Shear Strengthening of RC Beams with Near-Surface-Mounted CFRP Laminates

by S. Dias and J. Barros

Synopsis: The efficacies of the Near Surface Mounted (NSM) and Externally Bonded Reinforcing (EBR) techniques for the shear strengthening of rectangular cross section RC beams are compared. Both techniques are based on the use of carbon fiber reinforced polymer (CFRP) materials. The NSM was the most effective technique, and was also the easiest and fastest to apply, and assured the lowest fragile failure modes. The performance of the *ACI* and *fib* analytical formulations for the EBR shear strengthening was appraised. In general, the contribution of the CFRP systems predicted by the analytical formulations was larger than the values registered experimentally. The capability of the De Lorenzis formulation of predicting the contribution of the NSM technique for the shear strengthening of RC beams was appraised using bond stress and CFRP effective strain values obtained in pullout bending tests. This formulation provided values 61% lower than the values obtained experimentally.

Keywords: carbon fiber reinforced polymers; externally bonded reinforcing; near surface mounted; shear strengthening

Salvador Dias is a PhD Student at the Department of Civil Engineering of Minho University, Portugal. In 2001 he concluded his MSc from the Faculty of Engineering of Porto University, Portugal. His research interests include the application of fiber-reinforced polymer materials for the structural strengthening and rehabilitation.

ACI member **Joaquim Barros** is Professor of the Structural Division of Minho University, Portugal. He received his BS, MSc and PhD from Faculty of Civil Engineering of Porto University, Portugal. He is a member of ACI Committees 440 (Fiber reinforced polymers), 506 (Shotcrete) and 544 (Fiber reinforced concrete). His research interests include structural strengthening, composite materials, fiber reinforced concrete and finite element method.

INTRODUCTION

The use of fiber reinforced polymer (FRP) materials for structural repair and strengthening has continuously increased in the last years, due to several advantages resulting from opting for these composites in detriment of traditional construction materials such as steel, wood and concrete. These benefits include low weight, easy installation, high durability (non corrosive) and tensile strength, electromagnetic neutrality and practically unlimited availability in size, geometry and dimension [1, 2, 3].

Externally bonded reinforcing (EBR) technique using FRP laminates and wet lay-up sheets has been used to increase the shear resistance of RC beams [4]. The analysis of research studies confirmed that the shear resistance of RC beams can be significantly increased from applying the EBR technique. The carried out research has, however, revealed that this technique cannot mobilize the full tensile strength of FRP materials, due to their premature debonding. Furthermore, EBR reinforcements could be highly susceptible to damage from collision, fire and temperature variation, ultraviolet rays, and moisture absorption [5]. In an attempt at overcoming these drawbacks, a strengthening technique designated by near surface mounted (NSM) was proposed, where FRP rods are fixed into pre-cut grooves opened on the concrete cover of the elements to be strengthened [6]. Barros and Dias [7] proposed a similar strengthening technique based on installing CFRP laminate strips into pre-cut slits opened on the concrete cover. The CFRP was bonded to concrete by epoxy adhesive. This strengthening technique has already been used to increase the load carrying capacity of concrete structures failing in bending [8, 9, 10]. The obtained results showed that this technique is more efficient and easy to apply than EBR technique. This higher effectiveness is derived from the larger CFRP laminate-concrete bond stress values that can be mobilized in the NSM technique [11].

To assess the efficacy of the NSM technique for increasing the shear resistance of RC beams, an experimental program of four-point bending tests was carried out. Influences of the longitudinal tensile steel reinforcement, ρ_{sl}, laminate strip inclination and beam depth on the efficacy of the NSM technique were analyzed. This efficacy was assessed not only in terms of the increase of maximum load and deflection at beam rupture, but also in terms of the beam strengthening performance per unit length of the applied material. The performance of the analytical formulations proposed by *ACI* [1], *fib* [2] and De Lorenzis [6] for the shear strengthening was appraised.

RESEARCH SIGNIFICANCE

The efficacies of the NSM and EBR techniques for the shear strengthening of rectangular cross section RC beams are compared in terms of the increase of maximum load, the deflection at beam rupture and the failure mode. For the NSM technique, the beam strengthening performance per unit length of the applied material is assessed. The performance of the *ACI* and *fib* analytical formulations for the shear strengthening with externally bonded wet lay-up FRP systems is appraised. The capability of the De Lorenzis formulation of predicting the contribution of the NSM technique for the shear strengthening of RC beams is checked.

EXPERIMENTAL PROGRAM

The experimental program is composed of the four test series represented in Fig. 1. Each series is made up of a beam without any shear reinforcement (R) and a beam for each of the following shear reinforcing systems: steel stirrups of ϕ6 mm (S), U shaped strips of wet lay-up CFRP sheet (M) and CFRP laminate strips at 45º (IL) or at 90º (VL) in relation to the beam axis. The M beams were strengthened by EBR technique, while in IL and VL beams laminate strips of CFRP were installed into pre-cut slits opened on the concrete cover of the beam's lateral surfaces (NSM technique), see Fig. 2. Series A10 and A12 are composed of beams with a cross section of 0.15x0.30 m^2 and a span length of 1.5 m. Series B10 and B12 are constituted of beams with a cross section of 0.15x0.15 m^2 and a span length of 0.9 m. To evaluate the influence of ρ_{sl}, series A10 and B10 had 4ϕ10 steel bars at bottom surface, while A12 and B12 series had 4ϕ12. The shear span, *a*, (Fig. 1) in both series of beams was two times the depth of the corresponding beams. At top surface, the beams of all series were reinforced with 2ϕ6 steel bars. The concrete clear cover for the top, bottom and lateral faces of the beams was 15 mm. Table 1 includes general information of the beams composing the four series. Further information can be found elsewhere [7].

The amount of shear reinforcement applied on the four reinforcing systems was evaluated in order to assure that all beams would fail in shear, at a similar load carrying capacity. The percentage of the CFRP shear reinforcing systems was evaluated to provide a contribution for the beam shear resistance similar to the one of the steel stirrups. For the strips of wet lay-up CFRP sheets of U shape, the recommendations of the ACI Committee 440 were followed [1]. For the NSM CFRP laminate strips, the formulation used for the steel stirrups was adopted, but the yield stress was replaced by an effective stress that was determined assuming a CFRP strain value of 4‰, that is the maximum effective strain value recommended by ACI Committee 440 for the EBR shear reinforcing systems. Steel stirrups were not applied in the series reinforced with CFRP systems. The authors are aware that this scenario would probably never be encountered in practical situations since a certain percentage of steel stirrups always exist in reinforced concrete elements, even if it is inadequate. However, since the main purpose of the present research is to assess the effectiveness of NSM shear strengthening technique, the interaction between the CFRP shear reinforcement and the steel stirrups will be only investigated in future experimental programs.

Tables 2 and 3 include the main properties of the concrete and steel bars used in the experimental program, respectively. The average values of the concrete compression strength at 28 days and at the date of testing the beams were evaluated from uniaxial compression tests with cylinders of 150 mm diameter and 300 mm height. The properties of the steel bars were obtained from uniaxial tensile tests. Two CFRP systems were used on the present work: unidirectional wet lay-up sheets of 25 mm width and precured laminates of $1.4\times10\ mm^2$ cross-section. These CFRP systems have the properties indicated in Table 4.

The relationship between the force and the deflection at mid span of the tested beams is represented in Figure 3. Table 5 includes the main results obtained in the four tested beam series. Adopting the designation of F_{max,K_R} and F_{max,K_S} for referring the maximum load of a beam without shear reinforcement and a beam reinforced with steel stirrups, respectively, (K represents the beam series) the ratios $F_{max}/F_{max,K\_R}$ and $F_{max}/F_{max,K\_S}$ were determined for assessing the efficacy of the shear strengthening techniques, in terms of increasing the beam load carrying capacity.

From the results obtained in the experimental program, the following main conclusions can be pointed out:

- The CFRP shear strengthening systems applied in the present work increased significantly the shear resistance of concrete beams;
- The NSM shear strengthening technique was the most effective of the CFRP systems. This effectiveness was not only in terms of the beam load carrying capacity, but also in terms of the deformation capacity at beam's failure. Using the load carrying capacity of the unreinforced beams for comparison purposes, the beams strengthened by EBR and NSM techniques showed an average increase of 54% and 83%, respectively;
- Increasing the beam depth, laminates at 45º became more effective than vertical laminates;
- F_{max} of the beams reinforced with steel stirrups and F_{max} of the beams strengthened by NSM technique were almost similar;
- Failure modes of the beams strengthened by the NSM technique were not so fragile as the ones observed in the beams strengthened by the EBR technique.

APPRAISAL THE PERFORMANCE OF ANALYTICAL FORMULATIONS

Taking the results obtained in the tested beams strengthened with EBR technique, the performance of the analytical formulations proposed by *ACI* [1] and *fib* [2] was appraised. The documents published by these institutions are not yet dealing with the NSM technique. Thereby, the applicability of the analytical formulation proposed by De Lorenzis [6] was checked, using for this purpose the experimental results obtained in the beams strengthened with NSM laminate strips. Since De Lorenzis's formulation was developed for FRP reinforcing rod elements, the necessary adjustments were introduced to take into account that FRP elements are now laminate strips. New estimates for the parameters of this model are proposed in order to take into account the bond stress and the CFRP effective strain values recorded in the pullout bending tests [11] and to obtain an appropriate safety factor for the CFRP contribution towards shear resistance of concrete beams.

ACI recommendations for EBR technique

According to *ACI*[1], the design value of the contribution of the FRP shear reinforcement is given by,

$$V_{fd} = \phi \, \psi_f \, \frac{A_{fv} \, f_{fe} \, d_f}{s_f} \tag{1}$$

where ϕ is the strength-reduction factor required by *ACI* [12] that, for shear strengthening of concrete elements, has a value of 0.85, ψ_f is an additional reduction factor of 0.85 for the case of three-sided U-wraps (see Fig. 4), s_f is the spacing of the wet lay-up strips of FRP sheets, A_{fv} is the area of FRP shear reinforcement within spacing s_f,

$$A_{fv} = 2 n t_f w_f \tag{2}$$

with n, t_f and w_f being the number of layers per strip, the thickness of a layer and the width of the strips. The effective stress in the FRP, f_{fe}, is obtained multiplying the elasticity modulus of the FRP, E_f, by the effective strain,

$$\varepsilon_{fe} = k_v \varepsilon_{fu} \leq 0.004 \quad \text{(for U-wraps)} \tag{3}$$

where k_v is a bond-reduction coefficient that is a function of the concrete strength, the type of wrapping scheme used, and the stiffness of the FRP,

$$k_v = \frac{k_1 k_2 L_e}{11900 \varepsilon_{fu}} \leq 0.75 \tag{4}$$

with,

$$L_e = \frac{23300}{\left(n t_f E_f\right)^{0.58}} \tag{5}$$

$$k_1 = \left(\frac{f_c'}{27}\right)^{2/3} \tag{6}$$

$$k_2 = \frac{d_f - L_e}{d_f} \quad \text{(for U-wraps)} \tag{7}$$

In (1) and (7) d_f is the depth of FRP shear reinforcement (see Fig. 4), and f_c' is the characteristic value of the concrete compression strength [12]. The length and the force unities of the variables in (4) to (7) are millimeter and Newton, respectively.

In Table 6, the values obtained with this formulation are compared to those registered experimentally. Apart beam B10_M, the *ACI* formulation has estimated a FRP contribution for the shear strengthening that was larger than the contribution recorded experimentally. A deficient bond of the strip crossed by the shear failure crack might have caused the high abnormal value of $V_{fd}^{ana.} / V_f^{exp.}$ of A10_M beam, since this strip has debonded prematurely (see Fig. 5).

Fib recommendations for EBR technique

According to *fib* recommendations [2], the contribution of wet lay-up strips of FRP sheets for shear strengthening is evaluated by the following expression,

$$V_{fd} = 0.9\,\varepsilon_{fe,d}\,E_f\,\rho_f\,b_w\,d \tag{8}$$

where b_w and d are the width of the beam cross section and the distance from extreme compression fiber to the centroid of the nonprestressed steel tension reinforcement. In (8) ρ_f is the FRP shear reinforcement ratio,

$$\rho_f = \frac{A_{fv}}{b_w s_f} \tag{9}$$

and $\varepsilon_{fe,d}$ is the design effective strain in the FRP, that can be obtained from ε_{fe},

$$\varepsilon_{fe} = \min\left[0.65\left(\frac{f_{cm}^{2/3}}{E_f\,\rho_f}\right)^{0.56} \times 10^{-3};\ 0.17\left(\frac{f_{cm}^{2/3}}{E_f\,\rho_f}\right)^{0.30} \varepsilon_{fu}\right] \text{ (f_{cm} in MPa and E_f in GPa)} \tag{10}$$

applying two safety factors, $\varepsilon_{fe,d} = 0.8\varepsilon_{fe}/1.3$, the first one, 0.8, to convert ε_{fe} in a characteristic value and the second one, 1.3, that depends on the FRP failure mode (debonding in the present case). In (10) f_{cm} is the cylinder average concrete compression strength and ε_{fu} is the ultimate FRP strain. The analytical and the experimental results are compared in Table 7. Apart beam B12_M, *fib* formulation has also predicted an FRP contribution larger than the experimentally registered values. Like in the *ACI* formulation, an abnormal high $V_{fd}^{ana.} / V_f^{exp.}$ value was also obtained in A10_M beam, which stresses the suspicious that the strip crossing the shear failure crack was deficiently bonded.

Fig. 6 compares the values of the CFRP contribution for the shear strengthening according to *ACI* and *fib* formulations. In general, all the formulations have estimated large values than the ones registered experimentally. Apart B12_M beam, in the remaining beams the *ACI* formulation estimated lower values than *fib*. The differences between the values from *ACI* and *fib* are, however, not too significant.

De Lorenzis analytical formulation for NSM technique

According to De Lorenzis [6], the contribution of the NSM FRP elements for shear strengthening is the minimum value of V_{1f} and V_{2f},

$$V_f = min\,(V_{1f},\ V_{2f}) \tag{11}$$

where V_{1f} is the term associated with the FRP-concrete bond strength, while V_{2f} derives from a strain limit of ε_{fe} imposed on the FRP. The De Lorenzis formulation was developed for NSM FRP rod systems. To adjust this formulation for the case of laminate strips, the diameter of the rod cross section was conveniently replaced by the dimensions of the laminate cross section, a_l and b_l, resulting in the following expression for the V_{1f} term,

$$V_{1f} = 4 \cdot (a_l + b_l) \cdot \tau_b \cdot L_{tot\ min} \tag{12}$$

In this expression τ_b represents the average bond stress of the FRP elements intercepted by the shear failure crack and, for vertical laminates, $L_{tot\ min}$ is obtained from,

$$\begin{aligned} L_{tot\ min} &= d_{net} - s_f \quad &\text{if} \quad \frac{d_{net}}{3} \le s_f < d_{net} \\ L_{tot\ min} &= 2d_{net} - 4s_f \quad &\text{if} \quad \frac{d_{net}}{4} < s_f < \frac{d_{net}}{3} \end{aligned} \tag{13}$$

while for laminates at 45º,

$$\begin{aligned} L_{tot\ min} &= \left(2d_{net} - s_f\right)\frac{\sqrt{2}}{2} \quad &\text{if} \quad \frac{2d_{net}}{3} \le s_f < 2d_{net} \\ L_{tot\ min} &= \left(d_{net} - s_f\right)2\sqrt{2} \quad &\text{if} \quad \frac{d_{net}}{2} < s_f < \frac{2d_{net}}{3} \end{aligned} \tag{14}$$

where s_f is the FRP spacing and d_{net} is a reduced value for the effective length of the laminate (see Fig. 7),

$$d_{net} = d_r - 2c \tag{15}$$

with d_r being the actual length of the laminate and c the concrete clear cover.

The term V_{2f} is evaluated from,

$$\begin{aligned} V_{2f} &= 4 \cdot (a_l + b_l) \cdot \tau_b \cdot \overline{L}_i \quad &\text{if} \quad \frac{d_{net}}{2} \le s_f < d_{net} \\ V_{2f} &= 4 \cdot (a_l + b_l) \cdot \tau_b \cdot \overline{L}_i \cdot \frac{3d_{net} - 4s_f}{d_{net}} \quad &\text{if} \quad \frac{d_{net}}{4} < s_f < \frac{d_{net}}{2} \end{aligned} \tag{16}$$

for the vertical laminates, and

$$\begin{aligned} V_{2f} &= 4 \cdot (a_l + b_l) \cdot \tau_b \cdot \overline{L}_i \quad &\text{if} \quad d_{net} \le s_f < 2d_{net} \\ V_{2f} &= 4 \cdot (a_l + b_l) \cdot \tau_b \cdot \overline{L}_i \cdot \frac{3d_{net} - 2s_f}{d_{net}} \quad &\text{if} \quad \frac{d_{net}}{2} < s_f < d_{net} \end{aligned} \tag{17}$$

for the laminates at 45^o, where

$$\overline{L}_i = \frac{\varepsilon_{fe}}{2} \cdot \frac{a_l \cdot b_l}{a_l + b_l} \cdot \frac{E_f}{\tau_b} \tag{18}$$

According to De Lorenzis [6], if

$$d_{net} < 2\overline{L}_i \tag{19}$$

in the case of vertical laminates, or if

$$d_{net} < \sqrt{2}\,\overline{L}_i \tag{20}$$

in the case of laminates at 45º, it is not necessary to calculate V_{2f}, since V_{1f} is the conditioning term, giving the lowest value. The design shear contribution of FRP to the RC beam shear capacity is evaluated from,

$$V_{fd} = 0.7 \times V_f \tag{21}$$

The average bond stress, τ_b, was obtained from the results registered in pullout-bending tests [11]. From the obtained peak pullout forces a τ_b of 16.1 MPa was determined, which is much larger than the value recommended by De Lorenzis for the NSM FRP rod strengthening system (τ_b = 6.9 MPa). The CFRP average strain (ε_{fe}) in the bond length at peak pullout force was 5.9‰, which is larger than the value recommended by De Lorenzis for the NSM FRP rod strengthening system (ε_{fe}= 4.0‰).

Assuming that τ_b, ε_{fe} and E_f are equal to 16.1 MPa, 5.9‰ and 166 GPa, respectively, the analytical results indicated in Table 8 were obtained. This table does not include the data of the B10_VL beam since, according to the De Lorenzis formulation, the FRP contribution is null in beams with s_f larger than d_{net}. If the experimental results ($V_f^{exp.}$) are compared to the analytical ones ($V_{fd}^{ana.}$), an average $V_f^{exp.}/V_{fd}^{ana.}$ ratio of about 1.65 was obtained. Since a safety factor of 1.79 ($V_c^{exp.}/V_{cd}^{ana.}$ = 1.79) was obtained in the beams without any shear reinforcement, and a safety factor of 1.24 ($V_{sw}^{exp.}/V_{swd}^{ana.}$ = 1.24) was determined for the contribution of the steel stirrups for the shear resistance, the safety factor of 1.65 seems to be an appropriate value for the contribution of the NSM CFRP systems.

PROFITABILITY OF THE NSM TECHNIQUE

To assess the influence of the CFRP laminate orientation, not only in terms of increasing the beam load carrying capacity (F_{max}), but also in terms of the amount of consumed CFRP, the ratio $\Delta F/l_{CFRP}$ of the beams strengthened by the NSM technique was evaluated (designated by profitability index), where ΔF is the increase in the F_{max} and l_{CFRP} is the total length of the laminates applied in the beam. The values included in Table 9 show that (see also Fig. 8), independent of the beam height and the longitudinal steel reinforcement ratio (ρ_{sl}), the profitability index was larger in the beams with laminates at 45º. For both the A series, the profitability index increased with the increase of ρ_{sl}. This tendency was not observed in both B series since the reduced bonded lengths of the CFRP laminates in these shallow beams limited the increase on the ΔF.

CONCLUSIONS

The main purpose of the present research is to assess the effectiveness of the near surface mounted (NSM) technique for the shear strengthening of RC beams. In comparison to the performance of the experimentally bonded reinforcing (EBR) technique, the NSM was the more effective technique, and was also easier and faster to apply, and assured lower fragile failure modes.

Using the *ACI* and *fib* formulations for the evaluation of the contribution of the CFRP EBR strengthening systems for the beam shear resistance, it was verified that these formulations have given design values 2% and 8% higher than the values registered experimentally, respectively, (a beam with a deficient bonding was not considered in this analysis). Using similar EBR shear strengthening configuration, other researchers have obtained larger safety factors. However, these researchers have used wet lay-up CFRP sheets of Young's modulus (E_f) of about 220 GPa, and, in the major cases, the shear CFRP strips were formed of one layer. In the present research a CFRP sheet of E_f=390 GPa and strips of two layers were used. This indicates that the expressions of ACI and *fib* formulations defining the FRP effective strain were not well calibrated for this situation, since they are providing too high effective strain values when using stiffer shear CFRP systems. Therefore, more research is needed in this field.

Assuming a bond stress of 16.1 MPa and an effective strain of 5.9‰ (average values of the data recorded in pullout bending tests), the De Lorenzis formulation predicted a CFRP contribution around 61% of the experimentally registered values, which seems to provide an appropriate safety factor (1.65).

ACKNOWLEDGMENTS

The authors of the present work wish to acknowledge the materials provided by the degussa® Portugal, S&P® and Unibetão (Braga). The study reported in this paper forms a part of the research program "CUTINSHEAR - Performance assessment of an innovative structural FRP strengthening technique using an integrated system based on optical fiber sensors" supported by FCT, POCTI/ECM/59033/2004.

REFERENCES

1. ACI Committee 440, 2002, *"Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures"*, American Concrete Institute, 118 pp.

2. CEB-FIP Model Code, 1993, Comite Euro-International du Beton, Bulletin d'Information nº 213/214.

3. Bakis, C.E., Bank, L.C., Brown, V.L., Cosenza, E., Davalos, J.F., Lesko, J.J., Machida, A., Riskalla, S.H. and Triantafillou, T.C., 2002, *"Fiber-Reinforced Polymer Composites for Construction – State-of-the-art Review"*, Journal of Composites for Construction, Vol. 6, Nº2, May, pp. 73-87.

4. Bousselham A. and Chaallal, O., 2004, *"Shear Strengthening Reinforced Concrete Beams with Fiber-Reinforced Polymer: Assessment of Influencing Parameters and Required Research"*, ACI Structural Journal, Vol. 101, Nº 2, March-April, pp. 219-227.

5. ACI Committee 440, 1996, *"State of the art report on fiber reinforced plastic reinforcement for concrete structures"* (Reapproved 2002), ACI Committee 440, 68 pp.

6. De Lorenzis, Laura, 2002, *"Strengthening of RC Structures with Near-Surface Mounted FRP rods"*, PhD Thesis in Civil Engineering, Universita' Degli Studi di Lecce, Italy, May, 289 pp.

7. Barros, J.A.O. and Dias, S.J.E., 2003, *"Shear strengthening of reinforced concrete beams with laminate strips of CFRP"*, Proceedings of the International Conference Composites in Constructions - CCC2003, Italia, September, pp. 289-294.

8. Blaschko, M. and Zilch, K., 1999, *"Rehabilitation of concrete structures with CFRP strips glued into slits"*, Proceedings of the Twelfth International Conference of Composite Materials, ICCM 12, Paris, France (CD-ROM).

9. El-Hacha, R. and Riskalla S.H., 2004, *"Near-Surface-Mounted Fiber-Reinforced Polymer Reinforcements for Flexural Strengthening of Concrete Structures"*, ACI Structural Journal, Vol. 101, Nº5, September-October, pp. 717-726.

10. Barros, J.A.O., Sena-Cruz, J.M., Dias, S.J.E., Ferreira, D.R.S.M. and Fortes, A. S., 2004, *"Near surface mounted CFRP-based technique for the strengthening of concrete structures"*, Workshop on R+D+I in Technology of Concrete Structures - tribute to Dr. Ravindra Gettu, Barcelona, Spain, October, pp. 205-217 (CD-ROM).

11. Sena-Cruz, J.M. and Barros, J.A.O., 2004, *"Bond between near-surface mounted CFRP laminate strips and concrete in structural strengthening"*, Journal of Composites for Construction, Vol. 8, Nº 6, pp. 519-527.

12. ACI Committee 318, 2002, *"Building code requirements for structural concrete and commentary",* American Concrete Institute, Reported by ACI Committee 118.

Table 1 — Shear strengthening arrangements of the tested series

Beam's designation			Shear strengthening systems			
			Material	Quantity	Spacing (mm)	Angle (°)
A series	A10	A10_R	-	-	-	-
		A10_S	Steel stirrups	6ϕ6 of two branches	300	90
		A10_M	Strips of S&P C-Sheet 530	8×2 layers of 25 mm (U shape)	190	90
		A10_VL	S&P laminate strips of CFK 150/2000	16 CFRP laminates	200	90
		A10_IL	S&P laminate strips of CFK 150/2000	12 CFRP laminates	300	45
	A12	A12_R	-	-	-	-
		A12_S	Steel stirrups	10ϕ6 of two branches	150	90
		A12_M	Strips of S&P C-Sheet 530	14×2 layers of 25 mm (U shape)	95	90
		A12_VL	S&P laminate strips of CFK 150/2000	28 CFRP laminates	100	90
		A12_IL	S&P laminate strips of CFK 150/2000	24 CFRP laminates	150	45
B series	B10	B10_R	-	-	-	-
		B10_S	Steel stirrups	6ϕ6 of two branches	150	90
		B10_M	Strips of S&P C-Sheet 530	10×2 layers of 25 mm (U shape)	80	90
		B10_VL	S&P laminate strips of CFK 150/2000	16 CFRP laminates	100	90
		B10_IL	S&P laminate strips of CFK 150/2000	12 CFRP laminates	150	45
	B12	B12_R	-	-	-	-
		B12_S	Steel stirrups	10ϕ6 of two branches	75	90
		B12_M	Strips of S&P C-Sheet 530	16×2 layers of 25 mm (U shape)	40	90
		B12_VL	S&P laminate strips of CFK 150/2000	28 CFRP laminates	50	90
		B12_IL	S&P laminate strips of CFK 150/2000	24 CFRP laminates	75	45

Table 2 — Concrete properties

Beam's series	f_{cm} (MPa)	
	28 days	At beam testing
A	37.6	49.2 (227 days)
B	49.5	56.2 (105 days)

Table 3 — Properties of the conventional steel bars

Beam's series	ϕ6 (longitudinal)	ϕ6 (stirrups)	ϕ10	ϕ12
A	f_{sym} = 622 MPa	f_{sym} = 540 MPa	f_{sym} = 464 MPa	f_{sym} = 574 MPa
	f_{sum} = 702 MPa	f_{sum} = 694 MPa	f_{sum} = 581 MPa	f_{sum} = 672 MPa
B	f_{sym} = 618 MPa	f_{sym} = 540 MPa	f_{sym} = 464 MPa	f_{sym} = 571 MPa
	f_{sum} = 691 MPa	f_{sum} = 694 MPa	f_{sum} = 581 MPa	f_{sum} = 673 MPa

Table 4 — Properties of the CFRP systems

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	54	3	25	-
	Sheet (S&P C-Sheet 530)	3000	390	8	0.167
Precured laminate	Adhesive	-	7	-	-
	Laminate (S&P laminate CFK 150/2000)	2200	150	14	1.4
		2286[1]	166[1]	13[1]	1.4[1]

[1] Evaluated from experimental tests carried out in the present research program

Table 5 — Main results of the four tested beam series

Beam's A series (4ϕ10)	F_{max}^* (kN)	$\frac{F_{max}}{F_{max,A10\_R}}$	$\frac{F_{max}}{F_{max,A10\_S}}$	Beam's A series (4ϕ12)	F_{max}^* (kN)	$\frac{F_{max}}{F_{max,A12\_R}}$	$\frac{F_{max}}{F_{max,A12\_S}}$
A10_R	100.40	1.00	0.59	A12_R	116.50	1.00	0.54
A10_S	169.35	1.69	1.00	A12_S	215.04	1.85	1.00
A10_M	122.06	1.22	0.72	A12_M	179.54	1.54	0.83
A10_VL	158.64	1.58	0.94	A12_VL	235.11	2.02	1.09
A10_IL	157.90	1.57	0.93	A12_IL	262.38	2.25	1.22
Beam's B series (4ϕ10)	F_{max}^* (kN)	$\frac{F_{max}}{F_{max,B10\_R}}$	$\frac{F_{max}}{F_{max,B10\_S}}$	Beam's B series (4ϕ12)	F_{max}^* (kN)	$\frac{F_{max}}{F_{max,B12\_R}}$	$\frac{F_{max}}{F_{max,B12\_S}}$
B10_R	74.02	1.00	0.61	B12_R	75.7	1.00	0.48
B10_S	120.64	1.63	1.00	B12_S	159.1	2.10	1.00
B10_M	111.14	1.50	0.92	B12_M	143.0	1.89	0.90
B10_VL	131.22	1.77	1.09	B12_VL	139.2	1.84	0.87
B10_IL	120.44	1.63	1.00	B12_IL	148.5	1.96	0.93

* $F_{max} = 2P_{max}$ (see Fig. 1)

Table 6 — Analytical *vs* experimental results (*ACI* analytical formulation)

Beam's designation	Experimental $V_f^{exp.}$ (kN)	Analytical $V_{fd}^{ana.*}$ (kN)	$V_{fd}^{ana.}/V_f^{exp.}$
A10_M	10.8	17.0	1.57
A12_M	31.5	33.8	1.07
B10_M	18.6	17.7	0.95
B12_M	33.7	35.0	1.04

* f_c' values were obtained at the age of the beam tests (f_c' = 40.2 MPa for A series and f_c' = 46.5 MPa for B series).

Table 7 — Analytical *vs* experimental results (*fib* analytical formulation)

Beam's designation	Experimental	Analytical	$V_{fd}^{ana.} / V_f^{exp.}$
	$V_f^{exp.}$ (kN)	$V_{fd}^{ana.*}$ (kN)	
A10_M	10.8	24.0	2.22
A12_M	31.5	38.9	1.23
B10_M	18.6	20.5	1.10
B12_M	33.7	30.9	0.92

* f_{cm} values were obtained at the age of the tested beams.

Table 8 — Analytical *vs* experimental results

(De Lorenzis analytical formulation with $\varepsilon_f = 5.9‰$, $\tau_b = 16.1$ MPa and $E_f = 166$ GPa)

Beam's designation	Series	Experimental	Analytical	$V_f^{exp.} / V_{fd}^{ana.}$
		$V_f^{exp.}$ (kN)	$V_{fd}^{ana.}$ (kN)	
A10_VL	A (4ϕ10)	29.1	19.2	1.52
A10_IL	A (4ϕ10)	28.8	19.2	1.50
A12_VL	A (4ϕ12)	59.3	26.4	2.25
A12_IL	A (4ϕ12)	72.9	34.2	2.13
B10_IL	B (4ϕ10)	23.2	19.2	1.21
B12_VL	B (4ϕ12)	31.8	19.2	1.66
B12_IL	B (4ϕ12)	36.4	27.6	1.32

Table 9 — Profitability of the NSM technique

Series		Beam's designation	F_{max} (kN)	ΔF (kN)	l_{CFRP} (m)	$\Delta F/l_{CFRP}$ (kN/m)
A (*h = 0.30m*)	(4ϕ10)	A10_R	100.4	-	-	-
		A10_VL	158.64	58.24	4.8	12.13
		A10_IL	157.9	57.5	3.68	15.63
	(4ϕ12)	A12_R	116.5	-	-	-
		A12_VL	235.11	118.61	8.4	14.12
		A12_IL	262.38	145.88	7.35	19.85
B (*h = 0.15m*)	(4ϕ10)	B10_R	74.02	-	-	-
		B10_VL	131.22	57.2	2.4	23.83
		B10_IL	120.44	46.42	1.97	23.56
	(4ϕ12)	B12_R	75.7	-	-	-
		B12_VL	139.2	63.5	4.2	15.12
		B12_IL	148.5	72.8	3.91	18.62

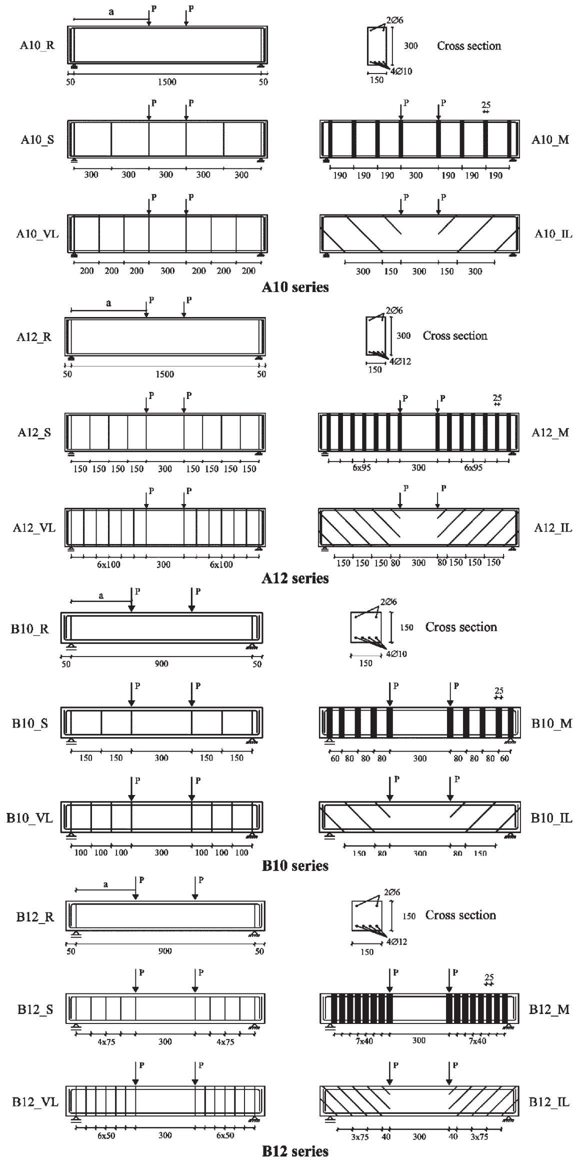

Figure 1 — Tested series

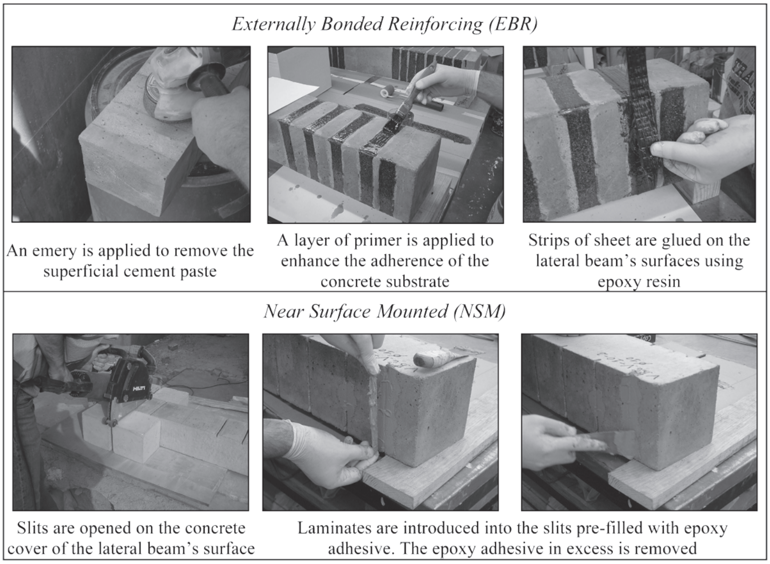

Figure 2 — Techniques for the shear strengthening of reinforced concrete beams

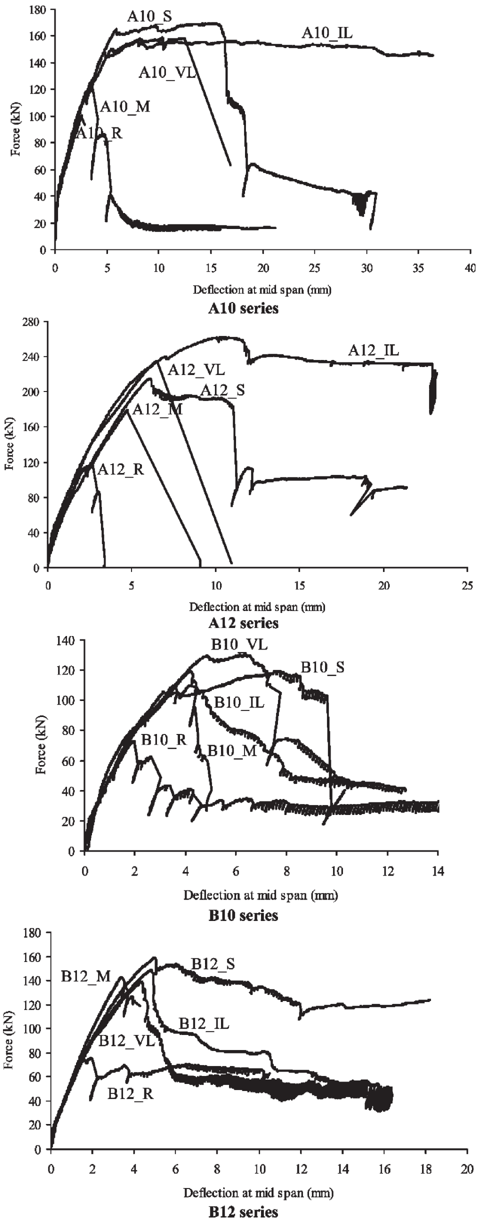

Figure 3 — Force-deflection relationship of the four tested beams series

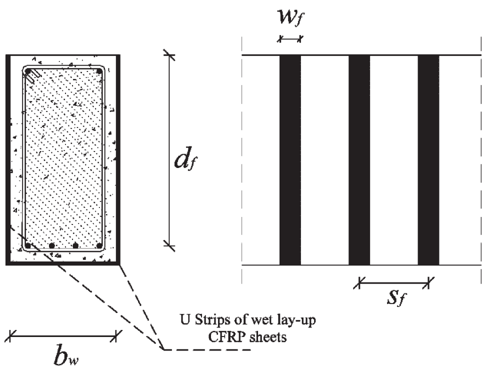

Figure 4 — Data for the externally bonded shear strengthening technique

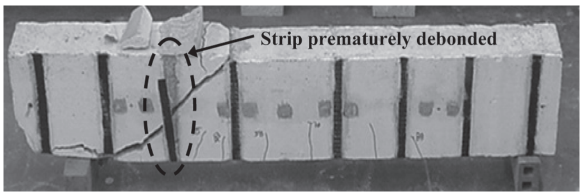

Figure 5 — Failure of A10_M beam

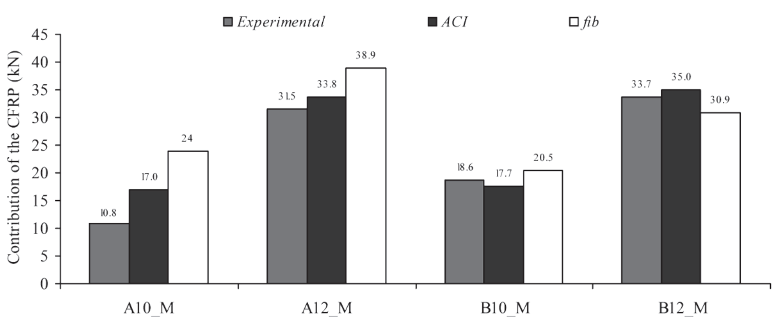

Figure 6 — Analytical *vs* experimental results (*ACI* and *fib* analytical formulation)

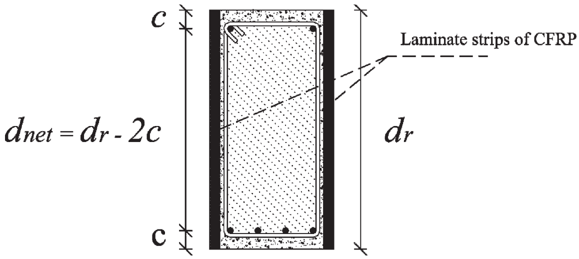

Figure 7 — Data for the near surface mounted shear strengthening technique

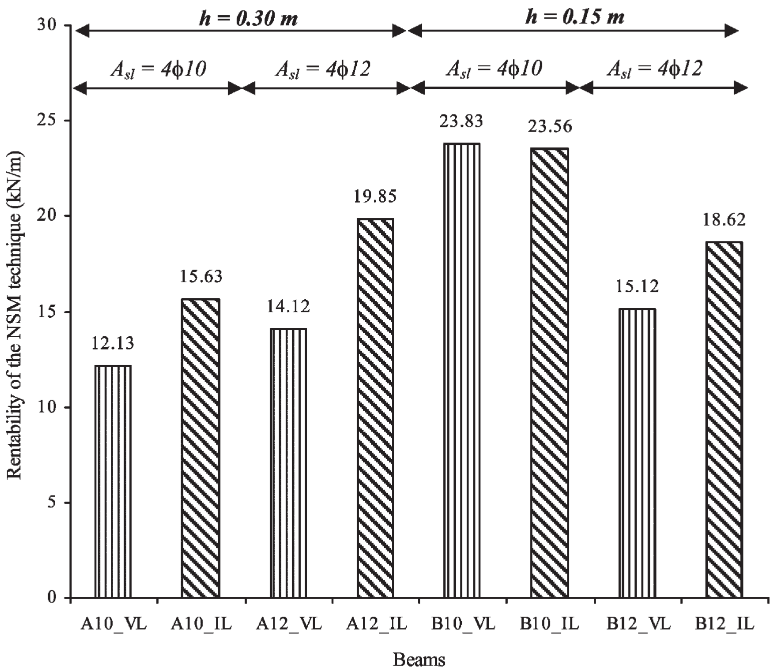

Figure 8 — Representation of the profitability index for the NSM technique