NEAR SURFACE MOUNTED TECHNIQUE FOR THE FLEXURAL AND SHEAR STRENGTHENING OF CONCRETE BEAMS



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ABSTRACT

The efficacies of the Near Surface Mounted and Externally Bonded Reinforcing techniques for the flexural and shear strengthening of reinforced concrete beams are compared. Both techniques are based on the use of carbon fiber reinforced polymer materials. In the present work the carried out tests are described and the main results are presented and analyzed.

1. INTRODUCTION

Near Surface Mounted (NSM) is a strengthening technique based on the use of laminate strips of carbon fiber reinforced polymer (CFRP) materials installed into precut slits opened on the concrete cover of the elements to strengthen [1]. This strengthening technique requires no surface preparation work and, after cutting the slit, requires minimal installation time compared to the Externally Bonded Reinforcing (EBR) technique. A further advantage associated with NSM is its ability to significantly reduce the probability of harm resulting from acts of vandalism, mechanical damages and aging effects.

In the present work the efficacies of the NSM and EBR techniques for the flexural and shear strengthening of reinforced concrete beams are compared. For the flexural strengthening, the influence of the longitudinal equivalent reinforcement ratio, $\rho_{l,eq}$, on the strengthening efficiency of both techniques is assessed. For the shear strengthening, the influences of the longitudinal steel reinforcement ratio, ρ_{sl}, and the beam depth on the strengthening efficacy of both techniques are evaluated. In this last experimental program, the influence of the inclination of the CFRP laminates in the NSM technique is also investigated. In the present paper the experimental program is described and the results are presented and analyzed.

2. STRENGTHENING TECHNIQUES

The NSM technique was made up of the following steps: 1) using a diamond cutter, slits of 4 to 5 mm width and 12 to 15 mm depth were cut on the concrete surface of the elements to strengthen; 2) slits were cleaned by compressed air; 3) CFRP laminates were cleaned by acetone; 4) epoxy adhesive was produced according to supplier recommendations; 5) slits were filled with the epoxy adhesive; 6) epoxy adhesive was applied on the faces of the laminate; and 7) laminates were introduced into the slits and epoxy adhesive in excess was removed.
To apply the wet lay-up strips of CFRP sheet by EBR technique, the following procedures were executed: 1) on the zones of the beam's surfaces where the strips of sheet would be glued, an emery was applied to remove the superficial cement paste (in the shear strengthening experimental program the beam edges were also rounded); 2) the residues were removed by compressed air; 3) a layer of primer was applied to regularize the concrete surface and to enhance the adherence capacity of the concrete substrate; and 4) strips of sheet were glued on the faces of the beam by epoxy resin.

3. MATERIALS

3.1 Concrete and steel bars

Table 1 includes the main properties of the concrete and steel bars used in the experimental program. The average values of the concrete compression strength at 28 days (f_{cm}) and at the date of testing the beams ($f_{cm,j}$) were evaluated from uniaxial compression tests (3 for each series, at least) with cylinders of 150 mm diameter and 300 mm height. Steel bars were tested and each result is the average of at least five tests.

Table 1 - Properties of the concrete and steel bars

Element type	Concrete		Steel		
	f_{cm} (MPa)	$f_{cm,j}$ (MPa)	ϕ_s (mm)	f_{sym} (MPa)	f_{sum} (MPa)
Flexural strengthening program	44.2	52.2 (70 days)	5	620	700
			6.5	480	570
Shear strengthening program	37.6 [1] 49.5 [2]	49.2 [1] (227 days) 56.2 [2] (105 days)	6 (stirrups)	540	694
			6 (long.)	622 [1] 618 [2]	702 [1] 691 [2]
			10	464	581
			12	574 [1] 571 [2]	672 [1] 673 [2]

[1] A series; [2] B series

3.2 CFRP systems

Two CFRP systems were used on the present work: unidirectional wet lay-up sheets of 80 mm width and precured laminates of 1.4×9.6 mm^2 cross-section. These CFRP systems have the properties indicated in Table 2.

Table 2 - Properties of the CFRP materials

CFRP system				Main properties			
Type		Material		Tensile strength (MPa)	Young's modulus (GPa)	Ultimate strain (%)	Thickness (mm)
S&P C-Sheet (wet lay-up sheet)		Primer [1]		12	0.7	3.0	-
		Epoxy [1]		54	3	2.5	-
	Sheet	Flexural strengthening prog.	C-Sheet 240[1]	3700	240	1.5	0.111
		Shear strengthening prog.	C-Sheet 530[1]	3000	390	0.8	0.167
CFK 150/2000 (precured laminate)		Adhesive [1]		16-22	5	-	-
	Laminate	Flexural strengthening prog. [2]		2740	158.8	1.7	1.4
		Shear strengthening prog. [2]		2286	166	1.3	1.4

[1] According to the supplier; [2] Evaluated from experimental tests

4. FLEXURAL STRENGTHENING

Figure 1 represents the geometry of the beams, the reinforcement arrangement and the number and position of the CFRP. The load configuration and the support conditions are also schematized. The cross-section area of the CFRP systems was evaluated in order to be similar the $A_f\,E_f\,/\,A_{sl}\,E_s$ ratio for the tested series, where A_f and E_f are the CFRP cross-section area and the Young's Modulus of the CFRP systems, and A_{sl} and E_s (200 GPa) are the cross-section area and the Young's Modulus of the longitudinal tensile steel bars. In this evaluation the distinct effective depth of the CFRP systems was not considered, but its influence is marginal. Shear reinforcement was selected to assure bending failure prior to shear failure for all beams. The beams were tested at the age of about 70 days [2].

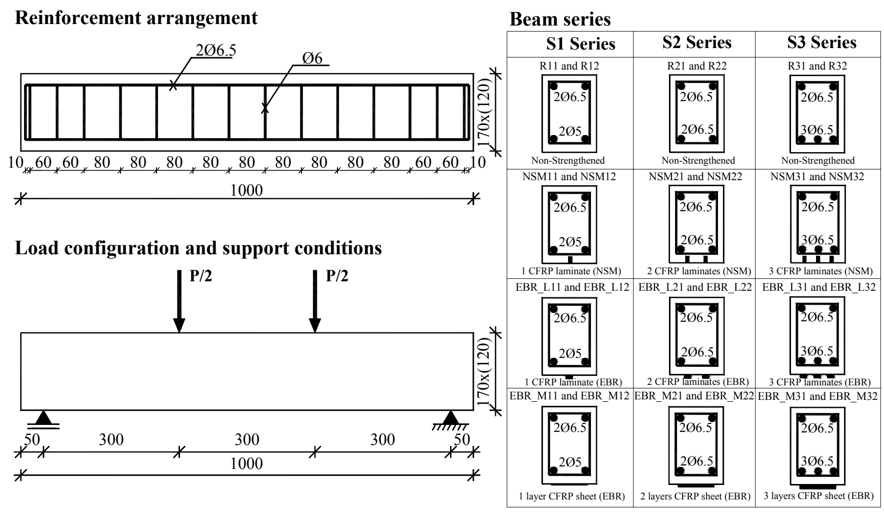

Figure 1: Beam series for the flexural strengthening

The force-deflection relationships for the series of tested beams are depicted in Figure 2. The strengthening efficacy is evaluated in terms of the service (P_{serv}) and the maximum (P_{max}) load, see Table 3. P_{serv}(S) and P_{max}(S) are the service and maximum load of a strengthened beam, respectively, while P_{serv}(R) and P_{max}(R) are the service and maximum load of the reference beam. In Table 3 the equivalent reinforcement ratio, $\rho_{l,eq}=A_{sl}/(b\,d_s)+(A_f E_f/E_s)/(b\,d_f)$, is also indicated, where b is the beam width and d_s and d_f are the effective depth of the longitudinal steel bars and CFRP systems, respectively. The influence of the $\rho_{l,eq}$ on the strengthening efficacy index is graphically represented in Figure 3. In terms of the beam load carrying capacity the NSM technique was the most effective one. The effectiveness, however, decreases with the increasing of $\rho_{l,eq}$. In terms of service load, the EBR based on the use of wet lay-up CFRP sheets was the most efficient, since E_f and d_f were the largest ones. The beams strengthened by EBR laminates have failed by the premature debonding of the laminates. Two failure modes occurred in the beams strengthened by EBR sheets: in the beams strengthened by one and two layers, the CFRP sheets have ruptured, while in the beams strengthened by three layers, the beam concrete cover has detached, having been bonded to the CFRP sheet. This last failure mode was also occurred in the beams strengthened by the NSM technique, but the detached concrete layer had larger thickness [2].

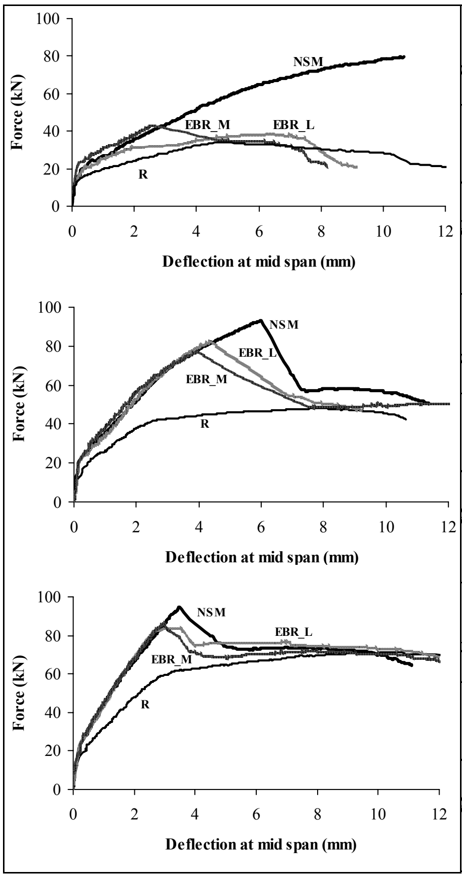

Figure 2: Force-deflection relationships of the flexural strengthening beams

Series	Beam's designation	$\rho_{l,eq}$ (%)	P_{serv} (kN)	$\frac{P_{ser}(S)-P_{ser}(R)}{P_{ser}(R)}$ (%)	P_{max} (kN)	$\frac{P_{max}(S)-P_{max}(R)}{P_{max}(R)}$ (%)
S1 series	R	-	22.1	-	36.6	-
	NSM	0.28	37.5	70	79.9	118
	EBR_L	0.28	31.9	44	38.6	5
	EBR_M	0.28	40.3	82	43.0	17
S2 series	R	-	40.5	-	48.5	-
	NSM	0.49	56.3	39	93.3	92
	EBR_L	0.48	57.6	42	83.5	72
	EBR_M	0.48	59.5	47	79.5	64
S3 series	R	-	51.5	-	71.8	-
	NSM	0.73	71.5	39	96.6	35
	EBR_L	0.73	74.1	44	86.5	20
	EBR_M	0.73	73.4	43	87.3	22

Table 3 - Main results of the flexural strengthening beam series

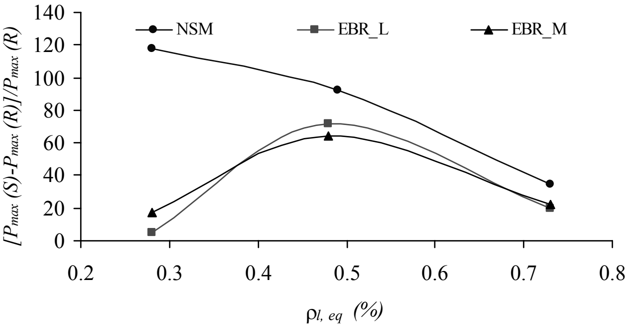

Figure 3: Strengthening efficacy index *vs* longitudinal equivalent reinforcement ratio

5. SHEAR STRENGTHENING

The experimental program was composed by four series of tests. The geometry, reinforcement arrangement and support conditions of the beams of these series are indicated in Figure 4. Each series was constituted by a beam without any shear reinforcement (R) and a beam for each of the following shear reinforcing systems: steel stirrups (S), strips of CFRP sheet (M), laminate strips of CFRP at 90º with the beam axis (VL), and laminate strips of CFRP at 45º with the beam axis (IL). The shear span, *a*, on the series of beams was two times the depth of the corresponding beams. The concrete clear cover for the top, bottom and lateral faces of the beams was 15 mm. 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 [3, 4]. Table 4 includes general information of the beams composing the four series. Further information can be found elsewhere [5]. The relationship between the force and the deflection at mid span of the tested beams is represented in Figure 5. Table 5 includes the main results obtained in the four 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 series of tests) 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.

The unreinforced shear R beams have failed by the formation of one shear failure crack without the longitudinal tensile reinforcement has yielded. In the beams reinforced with steel stirrups (S beams) a shear failure crack has occurred. The sudden loss of the load carrying capacity in the S beams corresponds to the moment when a stirrup crossing the shear failure crack has ruptured. In general, beams M have failed by the formation of a shear crack and have pilled off. B12_M beam had a distinct failure mode. This beam has failed by the formation of two "concrete lateral walls" that have separated from the interior concrete volume. A shear crack has formed in this interior concrete volume, and finally the "lateral walls" have ruptured. This complex type of failure has also occurred in B10_VL, B10_IL, B12_VL and B12_IL beams. In A10_VL beam, after the longitudinal tensile reinforcement has yielded, a shear failure crack has formed. A12_VL beam has failed in shear and the shorter bond length of the CFRP laminate strip crossing this crack has slid. Finally, A10_IL and A12_IL beams have ruptured by the formation of a flexural failure crack.

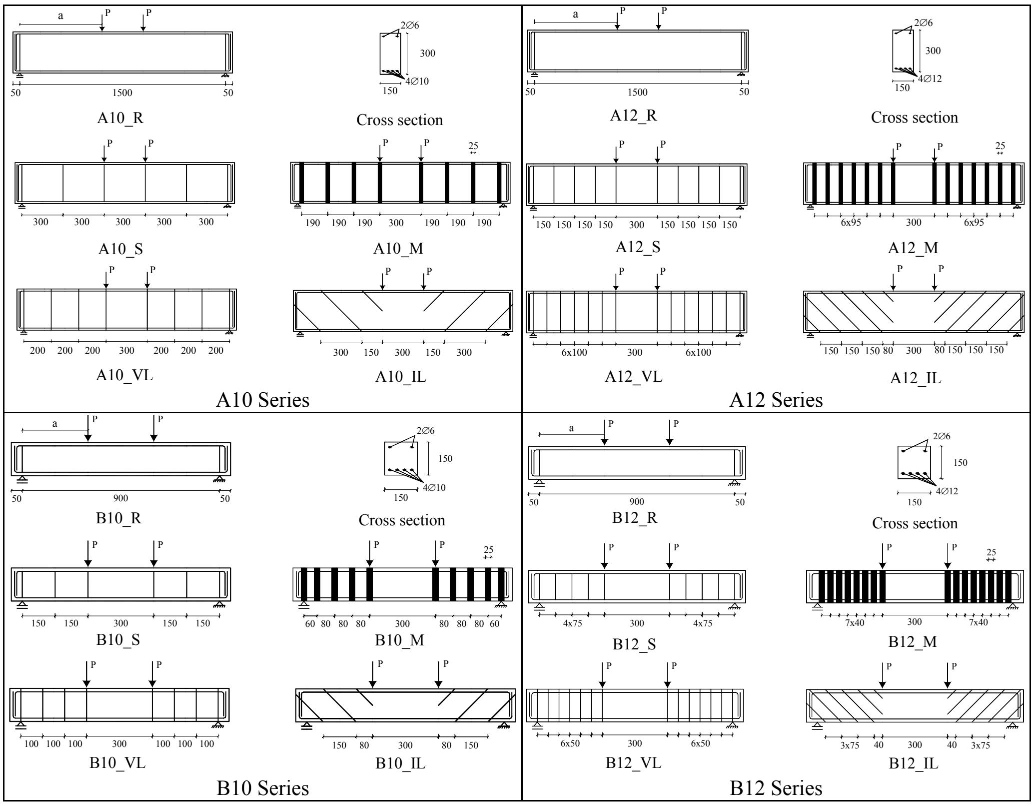

Figure 4: Beam series for the shear strengthening

Table 4 - Beam series for the shear strengthening

Beam's designation			Shear strengthening systems			
			Material	Quantity	Spacing (mm)	Angle (º)
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

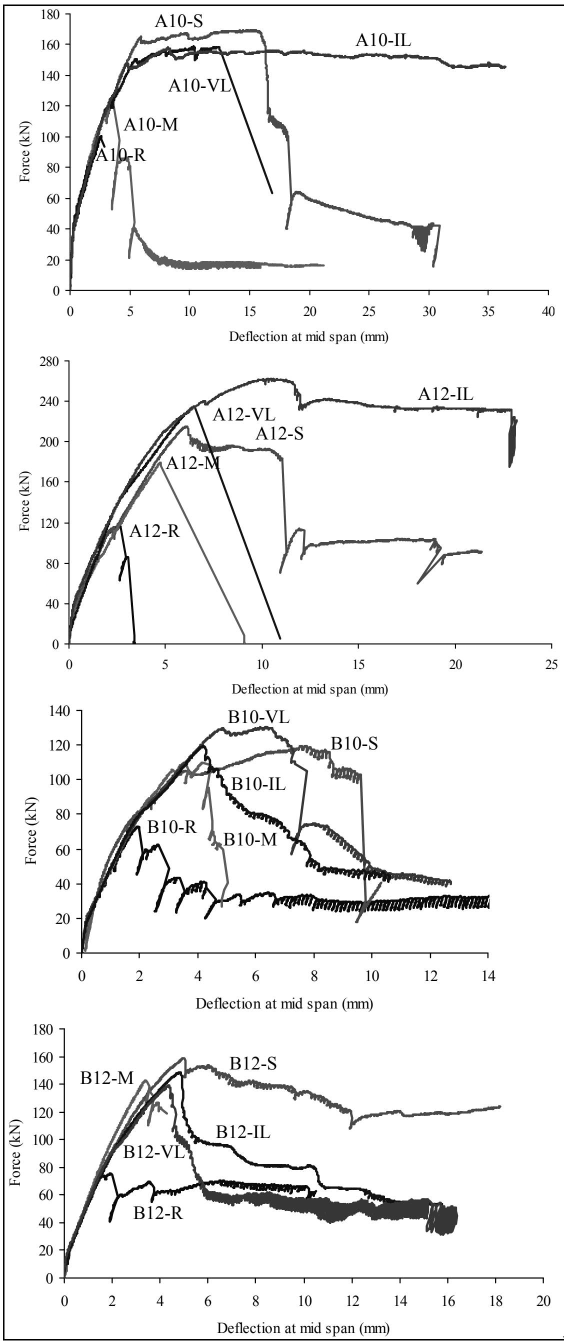

Figure 5: Force-deflection relationships of the shear strengthening beams

Beams Series A (ϕ10)	F_{max} (kN)	$\frac{F_{max}}{F_{max,A10\_R}}$	$\frac{F_{max}}{F_{max,A10\_S}}$
A10-R	100.40	1.00	0.59
A10-S	169.35	1.69	1.00
A10-M	122.06	1.22	0.72
A10-VL	158.64	1.58	0.94
A10-IL	157.90	1.57	0.93
Beams Series A (ϕ12)	F_{max} (kN)	$\frac{F_{max}}{F_{max,A12\_R}}$	$\frac{F_{max}}{F_{max,A12\_S}}$
A12-R	116.50	1.00	0.54
A12-S	215.04	1.85	1.00
A12-M	179.54	1.54	0.83
A12-VL	235.11	2.02	1.09
A12-IL	262.38	2.25	1.22
Beams Series B (ϕ10)	F_{max} (kN)	$\frac{F_{max}}{F_{max,B10\_R}}$	$\frac{F_{max}}{F_{max,B10\_S}}$
B10-R	74.02	1.00	0.61
B10-S	120.64	1.63	1.00
B10-M	111.14	1.50	0.92
B10-VL	131.22	1.77	1.09
B10-IL	120.44	1.63	1.00
Beams Series B (ϕ12)	F_{max} (kN)	$\frac{F_{max}}{F_{max,B12\_R}}$	$\frac{F_{max}}{F_{max,B12\_S}}$
B12-R	75.7	1.00	0.48
B12-S	159.1	2.10	1.00
B12-M	143.0	1.89	0.90
B12-VL	139.2	1.84	0.87
B12-IL	148.5	1.96	0.93

Table 5 - Main results of the shear strengthening beam series

From the results obtained, 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 efficacy was not only in terms of the beam load carrying capacity, but also in terms of deformation capacity at beam failure. Using the load carrying capacity of the unreinforced beams for comparison purposes, the beams strengthened by EBS 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 EBS technique.

6. CONCLUSIONS

The effectiveness of the NSM and EBR techniques for the flexural and shear strengthening of RC beams was compared. For the flexural strengthening, the NSM technique was the most effective, but the difference between the efficacy of NSM and EBR techniques has decreased with the increase of the longitudinal equivalent reinforcement ratio. For the shear strengthening, the NSM was also the most effective technique, and was also the easiest and fastest to apply, and assured the lowest fragile failure modes.

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