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NSM CFRP laminates for the shear strengthening of high strength concrete beams

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ABSTRACT: The effectiveness of the Near Surface Mounted (NSM) shear strengthening technique with Carbon Fiber Reinforced Polymer (CFRP) laminates applied in relatively high-strength concrete beams was assessed by experimental research. Six NSM shear strengthening configurations (three CFRP orientations and two levels of CFRP percentage) were applied in T cross section Reinforced Concrete (RC) beams with a steel stirrups percentage of 0.10% (ρ_{sw} = 0.10%). Four of these NSM configurations were also applied in beams with ρ_{sw} = 0.16%. The concrete of the beams had a compressive strength of 59.4 MPa at the age of beam tests. The main results of this experimental research are presented and analyzed in terms of the structural behaviour of the beams, failure modes and performance of the NSM technique with CFRP laminates. The results showed that NSM shear strengthening technique with CFRP laminates has a high performance in RC beams with high-strength concrete, not only in terms of increasing the load carrying capacity of the beams but also in mobilizing more effectively the tensile properties of the CFRP.

1. INTRODUCTION

RC beams failing in shear can be strengthened using the NSM technique with CFRP laminates (Barros and Dias, 2006; Kotynia, 2007; El-Hacha and Wagner, 2009). This technique is based on the introduction of the laminates into slits made on the concrete cover of the lateral faces of the beams to be strengthened. Previous experimental work (Dias and Barros, 2011) showed that the concrete quality has an important role on the effectiveness of the NSM shear strengthening technique with CFRP laminates. Namely, the lower is the concrete strength class the lesser is the effectiveness of the NSM technique. This fact indicates that NSM can have a high performance for the case of RC structures with relatively high-strength concrete. To appraise the performance of the application of NSM CFRP laminates for the shear strengthening of T cross sectional reinforced high strength concrete beams having a certain percentage of existing steel stirrups, an experimental program was carried out.

2. EXPERIMENTAL PROGRAM

Fig. 1 presents the T cross section of the beams adopted in the experimental program, the lateral geometry of the type of beam and the steel reinforcement common to all tested beams (twelve). The reinforcement systems were designed in order that all beams fail in shear. To avoid shear failure in the L_r beam span, steel stirrups of 8 mm diameter spaced at 80 mm (ϕ8@80mm) were applied in this span, as shown in Fig. 1. The differences between the tested beams are restricted to the shear reinforcement systems applied in the L_i beam span. The monitored shear span L_i is 3.3 times the effective depth of the beam (L_i/d=3.3).

The experimental program was made up of seven beams with steel stirrups ϕ6@300mm (ρ_{sw} = 0.10%) and five beams with steel stirrups ϕ6@200mm (ρ_{sw} = 0.16%). According to Table 1, six NSM CFRP shear strengthening configurations were applied in beams with ρ_{sw} = 0.10% (beams 3S-6LV, 3S-10LV, 3S-5LI45, 3S-9LI45, 3S-5LI60 and 3S-8LI60 – XS means X steel stirrups, YLV means Y vertical laminates and ZLIWW means Z inclined laminates at WW degrees). Two distinct levels of percentage of CFRP laminates were studied and, for each CFRP percentage (ρ_f), three inclinations for the laminates, 90º, 60º and 45º, were analysed (Table 1 and Fig. 2). For both percentages of CFRP, the spacing of laminates for each inclination was obtained with the purpose that the contribution of the CFRP would be similar (Dias and Barros, 2010). Four of the above mentioned NSM configurations were also applied in beams with ρ_{sw} = 0.16% (beams 5S-5LI45, 5S-9LI45, 5S-5LI60 and 5S-8LI60). As schematically represented in Fig. 1, the laminates were distributed along the AB line, where A represents the beam's support at its "test side" and B is obtained assuming load degradation at 45º.

The three point beam bending tests (Fig. 1) were carried out using a servo closed-loop control equipment, taking the signal read in the displacement transducer (LVDT), placed at the loaded section, to control the test at a deflection rate of 0.01 mm/second. 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 ϕ6@65mm horizontal stirrups and ϕ10@50mm vertical stirrups (Fig. 1). To overcome the difficulties to bend ϕ32 mm longitudinal tensile bars, their ends were welded to steel plates.

With the purpose of obtaining the strain variation along the three laminates (CFRP A, CFRP B and CFRP C: see the 3S-6LV beam in Fig. 2) that have the highest probability of providing the largest contribution for the shear strengthening of the RC beam, four strain gauges (SG_L) were bonded in CFRP B and three SG_L were bonded in CFRP A and C according to the arrangements represented in Fig. 3 (L is the length of the laminate). One steel stirrup was monitored with three strain gauges (SG_S) installed according to the configuration represented in Fig. 3. The location of the monitored laminates and stirrups in the tested beams is represented in Fig. 2

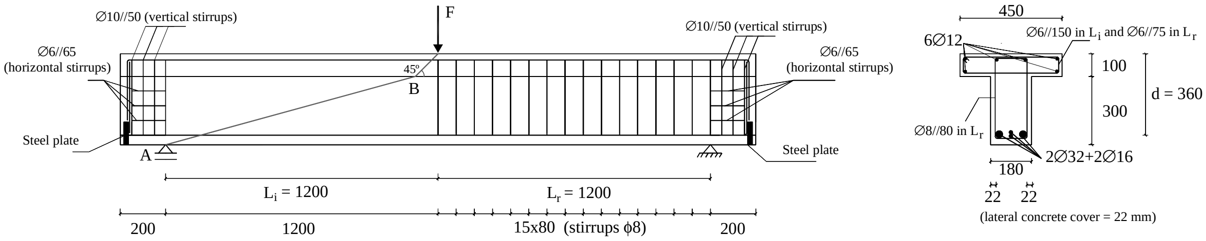
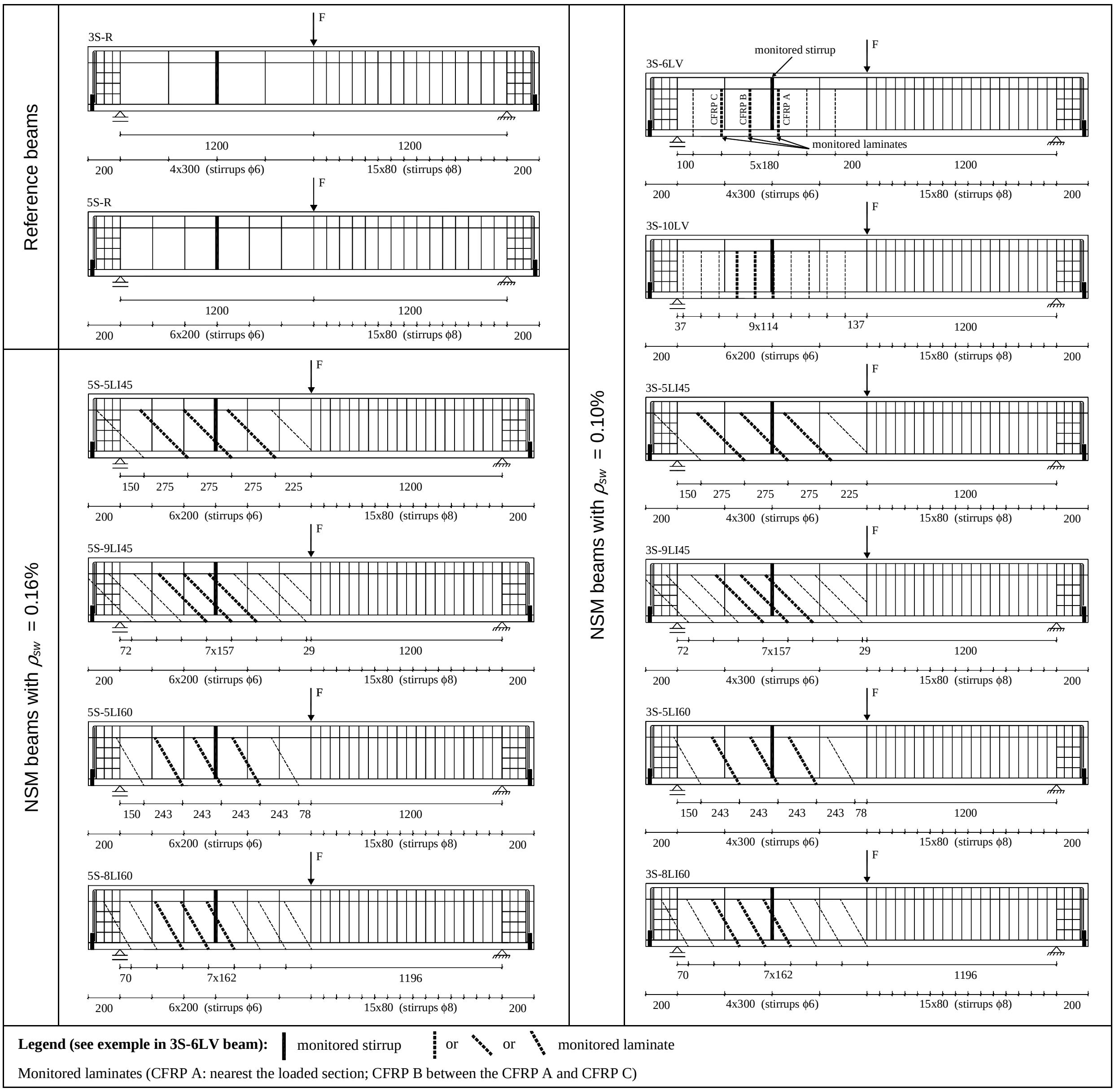


Fig. 1 – Geometry of the type of beam, steel reinforcements common to all beams, support and load conditions (dimensions in mm).

Table 1 – CFRP shear strengthening configurations of the tested beams.

Beams		Laminates	CFRP angle [θ_f] (º) [c]	CFRP spacing [s_f] (mm)	CFRP percentage [ρ_f] (%) [d]
ρ_{sw} = 0.10% [a]	ρ_{sw} = 0.16% [b]				
3S-6LV	-	2×6	90	180	0.08
3S-10LV	-	2×10		114	0.13
3S-5LI45	5S-5LI45	2×5	45	275	0.08
3S-9LI45	5S-9LI45	2×9		157	0.13
3S-5LI60	5S-5LI60	2×5	60	243	0.07
3S-8LI60	5S-8LI60	2×8		162	0.11

[a] 3S-R is the reference beam without CFRP (Fig. 2); [b] 5S-R is the reference beam without CFRP (Fig. 2); [c] Angle between the CFRP fiber direction and the beam axis; [d] The CFRP percentage was obtained from $\rho_f = (2 \cdot a_f \cdot b_f)/(b_w \cdot s_f \cdot sin\,\theta_f)$ where a_f = 1.4 mm and b_f = 9.5 mm are the dimensions of the laminate cross section, and b_w = 180 mm is the beam web width.



Legend (see exemple in 3S-6LV beam): | monitored stirrup ⋮ or ⋱ or ⋱ monitored laminate

Monitored laminates (CFRP A: nearest the loaded section; CFRP B between the CFRP A and CFRP C)

Fig. 2 – Localization of the steel stirrups (continuous line) and CFRP laminates (dashed line) in the tested beams (dimensions in mm).

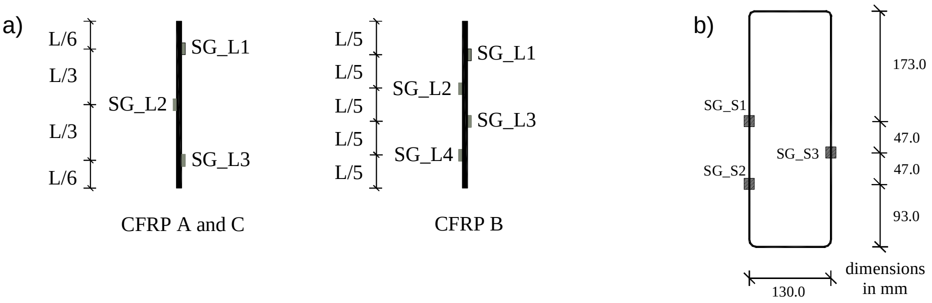


Fig. 3 – Positions of the strain gauges in the monitored: a) laminates; b) stirrups.

The concrete compressive strength at the date of beam testing was evaluated from uniaxial compression tests with cylinders (150 mm diameter and 300 mm height) according to EN 206-1 (2000) and the average value obtained was 59.4 MPa. The properties of the steel bars (Table 2) were obtained from uniaxial tensile tests, carried out according to EN 10002-1 (1990). For the laminates (S&P Laminates CFK 150/2000), uniaxial tensile tests were carried out according to the ISO 527-5 (1997) recommendations, from which the following average values were obtained: maximum tensile strength = 2847.9 MPa, Young's modulus = 174300 MPa, ultimate tensile strain = 1.63%. The MBrace Resin 220 was used to bond the laminates to the concrete. This type of adhesive was tested by Bonaldo *et al.* (2005) and the average values obtained in terms of maximum tensile strength, Young's modulus and ultimate tensile strain were 33 MPa, 7470 MPa and 4.83%, respectively.

Table 2 – Properties of the steel bars (average values).

Property	ϕ6	ϕ8	ϕ12	ϕ16 (type 1)	ϕ16 (type 2)	ϕ32
Yield stress (MPa)	551	470	450	434	544	716
Tensile strength (MPa)	602	611	579	572	658	908

3. RESULTS

3.1 Load Carrying Capacity of the Tested Beams

The recorded force-displacement diagrams (*F-u*) in the loaded section obtained for the tested beams are reported in Fig. 4. Assuming that $\Delta F_{max} = F_{max} - F_{max}^{ref}$, being F_{max}^{ref} and F_{max} the maximum force of the reference beam (3S-R or 5S-R) and of the shear strengthened beam, respectively, the $\Delta F_{max} / F_{max}^{ref}$ ratio was evaluated. The values for F_{max}, $\Delta F_{max} / F_{max}^{ref}$, and the deflection at loaded section corresponding to F_{max} ($u_{F_{max}}$) are included in Table 3.

Fig. 4 show that, for deflections higher than the one corresponding to the formation of the first shear crack in the reference beams, the adopted CFRP configurations provided an increase in the beam load carrying capacity. In fact, the CFRP shear strengthening configurations provided an increase in terms of stiffness (after shear crack formation) and in terms of maximum load (F_{max}). Furthermore, apart the 3S-6LV beam, the values of the deflection at the loaded section in correspondence to $F_{max}(u_{F_{max}})$ of the strengthened beams were higher than those occurred in the reference beams.

The strengthening arrangements corresponding to the lower percentage of CFRP had the following increments in terms of beam load carrying capacity ($\Delta F_{max} / F_{max}^{ref}$): 7.5%, 36.7% and 38.3% for the beams with ρ_{sw} = 0.10% and strengthened with laminates at 90º (3S-6LV beam), 45º (3S-5LI45 beam) and 60º (3S-5LI60 beam), respectively; 36.6% and 35.8% for the beams with ρ_{sw} = 0.16% and strengthened with laminates at 45º (5S-5LI45 beam) and laminates at 60º (5S-5LI60 beam), respectively.
The strengthening arrangements corresponding to the higher percentage of CFRP had the following increments in terms of beam load carrying capacity ($\Delta F_{max} / F_{max}^{ref}$): 36.6%, 56.6% and 62.4% for the beams with ρ_{sw} = 0.10% and strengthened with laminates at 90º (3S-10LV beam), 45º (3S-9LI45 beam) and 60º (3S-8LI60 beam), respectively; 53.2% and 59.8% for the beams with ρ_{sw} = 0.16% and strengthened with laminates at 45º (5S-9LI45 beam) and laminates at 60º (5S-8LI60 beam), respectively.

The results showed that regardless the CFRP percentage, inclined laminates were more effective than vertical laminates. After the formation of a shear crack in the reference beam, the $\Delta F_{max} / F_{max}^{ref}$ values of the strengthened beams with the larger percentage of CFRP (ρ_f) were higher than the corresponding values of the beams strengthened with the lower ρ_f. The effectiveness of the CFRP was higher in the beams with the lower percentage of steel stirrups analyzed. According to the experimental results, for an increase from 0.10% to 0.16% in the percentage of steel stirrups in the L_i beam span, the NSM strengthening effectiveness has an average decrease of 4%.

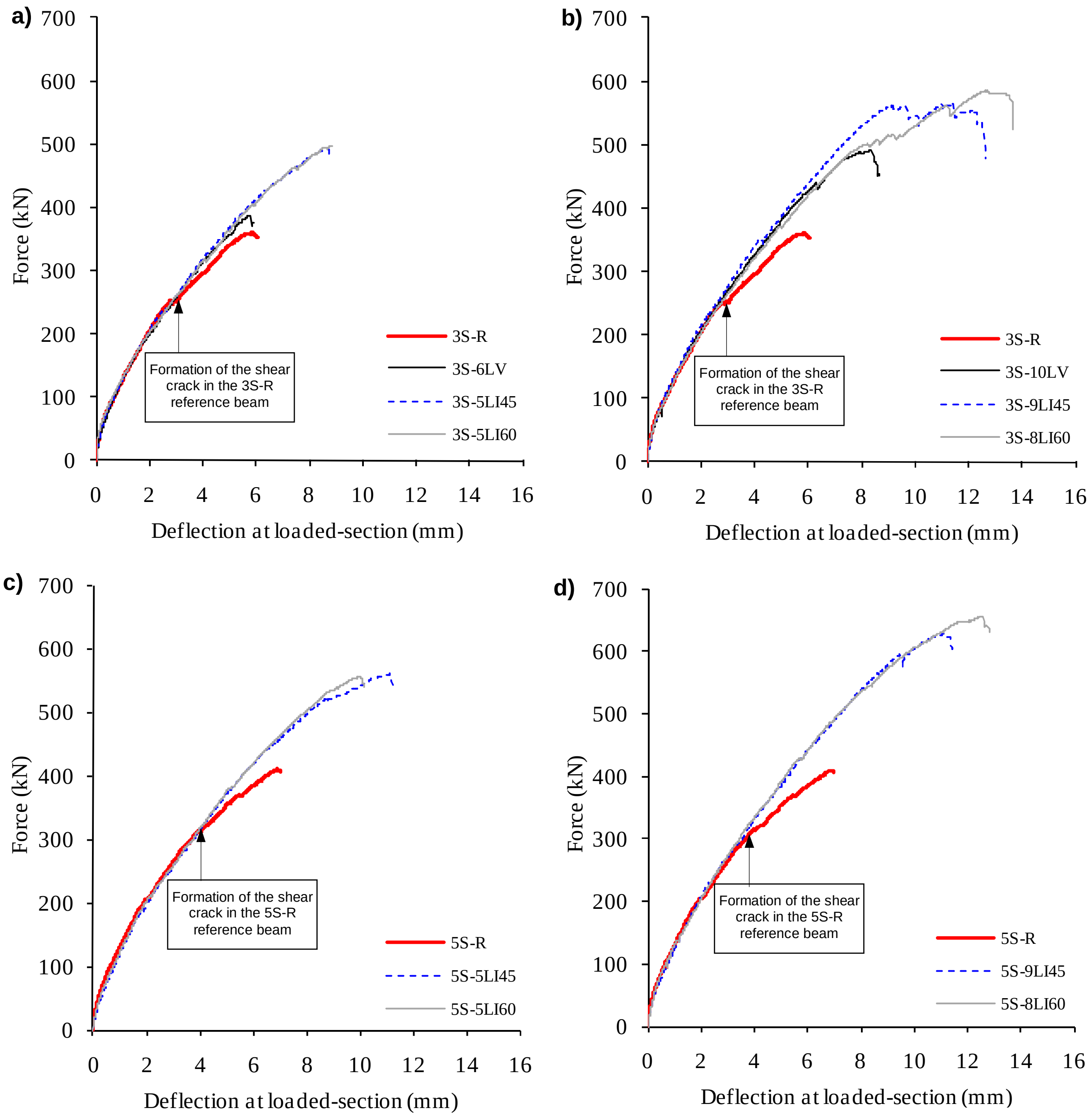


Fig. 4 – Beams with ρ_{sw} = 0.10%: Force *vs* deflection at the loaded-section for the beams with the lower (a) and higher (b) percentage of CFRP shear strengthening. Beams with ρ_{sw} = 0.16%: Force *vs* deflection at the loaded-section for the beams with the lower (c) and higher (d) percentage of CFRP shear strengthening.

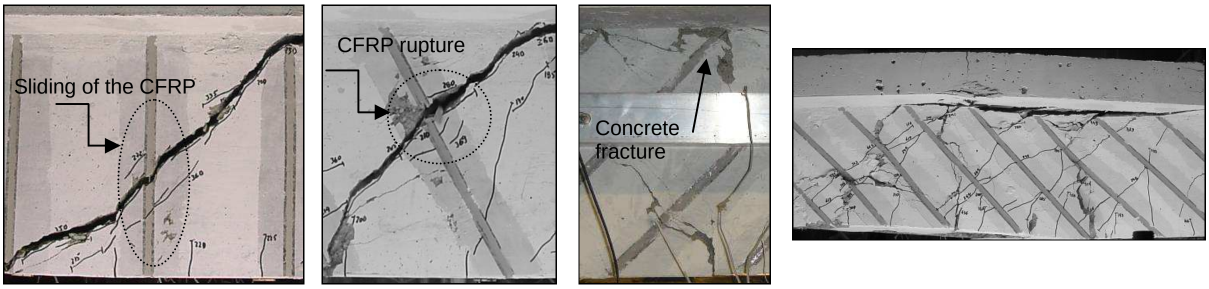
Table 3 – Relevant results.

Beams		F_{max} (kN)	$\Delta F_{max}/F_{max}^{ref}$ (%)	$u_{F_{max}}$ (mm)	ε_{CFRP}^{max} (%)
$\rho_{sw} = 0.10\%$	3S-R	359.9	-	5.86	-
	3S-6LV	387.0	7.5	5.78	0.82
	3S-10LV	491.7	36.6	8.32	0.85
	3S-5LI45	492.1	36.7	8.54	1.20
	3S-9LI45	563.6	56.6	11.40	1.04
	3S-5LI60	497.9	38.3	8.83	1.50
	3S-8LI60	584.5	62.4	12.69	0.90
$\rho_{sw} = 0.16\%$	5S-R	409.7	-	6.86	-
	5S-5LI45	559.5	36.6	11.09	1.28
	5S-9LI45	627.5	53.2	11.18	0.84
	5S-5LI60	556.4	35.8	9.98	1.41
	5S-8LI60	654.6	59.8	12.47	0.88

3.2 Failure Modes

As expected, all tested beams failed in shear in the L_i shear span. For the reference beams (3S-R and 5S-R), the maximum load was attained when one stirrup that crossed the shear failure crack has ruptured.

Two types of failure modes have essentially occurred in the beams with the lowest percentage of CFRP: the sliding of the CFRP (interface between the CFRP and the adhesive) crossed by the shear failure crack (Fig. 5a) that was occurred in the 3S-6LV, 3S-5LI45, 5S-5LI45 and 5S-5LI60 beams; the rupture of the laminate (Fig. 5b) that was occurred in the 3S-5LI60 beam. Debond through the laminate-adhesive interface (laminate sliding) was the predominant failure mode of the beams with the higher percentage of CFRP. In beams where the laminates were crossed by the critical shear crack, in such a way that the bond transference length of these laminates was relatively small, the failure occurred due to the concrete fracture, having the concrete become adhered to the laminates along this length (Fig. 5c). In the 5S-9LI45 beam, due to the relatively small spacing between laminates, the group effect has conducted to the detachment of the concrete cover (Fig. 5c).



a) Sliding of the CFRP b) CFRP rupture c) Failure occurred due to the concrete fracture

Fig. 5 – Details of the failure modes of the NSM beams.

3.3 Strains in the CFRP and Steel Stirrups

The maximum strain recorded in the monitored laminates up to the maximum load of the beams (ε_{CFRP}^{max} - see Table 3) has ranged from 0.82% (3S-6LV beam) to 1.5% (3S-5LI60 beam). For all tested strengthened beams the average value of ε_{CFRP}^{max} was 1.07%. In terms of CFRP orientation, the average value of the maximum strain (ε_{CFRP}^{max}) was 1.09%, 1.17% and 0.84% for the beams with laminates at 45º, 60º and 90º, respectively. These values range from 51% to 72% of the CFRP ultimate rupture strain obtained in the uniaxial tensile tests of the laminates (ε_{fu} = 1.63%).

A very important aspect of the effectiveness of the NSM technique, regarding the analyzed beams, is the capacity of this technique to mobilize the yield stress of the stirrups before the maximum load of the strengthened beams has been attained.

4. CONCLUSIONS

From the obtained results it can be concluded that the NSM shear strengthening technique with CFRP laminates is highly effective in RC beams of an average concrete compressive strength of about 60 MPa. Apart 3S-6LV beam, the CFRP shear strengthening configurations provided an increase in terms of maximum load that ranged between 36% and 62% of the maximum load of the reference beams. For all the considered percentages of CFRP, the inclined laminates were more effective than vertical laminates, and the beam load carrying capacity has increased with the percentage of CFRP.

Debond through the laminate-adhesive interface (laminate sliding) was the predominant failure mode of the tested beams. In the beams where the laminates were crossed by the critical shear crack and presented a relatively small bond transference length, the failure occurred due to concrete fracture, with the concrete adhered to the laminates. In 3S-5LI60 beam the laminate crossed by the shear failure crack was ruptured.

Due to the relatively high-strength concrete used, the resistance to the concrete fracture propagation during the debond process of the laminates crossing the critical diagonal crack has contributed to significantly mobilize the tensile capacity of the CFRP laminates. In fact, the maximum strain recorded in the laminates up to the maximum load has ranged between 0.82% and 1.5%. These values correspond to 50% and 92% of the CFRP ultimate strain (1.63%), respectively.

5. ACKNOWLEDGEMENT

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