Shear strengthening of reinforced concrete beams with laminate strips of CFRP

J. Barros & S. Dias
Dep. Eng^a Civil, Universidade do Minho, Campus de Azurém, 4800-058 Guimarães, Portugal

ABSTRACT: A conventional and three distinct CFRP-based shear reinforcing systems were used to assess the most effective one on the shear strengthening of reinforced concrete beams. Nowadays, one of these CFRP-based shear reinforcing systems is currently applied, wrapping the beam with strips of CFRP sheets. The two others CFRP-based shear reinforcing systems are based on bonding, with epoxy adhesive, laminate strips of CFRP into slits cut on the concrete cover of the lateral surfaces of the concrete beams. These two CFRP-based reinforcing systems only differ on the direction of the laminates. To evaluate the influence of the beam height, two series of tests with beams of distinct height were carried. These last reinforcing systems were more effective than the one based on strips of CFRP sheet, not only in terms of increasing the load bearing capacity, but also enhancing the beam ductility. They are also much more simple and faster to apply. In the present work the tests carried out are described and the main results are presented and analyzed.

1 INTRODUCTION

To increase the shear resistance of concrete beams, sheets and laminates of carbon fiber reinforcing polymers (CFRP) are generally applied on the faces of the elements to be strengthened, using externally bonded reinforcing (EBR) techniques. Adopting EBR techniques, several researchers have verified that the shear resistance of concrete beams can be increased significantly (Taerwe et al. 1997, Chaallal et al. 1997, Triantafillou 1998, Khalifa et al. 1998 Triantafillou & Antonopoulos 2000, Etman et al. 2001). However, due to premature debonding of the CFRP systems, the maximum strain mobilized by these systems is well below of its ultimate strain.

To overcome this drawback some attempts have been doing, a promising one was proposed by De Lorenzis et al. (2000). Using rods of CFRP embedded into grooves made on the concrete cover of the lateral faces of the beams, a significant increase on the load bearing capacity of the beams was obtained. It was also reported that the shear resistance can be increased by decreasing the rod spacing, anchoring the vertical rods to the web of the beam and changing the orientation of the rods from vertical to an inclination of 45º (keeping the same amount of rods). Anchoring the vertical rods to the web of the beam was the most efficacy procedure. Inclining rods was more effective than decreasing the spacing of vertical rods.

In the present work a technique similar to the previous one, but using laminate strips of CFRP (LS-CFRP) instead of rods, was used for shear strengthening of concrete beams. The LS-CFRP were bonded to concrete by epoxy adhesive. The influence of the LS-CFRP orientation and beam height on the shear strengthening effectiveness was analyzed.

This strengthening technique was already used for increasing the load bearing capacity of concrete columns (Ferreira 2000) and concrete beams (Barros & Fortes 2002) failed by bending. The results obtained showed that this technique is more efficient and easy to apply than EBR techniques. Pullout bending tests revealed that larger bond shear strength can be obtained, and the bond behavior is independent of the concrete strength class (Sena-Cruz & Barros 2002).

To evaluate the efficacy of the shear strengthening technique proposed on the present work, the behavior of beams strengthened according to this technique was compared to the behavior of beams strengthened by two other techniques: using conventional stirrups; applying strips of CFRP sheet.

The tests carried out are described and the main results are presented and analyzed. The failure modes are also commented.

2 EXPERIMENTAL RESEARCH

2.1 *Beam models*

The experimental campaign is composed by four series of tests, but at this stage only two series of beams were tested. Each series is constituted by a beam without any shear reinforcement and a beam for each of the following shear reinforcing systems: steel stirrups, strips of CFRP sheet, LS-CFRP at 90º with the beam axis (vertical LS-CFRP), LS-CFRP at 45º with the beam axis. Series A is composed by beams of cross section of 0.15x0.30 m^2, length of 1.6 m and span of 1.5 m. Series B is composed by beams of cross section of 0.15x0.15 m^2, length of 1.0 m and span of 0.9 m. The shear span, *a*, on the both series of beams was two times the height of the beams. The conventional longitudinal reinforcement at bottom and top surface was composed by 4ϕ10 and 2ϕ6, respectively, on the beams of both series. The amount of shear reinforcement applied on the four reinforcing systems was evaluated in order to assure that all beams would fail by shear, at a similar load bearing capacity (CEB-FIP 1993, ACI Committee 440 1999). Table 1 includes general information of the beams composing the two series. Figures 1 and 2 represent the geometry and the reinforcement arrangement of the beams of these series.

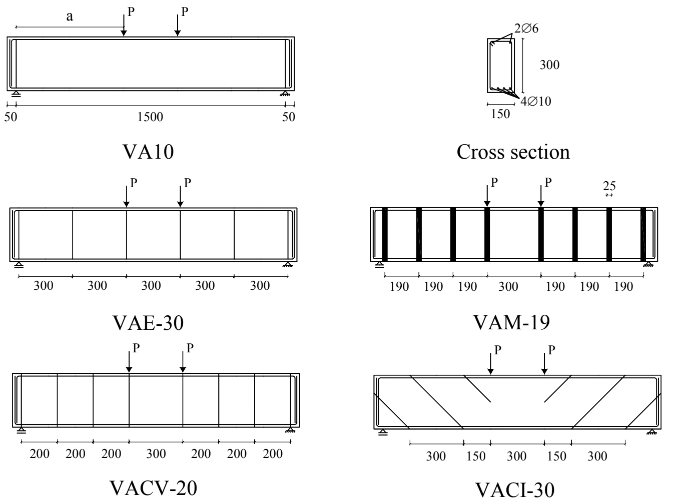
Table 1. Tests specimens.

	Beam designation	Shear reinforcing system
Series A	VA10	-
	VAE-30	Stirrups at 90 degrees (6ϕ6, 2r, 300 mm spacing)
	VAM-19	Strips of sheet MBrace C5-30 at 90 degrees (8×2layers, 25 mm width, 190 mm spacing)
	VACV-20	Laminate strips MBrace LM at 90 degrees (16 LS-CFRP, 200 mm spacing)
	VACI-30	Laminates strips MBrace LM at 45 degrees (12 LS-CFRP, 300 mm spacing)
Series B	VB10	-
	VBE-15	Stirrups at 90 degrees (6ϕ6, 2r, 150 mm spacing)
	VBM-8	Strips of sheet MBrace C5-30 at 90 degrees (10×2layers, 25 mm width, 80 mm spacing)
	VBCV-10	Laminate strips MBrace LM at 90 degrees (16 LS-CFRP, 100 mm spacing)
	VBCI-15	Laminate strips MBrace LM at 45 degrees (12 LS-CFRP, 150 mm spacing)

2.2 *Properties of the materials*

2.2.1 *Concrete and conventional steel bars*

The average compression strength at 28 days and at the date of testing the beams was evaluated from uniaxial compression tests with cylinders of 150 mm diameter and 300 mm height. The properties of the conventional reinforcement were evaluated from uniaxial tensile tests, carried out according to European standard EN 10 002-1 (1990). The results obtained are included in Table 2.

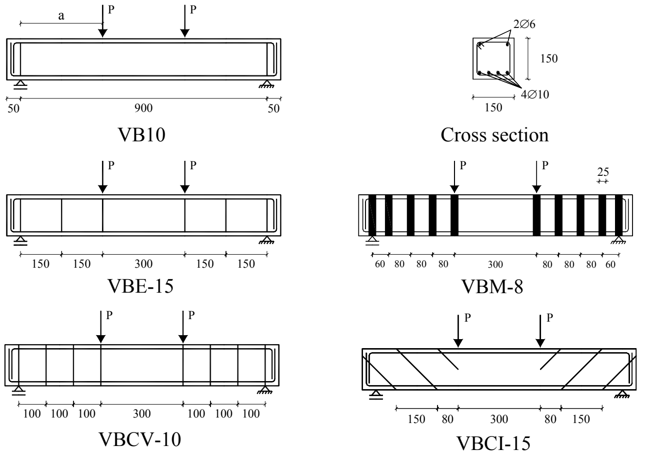


VA10 Cross section

VAE-30 VAM-19

VACV-20 VACI-30

Figure 1. Beams of series A (unities in mm).



VB10 Cross section

VBE-15 VBM-8

VBCV-10 VBCI-15

Figure 2. Beams of series B (unities in mm).

Table 2. Characteristics of the concrete and conventional steel.

	Beams	At 28 days	At the age of beam testing		
Concrete	Series A	f_{cm} = 37.6 MPa (C30/37) *	f_{cm} = 49.2 MPa (227 days)		
	Series B	f_{cm} = 49.5 MPa (C40/50) *	f_{cm} = 56.2 MPa (105 days)		
	Beams	Stress	ϕ6 (long.)	ϕ6 (tran.)	ϕ10
Steel bars	Series A	f_{sym} **	622 MPa	540 MPa	464 MPa
		f_{sum} ***	702 MPa	694 MPa	581 MPa
	Series B	f_{sym} **	618 MPa	540 MPa	464 MPa
		f_{sum} ***	691 MPa	694 MPa	581 MPa

Concrete strength class according to EN 206; ** f_{sym} - Average value of the yield stress; *** f_{sum} - Average value of the maximum stress.

2.2.2 *CFRP systems*

Two CFRP systems were used on the present work: unidirectional wet lay-up sheets with the trademark of "MBrace C5-30"; precured laminate with the trademark of "MBrace LM". According to the supplier, these CFRP systems have the properties indicated in Table 3. The LS-CFRP made from the MBrace LM had a cross section of 9.59±0.09 mm width and 1.45±0.005 mm thickness.

Table 3. Properties of the CFRP systems, according to the supplier.

CFRP system		Main properties			
Type	Materials	Tensile strength (MPa)	Young's modulus (GPa)	Ultimate strain (‰)	Thickness (mm)
Wet lay-up sheet	Primer	12	0.7	30	-
	Epoxy adhesive	54	3	25	-
	MBrace C5-30	3000	390	8	0.167
Precured laminate	Epoxy adhesive	-	7	-	-
	MBrace LM	2200	150	14	1.4

2.3 *Reinforcing techniques*

To apply the wet lay-up reinforcing system the following procedures were done: 1) on the zones of the beam lateral surfaces where the strips of CFRP sheet would be glued, an emery was passed to remove the superficial cement paste and to round the beam edges; 2) the residues were removed by compressed air; 3) a layer of primer was applied to enhance the concrete adherence; 4) strips of CFRP sheet were fixed to concrete by epoxy resin. Each strip is composed by two layers.

To apply the precured LS-CFRP reinforcing system the following procedures were mobilized: 1) slits of about 5 mm width and 12 mm deep were made on the both lateral surfaces of the beam, in places previously marked; 2) the slits were cleaned by compressed air; 3) the LS-CFRP were cleaned by acetone; 4) the slits were filled with epoxy adhesive manufactured according to the supplier recommendations. A special care was taken to assure that the slits were completely filled by the epoxy adhesive, without the formation of voids. Figure 3 shows the appearance of the two CFRP reinforcing systems.

2.4 *Test set up*

The beams were submitted to four point loads (see Figures 1, 2 and 4). The force was measured from a load cell of 300 kN maximum load bearing capacity and 0.06 % linearity. To evaluate the beam deflection, five LVDTs of 25 mm and 50 mm of full stroke were used, according to the arrangement represented in Figure 5. To avoid the register of extraneous deflections, the LVDTs were supported on a "Japanese Yoke" system (Barros & Sena-Cruz 2001). The tests were carried out under displacement control, using a deflections ratio of 10μm/s imposed on the LVDT placed at the mid span of the beam.

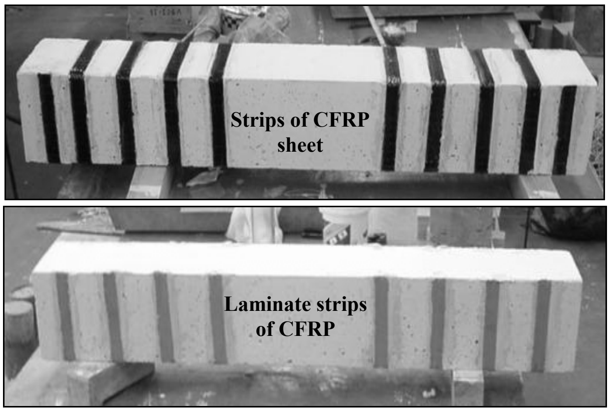


Figure 3. Wet lay-up and precured shear reinforcing systems.

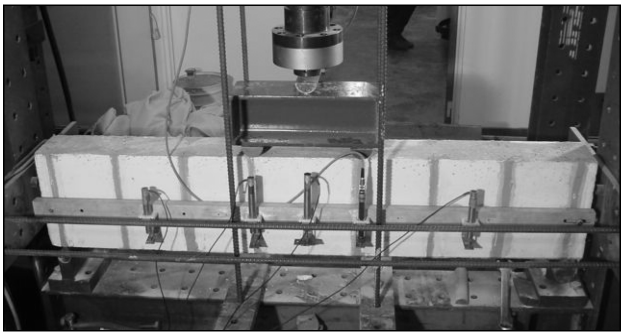


Figure 4. Test set up.

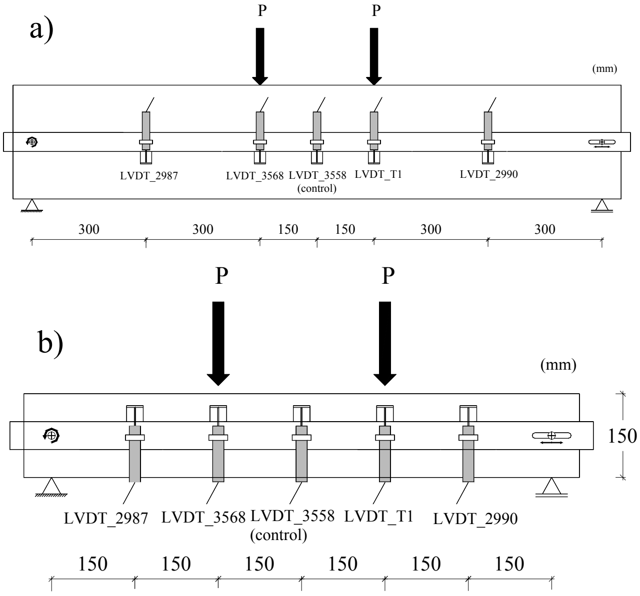


Figure 5. Arrangement of the displacement transducers (LVDT´s): (a) series A; (b) series B.

3 RESULTS

3.1 *Series A*

The relationship between the force and the deflection at the mid span of the beams of series A is depicted in Figure 6. Adopting the designation of $F_{max,VA10}$ and $F_{max,VAE-30}$ to referring the maximum load of the beam without shear reinforcement and beam reinforced with steel stirrups, respectively, the ratios $F_{max}/F_{max,VA10}$ and $F_{max}/F_{max,VAE-30}$ were determined for assessing the efficacy of the shear strengthening techniques, in terms of load increase.

To define the level of ductility provided by each shear strengthening technique, a deflection for $0.95F_{max}$ after the deflection at the peak load, δ_p, was taken (see Figure 7). The ductility was obtained from the ratios $\delta_p/\delta_{p,VA10}$ and $\delta_p/\delta_{p,VAE\text{-}30}$ (designated by ductility index) where $\delta_{p,VA10}$ and $\delta_{p,VAE\text{-}30}$ are the deflections for $0.95F_{max,VA10}$ and $0.95F_{max,VAE\text{-}30}$, respectively. All these data are included in Tables 4 and 5.

When compared to the maximum force of the unreinforced beam (VA10), Figure 6 and Table 4 show that the shear reinforcing systems increased significantly the maximum load: increase of 69% on beam reinforced with stirrups, increase between 22% and 58% in beams reinforced with CFRP systems. Amongst CFRP reinforcing-systems, the highest and the lowest load increase was registered in beam with vertical LS-CFRP (VACV-20) and beam with strips of CFRP sheet (VAM-19), respectively.

The F_{max} of the beams VAM-19, VACV-20 and VACI-30 (reinforced with CFRP systems), are 28%, 6% and 7% lesser than the F_{max} of the beam reinforced with steel stirrups.

In terms of ductility (see Table 5), the inclined LS-CFRP reinforcing system provided the highest ductility index. In comparison to $\delta_{p,VA10}$ (unreinforced beam), $\delta_{p,VAE\text{-}30}$, $\delta_{p,VAM\text{-}19}$, $\delta_{p,VACV\text{-}20}$ and $\delta_{p,VACI\text{-}30}$ were 480%, 34%, 359%, 1006% larger. Therefore, the ductility of the beam VACI-30 was 191% higher than the ductility of the beam reinforced with stirrups (VAE-30).

The failure modes of the beams of series A are shown in Figure 8. Beam VA10 failed by the occurrence of a unique shear crack at one of the beam shear spans, after the development of a reduced number of bending cracks. In beam reinforced with steel stirrups, after the development of flexural cracks (in a larger number than on the previous beam), one crack at each beam shear span was arisen. The failure was accompanied by an excessive opening of one of these two shear cracks and the closing of the remainder cracks. A stirrup crossing the failure crack ruptured. The beam reinforced with strips of CFRP sheet (VAM-19) failed abruptly, by peeling just after the formation of the failed shear crack. Much more ductile failure modes have occurred on the beams reinforced with LS-CFRP systems, mainly the beam with inclined LS-CFRP, that have failed by bending. In beams reinforced with LS-CFRP, after the deflection corresponding to the maximum force, a very high residual force was sustained up to large deflections, which was not happen on the beam reinforced with strips of CFRP sheet (see Figure 6).

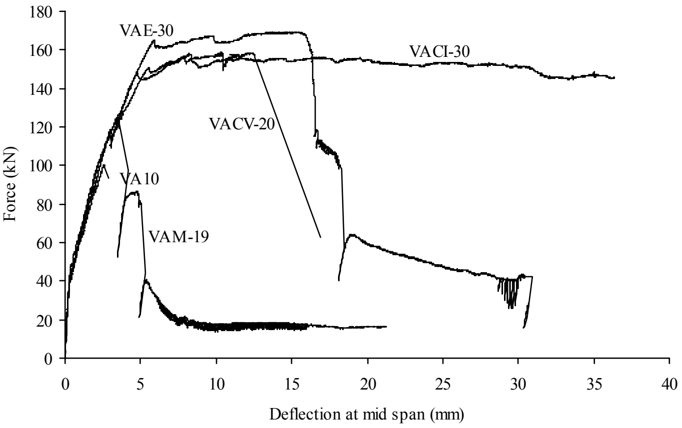


Figure 6. Force *vs* deflection of the beams of series A.

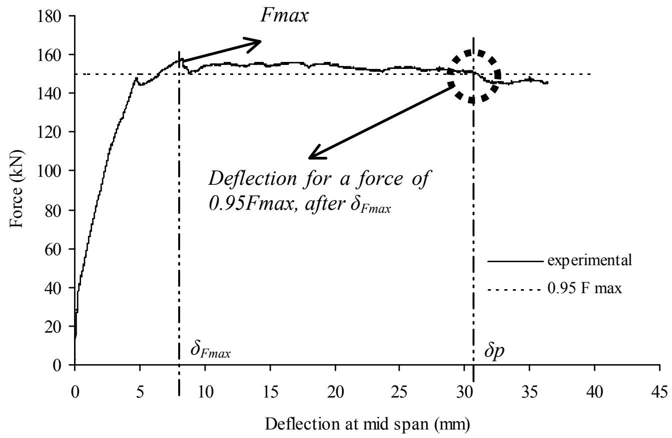


Figure 7. Concept of δ_p: deflection at 0.95F*max*, after δ_{Fmax}.

Table 4. Main results of the beams of series A (maximum load).

Beams	Shear reinforcing system	F_{max} (kN)	$F_{max}/F_{max,VA10}$	$F_{max}/F_{max,VAE-30}$
VA10	-	100.40	1.00	0.59
VAE-30	Stirrups	169.35	1.69	1.00
VAM-19	Strips CFRP sheet	122.06	1.22	0.72
VACV-20	Vertical LS-CFRP	158.64	1.58	0.94
VACI-30	Inclined LS-CFRP	157.90	1.57	0.93

Table 5. Main results of the beams of series A (ductility index).

Beams	Shear reinforcing system	δ_p (mm)	$\delta_p/\delta_{p,VA10}$	$\delta_p/\delta_{p,VAE-30}$
VA10	-	2.80	1.00	0.17
VAE-30	Stirrups	16.25	5.80	1.00
VAM-19	Strips CFRP sheet	3.75	1.34	0.23
VACV-20	Vertical LS-CFRP	12.86	4.59	0.79
VACI-30	Inclined LS-CFRP	30.96	11.06	1.91

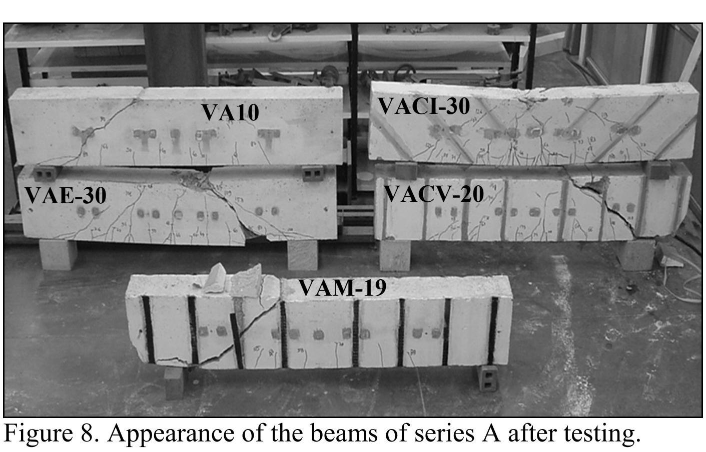


Figure 8. Appearance of the beams of series A after testing.

3.2 *Serie B*

The relationship between the force and the deflection at the mid span of the beams of series B is depicted in Figure 9. The main results obtained are included in Tables 6 and 7. $F_{max,VB10}$ and $F_{max,VBE\text{-}15}$ represent the maximum load registered on the beam without shear reinforcement (VB10) and on the beam reinforced with steel stirrups (VBE-15), respectively, while $\delta_{p,VB10}$ and $\delta_{p,VBE\text{-}15}$ are the deflections at mid span for $0.95F_{max,VB10}$ and for $0.95F_{max,VBE\text{-}15}$ (Figure 7).

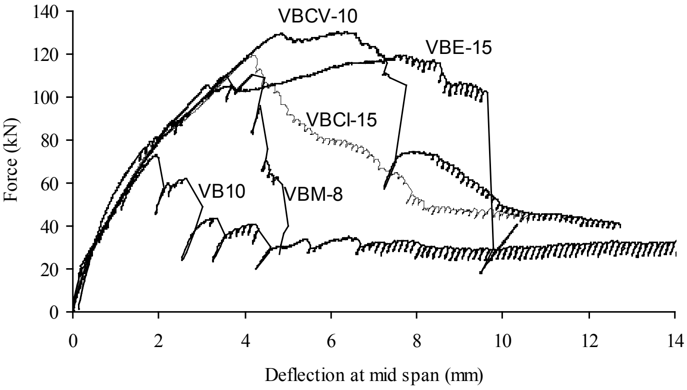


Figure 9. Force *vs* deflection of the beams of series B.

Figure 9 and the results from Table 6 show that CFRP reinforcing systems increased significantly the shear resistance of the concrete beams of series B. When compared to the maximum load of the beam without any shear reinforcement, $F_{max,VB10}$, it is verified that stirrups provided an increase on the F_{max} of 63%, while the increase assured by CFRP shear reinforcing systems ranged from 50% to 77%, the highest one was registered on beam with vertical LS-CFRP (VBCV-10), and the lowest one on the beam with strips of CFRP sheet (VBM-8).

Table 6. Main results of series B beams (maximum load).

Beams	Shear reinforcing system	$F_{\max}$ (kN)	$F_{\max}/F_{\max,VB10}$	$F_{\max}/F_{\max,VBE-15}$
VB10	-	74.02	1.00	0.61
VBE-15	Stirrups	120.64	1.63	1.00
VBM-8	Strips CFRP sheet	111.14	1.50	0.92
VBCV-10	Vertical LS-CFRP	131.22	1.77	1.09
VBCI-15	Inclined LS-CFRP	120.44	1.63	1.00

Table 7. Main results of series B beams (ductility index).

Beams	Shear reinforcing system	δ_p (mm)	$\delta_p/\delta_{p,VB10}$	$\delta_p/\delta_{p,VBE-15}$
VB10	-	2.00	1.00	0.23
VBE-15	Stirrups	8.53	4.27	1.00
VBM-8	Strips CFRP sheet	4.40	2.20	0.52
VBCV-10	Vertical LS-CFRP	6.83	3.42	0.80
VBCI-15	Inclined LS-CFRP	4.27	2.14	0.50

Taking the maximum force of the beam reinforced with steel stirrups ($F_{max,VBE\text{-}15}$) as a basis of comparison, it was verified that the maximum load of beams VBM-8, VBCV-10 and VBCI-15 was 92%, 109% and 100% of $F_{max,VBE\text{-}15}$, respectively (see Table 6). The better performance of the vertical LS-CFRP shear reinforcing system is more highlighted in terms of ductility. Assuming δ_p as an ductility index (see Figure 7), it is verified that, beams reinforced with steel stirrups, vertical LS-CFRP, inclined LS-CFRP and strips of CFRP sheet had an ductility index of 327%, 242%, 114% and 120% larger than the ductility index of the beam without any shear reinforcement. Therefore, in terms of ductility, the performance of the beam reinforced with vertical LS-CFRP was 80% of the one of the beam reinforced with stirrups (see Table 7).

The failure modes of the series B beams are shown in Figure 10. Beam VB10 failed by the occurrence of one shear crack at one of the beam shear spans, after the development of a few number of bending cracks. In beam reinforced with stirrups (VBE-15), after the development of bending cracks (in a larger number than in previous beam), two shear cracks arisen, one in each beam shear spans. During the deflection process of this beam, the crack width of one of these cracks increased continuously up to the moment when a stirrup crossing this crack has ruptured, fixing the moment of the failure of the beam. The increase of the crack width of the failure crack was accompanied by a reduction of the crack width of the remainder cracks.

In the beam reinforced with strips of CFRP sheet (VBM-8) a very fragile rupture occurred after the formation of the failure shear crack. The strips of CFRP sheet crossing the failure shear crack were ruptured at the beam edges. Delamination between these strips of CFRP and concrete was also observed. Due to the high level of energy released by these strips at the moment of its failure, the controller device of the servo-mechanism was not able to control the test after this moment.

The failure mode of the beams reinforced with LS-CFRP were not so fragile than the failure mode of beam reinforced with strips of CFRP sheet, mainly the failure mode of the beam reinforced with vertical LS-CFRP (VBCV-10). For deflections larger than the deflection corresponding to peak load, the beams reinforced with LS-CFRP sustained appreciable residual force, which was not the case of beam VBM-8 and beam VBE-15 after the rupture of the stirrup crossing the shear failure crack. This is an important attribute of the LS-CFRP reinforcing system, mainly for structural elements that can be submitted to loads of high magnitude, like a seismic. In the beam reinforced with vertical LS-CFRP, the cracks in the shear spans were almost enclosed between the two first LS-CFRP, from point load to support (see Figure 10). Due to the high inclination of these cracks, some plastification occurred on the longitudinal steel bars, responsible for the "plateau" on the force-deflection relationship, after peak load (see Figure 9).

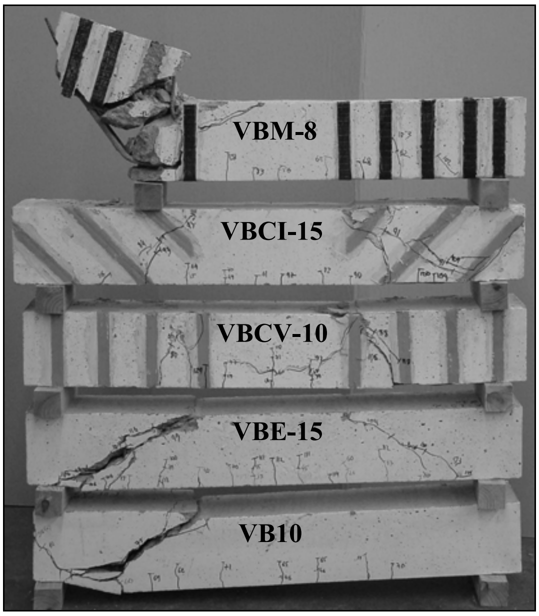


Figure 10. Appearance of the beams of series B after testing.

4 CONCLUSIONS

To assess the most effective CFRP shear reinforcing system, two series of beams of different height were tested under four point loads. Each series was composed by one beam without any shear reinforcement and one beam using the following shear reinforcing system: conventional steel stirrups; strips of CFRP sheet embracing the beam; laminate strips of CFRP (LS-CFRP) embedded into vertical and inclined (45 degrees) saw cuts made on the concrete cover of the beam lateral surfaces. The strips of CFRP sheet were fixed to concrete by resin epoxy, while LS-CFRP were bonded to concrete by epoxy adhesive. From the results obtained it can be pointed out the following main observations:

- The load bearing capacity of reinforced concrete beams failed by shear can be significantly increased using the CFRP shear reinforcing systems used in the present work;
- The shear reinforcing system composed by LS-CFRP was the most effective. This effectiveness is not only in terms of the beam load bearing capacity, but also in terms of the ductility of the beam's behavior. This shear reinforcing system is also easier and faster to apply;
- The maximum load and the ductility index of the beams reinforced with LS-CFRP were similar to the values registered on beams reinforced with conventional stirrups, of identical shear reinforcement ratio;
- In the structural softening phase (after peak load), the beams reinforced with LS-CFRP showed the largest residual strength;
- Less brittle failures modes occurred on the beams reinforced with LS-CFRP system;
- Increasing the height of the beam, inclined LS-CFRP became more effective than vertical LS-CFRP;
- LS-CFRP shear reinforcing system provides higher protection against fire and vandalism acts than externally bonded reinforcing technique.

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