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CFRP Composites on the Shear Strengthening of Reinforced Concrete Beams

Compósitos de CFRP no Reforço ao Cisalhamento de Vigas de Concreto Armado


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Abstract

This study aims to explore the main structural implications on the use of *CFRP* composites for the shear strengthening of R/C beams. Thirty beams 300 cm long with a 15 x 30 cm cross-section were fabricated and strengthened in shear using different strengthening schemes, applying two *CFRP* composite systems. Failure loads and modes are analysed. The strengthening schemes are also analysed in order to provide valuable information regarding the rational usage of such peculiar material. Experimental results corroborate how versatile the *CFRP* composites can be, especially when tailored for a particular situation.

Keywords: shear strengthening; shear failure; concrete; CFRP; efficacy.

Resumo

Este estudo tem por objetivo explorar as principais implicações estruturais da aplicação dos compósitos de *CFRP* ao cisalhamento de vigas de concreto armado. Para o desenvolvimento desse estudo foram construídas 30 vigas com seção transversal 15x30 cm com 300 cm de comprimento. Destas, duas serviram como referência e as demais foram reforçadas, adotando-se diferentes configurações de reforço ao cisalhamento, empregando dois tipos de sistema de reforço. Os resultados de cargas de ruptura, assim como seus respectivos modos, são analisados e confrontam-se as diferentes configurações de reforço estudadas. Do ponto de vista de aplicação, observou-se a grande versatilidade dos compósitos, permitindo uma infinidade de configurações, especialmente desenvolvidas para uma determinada situação. Além de consideráveis incrementos na resistência das vigas reforçadas, a avaliação de diferentes configurações de reforço permite uma aplicação mais racional dos compósitos, cujo custo é bastante elevado.

Palavras-chave: reforço ao cisalhamento, concreto armado, compósitos de CFRP.

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1 Introduction

During the last years several research centers worldwide have been studying numerous materials and methods for the repair and strengthening of reinforced concrete structures. One of the most remarkable techniques involves the bonding of composite materials and more specifically *CFRP* composites as a feasible substitute for the traditional epoxy-bonded steel plates, which have been used with undoubted success since the 1960's [1].

Initially *CFRP* composites were developed for aerospace, automotive, naval, sporting goods and military applications. Nowadays, however, they represent a viable solution for the strengthening of reinforced and prestressed concrete structures. By embedding continuous fibers in a resin matrix the mechanical properties of composites can be tailored to a particular application varying the amount and orientation of the fibers in different directions [1]. Some of these advantages may be summarized as follows: immunity to corrosion; low self-weight; high strength-to-weight and stiffness-to-weight ratios; enhanced durability and the ability to form complex shapes [2].

The number of *CFRP* composites applications however, is still reduced especially due to high material costs. Nevertheless there is great potential in the use of *CFRP* composites for the rehabilitation concrete structures. *CFRP* composites may represent a practical solution to extending the service life of a particular structure, which could not be strengthened using traditional construction materials [3]. Additionally, the ability of carrying out the entire strengthening procedure in short periods of time without disrupting the use of the structure is undoubtedly the major advantage of the composites.

2 *CFRP* composites in the strengthening of R/C beams

The feasibility of the flexural strengthening of R/C beams is based on refined analytical models allowing fairly precise results. In some cases, however, the shear failure load may be exceeded [4, 5, 6]. Therefore it is interesting to guarantee that the beam's shear strength be higher than its flexural strength. The reliability of flexural strengthening with *CFRP* composites has opened up the possibility of extending this technique to strengthen the shear capacity of R/C beams [7].

In such cases, *CFRP* composites are also efficient in increasing the shear capacity of R/C beams. Nevertheless the number of applications is significantly reduced and very few studies have addressed the subject.

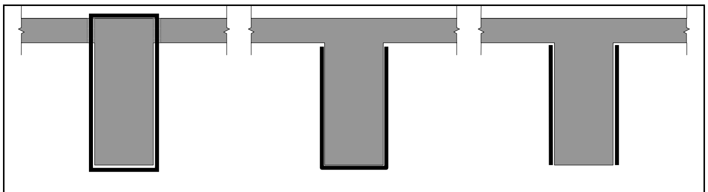


Figure 1 - Shear strengthening schemes.

The most efficient shear strengthening scheme is *total wrapping* that is the wrapping of the entire beam cross section [figure 1(a)]. Occasionally this option may not be practical. Other structural elements such as an adjacent slab may prevent the wrapping procedure. Holes may be made in order to allow the wrapping of *CFRP* strips; however this option may be complex and costly.

The commonest scheme is done by bonding *CFRP* composites on to the sides and bottom of the beam [figure 1(b)]. This scheme is known as *"U" wrap*. It constitutes a practical and efficient solution in enhancing the shear strength of beams [8, 9].

Finally in some cases it may not be possible to bond the *CFRP* composites on to the bottom of the beam. In these cases *CFRP* composites are only bonded to the sides [figure 1(c)]. The efficiency of such scheme is uncertain due to possible anchorage deficiencies.

Shear strengthening with *CFRP* composites may also be done continuously or by means of strips, conveniently spaced. The use of strips may be interesting in terms of material optimization. Researchers have reported using 40% less material for the same increase in shear capacity [4]. Additionally, if the whole beam length should be strengthened, the use of strips may allow moisture migration.

3 Experimental program

The experimental work consisted of testing 30 simply supported, unloaded, rectangular beams externally strengthened in shear with no additional anchorage devices. The main objective of this study was the evaluation of failure loads and modes of failure for 12 different strengthening schemes. All the beams had a rectangular cross-section with a 15cm width, 30cm height and a length of 300cm as observed in figure 2.

These beams did not receive any shear reinforcement but were heavily reinforced in flexure with six 16mm steel bars (two layers) at the tension side two 16mm steel bars at the compression side. All the rebars had a 1.5cm concrete cover. The absence of shear reinforcement was induced in order to isolate the strengthening effect on the enhancement of shear strength. The use of stirrups would mean the introduction of another variable, which could prevent the development of reliable theoretical models.

Table 1 presents, schematically, the strengthening schemes tested in this study. Beams V8_A and V8_B These beams did not receive any shear reinforcement but were heavily reinforced in flexure with six 16mm steel bars (two layers) at the tension side two 16mm steel bars at the compression side. All the rebars had a 1.5cm concrete cover. The absence of shear reinforcement was induced in order to isolate the strengthening effect on the enhancement of shear strength. The use of stirrups would mean the introduction of another variable, which could prevent the development of reliable theoretical models.

Table 1 presents, schematically, the strengthening schemes tested in this study. Beams V8_A and V8_B were not strengthened at all and acted as control beams.

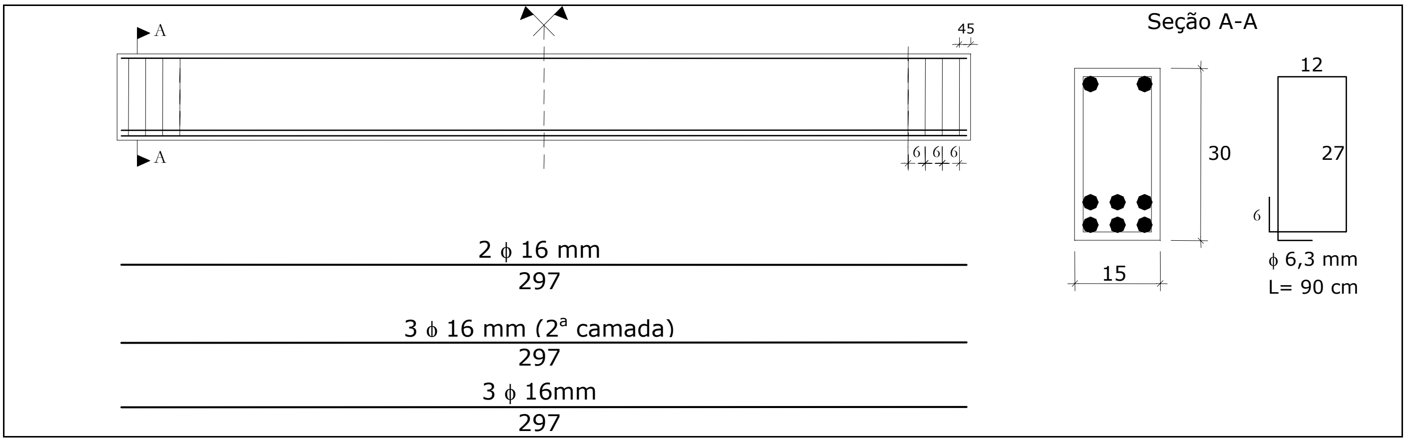
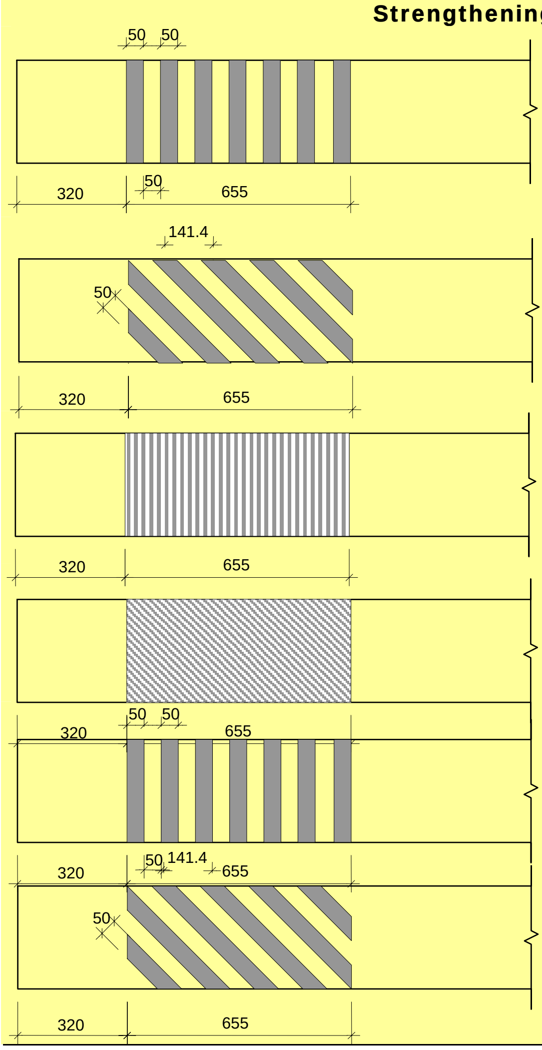


Figure 2 - Details of test specimens [units in cm].

Table 1 - Strengthening schemes.



Strengthening scheme	Material	Parameters	Type	Beams		
	Replark 20	s_f = 100mm, w_f = 50mm, β= 90°	side bonding	V9_A	V9_B	V21_A
			"L" wrap	V10_A	V10_B	V17_A
			"U" wrap	V11_A	V11_B	V17_B
			Fully wrap	V12_A	V18_A	V20_A
	Replark 20	s_f = 141.4mm, w_f = 50mm, β= 45°	side bonding	V12_B	V14_B	
			"L" wrap	V19_A	V19_B	
	Replark 20	s_f = 655mm, w_f = 655mm, β= 90°	side bonding	V13_A	V13_B	
			"U" wrap	V15_B	V16_B	
			fully wrap	V18_B	V_16_A	
	Replark 20	s_f = 655mm, w_f = 655mm, β= 45°	side bonding	V14_A	V15_A	
	CFK 200/2000	s_f = 100mm, w_f = 50mm, β= 90°	side bonding	V22_B	V20_B	
	CFK 200/2000	s_f = 141.4mm, w_f = 50mm, β= 45°	side bonding	V21_B	V22_A	

A local batch plant supplied concrete used in the construction of the beams. Each batch provided concrete for one beam and nine 10 x 20cm cylindrical test specimens used to determine concrete's mechanical properties. The specimens were tested for compression and tension. The average concrete compressive strength was 32.8 MPa, with a variation coefficient of 5.24%. The average concrete tension strength was 2.9 MPa, with a variation coefficient of 9.09%.

The CA50 steel bars were tested under uniaxial tension. The average measured yield stress for the bars was 625.1 MPa.

Two *CFRP* strengthening systems, currently available in the market, were used in this research program (one prefabricated and one cured in situ). The mechanical properties according to the manufacturers of these strengthening systems are presented in table 2 [1,10].

Table 2 - CFRP strengthening systems.

Property	Prefabricated laminates [10]	Cured *in situ sheets* [1]
Tensile strength	2500 MPa	3400 MPa
Modulus of elasticity	205000 MPa	230000 MPa
Failure strain	0.0122	0.0148
Weight by unit area	-	200 g/m^2
Thickness	1.4mm	0.111mm
Width	5cm	25cm

All members were subjected to four-point loading with two equivalent symmetric point loads. Assessment of structural performance of each strengthening schemes was carried out based on the monitoring of loads, displacements and strains, throughout a computerized system. The test set up may be observed in figure 3.

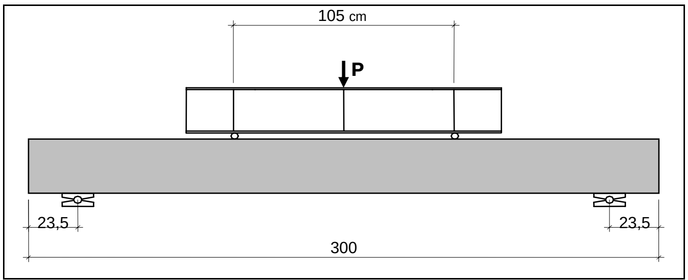


Figure 3 - Test set-up [unit in cm].

The monotonic static load was applied incrementally at a rate of 2 mm/s through a programmable servo-hydraulic testing machine. Loads were measured by a load cell. Deflections were measured using linear variable displacement transducers (LVDT).

4 Test results and discussion

The use of *CFRP* composites in the shear strengthening implies significant modifications on the behavior of R/C beams. Increases in failure load were significant. In some cases the use the failure mode changed from shear controlled to a bending controlled mode.

Particularly for the beams in this study, the total shear strength was resisted by the sum of the concrete and composite contributions, since these beams did not have any shear reinforcement.

The observed failure modes in this study included: diagonal tension (control beams), *CFRP* rupture associated with debonding and, in some cases, concrete cover failure.

Loads and modes of failure results for each bema are presented in table 3. Beams were grouped in order to allow the comparison regarding orientation, distribution, amount and type of strengthening system.

Beams V8_A and V8_B behaved as expected. Since these beams did not have any shear reinforcement, failure mode was controlled by diagonal tension in a sudden way with the formation of a classical shear crack at a 45° inclination related to the longitudinal axis. It is important to stress that the beams were tested up side down, therefore all the shear cracks will appear inverted in the pictures.

4.1 Beams strengthened with strips at 90°

The observation of these beams confirmed the expectation that total wrapping although complex presented the best performance. Failure load was increased up to 146.2%.

On the other hand, the performance of remaining beams was relatively similar especially in terms of increasing failure load. It is important to mention a relative dispersion observed in the results for the same strengthening schemes. This situation can be partially explained by the inherent difficulties in preparing the beam edges in "L" and "U" strengthening schemes.

Despite presenting similar increases in strength, failure modes presented by the beams with strips bonded only to the sides, "L" type and "U" type, oriented at 90°, were different. Failure modes presented by the beams with strips bonded only to the sides was controlled by *CFRP* debonding, as observed in figure 4. In this figure it is also possible to see the formation of a major crack, oriented approximately at 45° along almost the entire shear span. This crack crosses the strips defining as a result the anchorage lengths of each strip.

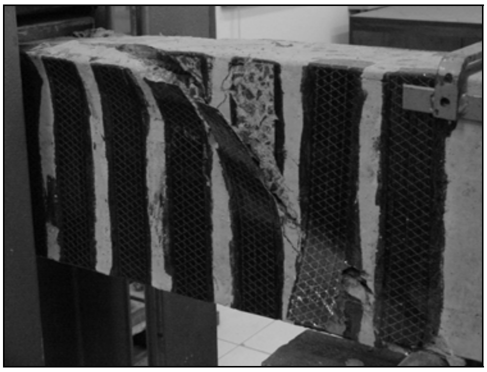
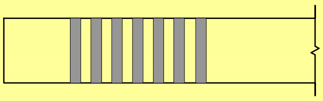
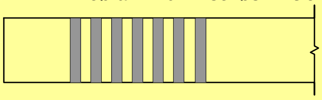
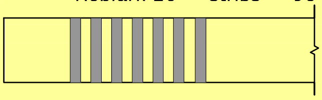
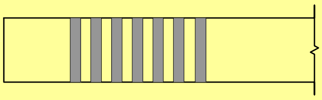
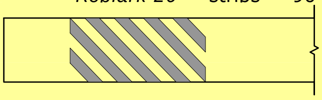
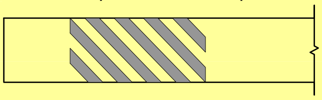
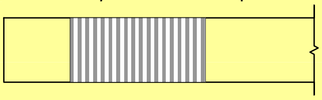
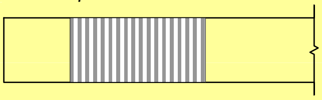
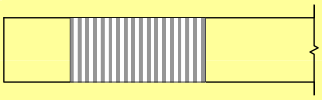
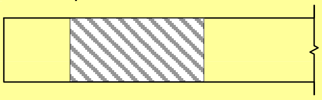
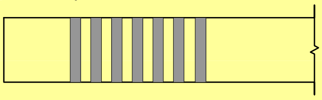
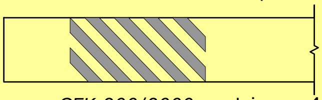


Figure 4 - Detail of failure mode in beams V9_A, V9_B e V21_A.

The "L" type presented the most stable results of this group. Increase in failure load fluctuated between 80.6% and 88.8%. The idea of applying "L" strips was motivated by two aspects: enhance the anchorage conditions and allow the comparison with the results provided by the inclined strips. Failure mode for these beams was characterized by the combination of debonding and *CFRP* tension rupture.

Table 3 - Loads and modes of failure.

Beam	Strengthening scheme		CFRP amount [m²]	Failure mode	Failure load [kN]	Increase [%]
V8_A	-	-	-	diagonal tension	114.70	-
V8_B					112.98	-
V9_A	 Replark 20 — strips — 90°	*side bonding*	0.4200	CFRP debonding	196.24	72.4
V9_B					208.58	83.2
V21_A					230.38	102.4
V10_A	 Replark 20 — strips — 90°	*"L" wrap*	0.5824	CFRP debonding followed by rupture	214.97	88.8
V10_B					211.98	86.2
V17_A					205.57	80.6
V11_A	 Replark 20 — strips — 90°	*"U" wrap*	0.5075	CFRP debonding followed by rupture	196.85	72.9
V11_B					249.60	119.3
V17_B					185.86	63.3
V12_A	 Replark 20 — strips — 90°	*fully wrap*	0.6615	CFRP rupture	232.71	104.4
V18_A					254.57	123.6
V20_A					280.24	146.2
V12_B	 Replark 20 — strips — 45°	*side bonding*	0.3891	CFRP debonding	203.30	78.6
V14_B					183.30	61.0
V19_A	 Replark 20 — strips — 45°	*"L" wrap*	0.5489	CFRP debonding followed by rupture	236.83	108.0
V19_B					230.26	102.3
V13_A	 Replark 20 — continuous— 90°	*side bonding*	0.7860	CFRP debonding	244.01	114.3
V13_B					251.50	120.9
V15_B	 Replark 20 — continuous — 90°	*"U" wrap*	0.9498	CFRP debonding	276.74	143.1
V16_B					224.85	97.5
V16_A	 Replark 20 — continuous — 90°	*fully wrap*	1.230	concrete crushing (flexure)	367.92	223.2
V18_B					404.82	255.6
V14_A	 Replark 20 — continuous — 45°	*side bonding*	0.7860	CFRP debonding	256.78	125.6
V15_A					241.12	111.8
V20_B	 CFK 200/2000 — strips — 90°	*side bonding*	0.4200	CFRP debonding	285.82	151.1
V22_B					225.02	97.7
V21_B	 CFK 200/2000 — strips — 45°	*side bonding*	0.3891	CFRP debonding	271.40	138.4
V22_A					251.19	120.7

Experimental evidence observed in this study show, in this case, that the debonding starts at the compression side since the strip has enough anchorage at the beam soffit. Nevertheless *CFRP* rupture occurs near the tension side at the diagonal crack where the strip is severely stressed.

Finally the beams with total wrapping presented a failure mode associated exclusively to *CFRP* rupture. In this circumstance, by having enough anchorage length the strips have an enhanced behavior allowing for higher increases in load. This scheme also contributes for retarding the onset of a diagonal tension crack, because the partial confinement provided by the strips. This effect may be observed in figure 5.

Figure 5 - Detail of failure mode in beams V12_A, V18_A e V20_A.

The performance of the beams with strips bonded only to the sides, "L" type and "U" type was fairly similar. The average increase in strength was 85% when compared to the control beams. Nonetheless the "L" type uses a *CFRP* amount 15% larger than the "U" type and 39% larger than the scheme of strips bonded only to the sides.

4.2 Beams strengthened with strips at 45°

Due to its anisotropic nature it is recommended to orientate the *CFRP* fibers preferably along the principal direction of stress. In order to test this condition, a group of beams was strengthened with strips oriented at 45°. Two strengthening schemes were tested: strips bonded only to the sides and "L" type. The failure mode of the beams which received strips bonded only to the sides was characterized by debonding as well as for the strips oriented at 90°. On the other hand, the "L" type scheme presented a failure mode combining *CFRP* debonding near the compression side and *CFRP* rupture at the tension side by the diagonal crack origin.

The average increase in strength for the beams strengthened with strips bonded only to the sides and "L" type were, respectively, 70% and 105%. The higher performance of the "L" type scheme is justified because it provides larger anchorage lengths, despite using a *CFRP* amount 41% higher.

4.3 Beams with continuous strengthening

Besides the strips, a *CFRP* can be applied continuously. Despite representing higher material costs, in some circumstances it may provide a viable solution where the partial confinement of the cross section could be relevant.

These beams were strengthened along the entire shear span oriented at 90° in relation to the longitudinal axis. Three schemes were tested: *CFRP* bonded only to the sides, "U" type and total wrapping. Even though the largest amount of *CFRP* was applied in the total wrapping scheme, it provided an increase of 240% in the failure load.

Additionally this scheme modified the overall behavior of beams V16_A and V16_B. Opposed to a shear controlled failure mode, these beams presented a classical flexural failure with concrete crushing and buckling of the compression reinforcement, as it can be observed in figure 6.

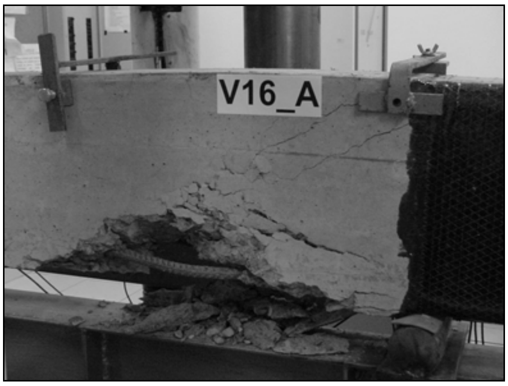


Figure 6 - Detail of failure mode in beams V16_A e V18_B.

The behavior of the *CFRP* continuous sheet bonded to the sides only and "U" type was fairly similar, regardless the *CFRP* amount of the "U" type scheme being 21% larger. The increase in failure load fluctuated between 114% and 143% and their failure modes were identical combining *CFRP* debonding and concrete cover rupture.

The mechanism of force transfer between concrete and composite helps to explain the concrete cover rupture observed in all the beams with continuous strengthening. Since the strengthening surface is quite large (the whole shear span) all the concrete cover in this area is stressed. As load increases cracks may occur along the concrete cover forming a fracture plane. At the time of debonding due to significant changes in this stress distribution, the concrete cover is fails along with the *CFRP* sheet. This failure mode may be observed in figure 7.

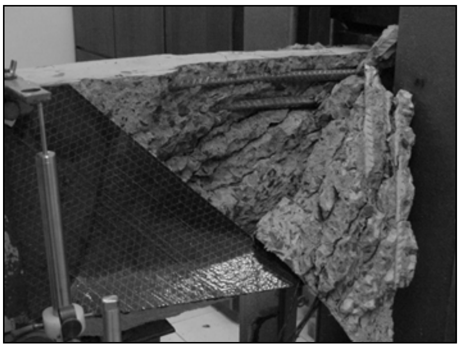


Figure 7 - Detail of failure mode in beams V14_A e V15_A.

Beams with continuous strengthening oriented at 45° bonded only to the sides, showed similar behavior to those with continuous strengthened oriented at 90°. There was an increase of approximately 119% in the failure load. Failure mode was also characterized by debonding associated with concrete cover rupture.

The main feature of *CFRP* cured in situ system is its great application versatility. The use of *CFRP* sheets allows numerous strengthening schemes and anchorage solutions. Nevertheless, some of these schemes can be quite unpractical despite being structurally efficient.

This study, in particularly, showed that in spite of continuous sheet oriented at 45° have presented similar results to the other schemes, its application procedure is somewhat complex. Surface preparation is highly complex especially for the strengthening with strips. Besides that, the cutting of the sheets is also labor costly and it generates a lot of waste in material.

4.4 Beams with prefabricated laminates

The last group of beams was strengthened using prefabricated laminates. Beams were strengthened with strips oriented at 45° and 90° bonded only to the sides. The average increase in failure load fluctuated between 124% and 129% for 90° and 45°, respectively.

4.5 Distribution and orientation

A performance comparison among different distributions and orientations provides an indication on the efficiency of each tested scheme. For beams with composites bonded only to the sides (at 45° and 90°) it was observed a slight advantage for the fibers oriented at 90° despite needing a *CFRP* amount 8% higher.

Alternatively, "L" type at 45° scheme not only used a 6% less *CFRP* but also showed an average increase in failure load 10% higher than "L" type at 90°. This superiority can be explained in part by a longer anchorage length at the soffit duet to its orientation. While the anchorage length was 15 cm for the 90° strips, in the 45° strips it was 21 cm.

Another important aspect in assessing the efficiency of a strengthening scheme is optimization. It means that under certain conditions (loading, supports, geometry, resistance, etc.) it is possible to say that larger amount of *CFRP* would not necessarily mean higher failure loads. Experimental evidences of this study confirm this possibility.

Beams with continuous strengthening bonded to sides only and "U" type used a *CFRP* amount 87% higher than the beams strengthened with strips under the same conditions. Even though there was an increase in the amount of *CFRP* these beams presented failure loads only 38% higher than the control beams. Beams with fibers oriented at 45° presented even worse results where an increase in failure load of 38% demanded twice the amount of *CFRP*.

These results once more corroborate the idea of a breakeven point between the amount of *CFRP* and the increase in failure load, depending upon certain conditions inherent of each situation.

The use of prefabricated laminates was less versatile than the cured in situ sheets. Their main limitation regards the possible anchorage configurations. Notwithstanding presenting higher performance than the cured in situ sheets, their failure mode was characterized by debonding which prevents higher failure loads.

It means that unless additional anchorage devices are placed the use of prefabricated laminates might not represent a viable solution. It should not be forgotten that these two strengthening systems are entirely different and the choice between them must take into consideration technical and economical aspects.

Finally the prefabricated laminates present higher stiffness, which was also important in determining the failure mode. In spite of being controlled by debonding and concrete cover rupture, damage in these beams was quite severe.

5 Conclusions

Results of this stuffy confirmed the feasibility of the use of CFRP composite in the shear strengthening of R/C beams. Increases in failure load were impressive up to 255.6%. Besides that by changing fiber orientation, distribution and anchorage solution, numerous schemes may be derived.

Generally the behavior of the strengthened beams was basically controlled by two failure modes. Debonding was more frequent and it is associated to the force transfer mechanism between concrete and composite. Nevertheless for the beams with sufficient anchorage *CFRP* rupture becomes the dominant failure mode. In some cases a combination of both failure modes was observed.

The most impressive result was observed in the beams with continuous strengthening at 90° where the entire cross section was wrapped by the composite. In this case there was a dramatic change in the behavior of the beams. In opposition to a shear-controlled failure these beams presented a flexural controlled failure with concrete crushing and compression reinforcement buckling.

In the case of beams strengthened with strips oriented at 45° the "L" type anchorage solution was very effective in increasing failure load. Nonetheless this scheme can be somewhat complex and labor costly.

The application of larger amounts of *CFRP* not necessarily means similar increases in failure loads. This evidence corroborates the idea of a breakeven point between the amount of *CFRP* and increases in failure load.

Finally the use of prefabricated laminates allows significant increases in failure load. However because of its peculiarities the only anchorage solution is the bonding of the laminates to the sides of the beams. This limitation prevents higher increases in failure loads since the failure mode will be controlled by debonding. In some cases therefore, the versatility of cured in situ sheets may represent an advantage.

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