Materiali ed Approcci Innovativi per il Progetto in Zona Sismica e la Mitigazione della Vulnerabilità delle Strutture
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Low strength T-cross section RC beams shear-strengthened by NSM technique

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ABSTRACT: In 2003 a research program started with the aim of developing design guidelines for the shear strengthening of T cross section reinforced concrete (RC) beams using carbon fiber reinforced polymer (CFRP) laminates applied according to the Near Surface Mounted (NSM) technique. The previous series of tested beams were mainly conceived to appraise the influence of parameters such as percentage and orientation of laminates. The occurrence of a failure mode consisting in the separation of the strengthened cover of the web lateral faces, prompted the authors to further investigate the influence of the concrete mechanical properties. The series described in the present work comprehends ten beams characterized by low strength concrete. The main results are presented and analyzed also by comparison with those regarding a previous series characterized by the same test set-up and higher concrete strength.

1 EXPERIMENTAL PROGRAM

1.1 *Beam prototypes*

Figure 1 presents the T cross section beam prototype used in the experimental program, which was composed of ten NSM shear-strengthened beams and three reference ones. The reinforcement systems were designed to assure shear failure for all the tested beams. To localize the shear failure in one only of the beam shear spans, a three point load configuration of distinct length of the beam shear spans was selected, as Figure 1 shows. The monitored beam span (L_l) is 2.5 times the effective depth of the beam cross section (L_l/d = 2.5). To avoid shear failure in the L_r span, it was reinforced with steel stirrups Φ6@75mm. The differences between the tested beams are limited to the shear reinforcement systems applied in the L_l span. The experimental program (see Tab. 1 and Fig. 1) is composed of three reference beams and two groups of NSM shear-strengthened beams. The reference beams comprehend: one beam without any shear reinforcement (C-R beam), one with steel stirrups Φ6@300mm (2S-R beam) and another one with steel stirrups Φ6@180mm (4S-R beam). The first group is composed by five beams presenting the same stirrups ratio as the 2S-R reference beam, and having the CFRP shear strengthening arrangements indicated in Table 1. The second group also comprehends five beams, having the same stirrups ratio as the 4S-R reference beam, and the adopted strengthening configurations were those used in the first group of beams. Within each of the above groups, the beams with the lower percentage of laminates placed at 45° and 60°, and those with the higher ratio of laminates at 90°, 45° and 60°, were designed so as to present a similar maximum load. The beams were tested at an age of 51 days.

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Table 1. Shear reinforcement configurations of the tested beams.

Beam label	Shear reinforcement system in the smaller beam shear span (L_l)			
	Material	Quantity	Spacing (mm)	Angle (°)
C-R	-	-	-	-
2S-R	Steel stirrups	2ϕ6*	300	90
4S-R	"	4ϕ6*	180	90
2S-7LV	CFRP laminates	2x7 laminates**	114	90
2S-4LI45	"	2x5 laminates**	275	45
2S-7LI45	"	2x7 laminates**	157	45
2S-4LI60	"	2x4 laminates**	243	60
2S-6LI60	"	2x6 laminates**	162	60
4S-7LV	CFRP laminates	2x7 laminates**	114	90
4S-4LI45	"	2x4 laminates**	275	45
4S-7LI45	"	2x7 laminates**	157	45
4S-4LI60	"	2x4 laminates**	243	60
4S-6LI60	"	2x6 laminates**	162	60

Moreover, the two groups were conceived to study the influence of the amount of existing steel stirrups on the effectiveness of the NSM Technique. The distribution of the laminates followed the criterion represented in Fig. 1. The laminates were distributed along the AB line, where A is the beam support at the tested shear span and B was obtained assuming load degradation at 45°. To prevent brittle spalling of the concrete cover at the supports, the beam ends were strengthened by confining the concrete with a two-directional cage of stirrups of Φ 6 mm diameter. To overcome the difficulties to bend Φ32 mm longitudinal tensile bars, their ends were welded to steel plates.

1.2 *Materials*

The concrete compressive strength was evaluated at 28 days and at the age of beam testing, carrying out direct compression tests with cylinders of 150 mm diameter and 300 mm height, according to EN 206-1 Standards. In the tested beams, deformed steel bars of 6, 12, 16 and 32 mm diameter were used. The values of their main tensile properties were obtained from uni-axial tensile tests performed according to the EN 10002 recommendations.

Table 2. Values of the properties of the applied materials.

Concrete	Compressive strength				
	f_{cm} = 15.9 MPa (at 28 days)		f_{cm} = 18.6 MPa (at 51 days - beam tests)		
Steel	Stress	ϕ6	ϕ12	ϕ16	ϕ32
	f_{sym} a)	539 MPa	453 MPa	429 MPa	734 MPa
	f_{sum} b)	595 MPa	581 MPa	563 MPa	885 MPa
CFRP laminates	Tensile strength	Young's Modulus	Maximum strain ***	Thickness	
	f_{fum} = 2952 MPa c)	E_{fm} = 166.6 GPa c)	ε_{fum} = 17.7 ‰ c)	1.4 mm	

a) Average value of the yield stress; b) Average value of the maximum stress; c) Obtained from Hooke's law.

The tensile properties of the S&P laminates, CFK 150/2000 (S&P Reinforcement, 2002), were characterized by uni-axial tensile tests carried out according to ISO 527-5. These laminates have a cross section of 10×1.4 mm^2. Table 2 includes the average values of the mechanical properties for the employed materials. MBrace Resin 220 (Degussa Construction Chemicals Portugal 2003) adhesive was used to bond the laminates to the concrete.

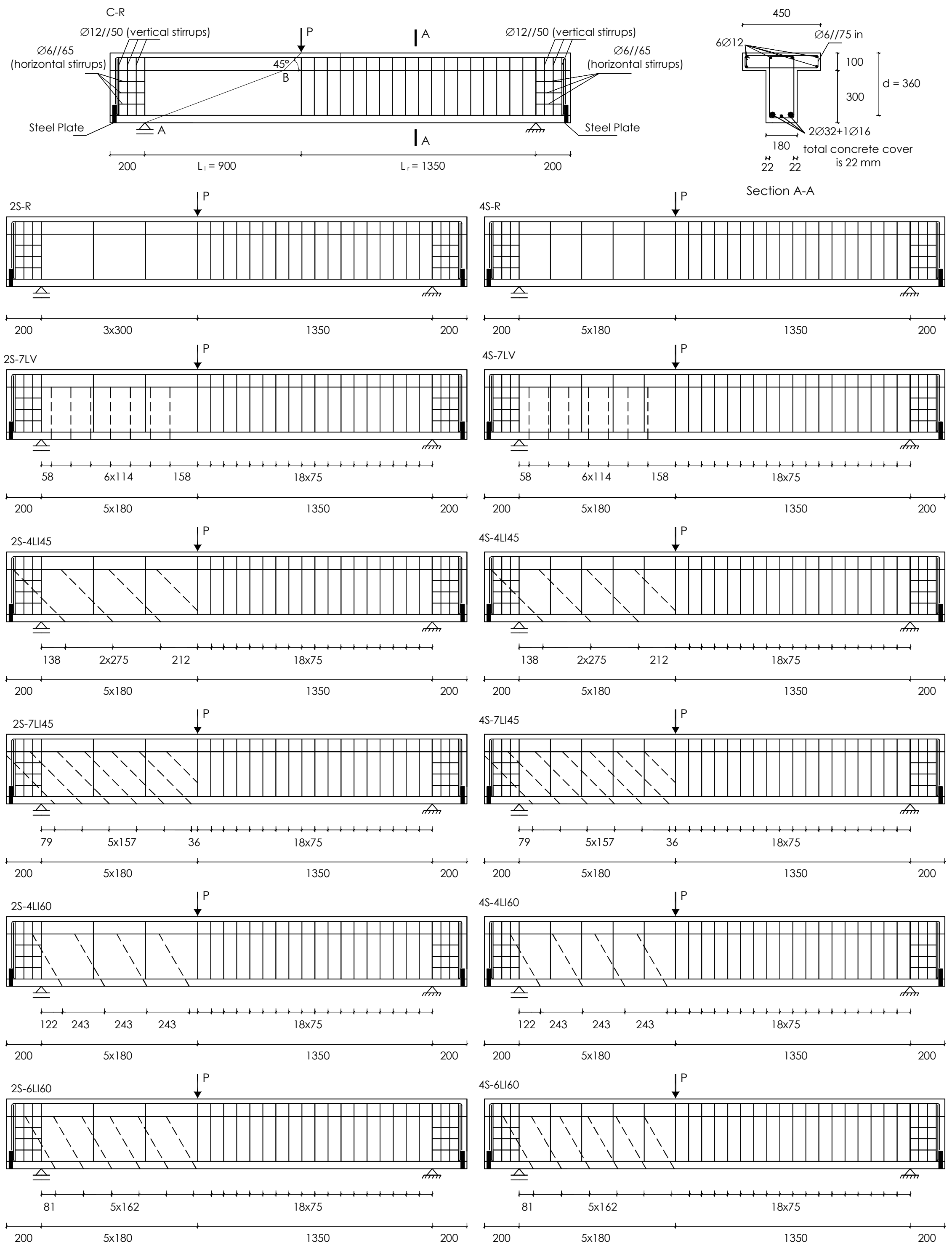


Figure 1. Tested beams: localization of the steel stirrups (thick lines) and CFRP laminates (dashed lines)

1.3 *Strengthening technique*

The NSM technique was made up of the following steps: 1) using a diamond cutter, slits of 5 mm width and 12 mm depth were cut on the concrete cover (of about 22 mm thickness) of the lateral surfaces of the beam's web, according to the pre-defined arrangement for the laminates (the laminates were not anchored in the beam's flange, but they were restricted to the beam's web); 2) slits were cleaned by compressed air; 3) CFRP laminates were cleaned by acetone; 4) epoxy adhesive was prepared according to the supplier's recommendations; 5) slits were filled with the epoxy adhesive;

6) epoxy adhesive was applied on the faces of the laminates; and 7) the laminates were introduced into the slits and the adhesive in excess was removed.

1.4 *Test set-up*

The beams were submitted to three point bending tests (see Fig. 1). The tests were carried out using a servo closed-loop control equipment, taking the signal read in the LVDT placed at the loaded section to control the test at a deflection ratio of 0.01 mm/s.

2 RESULTS

2.1 *Load carrying capacity up to failure and failure modes*

The recorded force-displacement diagrams in the loaded section obtained for the tested beams are reported, for the beams of both the groups, in Figure 2. The typical diagram of a strengthened beam is characterized by a first branch, from zero displacement up to the formation of the shear crack, in which it almost coincides with the one of the reference beam, and a following branch, up to the peak load, in which the load carrying capacity, corresponding to each displacement, is higher than the reference beam's. The displacement values where the shear crack occurred are 1.29 and 1.26 mm for the 2S-R and 4S-R beam, respectively. To appraise the increase in load-carrying capacity, attention was focused on the difference in behaviour between the strengthened beam and the corresponding reference one, for the displacement range from the crack formation up to the displacement where the reference beam attained the peak load. The following parameters were calculated: the maximum value of the ratio $\left(\Delta F/F^{ref}\right)_{max}$ between the increment of resisting force with respect to the reference beam and the corresponding displacement $u\left[\left(\Delta F/F^{ref}\right)_{max}\right]$ (see Fig. 2a). For the beams belonging to the first group, the maximum value of $\Delta F/F^{ref}$ was reached for a displacement lower than the one corresponding to failure of the reference beam (5.28 mm) and the average value of it amounted to 28.85%. Also for the beams of the second group, the maximum $\Delta F/F^{ref}$ value occurred in correspondence of a displacement lower than the one corresponding to failure of the reference beam (7.21 mm) and the average value, obtained neglecting the beam 2S-7LV, amounted to 18.06%. In the following, the data regarding the 2S-7LV beam will be neglected because they are deemed affected by some disturbance that the post-test inspections, currently underway, are about to clarify. As regards parameters related to the ultimate state, for each of the tested beams, the value of the maximum force, F_{max}, the corresponding displacement $u(F_{max})$ and the ratio of the maximum force increment with respect to the reference beam divided by the maximum force of this latter, $\Delta F_{max}/F_{max}^{ref}$, were calculated and listed in Table 3. The maximum value of the $\Delta F_{max}/F_{max}^{ref}$ ratio for the 2S-7LI45 and 2S-6LI60 beams was 35.32 and 31.46%, respectively, meaning that the solution with laminates at 45 and 60° resulted to be the most effective. The same trend can be observed for the beams with the higher amount of stirrups. In fact the maximum value of the $\Delta F_{max}/F_{max}^{ref}$ ratio, observed for the 4S-7LI45 and 4S-6LI60 beams, was 17.31 and 19.25%, respectively. The average value of $\Delta F_{max}/F_{max}^{ref}$ varies from 27.40% to 16.15% when the amount of stirrups changes from Φ6/300 mm to Φ6/180 mm, meaning that the interaction with stirrups plays a detrimental effect on the effectiveness of the NSM strengthening system. It has to be outlined that the behavior at ultimate of all of the strengthened beams was characterized by the progressive detachment of the concrete cover from the lateral faces of the web, as it can be gathered from the post-test photographic documentation (see Fig. 3).

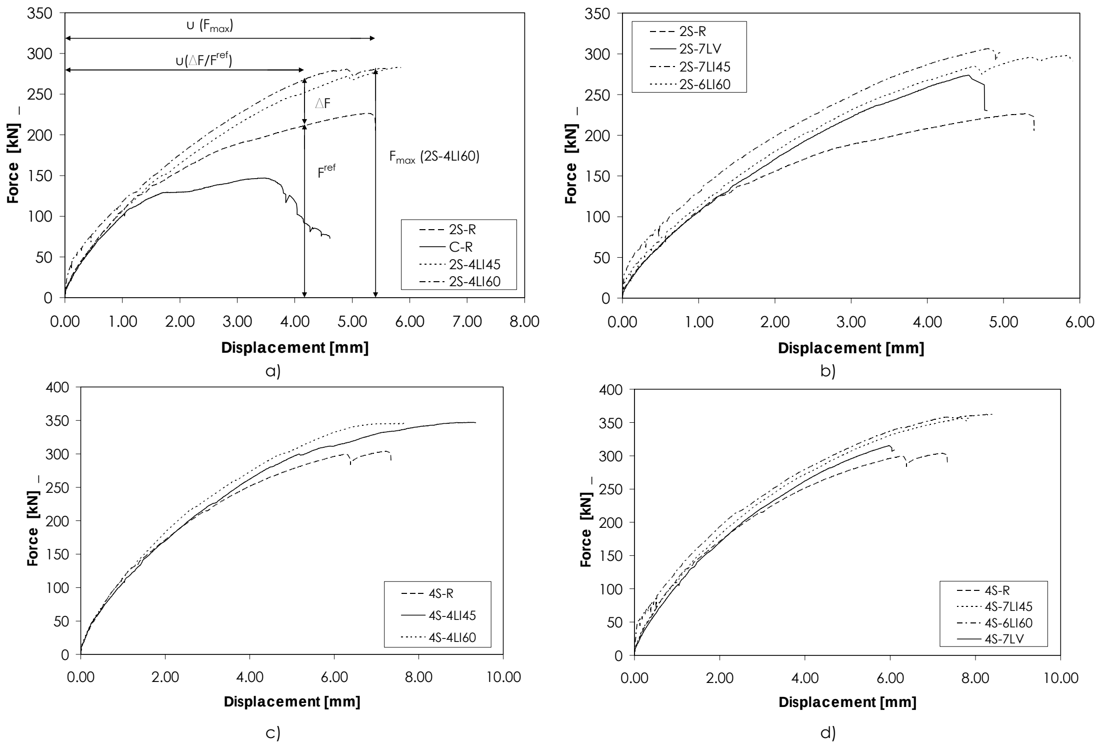


Figure 2. Force vs. deflection at loaded section of the tested beams: beams with 2 stirrups and lower (a) and higher (b) percentage of laminates; beams with 4 stirrups and lower (c) and higher (d) percentage of laminates

Table 3. Indicators of the NSM stiffness

Beam label	$\left(\Delta F/F^{ref}\right)_{max}$ (%)	$u\left[\left(\Delta F/F^{ref}\right)_{max}\right]$ (mm)	F_{max} (kN)	$\Delta F_{max}/F^{ref}_{max}$ (%)	$u\left(F_{max}\right)$ (mm)
C-R	-	-	146.99	-	
2S-R	-	-	226.47	-	5.28
4S-R	-	-	303.81	-	7.21
2S-7LV	26.07	4.46	273.74	20.87	4.54
2S-4LI45	22.03	4.93	283.04	24.98	5.80
2S-7LI45	38.45	4.50	306.46	35.32	4.80
2S-4LI60	27.40	4.45	281.61	24.35	5.54
2S-6LI60	30.32	4.60	297.73	31.46	5.84
4S-7LV	6.90	6.38	315.23	3.76	5.98
4S-4LI45	12.17	6.38	347.18	14.27	9.28
4S-7LI45	19.37	6.38	356.40	17.31	7.83
4S-4LI60	19.67	6.38	345.62	13.76	7.67
4S-6LI60	21.03	6.38	362.31	19.25	8.36

2.2 *Contribution of the CFRP strength configurations for the beam shear resistance*

The resisting shear force in the smaller shear span is equal to $V_r = 0.6\,F_{max}$ where F_{max} is the experimentally obtained maximum load. The NSM shear-strengthening contribution was determined based on the assumption that the contributions ascribed to stirrups, V_s, concrete, V_c, and CFRP, V_f, can be added directly. The results are listed in Table 4. It arises that, for the beams belonging to the first group, whose label starts with 2S (two stirrups), the ratio between the shear resistance provided by the CFRP strengthening configuration and the shear resistance of the reference beam, in percentage, is significant, ranging from 20.84% to 35.32%. As already pointed out (Dias & Barros 2006), the solutions with laminates at 45° and 60° provide the highest contribution for the beam shear resistance. The shear strengthening increment provided by the CFRP systems for the beams belonging to the second group, whose label starts with 4S (four stirrups), ranged from 13.76% to 19.26%, if the value regarding the beam 4S-7LV is excluded. The detrimental effect of the interaction with stirrups has to be outlined. It arises that, by nearly doubling the amount of stirrups, passing from Φ6/300 mm to Φ6/180 mm, the average shear strength increment provided by the CFRP systems passed from 27.37% to 16.16%. Note that this latter value was calculated by excluding beam 4S-7LV, whose peak load has to be confirmed by post-test inspection currently underway.

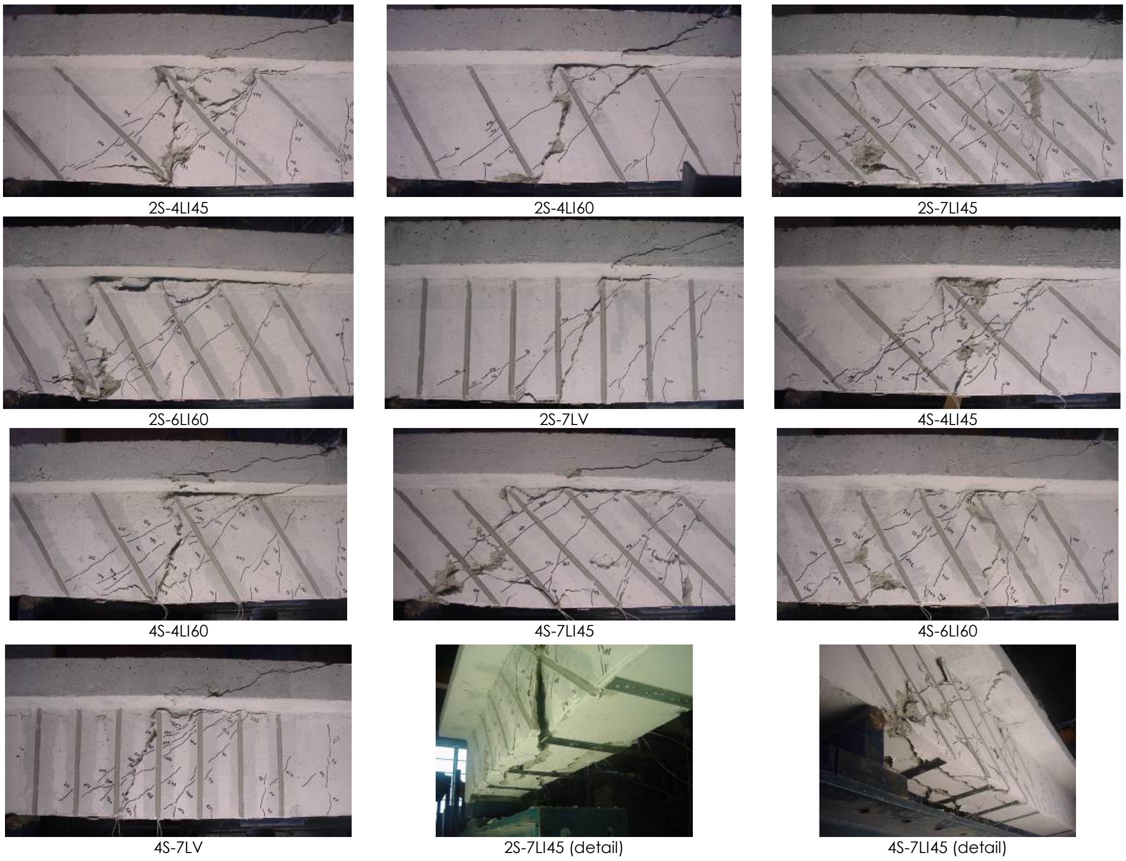
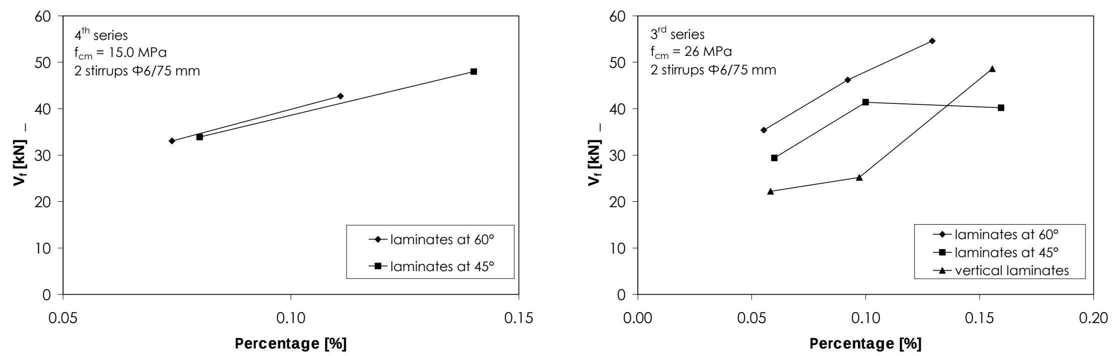


Figure 3. Details of the failure zone of the tested beams

The previous series of beams (Dias and Barros 2006) was characterized by: the same L_l/d value; the same percentage of stirrups in both the smaller shear span L_l (*i.e.* Φ6/300 mm) and the longer shear span L_r (*i.e.* Φ6/75 mm); and higher concrete compressive strength (26 MPa at 28 days and 31 MPa at the age of beam testing). This allows some comparisons to be made. As regards the influence of parameters such as inclination and ratio of laminates, it arises that the solution with vertical laminates is the least effective among the three examined configurations. Moreover, it emerges that, for the range of values of the percentage considered, an increase of the ratio of laminates, on average, produces an increase of the shear strengthening contribution by the laminates (Fig. 4). The influence of the mechanical properties of concrete were also analyzed for the beams with laminates placed at 45° and 60° and for the two different values of concrete compressive strength (Fig. 5). The experimental recordings were also compared with the predictions obtained by applying the formulation by Nanni et al. (2004). Provided that a larger amount of data is required and that the value regarding the highest percentage of laminates at 45° for the case of 26 MPa concrete is deemed affected by some disturbance, it can be outlined that the reduction of the mechanical properties of the concrete yields a reduction of the shear strengthening increment provided by the NSM laminates.

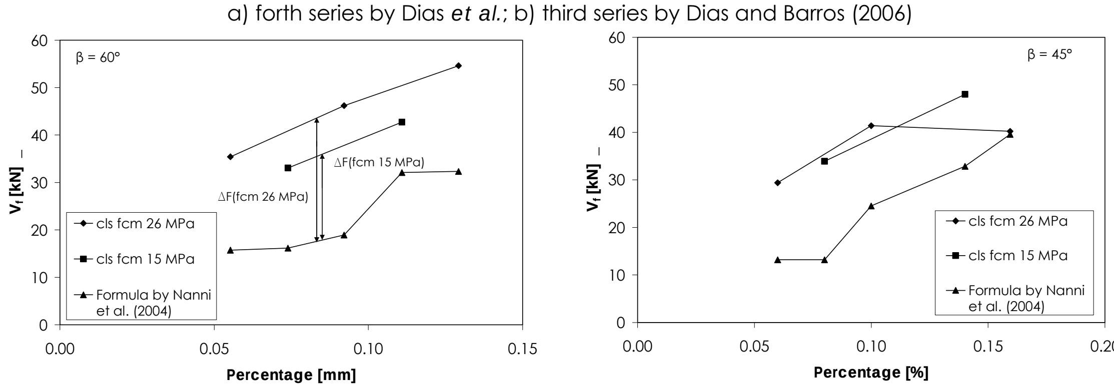
Table 4. Contribution of the reinforcement systems to the beam shear resistance.

Beam designation	Shear reinforcement configuration in the smaller beam shear span (L_l)	V_r (kN)	V_c (kN)	V_s (kN)	V_f (kN)	V_f / V_r^{ref} (%)
C-R	-	88.20	88.20	-	-	-
2S-R	Two steel stirrups	135.90	88.20	47.70	-	-
4S-R	Four steel stirrups	155.16	88.20	94.08	-	-
2S-7LV	Two steel stirrups + seven vertical laminates	164.22	88.20	47.70	28.32	20.84
2S-4LI45	Two steel stirrups + four laminates at 45°	169.80	88.20	47.70	33.90	24.94
2S-7LI45	Two steel stirrups + seven laminates at 45°	183.90	88.20	47.70	48.00	35.32
2S-4LI60	Two steel stirrups + four laminates at 60°	168.96	88.20	47.70	33.06	24.33
2S-6LI60	Two steel stirrups + six laminates at 60°	178.62	88.20	47.70	42.72	31.43
4S-7LV	Four steel stirrups + seven vertical laminates	189.18	88.20	94.08	6.90	3.79
4S-4LI45	Four steel stirrups + four laminates at 45°	208.32	88.20	94.08	26.04	14.29
4S-7LI45	Four steel stirrups + seven laminates at 45°	213.84	88.20	94.08	31.56	17.31
4S-4LI60	Four steel stirrups + four laminates at 60°	207.36	88.20	94.08	25.08	13.76
4S-6LI60	Four steel stirrups + six laminates at 60°	217.38	88.20	94.08	35.10	19.26



a) b)

Figure 4. Influence of NSM laminates inclination and percentage:
a) forth series by Dias *et al.*; b) third series by Dias and Barros (2006)



a) b)

Figure 5. Influence of concrete mechanical properties:
a) tested beams with laminates at 60°; b) tested beams with laminates at 45°

The design formula by Nanni et al. provides safe estimates of the NSM shear strength contribution, but the safety factor (ΔF in Fig. 5a) reduces when beams with lower concrete strength are analyzed. Thus, it is deemed necessary to outline that a comprehensive formulation cannot neglect the concrete mechanical properties.

3 CONCLUSIONS

The mechanical properties of the concrete of the RC beams strengthened in shear by means of NSM Technique play a paramount role on the efficacy of the strengthening technique. In fact, by reducing the concrete strength class, the detachment of the cover containing the glued laminates becomes more evident. In fact, it was observed that, all other parameters remaining equal, the shear resistance increase provided by an NSM laminates arrangement is lower as the concrete compressive strength decreases. Anyway, the maximum shear increment provided by the considered strengthening configurations, with respect to the reference beam, for the examined case of a concrete strength class of 15 MPa is still very significant. It also emerges that a formulation for the prediction of the NSM shear strengthening contribution cannot neglect the concrete mechanical properties.
As regards the influence of the NSM configuration, it has to be outlined that the solutions with laminates placed at 45° or at 60° with respect to the beam axis turns out to be the most effective in terms of shear strength contribution, regardless of either the concrete strength class or amount of existing steel stirrups.
The amount of existing steel stirrups also plays a very important role. In fact, it arises that, doubling the amount of stirrups, the NSM shear strength contribution seems to proportionally reduce.

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