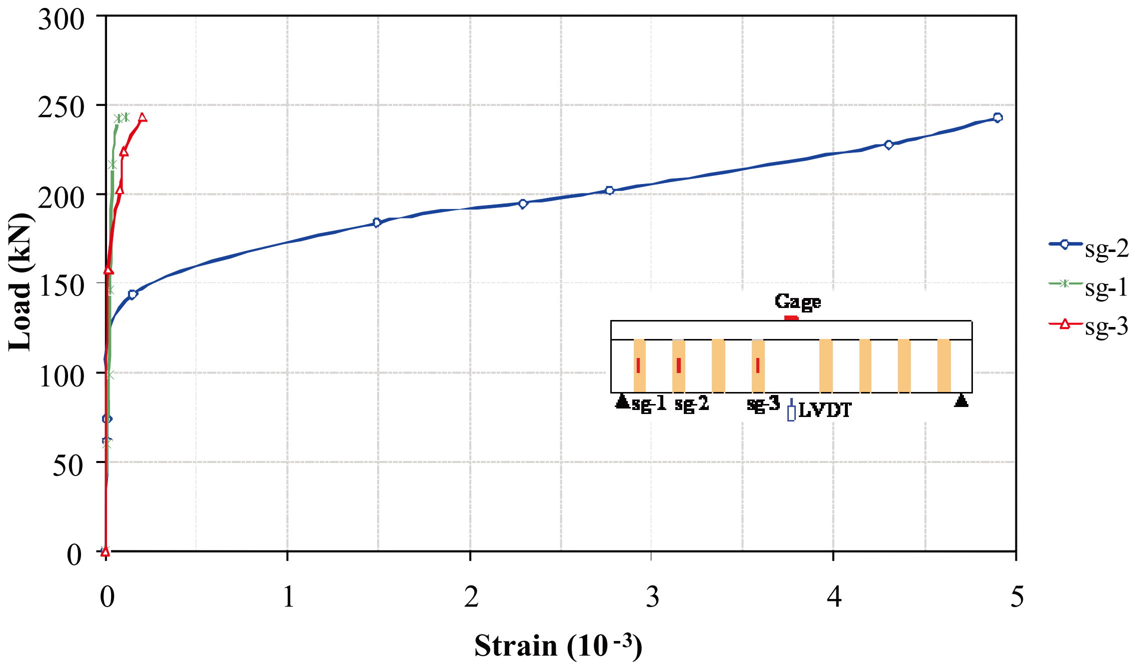
Table 5 – Experimental values found to the reference beams

Beam	f_c (MPa)	f_t (MPa)	P_{ref} (kN)	ε_s sg-4 (‰)	ε_c (‰)	Rupture Mode
RTC1	59.9	5.3	147	---	1.95	Shear
RTC2	60.1	5.3	143	6.1	1.74	Shear
Average	60.0	5.3	145	6.1	1.84	---

Table 6 – Experimental values found to the beams strengthened to shear with CFRP

		Mid-Span			Anchorage Area			
Beam	P_{max} (kN)	ε_s (sg-4) (‰)	ε_c (‰)	ε_f (sg-2) (‰)	ε_f (sg-1) (‰)	ε_f (sg-3) (‰)	Δ%	Rupture Mode
VTC1	220	3.88	1.67	4.98	---	---	51.7	Shear
VTC2	305	---	1.96	4.33	---	---	110.3	Break of CFRP
VTC3	243	2.73	1.30	4.90	0.11	0.20	67.6	Debonding
VTC4	275	---	2.00	4.34	0.35	---	89.6	Break of CFRP
VTC5	207	6.01	1.34	0.31	0.08	---	42.8	Shear

Figure 7 – Strain evolution of CFRP in three strain-gages (beam VTC3)



440 [7] is closer to the experimental V_f than those predicted by fib-14 [8];

c) for the beam VTC5 strengthened with laminate glued externally the values of “V_f” computed according to Chen; Teng [10] e Khalifa *et al.* [9] were higher than the experimental value due to the higher fiber area; in other words, these models seem not applicable to structures strengthened with externally glued laminates since they increase too much the “V_f” values, tendency that should be investigated with a larger number of tests; in this beam the values obtained from fib-14 [8] and ACI-440 [7] were below the experimental value, and the value obtained from Nollet; Chaallal; Perraton [11] has shown more appropriated; Khalifa *et al.* [9] and Täljsten [12] models are not applicable to beams strengthened with laminates.

d) the predictions of fib-14 [8] have shown more conservative, followed by Khalifa *et al.* [9] model;

6. Conclusions

Based on the results from the experimental investigations, the following conclusions can be drawn:

- The technique of strengthening to shear with carbon fiber reinforced polymer revealed to be very effective, especially when anchorage system of the CFRP wraps was used. For these cases the shear capacity has been substantially improved without significant changes of ductility in comparison with the original beams, not strengthened with CFRP.
- Predictions of ACI-440 [7] is suggested instead of fib-14 [8], which has shown too conservative when compared to the experimental values.
- Although conservative in most analyses, the analytical models, including those from international recommendations and design codes, were not capable of properly simulating the behavior of all beams tested in the experimental program.

7. Acknowledgments

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Table 7 – Comparison between analytical and experimental results

	V_f (kN)					Δ (%)			
Beams	Exp.	ACI	fib	Chen; Teng (10)	Khalifa *et al.* (9)	ACI	fib	Chen; Teng (10)	Khalifa *et al.* (9)
VTC1	37.5	30.5	10.04	29.76	19.93	+22.95	+273.5	+26.0	+88.15
VTC2	80	36.4	21.33	33.97	23.68	+119.8	+275.1	+135.5	+237.8
VTC3	49	22.1	9.45	24.42	18.30	+121.7	+418.5	+100.6	+167.76
VTC4	65	22.1	16.42	24.42	18.30	+194.1	+295.8	+166.2	+255.2
VTC5	31	12.6	10.66	44.83	154.6	+146.1	+190.8	-44.61	-398.71

Table 8 – Other comparative results from analytical models and experimental tests

Beams	Vf (kN)			Δ (%)	
	Experimental	Nollet; Chaallal; Perraton (11)	Täljsten (12)	Nollet; Chaallal; Perraton (11)	Täljsten (12)
VTC1	37.5	34.62	31.02	+8.32	+20.89
VTC2	80	41.55	29.58	+92.54	+170.5
VTC3	49	29.68	28.,41	+65.09	+72.47
VTC4	65	29.68	28.41	+119.00	+128.8
VTC5	31	33.94	---	-9.48	---

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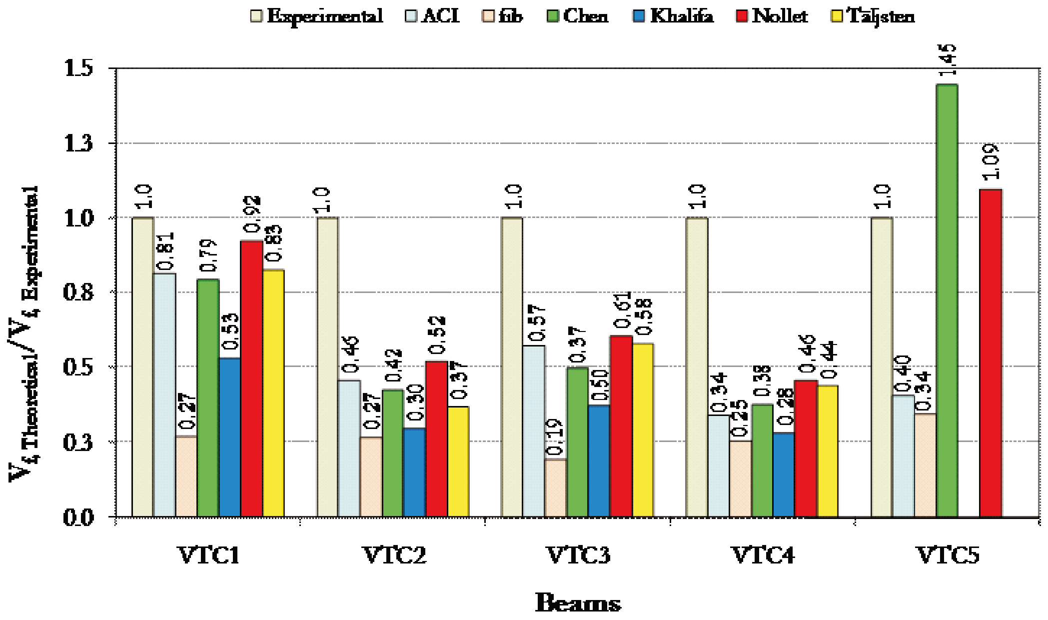
Figure 8 – Comparison between analytical and experimental results for "T" beams strengthened to shear



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