NSM CFRP Laminates for the Shear Strengthening of T Section RC Beams

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INTRODUCTION

The shear failure mode of a reinforced concrete (RC) element should be avoided since it is brittle and unpredictable. The assessement of the behaviour of RC elements failing in shear is a challenging task, since it depends on several parameters, such as: geometry of the element, loading conditions, percentage of steel stirrups, percentagem of longitudinal tensile steel reinforcement, concrete strength. When using Fiber Reinforced Polymer (FRP) materials for the shear strengthening of RC beams, new complexities are introduced, namely [1-4]:

i) FRP-concrete bond conditions that are distinct of the steel stirrup-concrete bond liaisons;
ii) FRP materials have a linear elastic behavior up to their “explosive” rupture, while steel reinforcement has a ductile hardening phase after its yielding initiation;
iii) Carbon, Glass and Aramid FRP materials (CFRP, GFRP and ARFP), Externally Bonded Reinforcing (EBR) or Near Surface Mounted (NSM) strengthening techniques, and distinct strenghtening arrangements can be used in the shear strengthening of RC beams.

EBR and NSM have been the techniques used for the shear strengthening of RC beams. In the EBR technique wet lay-up FRP sheets can be applied in distinct arrangements: full wrapping the beam cross section; bonding three sides of the beam cross section, in a U-wrap shape; bonding the two lateral beam surfaces [1-4]. Precured FRP laminates, bonded to lateral beam surfaces by epoxy adhesive [3-5] is also another shear strengthening configuration in the EBR technique. A L configuration CFRP laminate with high rugosity of the faces bonded to concrete was also proposed to enchance the strengthening efficacy of EBR systems [5]. In general, these EBR systems provide an increase of the shear resistance of RC beams, however, premature debond gets questionable the rentability of some of these strengthening configurations. More recently a technique based on fixing, by epoxy adhesive, FRP bars of circular [6] or rectangular [7] cross section shape, into slits opened on the concrete cover of the lateral beam surfaces has been used, with the designation of NSM.

The efficacy of the NSM technique, using rectangular cross section CFRP laminates, for the shear strengthening of rectangular cross section RC beams was already assessed, as well as, the applicability of available analytical formulations for the prediction of the contribution of the FRP systems for the shear resistance [7, 8].

The efficacy of the NSM technique for the shear strengthening of T cross section RC beams is investigated in the present work, carrying out three point bending tests. The influence of the percentage and inclination of the CFRP laminates on the increase of the beam shear resistance is analyzed.

Keywords: reinforced concrete, CFRP, shear failure, NSM

EXPERIMENTAL PROGRAM

Beam prototypes

Fig. 1 presents the T cross section beam prototype used in the experimental program, which was composed by twelve beams. The reinforcement systems were designed to assure shear failure for all the tested beams. To localize the shear failure in an only one of the beam shear spans, a three point load configuration of distinct length of the beam shear spans was selected, as Fig. 1 shows. The monitored beam span (L_l) is 2.5 times the beam effective depth (L_l/d=2.5). To avoid shear failure in the L_r beam span, steel stirrups ϕ6@75mm were applied in this span. The differences between the tested beams are restricted to the shear reinforcement systems applied in L_l beam span.

The experimental program (see Tab. 1) is composed of one beam without any shear reinforcement (C-R beam), one beam with steel stirrups ϕ6@130mm (6S-R beam), one beam with steel stirrups ϕ6@300mm (2S-R beam) and nine beams of ϕ6@300mm and also including distinct CFRP arrangements on the L_l beam span: three distinct percentages of CFRP laminates and, for each CFRP percentage, three types of inclination for the laminates, 90º, 45º and 60º (angle between the CFRP fibers direction and beam axis).

Tab. 1. Shear reinforcement configurations of the tested beams.

Beam designation	Age at beam test (days)	Shear reinforcement system in the smaller beam shear span (L_l)			
		Material	Quantity	Spacement (mm)	Angle (º)
C-R	65	-	-	-	-
2S-R	61	Steel stirrups	2ϕ6 (2 branches)	300	90
6S-R	62	Steel stirrups	6ϕ6 (2 branches)	130	90
2S-3LV	72	Steel stirrups	2ϕ6 (2 branches)	300	90
		CFRP laminates	2x3 laminates (1.4x10 mm^2)	267	90
2S-5LV	71	Steel stirrups	2ϕ6 (2 branches)	300	90
		CFRP laminates	2x5 laminates (1.4x10 mm^2)	160	90
2S-8LV	70	Steel stirrups	2ϕ6 (2 branches)	300	90
		CFRP laminates	2x8 laminates (1.4x10 mm^2)	100	90
2S-3LI45	66	Steel stirrups	2ϕ6 (2 branches)	300	90
		CFRP laminates	2x3 laminates (1.4x10 mm^2)	367	45
2S-5LI45	64	Steel stirrups	2ϕ6 (2 branches)	300	90
		CFRP laminates	2x5 laminates (1.4x10 mm^2)	220	45
2S-8LI45	68	Steel stirrups	2ϕ6 (2 branches)	300	90
		CFRP laminates	2x8 laminates (1.4x10 mm^2)	138	45
2S-3LI60	71	Steel stirrups	2ϕ6 (2 branches)	300	90
		CFRP laminates	2x3 laminates (1.4x10 mm^2)	325	60
2S-5LI60	67	Steel stirrups	2ϕ6 (2 branches)	300	90
		CFRP laminates	2x5 laminates (1.4x10 mm^2)	195	60
2S-7LI60	68	Steel stirrups	2ϕ6 (2 branches)	300	90
		CFRP laminates	2x7 laminates (1.4x10 mm^2)	139	60

For the three series of beams with laminates of distinct orientation, the highest CFRP percentage in each series was evaluated to assure that the corresponding beams have a maximum load similar to the beam reinforced with the highest percentage of stirrups (ϕ6@130mm, 6S-R beam). This leads to the arrangements indicated in Tab. 1 and Fig. 2: eight laminates in each beam lateral faces for the laminates at 90º and 45º; seven laminates in each beam lateral faces for the laminates at 60º. Independently of the orientation of the laminates, for beams with the lowest CFRP percentage, three laminates were applied in each lateral face of the beam, while five laminates were fixed for the intermediate CFRP percentage. The distribution of the laminates followed the criteria represented in Fig. 1. The laminates were distributed along the AB line, where A is the beam support at the shear span test and B was obtained assuming a load degradation at 45º.

To avoid concrete spalling at the most loaded beam support, a confinement system based on the use of wet lay-up CFRP sheet (three layers, with the fibers direction coinciding with the beam axis direction) was applied according to the configuration illustrated in Fig. 1.

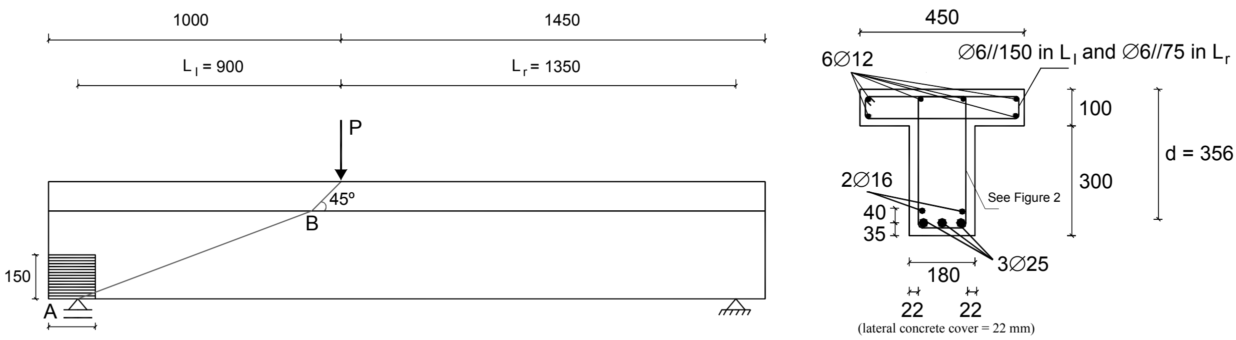

Fig. 1. Tested beams: geometry, steel reinforcements applied in all beams and CFRP-based strengthening configuration of the most loaded beam support (dimensions in mm).

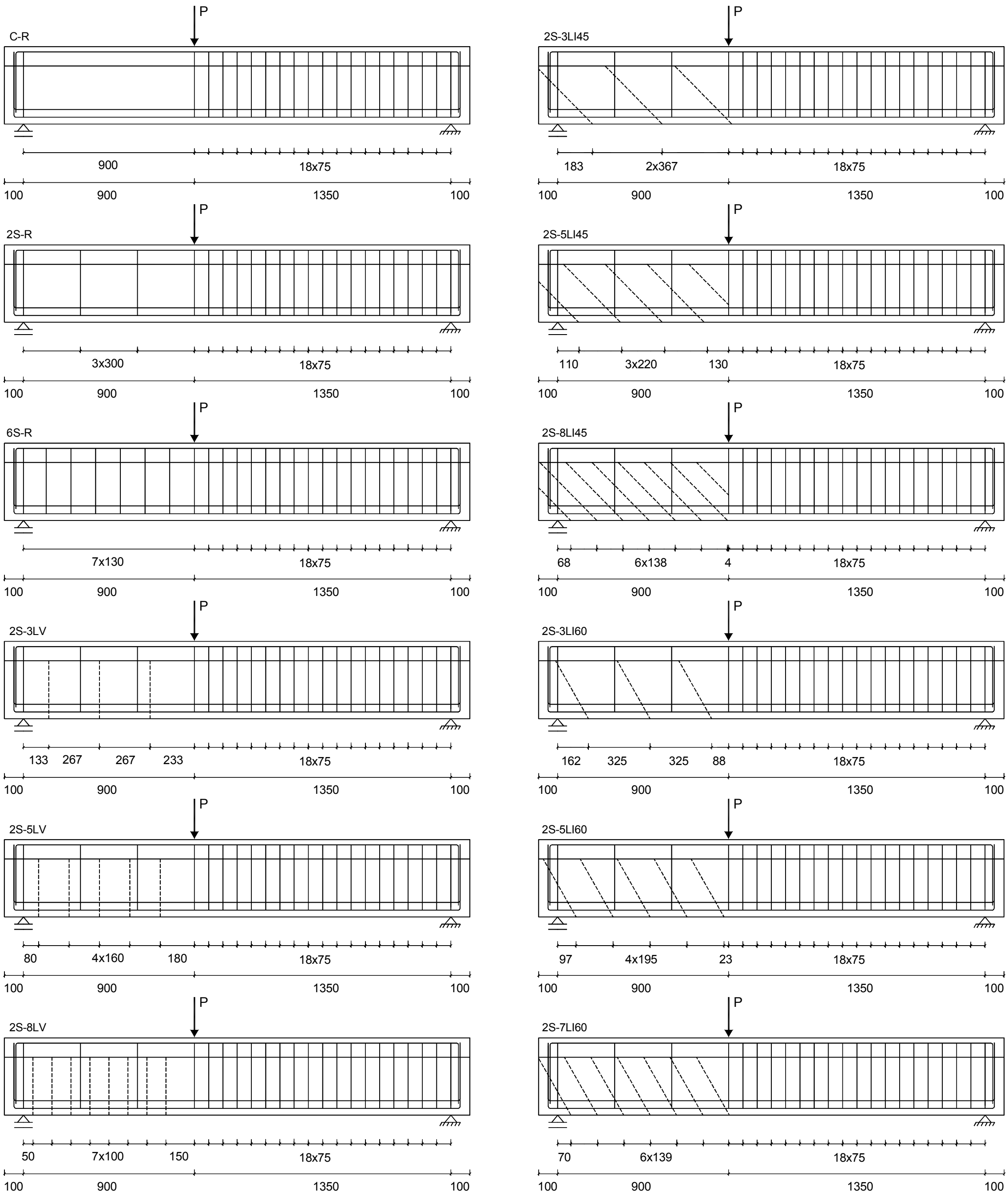

Fig. 2. Tested beams: localization of the steel stirrups (thick line) and CFRP laminates (dashed line).

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 Standard [9]. In the tested beams high bond steel bars of 6, 12, 16 and 25 mm diameter were used. The values of their main tensile properties were obtained from uniaxial tensile tests performed according to the recommendations of EN 10002 [10]. The tensile properties of the S&P laminates, CFK 150/2000 [11], were characterized by uniaxial tensile tests carried out according to ISO 527-5 [12]. These laminates have a cross section of 10×1.4 mm^2. Tab. 2 includes the average values obtained from these experimental programs. MBrace Resin 220 [13] adhesive was used to bond the laminates to the concrete. S&P C-Sheet 240 - 300 gr/m^2 [11] was applied in the beam left support, using a MBrace Resin 50 primer [13] and a MBrace Resin 55 epoxy resin [13].

Tab. 2. Values of the properties of intervening materials.

<table>
<tr><td rowspan="3">Concrete</td><td colspan="5">Compressive strength</td></tr>
<tr><td colspan="2">f_{cm} = 26.0 MPa
(at 28 days)</td><td colspan="3">f_{cm} = 31.1 MPa
(at 70 days - age of beam tests)</td></tr>
<tr></tr>
<tr><td rowspan="3">Steel</td><td>Stress</td><td>ϕ6</td><td>ϕ12</td><td>ϕ16</td><td>ϕ25</td></tr>
<tr><td>f_{sym} *</td><td>533 MPa</td><td>446 MPa</td><td>447 MPa</td><td>444 MPa</td></tr>
<tr><td>f_{sum} **</td><td>592 MPa</td><td>564 MPa</td><td>561 MPa</td><td>574 MPa</td></tr>
<tr><td rowspan="2">CFRP laminates</td><td>Tensile strength</td><td>Young's Modulus</td><td>Maximum strain ***</td><td colspan="2">Thickness</td></tr>
<tr><td>f_{fum} = 2952 MPa **</td><td>E_{fm} = 166.6 GPa</td><td>ε_{fum} = 17.7 ‰</td><td colspan="2">1.4 mm</td></tr>
</table>

* Average value of the yield stress; ** Average value of the maximum stress; *** Obtained from Hooke's law.

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, 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 produced according to supplier recommendations; 5) slits were filled with the epoxy adhesive; 6) epoxy adhesive was applied on the faces of the laminates; and 7) laminates were introduced into the slits and epoxy adhesive in excess was removed.

Test set-up

The beams were submitted to three point bending tests (see Fig. 1). The tests were carried out using a servo close-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.

RESULTS

Load carrying capacity up to failure

Tab. 3 includes the service load ($F_{L/400}$) and the maximum load (F_{max}) for each tested beam. The service load was considered as being the one, to which, the deflection at loaded section is equal to L/400 = 5.625 mm, where L is the beam span length, in mm. Giving to $F_{L/400}^{2S\text{-}R}$ and $F_{L/400}^{6S\text{-}R}$ the meaning of service load of the reference beams with the minimum and the maximum percentage of steel stirrups (2S-R beam: ϕ6@300mm; 6S-R beam: ϕ6@130mm, respectively), the values of the $F_{L/400}/F_{L/400}^{2S\text{-}R}$ and $F_{L/400}/F_{L/400}^{6S\text{-}R}$ ratios were evaluated and are indicated in Tab. 3. Similar procedure was followed for the maximum load, determining the $F_{max}/F_{max}^{2S\text{-}R}$ and $F_{max}/F_{max}^{6S\text{-}R}$ values, that are also indicated in Tab. 3, where $F_{max}^{2S\text{-}R}$ and $F_{max}^{6S\text{-}R}$ are the maximum load of the 2S-R and 6S-R reference beams, respectively.

Tab. 3. Load values at service and at failure.

Beam designation	$F_{L/400}$ (kN)	$F_{L/400}/F_{L/400}^{2S\text{-}R}$	$F_{L/400}/F_{L/400}^{6S\text{-}R}$	F_{max} (kN)	$F_{max}/F_{max}^{2S\text{-}R}$	$F_{max}/F_{max}^{6S\text{-}R}$
C-R	*	-	-	243	0.77	0.59
2S-R	311	1.00	0.84	315	1.00	0.77
6S-R	372	1.20	1.00	410	1.30	1.00
2S-3LV	*	-	-	316	1.00	0.77
2S-5LV	328	1.05	0.88	357	1.13	0.87
2S-8LV	387	1.24	1.04	396	1.26	0.97
2S-3LI45	327	1.05	0.88	328	1.04	0.80
2S-5LI45	378	1.22	1.02	384	1.22	0.94
2S-8LI45	*	-	-	382	1.21	0.93
2S-3LI60	369	1.19	0.99	374	1.19	0.91
2S-5LI60	382	1.23	1.03	392	1.24	0.96
2S-7LI60	403	1.30	1.08	406	1.29	0.99

* The deflection at *L/400*=5.625 mm was only attained after the deflection at F_{max}.

The relationship between the applied load and the deflection at the beam loaded section is represented in Figs. 3-6. In terms of service load, $F_{L/400}$, independentely of the CFRP percentage, the orientation of the laminates at 60º was the most effective, since it assured an average increase of 24%, when $F_{L/400}^{2S\text{-}R}$ is taken for comparison, while vertical laminates and laminates at 45º assured an average increase of 15% and 14%, respectively. This means that the adopted CFRP strengthening configurations provided an increase in the beam stiffness for the deflection level corresponding to serviciablity limit states. The largest increase on the service load (30%) was registered in the 2S-7LI60 beam, if 2S-R reference beam is considered for comparison. Amongst the beams with vertical laminates, the largest increase in the service load was also recorded in the beam with the highest percentage of laminates (an increase of 24% when $F_{L/400}^{2S\text{-}R}$ is taken for comparison). This tendency was not observed in the series of beams with laminates at 45º, since the largest increase in the service load (22%) was recorded in the beam with intermediate percentage of laminates (2S-5LI45 beam).

Comparing the service load of the 2S-R and 6S-R reference beams, an increase of 20% was registered when six steel stirrups was used instead of two. Therefore, for the CFRP strengthening configurations that were designed to provide a maximum load similar to the one of 6S-R reference beam, only the strengthening configuration of laminates at 45º did not exceed the service load increment provided by 6S-R reference beam. In this context, the performance of 2S-7LI60 beam should be highlighted, since the corresponding strengthening configuration assured an increase of 8% in the service load when 6S-R beam is taken for comparison. The increase in the service load assured by the strengthening configurations composed by five laminates at 45º and five laminates at 60º was also significant: $F_{L/400}^{2S\text{-}5LI45}/F_{L/400}^{6S\text{-}R}$ =1.02 and $F_{L/400}^{2S\text{-}5LI60}/F_{L/400}^{6S\text{-}R}$ =1.03, respectively.

If the maximum load of 2S-R reference beam ($F_{max}^{2S\text{-}R}$) is used for basis of comparison, it is verified that the reinforcing system of ϕ6@130mm (6S-R reference beam) provided an increase of 30% in the maximum load. When compared to the maximum load of the shear-unreinforced C-R beam, ϕ6@130mm (6S-R beam) and ϕ6@300mm (2S-R beam) assured an increase of 69% and 30% in the maximum load, respectively (see Fig. 3). If $F_{max}^{2S\text{-}R}$ is used for comparison, Tab. 3 and Figs. 4-6 show that, apart 2S-3LV beam, all adopted CFRP strengthening configurations provided an increase in the beam load carrying capacity, independentely of the percentage and orientation of the laminates. The strengthening arrangements using the lowest CFRP percentage had the smaller increments in terms of beam maximum load: 0%, 4% and 19% for the beams strengthened with laminates at vertical (2S-3LV beam), at 45º (2S-3LI45 beam) and at 60º (2S-3LI60 beam) direction, respectively, see Fig. 4. However, even for the 2S-3LV and 2S-3LI45 beams, after shear crack initiation of the 2S-R reference beam (corresponding to the abrupt load decay, see Fig. 4), those strengthened beams had a significant higher load carrying capacity than the one of 2S-R beam. In terms of maximum load, the level of strengthening efficacy provided by the three orientations for the laminates, when intermediate CFRP percentage was used, was similar to the level observed for the smaller CFRP percentage. In fact, the strengthening configurations of vertical laminates, laminates at 45º, and laminates at 60º assured an increase in the maximum load of 13%, 22% e 24%, respectively. The difference in terms of load carrying capacity of these strengthened beams, after the shear crack initiation of 2S-R beam is more pronounced that the differences recorded in the beams strengthened with the lowest CFRP percentage (compare Figs. 4 and 5). Amongst the beams strengthened with the highest CFRP percentage, the strengthening configuration of laminates at 60º was the most effective in terms of maximum load, since an increase of 29% was obtained, while an increase of 26% and 21% was recorded for the strengthening arrangements of vertical laminates and laminates at 45º, respectively.

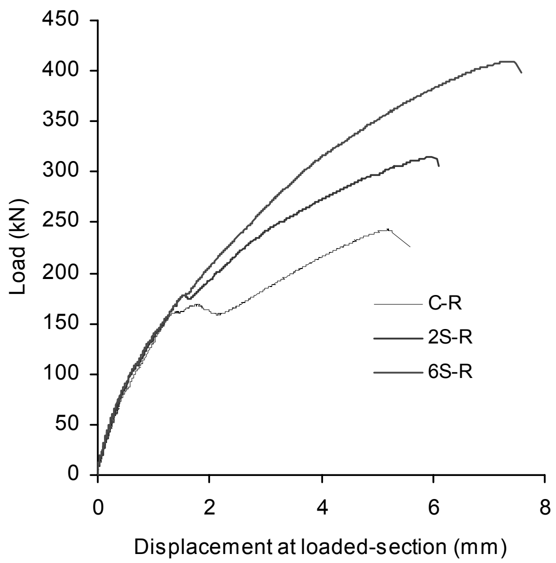

Fig. 3. Force *vs* deflection at loaded section of the reference beams (without CFRP strengthening systems).

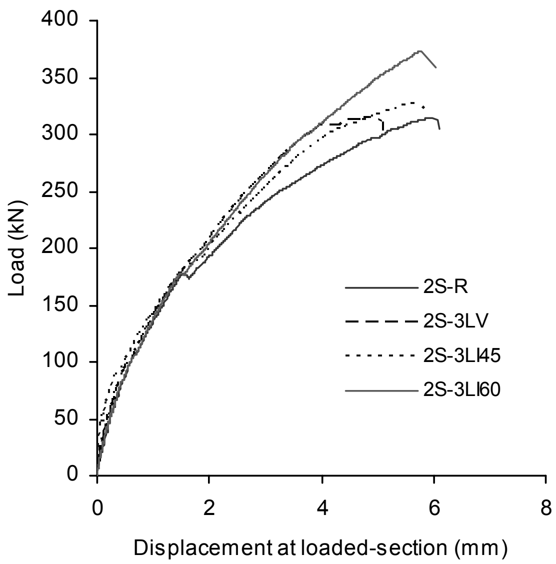

Fig. 4. Force *vs* deflection at loaded section of the beams with the lowest percentage of CFRP systems.

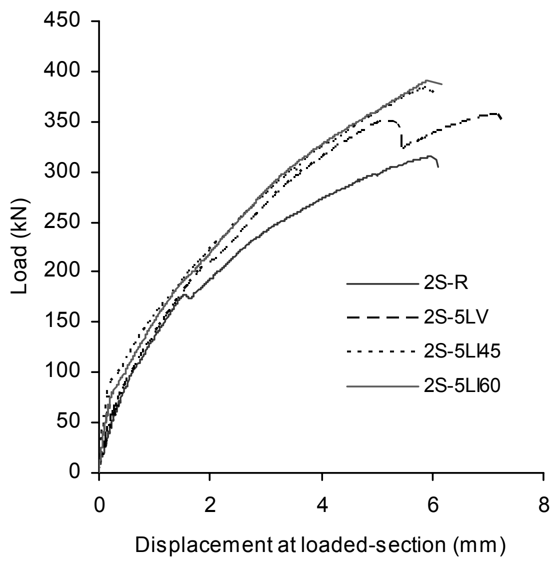

Fig. 5. Force *vs* deflection at loaded section of the beams with the intermediate percentage of CFRP systems.

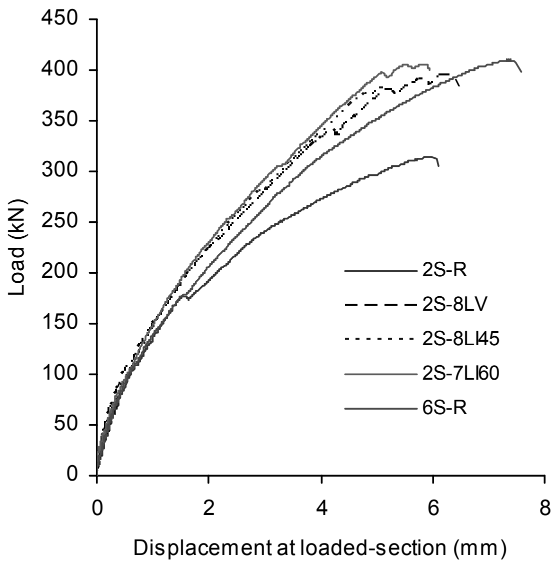

Fig. 6. Force *vs* deflection at loaded section of the beams with the highest percentage of CFRP systems.

As already mentioned, the highest CFRP percentage for each strengthening arrangement of the laminates was designed to assure beams of maximum load similar to the one of 6S-R refeference beam. The obtained experimental results show that, in general, this purpose was reached, since the maximum load of the beams with vertical laminates (2S-8LV), laminates at 45º (2S-8LI45) and laminates at 60º (2S-7LI60) had a maximum load 97%, 93% and 99% of the maximum load of the 6S-R reference beam, respectively, see Fig. 6. The most notable aspect is, however, the larger load carrying capacity of the strengthened beams than the one of 6S-R reference beam, after shear crack initiation of 2S-R beam (see Fig. 6). For the intermediate CFRP shear strengthening percentage, the beams with vertical laminates (2S-5LV), laminates at 45º (2S-5LI45) and laminates at 60º (2S-5LI60) had a maximum load 87%, 94% and 96% of the maximum load of the 6S-R reference beam, respectively, see Fig. 5. It was also significant the strengthening efficacy provided by the lowest CFRP shear strengthening percentage with the laminates applied at 60º, since the maximum load of 2S-3LI60 beam was 91% of the maximum load of 6S-R beam.

As expected, all beams failed in shear, with a formation of a shear failure crack in the smaller beam shear span. Fig. 7 includes details of the shear failure zones of all the tested beams (the steel stirrups at the smaller beam shear span are indicated by vertical lines, see also Fig. 2).

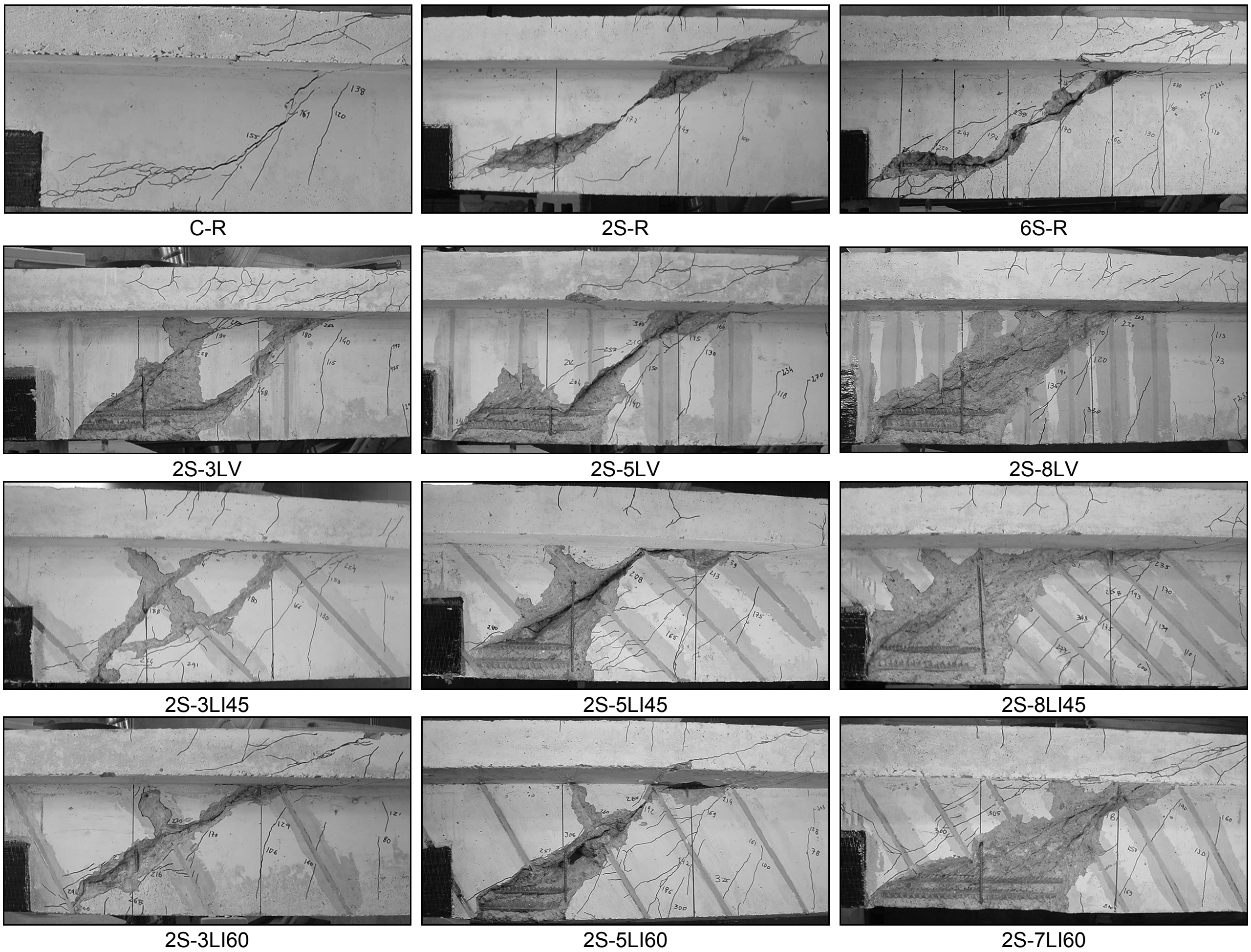

Fig. 7. Details of the failure zone of the tested beams.

Contribution of the CFRP strengthening configurations for the beam shear resistance

In the smaller beam shear span, the resistant shear force is $V_r = 0.6F_{max}$ (see Fig. 1) where F_{max} is the experimetally obtained beam maximum load (see Tab. 3). Assuming the contribution of the concrete (V_c), steel stirrups (V_s) and CFRP laminates (V_f) for the beam shear resistance can be added, results $V_r = V_c + V_s + V_f$. Tab. 4 includes the values of V_r for the tested beams, and the corresponding V_c, V_s and V_f components. The concrete contribution for the shear resistance, in all tested beams, was assumed equal to the shear resistance of the C-R reference beam (145.8 kN). The contribution of the two steel stirrups for the shear resistance of each strengthed beam was assumed equal to the contribution of the two steel stirrups in 2S-R reference beam ($V_s = V_r^{2S\text{-}R} - V_c^{2S\text{-}R}$ = 43.2 kN). The contribution of each CFRP shear strengthening configuration was obtained deducing to the shear resistance of this beam, the concrete (145.8 kN) and the two steel stirrups (43.2 kN) contribution: $V_f = V_r - V_c^{C\text{-}R} - V_s^{2S\text{-}R}$. Last column of Tab. 4 indicates the shear strengthening efficacy (relative increment of the shear resistance) provided by the distinct CFRP shear arrangements. From the analysis of the data included in Tab. 4, the main observations can be pointed out:

i) Concrete has provided the highest contribution;

ii) Two steel stirrups (2S-R beam) assured an increase of 43.2 kN in the beam shear resistance, while six stirrups (6S-R beam) provided an increase of 100.2 kN, indicating that the shear resistance has not a linear dependency on the percentage of steel stirrups;

iii) CFRP configuration of 2S-7LI60 beam assured a shear resistance increment of 54.6 kN, which is similar to the increase provided by 6S-R beam (100.2 – 43.2 = 57 kN). The CFRP strengthening configuration of 2S-8LV beam assured a contribution of 48.6 kN, which was 85% of the contribution of the steel stirrups of 6S-R beam. The CFRP shear contribution of the referred beams, and 2S-5LI45, 2S-8LI45 and 2S-5LI60 beams was higher than 70% of the contribution provided by the steel stirrups of 6S-R beam. The CFRP shear contribution of 2S-3LV e 2S-3LI45 was too low.

Tab. 4. Contribution of the reinforcement systems for 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)	$V_f / V_r^{2S\text{-}R}$ (%)
C-R	-	145.8	145.8	-	-	-
2S-R	Two steel stirrups	189.0	145.8	43.2	-	-
6S-R	Six steel stirrups	246.0	145.8	100.2	-	-
2S-3LV	Two steel stirrups + three vertical laminates	189.6	145.8	43.2	0.6	0.3
2S-5LV	Two steel stirrups + five vertical laminates	214.2	145.8	43.2	25.2	13.3
2S-8LV	Two steel stirrups + eight vertical laminates	237.6	145.8	43.2	48.6	25.7
2S-3LI45	Two steel stirrups + three inclined laminates at 45º	196.8	145.8	43.2	7.8	4.1
2S-5LI45	Two steel stirrups + five inclined laminates at 45º	230.4	145.8	43.2	41.4	21.9
2S-8LI45	Two steel stirrups + eight inclined laminates at 45º	229.2	145.8	43.2	40.2	21.3
2S-3LI60	Two steel stirrups + three inclined laminates at 60º	224.4	145.8	43.2	35.4	18.7
2S-5LI60	Two steel stirrups + five inclined laminates at 60º	235.2	145.8	43.2	46.2	24.4
2S-7LI60	Two steel stirrups + seven inclined laminates at 60º	243.6	145.8	43.2	54.6	28.9

Effect of the percentage and inclination of the CFRP strengthening systems

Fig. 8 represents the relationship between the shear strengthening efficacy provided by the CFRP arrangements and the CFRP percentage for the three shear strengthening configurations analyzed. The CFRP shear strengthening percentage, ρ_f, was obtained from the following expression:

$$\rho_f = \frac{2 \cdot a_f \cdot b_f}{b_w \cdot s_f \cdot sen\alpha} \times 100 \qquad (1)$$

where a_f and b_f are the dimensions of the laminate cross section. In equation (1), b_w is the width of the beam´s web, s_f is the CFRP spacing between consecutive laminates and α is the inclination of the laminates. In Fig. 9, the data are presented to highlight the influence of the orientation of the laminates on the CFRP shear strengthening efficacy. This figure shows that, independently of the CFRP percentage, the arrangement of laminates at 60º was the most effective amongst the adopted CFRP shear strengthening configurations. For the smaller CFRP percentage, the shear strengthening efficacy of the configuration at 60º was 4.6 times the one provided by the configuration at 45º. The CFRP arrangement of 2S-3LI60 beam assured an increase in the shear strengthening efficacy 1.4 times higher the one provided by 2S-5LV beam (ρ_f = 0.1%) and it was about 87% that of 2S-5LI45 (ρ_f = 0.1%) and 2S-8LI45 (ρ_f = 0.16%) beams. The smallest percentage of vertical laminates did not assure any benefit in terms of shear resistance. For this CFRP percentage, the laminates at 45º provided a reduced increase in the shear strengthening efficacy (about 4%).

Amongst the beams with the largest CFRP shear strengthening percentage (2S-8LV, 2S-8LI45 and 2S-7LI60 beams), the beam with laminates at 60º assured the largest increase in the shear strengthening efficacy (29%), in spite of being the one of smaller CFRP percentage (ρ_f = 0.13%) of the above mentioned beams (ρ_f = 0.16%). For the intermediate CFRP percentage a similar tendency was observed. The configuration of laminates at 60º (ρ_f = 0.09%) provided an increase of 24% in the shear strengthening efficacy, which is larger than the increase assured by vertical laminates (13%) and laminates at 45º (22%), both beams with a CFRP percentage of 0.1%. The strengthening efficacy in 2S-5LI60 was only exceeded by 2S-8LV (ρ_f = 0.16%) and 2S-7LI60 (ρ_f = 0.13%). The configuration with laminates at 45º, apart beam with the highest CFRP percentage (ρ_f = 0.16%), provided increments in the shear strengthening efficacy larger than those assured by the configuration of vertical laminates.

Fig. 8 shows, that, for the CFRP percentagens analyzed, apart beam with the highest percentage of laminates at 45º (2S-8LI45, ρ_f = 0.16%), in the remaining beams, the shear strengthening efficacy increased with the increment of ρ_f. However, it appears that the increase ratio will have a decreasing tendency with the increase of ρ_f.

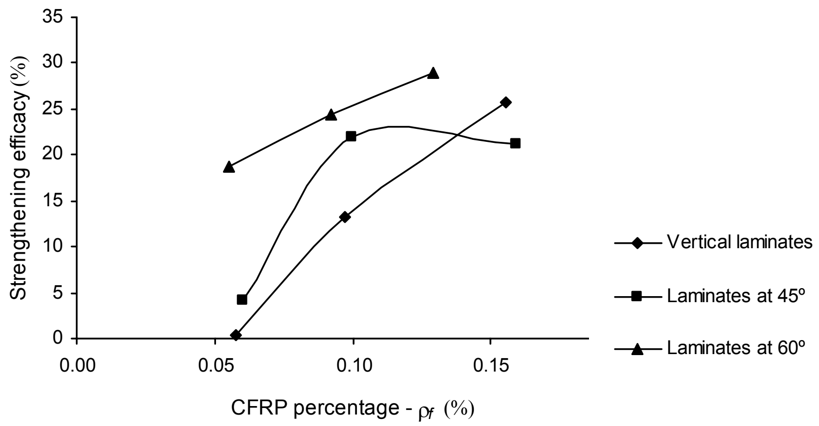

Fig. 8. Strengthening efficacy *vs* CFRP percentage.

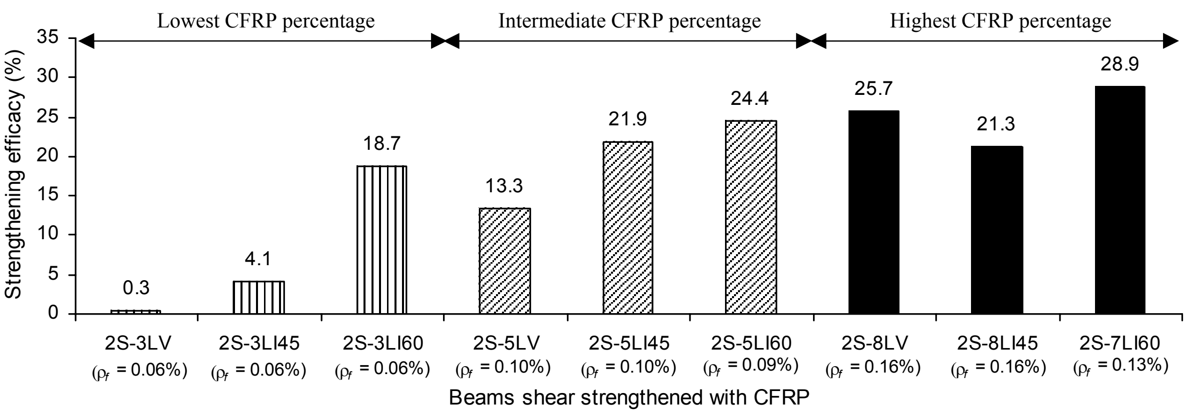

Fig. 9. Influence of the CFRP orientation on the CFRP shear strengthening efficacy.

ANALYTICA ANALYSIS

Taking the results obtained in the tested beams, the performance of the analytical formulation proposed by Nanni et al. [14] is checked. According to this formulation, the contribution of the NSM FRP elements for the shear strengthening is obtained from expression,

$$V_f = 4 \cdot \left(a_f + b_f\right) \cdot \tau_b \cdot L_{tot\,min} \tag{2}$$

where a_f and b_f are the dimensions of the laminate cross section, τ_b represents the average bond stress of the FRP elements intercepted by the shear failure crack, and $L_{tot\,min} = \sum_i L_i$, in which L_i represents the length of each single NSM laminate intercepted by a 45-degree shear crack expressed as (see Fig. 10),

$$L_i = \begin{cases} min\left(\dfrac{s_f}{cos\,\alpha + sen\,\alpha} i;\ l_{max}\right) & i = 1.....\dfrac{N}{2} \\ min\left(l_{net} - \dfrac{s_f}{cos\,\alpha + sen\,\alpha} i;\ l_{max}\right) & i = \dfrac{N}{2} + 1.....N \end{cases} \tag{3}$$

$L_{tot\ min}$ corresponds to an arrangement of the FRP reinforcements crossing the shear failure crack that leads to the minimum of the $\sum_i L_i$. In (3) α represents the slope of the FRP laminate with respect to the beam longitudinal axis and l_{net} is defined as,

$$l_{net} = l_b - \frac{2c}{sin\,\alpha} \tag{4}$$

which represents the net length of a FRP laminate, as shown in Fig. 10, to account for cracking of the concrete cover and installation tolerances. In (4), l_b is the actual length of a FRP laminate and c is the concrete clear cover. The first limitation of (3) takes into account bond as the controlling failure mechanism, and represents the minimum effective length of a FRP laminate intercepted by a shear crack as a function of the term N:

$$N = \frac{l_{eff}\left(1 + \cot\alpha\right)}{s_f} \tag{5}$$

where N is rounded off to the lowest integer (e.g., N=5.7 $\Rightarrow$ N = 5), and l_{eff} represents the vertical length of l_{net} , as shown in Fig. 10, evaluated from:

$$l_{eff} = l_b\, sin\,\alpha - 2c \tag{6}$$

The second limitation in (3), $L_i = l_{max}$, results from the force equilibrium condition, taking an upper bound value for the effective strain, ε_{fe} ,

$$l_{max} = \frac{\varepsilon_{fe}}{2} \cdot \frac{a_f \cdot b_f}{a_f + b_f} \cdot \frac{E_f}{\tau_b} \tag{7}$$

Adopting for ε_{fe} and τ_b the values obtained from pullout-bending tests [15], (5.9‰ and 16.1 MPa, respectively), and assuming for E_f the average value recorded in the experimental program, the values of V_f obtained from (2), included in Tab. 5, are compared to those registered experimentally. This table does not include the data of the 2S-3LV beam since according to the formulation by Nanni *et al.*, the FRP contribution is null in the cases where $s_f \geq l_{eff}$. According to the recommendations of ACI [3], V_f is multiplied by ϕ and ψ_f coefficients, which, for the present case, is assummed equal to 0.85. From the analysis of the values of Tab. 5 it can be concluded that the present formulation can not be applied for the beams of the lowest CFRP shear reinforcement ratio. If the values of these beams are not considered, the ratio between experimental results ($V_f^{exp.}$) and the analytical ones ($V_{fd}^{ana.}$), is of about 1.64, indicating that the formulation by Nanni *et al.* can be considered for the evaluation of the NSM CFRP laminates in the shear strengthening of concrete beams. However, the dispertion of the $V_f^{exp.} / V_{fd}^{ana.}$ values is high, which recommends that more research should be done in this field.

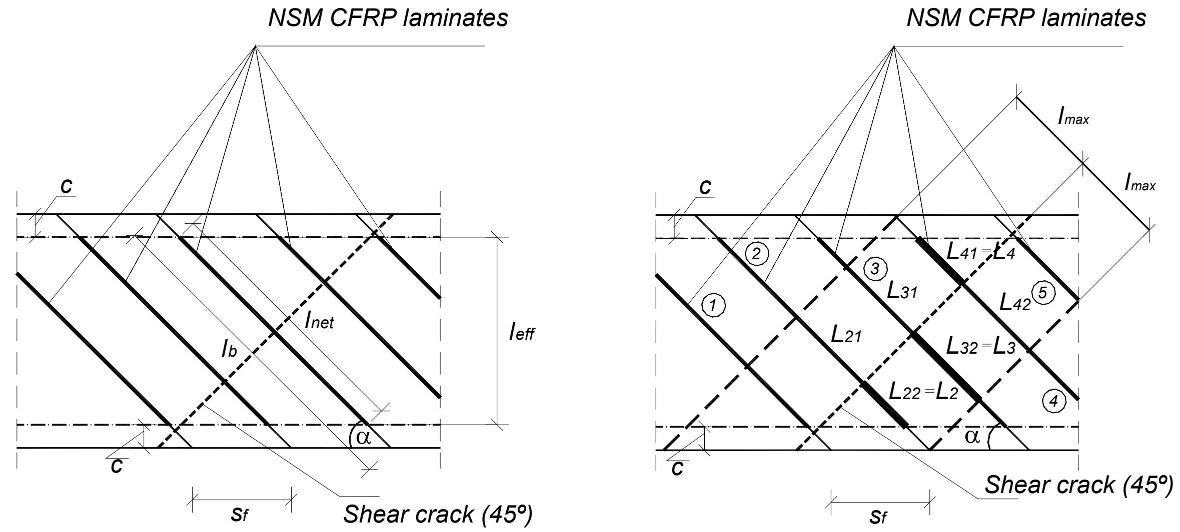

Fig. 10. Graphical representation of variables used in the formulation by Nanni *et al.*

Tab. 5. Analytical *vs* experimental results.

Beam designation	Experimental	Analytical	$V_f^{exp.}/V_{fd}^{ana.}$
	$V_f^{exp.}$ (kN)	$V_{fd}^{ana.}$ (kN)	
2S-3LV	0.6	*	-
2S-5LV	25.2	19.9	1.27
2S-8LV	48.6	26.3	1.85
2S-3LI45	7.8	19.9	0.39
2S-5LI45	41.4	19.9	2.08
2S-8LI45	40.2	43.5	0.92
2S-3LI60	35.4	3.6	9.83
2S-5LI60	46.2	19.9	2.32
2S-7LI60	54.6	39.8	1.37

* In this beam the analytical contribution of the CFRP for the beam shear resistance can not be evaluated.

CONCLUSIONS

An experimental program, composed of three point bending tests, was carried out with T cross section RC beams, shear strengthened by CFRP laminates applied according to the Near Surface Mounted technique (NSM). The experimental program was conceived to evidence the influence of the inclination of the laminates and the CFRP shear strengthening percentage. From the obtained results the following observations can be pointed out:

- Independently of the CFRP percentage and inclination of the laminates, NSM technique provided a significant contribution for the shear resistance of T section RC beams. Apart two beams of reduced CFRP percentage, the CFRP shear strengthening arrangements of the remaining beams assured a shear resistance contribution ranging between 13% and 29% of the shear resistance of the reference beam;
- Independently of the CFRP percentage, the configuration of laminates at 60º was the most effective amongst the adopted shear strengthening arrangements. Apart beam with the highest CFRP percentage, the beams strengthened with laminates at 45º were more effective than beams strengthened with vertical laminates;
- If 2S-R reference beam is taken for comparison, beams with laminates at 60º assured an increase in the beam maximum load of 19%, 24% and 29% for the CFRP percentage (ρ_f) of 0.06%, 0.09% and 0.13%, respectively;

- If 2S-R reference beam is taken for comparison, beams with laminates at 45º assured an increase in the beam maximum load of 4%, 22% and 21% for the CFRP percentage of 0.06%, 0.1% and 0.16%, respectively;
- If 2S-R reference beam is taken for comparison, beams with vertical laminates assured an increase in the beam maximum load of 0%, 13% and 26% for the CFRP percentage of 0.06%, 0.1% and 0.16%, respectively;
- The beams with the highest CFRP percentage assured a maximum load 97%, 99% and 93% of the maximum load of 6S-R reference beam for the CFRP configurations of laminates at 90º, 60º and 45º, respectively. The highest CFRP percentages had been designed to provide a maximum load similar to the one of 6S-R reference beam, with a reinforcing system composed of six steel stirrups;
- In terms of service load, the shear configuration of laminates at 60º was the most effective. The average increments of the service load assured by the configurations with laminates at 90º, 60º and 45º were 15%, 24% and 14%, respectively;
- After shear crack formation, the load carrying capacity of the beams shear strengthened with the highest CFRP percentage was significantly larger than the load carrying capacity of the 6S-R reference beam. This means that these CFRP shear strengthening arrangements contributed significantly for the increase of the beam stiffness after shear crack formation;
- 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), an analytical formulation for the NSM technique predicted a CFRP contribution around 61% of the experimentally registered values, which indicates to be a formulation that can be considered for the design of the contribution of the CFRP NSM shear strengthening system.

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