

1 **NSM SHEAR STRENGTHENING TECHNIQUE WITH CFRP LAMINATES APPLIED IN HIGH T CROSS**
2 **SECTION RC BEAMS**

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7
8 **ABSTRACT**

9 The effectiveness of the Near Surface Mounted (NSM) technique with Carbon Fiber Reinforced Polymer (CFRP)
10 laminates for the shear strengthening of relatively high T cross section ($h = 600$ mm) Reinforced Concrete (RC) beams
11 was assessed by experimental research. Two inclinations of the laminates were tested (52° and 90°) and, for each one,
12 two percentages of CFRP were adopted. The RC beams shear strengthened with NSM laminates had a percentage of
13 steel stirrups of 0.09%. The experimental results showed that NSM shear strengthening technique with CFRP laminates
14 is very effective in RC beams of relatively high cross section height, not only in terms of increasing the load carrying
15 capacity of the beams, but also in assuring higher mobilization of the tensile capacity of the CFRP. Furthermore, inclined
16 laminates were more effective than vertical laminates and the shear capacity of the beams increased with the percentage
17 of laminates. Taking into account available experimental results obtained with the same test setup, but using RC beams
18 of lower depth of T cross section ($h = 400$ mm), it can be concluded that the effectiveness of the NSM technique with
19 CFRP laminates increase with the increase of the depth of the cross section. The formulations provided by Nanni *et al.*
20 (2004) and Dias and Barros (2013) for the NSM shear strengthening technique predicted a CFRP contribution around
21 51% and 67%, respectively, of the experimentally registered values.

22
23 **KEYWORDS:** NSM CFRP laminates; High T cross section RC beams; Shear strengthening; Experimental results;
24 Analytical formulations.

25
26 **1. INTRODUCTION**

27 The shear failure mode of a reinforced concrete (RC) beam should be avoided because it is brittle and unpredictable.
28 Due to high strength-to-weight ratio, high durability - non corrosive, electromagnetic neutrality, ease of handling, rapid
29 execution with lower labor, and practically unlimited availability in size, geometry and dimension, carbon fiber
30 reinforced polymer (CFRP) materials are being used as competitive alternatives on the structural rehabilitation of RC

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1 structures. For the shear strengthening, CFRP can be applied according to the followings two main techniques:
2 Externally Bonded Reinforcement (EBR) where the CFRP (wet lay-up sheets or laminates) is bonded to the external
3 faces of the elements to be strengthened, by full wrapping the cross section, or applying in a U configuration, or in the
4 lateral faces of the beam [1-4]; Near Surface Mounted (NSM) where CFRP bars (circular, square or rectangular cross
5 section) are introduced into pre-cut slits opened on the concrete cover of the elements to strengthen [5-8]. Due to the
6 largest bond area and higher confinement provided by the surrounding concrete, narrow strips of CFRP laminates of
7 rectangular cross section, installed into thin slits and bonded to concrete by an epoxy adhesive, are the most effective
8 CFRP strengthening elements for the NSM technique [9].

9 Dias and Barros [10] concluded that NSM technique is more effective than EBR technique because NSM provided a
10 larger increase of load carrying capacity after shear crack formation. The use of NSM technique better mobilized the
11 tensile capacity of the CFRP reinforcement because higher tensile strains were measured in these composites when this
12 technique was used. NSM requires no surface preparation work and, after cutting and cleaning the thin slits, the
13 strengthening procedure is resumed to the installation of the CFRP laminates. A further advantage of the NSM
14 technique is its ability to significantly reduce the probability of harm resulting from acts of vandalism, mechanical
15 damages and aging effects. When NSM is used, the appearance of a structural element is practically unaffected by the
16 strengthening intervention.

17 The effectiveness of NSM shear strengthening technique with CFRP laminates applied for T cross section RC beams
18 with a certain percentage of steel stirrups was assessed by an extensive experimental research carried out by Dias and
19 Barros [11]. In this context, the influence of the following parameters was appraised: concrete strength; percentage of
20 existing steel stirrups; percentage and inclination of the CFRP laminates; existence of shear cracks when the RC beams
21 are shear strengthened with NSM CFRP laminates. The tested RC beams with a T cross section of 400 mm height, had
22 percentages of steel stirrups (ρ_{sw}) ranging between 0.10% and 0.17%. In terms of concrete strength, three types were
23 basically used: low strength ($f_{cm} = 18.6$ MPa, where f_{cm} is the average concrete compressive strength at the age of the
24 beams tests), medium strength ($f_{cm} = 31.1$ to 39.7 MPa), and high strength ($f_{cm} = 59.4$ MPa). Three orientations of the
25 laminates with respect to the beam's axis were tested ($\theta_f = 90^\circ$ - vertical laminates; $\theta_f = 45^\circ$ - laminates at 45° ; $\theta_f = 60^\circ$ -
26 laminates at 60°), and the levels of the CFRP percentage (ρ_f) analyzed ranged between 0.06% and 0.19%. Regardless of
27 the percentage of CFRP, percentage of existing steel stirrups and concrete strength, inclined laminates were more
28 effective than vertical laminates. It was also verified that the beam's shear capacity increased with ρ_f , while the NSM
29 shear strengthening effectiveness decreased with the increase of the percentage of existing steel stirrups. The main
30 difference of the behavior of NSM CFRP beams with and without pre-cracks resided in an expected loss of initial
31 stiffness in the pre-cracked beams. However, the pre-cracking had not affected the efficacy of the NSM shear

1 strengthening technique in terms of load carrying capacity and ultimate deflection. The contribution of the NSM CFRP
2 laminates for the beam shear resistance was limited by the concrete tensile strength. In fact, this technique was more
3 effective when applied to RC beams of high-strength concrete, not only in terms of increasing the load carrying capacity
4 of the beams, but also in assuring higher mobilization of the tensile capacity of the CFRP. This can be justified by the
5 physical interpretation of the types of failure modes developed during the shear crack propagation bridged by NSM
6 CFRP laminates described elsewhere [12]. However, considering the results of Dias and Barros [11], the shear
7 strengthening can still be significant in RC beams of relatively low concrete strength if a convenient bond length for the
8 CFRP laminates is assured.

9 There are several reasons that justify the relevance of a study on the use of the NSM technique with CFRP laminates
10 for the shear strengthening of relatively high T cross section RC beams: these kind of beams is quite current in
11 buildings and bridges; experimental results about the shear strengthening of RC beams using NSM technique with
12 CFRP laminates indicate that the bond length of the CFRP has an important role in the effectiveness of this
13 strengthening technique [11].

14 To appraise the possibility of the application of the NSM technique with CFRP laminates for the shear strengthening
15 of relatively high T cross section RC beams having a certain percentage of existing steel stirrups, an experimental
16 program was carried out. The height of the T cross section was 600 mm ($h = 600$ mm). The experimental program is
17 outlined and the specimens, materials, test set-up and monitoring system are described. The results are presented and
18 analyzed in terms of the structural behavior of the tested beams, modes of failure and effectiveness of the NSM CFRP
19 shear strengthening configurations. Taking into account available experimental results obtained with the same test set-
20 up but using RC beams of lower T cross section ($h = 400$ mm), the influence of the height of the RC beams in the
21 performance of the NSM technique with CFRP laminates for the shear strengthening of RC beams was assessed.

22 Additionally, the predictive performance of the formulations proposed by Nanni *et al.* [13] and Dias and Barros [11]
23 for the contribution of NSM CFRP systems for shear resistance of RC beams was appraised by taking the results
24 obtained in the present experimental program.

25

26 **2. EXPERIMENTAL PROGRAM**

27 **2.1 Beam prototypes**

28 The experimental program was composed of five T cross section RC beams: a reference beam (Fig. 1) and four
29 NSM CFRP shear strengthened beams (Fig. 2). The beams were 4600 mm long and the T cross section had overall
30 dimensions of 450 mm (width of flange) by 600 mm (total depth). The width of the web and the thickness of the flange
31 were 180 mm and 100 mm, respectively. Fig. 1 shows the T cross section geometry and the steel reinforcement details

1 for the series of beams, as well as the loading configuration and support conditions. The adopted reinforcement was
2 designed to assure shear failure mode for all the tested beams. To localize the shear failure in only one of the beam
3 shear spans, a three point loading configuration with a distinct length for the beam shear spans was selected, as shown
4 in Fig. 1. The monitored beam span (a) was 2.5 times the effective depth of the beam ($a/d=1400/558=2.5$), since
5 according to the available research [14], this is the minimum value that assures a negligible arch effect. To avoid shear
6 failure in the b beam span, steel stirrups of 6 mm diameter at a spacing of 112 mm ($\phi 6@112$ mm) were applied in this
7 span. To prevent brittle spalling of the concrete cover at the supports, the beam's ends were strengthened by confining
8 the concrete with a two-directional cage of $\phi 6@65$ mm horizontal stirrups and $\phi 10@50$ mm vertical stirrups (Fig. 1).
9 To overcome the difficulties of bending the $\phi 32$ mm longitudinal tensile bars, their ends were welded to a steel plate.

10 The differences between the tested beams were restricted to the CFRP shear reinforcement in the a beam span. The
11 reference beam without CFRP was designated as "3S-R" (three steel stirrups in the a shear span leading a steel shear
12 reinforcing ratio, ρ_{sw} , of 0.09%), while the following NSM strengthening configurations, with CFRP laminates of
13 1.4×10 mm² cross section, were adopted for the other four beams that also included three steel stirrups in the a shear
14 span (Fig. 2 and Table 1): 3S-4LV beam with four CFRP laminates per face installed in vertical slits ($\theta_f = 90^\circ$) with 350
15 mm of spacing; 3S-7LV beam with seven CFRP laminates per face installed in vertical slits ($\theta_f = 90^\circ$) with 175 mm of
16 spacing; 3S-4LI beam with four CFRP laminates per face with 350 mm of spacing and inclined at 52 degrees with
17 respect to the longitudinal axis of the beam ($\theta_f = 52^\circ$ - the same orientation of the line AB present in the beam 3S-4LI of
18 the Fig. 2); 3S-9LI beam with nine CFRP laminates per face with 175 mm of spacing and inclined at 52 degrees with
19 respect to the longitudinal axis of the beam ($\theta_f = 52^\circ$).

20 The CFRP laminates were installed in slits executed from the bottom surface of the flange to the bottom tensile
21 surface of the beam's web, i.e., bridging the total lateral surfaces of the beam's web (Fig. 3a). In fact, each CFRP
22 laminate was installed in the outer part of a slit of a depth of 15 mm and a width of 5 mm executed on the beam's web
23 lateral surfaces (the laminates were not anchored to the beam flange; they were restricted to the beam web). The
24 configuration adopted for the CFRP laminates avoided any type of injury in the steel reinforcements during the
25 execution of the slits (the concrete cover of the lateral faces of the beam's web was about 22 mm thickness). After
26 opening the slits, the NSM strengthening technique is composed of the following procedures: 1) the slits were cleaned
27 by compressed air; 2) the laminates were cleaned with acetone; 3) the epoxy adhesive was produced according to
28 supplier recommendations; 4) the slits were filled with the adhesive; 5) the adhesive was applied on the faces of the
29 laminates; and 6) the laminates were inserted into the slits (Fig. 3b) and adhesive in excess was removed. To guarantee
30 a proper curing of the adhesive, at least one week passed between the beam strengthening operations and the beam test.

1 The details of the shear strengthening configurations are indicated in Table 1. This table shows that the tested beams
2 had a percentage of longitudinal tensile steel bars (ρ_{sl}) of 2%, a percentage of steel stirrups (ρ_{sw}) of 0.09%, and a
3 percentage of NSM CFRP laminates (ρ_f) ranging from 0.044% to 0.113%.

5 2.2 Material properties

6 The concrete compressive strength was evaluated when the beam tests were realized. In order to do it, direct
7 compression tests were carried out with cylinders of 150 mm diameter and 300 mm high, according to EN 206-1 [15].
8 At the age of the test of the 3S-R, 3S-4LV and 3S-4LI beams the value of f_{cm} (average compressive strength) was 36.4
9 MPa. At the age of the test of 3S-7LV and 3S-9LI beams the value of f_{cm} was 40.4 MPa. The values of the main tensile
10 properties of the high bond steel bars used in the tested beams (Table 2) were obtained from uniaxial tensile tests
11 performed according to the recommendations of EN 10002-1[16]. CFK 150/2000 S&P laminates were used in the
12 present experimental research and the tensile properties were evaluated following the recommendations of ISO 527-5
13 [17]. The average value of the tensile strength (f_{tu}), elasticity modulus (E_f), and ultimate strain (ε_{fu}) of CFRP laminate
14 was, respectively, 3009.3 MPa, 169.2 GPa and 17.8%.

15 S&P Resin 220 epoxy adhesive was used to bond the CFRP laminates to the concrete substrate. The instantaneous
16 and long term tensile behavior of this adhesive was investigated by Costa and Barros [18]. At 3 days, at which the
17 elasticity modulus ($E_{0.5-2.5\%}$) attained a stabilized value, the tensile strength and the $E_{0.5-2.5\%}$ were determined in
18 accordance with the ISO 527-2 recommendations [19], and the obtained results were 20 MPa and 7 GPa, respectively.

20 2.3 Test setup and monitoring system

21 Three point beam bending tests (Fig. 3c) were carried out using a servo closed-loop control equipment, taking the
22 signal read in the displacement transducer (LVDT), placed at the loaded section, to control the test at a deflection rate of
23 0.01 mm/second. With the purpose to obtain the strain variation along two laminates that have the highest probability of
24 providing the largest contribution for the shear strengthening of the RC beam, four strain gauges (SG_L) were bonded
25 in each laminate as shown in Fig. 4. Adopting the same principle, one steel stirrup was monitored with three strain
26 gauges (SG_S) installed according to the configuration represented in Fig. 4. The location of the monitored laminates
27 and stirrups in the tested beams is indicated in Fig. 2.

1 3. EXPERIMENTAL RESULTS AND DISCUSSION

2 3.1 Load carrying capacity of the tested beams

3 The relationship between the applied force (F) and the deflection at the loaded section (u_{LS}) of the tested beams is
4 illustrated in Fig. 5a. In this figure, ΔF represents the increase of the load provided by the shear strengthening system,
5 while F^{3S-R} is the load capacity of the reference beam. The $\Delta F/F^{3S-R}$ ratio was evaluated for deflections greater than
6 the one corresponding to the formation of the first shear crack in the reference beam 3S-R, and the $\Delta F/F^{3S-R}$ vs. u_{LS}
7 relationship is illustrated in Fig. 5b. Assuming that $\Delta F_{max} = F_{max} - F_{max}^{3S-R}$, being F_{max}^{3S-R} and F_{max} the load carrying
8 capacity (maximum force) of the reference beam and of the NSM CFRP shear strengthened beam, respectively, the
9 $\Delta F_{max}/F_{max}^{3S-R}$ ratio was also evaluated. The values for F_{max} , $\Delta F_{max}/F_{max}^{3S-R}$ and the deflection at loaded section
10 corresponding to F_{max} ($u_{F_{max}}$) are presented in Table 3.

11 Fig. 5 and the results included in Table 3 show that, for deflections higher than the one corresponding to the
12 formation of the first shear crack in the reference beam, the adopted CFRP configurations provided an increase in the
13 beam's load carrying capacity. This reveals that the CFRP laminates bridging the surfaces of the shear crack offer
14 resistance, mainly to crack opening, resulting to a smaller degradation of the shear stress transfer between the faces of
15 the crack, due to aggregate interlock effect. Therefore, for deflections above the one corresponding to the formation of
16 the shear crack in the reference beam, an increase of the beam's stiffness was observed in the shear strengthened beams.
17 The crack opening resisting mechanisms provided by the laminates bridging the shear crack also contributed to increase
18 the load at which stirrups enter in their plastic phase.

19 The CFRP shear strengthening configurations provided an increase in terms of stiffness (after shear crack formation)
20 and maximum load (F_{max}). It is verified that $\Delta F_{max}/F_{max}^{3S-R}$ of the tested NSM CFRP shear strengthened beams has
21 varied between 21.2% and 82.6%. Regardless the percentage of the CFRP laminates, the strengthening arrangements
22 with vertical laminates had the small values of the increase in terms of beam's load carrying capacity ($\Delta F_{max}/F_{max}^{3S-R}$):
23 21.2% and 42.5% for the beams with four (3S-4LV beam with $\rho_f = 0.044\%$) and seven (3S-7LV beam with $\rho_f =$
24 0.089%) vertical laminates, respectively. The value of $\Delta F_{max}/F_{max}^{3S-R}$ for the beams 3S-4LI ($\rho_f = 0.056\%$) and 3S-9LI
25 ($\rho_f = 0.113\%$), both with laminates inclined at 52° , was 48.4% and 82.6%, respectively. The best performance of the
26 shear strengthening solutions with inclined laminates is justified by the orientation of the shear failure cracks that had a
27 tendency to be almost orthogonal to the inclined laminates. Furthermore, for vertical laminates the total resisting bond
28 length of the CFRP was lower than that of inclined laminates. After the formation of a shear crack in the reference

1 beam, the $\Delta F_{max} / F_{max}^{3S-R}$ values of the strengthened beams with the larger percentage of CFRP (ρ_f) were higher than
2 the corresponding values of the beams strengthened with the lower ρ_f .

3 The deflection at the loaded section in correspondence to $F_{max}(u_{F_{max}})$ in all the NSM CFRP shear strengthened
4 beams was similar or larger than the value of $u_{F_{max}}$ obtained in the reference beam 3S-R (10.68 mm). The strengthening
5 arrangements with vertical laminates had the small values of $u_{F_{max}}$: 11.78 mm and 10.58 mm for the beams 3S-4LV
6 and 3S-7LV, respectively. The value of $u_{F_{max}}$ for the beams 3S-4LI and 3S-9LI, both with laminates inclined at 52° ,
7 was 13.35 mm and 18.21 mm, respectively.

8

9 **3.2 Failure modes**

10 As expected, all the tested beams failed in shear in the shear span a . Fig. 6 shows the crack patterns at failure of the
11 tested beams in the shear span a . The maximum load of the reference beam (3S-R) was attained when one stirrup
12 crossing the shear failure crack has ruptured. In the NSM CFRP shear strengthened beams no laminate has ruptured up
13 to peak load.

14 In the 3S-4LV beam, at a load level of about 363 kN the second laminate from the loaded section debonded at its top
15 part (laminate 2 in Fig. 6b), with a formation of a concrete volume surrounding the laminate. This was followed by a
16 decay of the load carrying capacity of this beam (Fig. 5a). The load was transferred, mainly, to the third laminate from
17 the loaded section (laminate 3 in Fig. 6b), and the load was again increased up to the moment ($F_{max} = 401.8$ kN) when
18 occurred the debonding of the bottom part of this laminate, followed by a sudden and abrupt load decay. The maximum
19 load of the beam 3S-7LV ($F_{max} = 472.1$ kN) was attained immediately before the debonding of the bottom part of the
20 laminate 4 (Fig. 6c). After the maximum load, it was verified the debonding of the top part of laminate 3 (Fig. 6c).

21 In the 3S-4LI beam, at a load level of about 462 kN the 4th laminate from the loaded section debonded at its bottom
22 part (laminate 4 in Fig. 6d), with a formation of a concrete volume surrounding the laminate. This was followed by a
23 decay of the load carrying capacity of this beam (Fig. 5a). The load was transferred, mainly, to the second and third
24 laminates from the loaded section (laminates 2 and 3 in Fig. 6d), the ones crossing the critical shear crack, and the load
25 was again increased up to the moment ($F_{max} = 491.7$ kN) when occurred the debonding of the top part of the laminate
26 2, followed by a sudden and abrupt load decay. In the 3S-9LI beam, at a load level of about 562 kN the third laminate
27 from the loaded section debonded at its top part (laminate 3 in Fig. 6e), with a formation of a concrete volume
28 surrounding the laminate. This was followed by a decay of the load carrying capacity of this beam (Fig. 5a). The load
29 was transferred, mainly, to the 4th laminate from the loaded section (laminate 4 in Fig. 6e), and the load was again

1 increased up to the moment ($F_{max} = 605$ kN) when occurred the debonding of the top part of this laminate (Fig. 6e),
2 followed by a sudden and abrupt load decay.

3

4 **3.3 Strains in the CFRP laminates and steel stirrups**

5 Table 4 includes the strains measured in the monitored laminates at F_{max} , $\varepsilon_{CFRP}^{SG-Li}$ ($i=1$ to 4, see Fig. 4), and the
6 maximum strain in these laminates up to F_{max} , ε_{CFRP}^{max} , for the tested NSM CFRP shear strengthened beams. The strains
7 were dependent on the relative distance between the strain gauges (SG) and the shear failure crack crossing the
8 laminate. It was verified that the ε_{CFRP}^{max} has varied between 9.6‰ and 14.4‰. These values ranged between 54% and
9 81% of the ultimate tensile strain of the adopted CFRP laminates ($\varepsilon_{fu}=17.8‰$) justifying the high strengthening
10 effectiveness provided by NSM CFRP laminates for the shear strengthening of relatively high T cross section RC
11 beams. Comparing the ε_{CFRP}^{max} in the laminates at different orientations, a clear tendency for lower values of the strains
12 in vertical laminates is observable.

13 Fig. 7 illustrates the variation of the strains on the monitored laminates during the loading process of the beam up to
14 its maximum load. It is observed that the curves featured two phases. In the initial stage of loading, while the CFRP was
15 not crossed by a diagonal crack, the contribution of the laminate for the beam's load-carrying capacity was marginal.
16 The second stage initiates when the CFRP was crossed by a diagonal crack. The gradient of the strains registered in the
17 SGs was the higher the closer was the SG from the critical shear crack. This behavior was similar in the monitored
18 stirrups (Fig. 8). The evolution of the strains in the steel stirrups indicates that when the strengthened beams failed, the
19 steel stirrups had already developed a significant plastic deformation.

20

21 **3.4 Comparison of the shear strengthening effectiveness**

22 The shear capacity contributed by the CFRP (V_f) was obtained by subtracting the shear resistance of the reference
23 beam ($V_{ref.}$) from the shear resistance of the strengthened beam (V_t):

$$V_t = V_{ref.} + V_f \quad (1)$$

24 In this approach it is assumed that the steel stirrups give the same contribution in the strengthened and in the
25 corresponding reference beam.

26 By comparing the V_f values of the beams of the present experimental program (46.9 kN, 93.8 kN, 106.9 kN and
27 182.4 kN for the beams 3S-4LV, 3S-7LV, 3S-4LI and 3S-9LI, respectively) to those determined in NSM shear
28 strengthened RC beams [11] with the same kind of concrete ($f_{cm} = 39.7$ MPa) and the same test setup, but with RC

1 beams of smaller height of the cross section, 400 mm, (Fig. 9a), it can be concluded that the effectiveness of the NSM
 2 technique with CFRP laminates increases with the height of the cross section.

3 From the V_f values, the effective strain in the laminates, ε_{fe} , for the tested beams can be obtained from the following
 4 equation [11]:

$$\varepsilon_{fe} = V_f / \left(h_w \times \frac{A_{fv}}{s_f} \times E_f \times (\cot g \alpha + \cot g \theta_f) \times \sin \theta_f \right) \quad (2)$$

5 where h_w is the height of the beam's web, A_{fv} is the cross sectional area of a "laminates stirrup" that is formed by two
 6 lateral laminates ($A_{fv} = 2 \times a_f \times b_f$), s_f is the spacing of laminates, E_f is the elastic modulus of the laminate, α is the
 7 orientation of the shear failure crack (considered as 45°), and θ_f is the inclination of the laminates with respect to the
 8 beam axis (Fig. 10).

9 Fig. 9b compares the ε_{fe} values obtained in the present experimental program (6.9‰ for the beams with vertical
 10 laminates; 11.3‰ and 9.6‰ for the beams 3S-4LI and 3S-9LI, respectively) with those obtained in Dias and Barros
 11 [11] with the same kind of concrete ($f_{cm} = 39.7$ MPa) and the same test setup, where the height of the cross section was
 12 400 mm. In Fig. 9b is again visible that the effectiveness of the NSM technique with CFRP laminates increases with the
 13 height of the cross section.

14

15 4. APPRAISAL OF THE PREDICTIVE PERFORMANCE OF ANALYTICAL FORMULATIONS

16 Taking the results obtained in the tested beams shear strengthened using NSM technique with CFRP laminates, the
 17 performance of the analytical formulations proposed by Nanni *et al.* [13] and Dias and Barros [11] for the prediction of
 18 the contribution of NSM CFRP systems for the shear resistance of RC beams was appraised.

19

20 4.1 Formulation by Nanni *et al.* [13]

21 According to the formulation proposed by Nanni *et al.* [13], the term within the square brackets of the equation (3)
 22 is the force resulting from the tensile stress in the NSM FRP elements crossing the shear failure crack. The vertical
 23 projection of this force is the contribution of the FRP to the shear resistance of the beam (V_f),

$$V_f = [4 \cdot (a_f + b_f) \cdot \tau_b \cdot L_{tot\ min}] \cdot \sin \theta_f \quad (3)$$

24 being τ_b the average bond stress of the FRP elements intercepted by the shear failure crack, and $L_{tot\ min}$ is obtained
 25 from (see Fig. 11),

$$L_{tot\ min} = \sum_i L_i \quad (4)$$

1 where L_i represents the length of each single NSM laminate crossed by a 45-degree shear crack, determined from,

$$L_i = \begin{cases} \min \left(\frac{s_f}{\cos \theta_f + \sin \theta_f} i; l_{max} \right) & i = 1, \dots, \frac{N}{2} \\ \min \left(l_{net} - \frac{s_f}{\cos \theta_f + \sin \theta_f} i; l_{max} \right) & i = \frac{N}{2} + 1, \dots, N \end{cases} \quad (5)$$

2 $L_{tot \ min}$ corresponds to an arrangement of the FRP reinforcements crossing the shear failure crack that leads to the
3 minimum of the $\sum_i L_i$. In (5) l_{net} is defined as,

$$l_{net} = l_b - \frac{2c}{\sin \theta_f} \quad (6)$$

4 which represents the net length of a FRP laminate, as shown in Fig. 11, to account for cracking of the concrete cover
5 and installation tolerances. In (6), l_b is the actual length of a FRP laminate and c is the concrete clear cover thickness.

6 The first limitation of (5) takes into account bond as the controlling failure mechanism, and represents the minimum
7 effective length of a FRP laminate intercepted by a shear crack as a function of the term N ,

$$N = \frac{l_{eff} (1 + \cot \theta_f)}{s_f} \quad (7)$$

8 where N is rounded off to the lowest integer (e.g., $N=5.7 \Rightarrow N=5$), and l_{eff} represents the length of the vertical
9 projection of l_{net} as shown in Fig. 11,

$$l_{eff} = l_b \sin \theta_f - 2c \quad (8)$$

10 The second limitation in (5), $L_i = l_{max}$, results from the force equilibrium condition, taking an upper bound value for
11 the effective strain, ε_{fe} (see Fig. 12),

$$l_{max} = \frac{\varepsilon_{fe}}{2} \cdot \frac{a_f \cdot b_f}{a_f + b_f} \cdot \frac{E_f}{\tau_b} \quad (9)$$

12 Considering for ε_{fe} and τ_b the values recommended by Barros and Dias [7], respectively, 0.59% and 16.1 MPa,
13 and assuming for the elastic modulus of the laminate the average value recorded in the experimental program of the
14 present work (169.2 GPa), the values of the contribution of the NSM laminates for the shear strengthening of the tested
15 beams (V_f^{Ana}), included in Table 5, were compared to those registered experimentally (V_f^{Exp}). The values of the
16 $V_f^{Exp.}/V_f^{Ana}$ ratio ranged between 1.68 and 2.42, and an average value of about 1.96 for $V_f^{Exp.}/V_f^{Ana}$ was obtained (the
17 coefficient of variation was 18%). These values show that the formulation proposed by Nanni *et al.* [13] is very
18 conservative when the NSM CFRP laminates are installed into the slits of relatively high T cross section RC beams.

1 4.2 Formulation by Dias and Barros [11]

2 According to the formulation proposed by Dias and Barros [11], the contribution of the NSM CFRP laminates for
3 the shear capacity of a RC beam, identified by V_f , can be obtained using the equation (10):

$$V_f = h_w \times \frac{A_{fv}}{s_f} \times \varepsilon_{fe} \times E_f \times (\cot \theta_f + \cot \alpha) \times \sin \theta_f \quad (10)$$

4 The value of the effective strain in the laminates (ε_{fe}) is obtained from:

$$\varepsilon_{fe} = \left[3.76888 \times e^{(-0.1160261\theta_f + 0.0010437\theta_f^2)} \times \left[\frac{E_f \rho_f + E_s \rho_{sw}}{f_{cm}^{2/3}} \right]^{-0.460679} \times e^{(0.0351199\theta_f - 0.0003431\theta_f^2)} \right] / \gamma_f \quad (11)$$

5 In equation (11), ρ_f and ρ_{sw} are introduced like a ratio and not in percentage (values obtained with the equations in
6 the footnote of Table 1, but eliminating the term 100), f_{cm} is the average concrete compressive strength in cylinders (in
7 MPa), E_s is the elasticity modulus of the steel stirrups (in MPa, the same units should be use for the elasticity modulus
8 of the laminate E_f) and γ_f is an uncertainty factor equal 1.3. The meaning of the others parameters of equations (10) and
9 (11) was described in the section 3.4 (see also Fig. 10).

10 Adopting the formulation proposed by Dias and Barros [11], the obtained values of the contribution of the NSM
11 laminates for the shear strengthening of the tested beams (V_f^{Ana}) are included in Table 5 and were compared to those
12 registered experimentally (V_f^{Exp}). The values of the V_f^{Exp} / V_f^{Ana} ratio ranged between 1.37 and 1.63, and an average
13 value of about 1.51 for V_f^{Exp} / V_f^{Ana} was obtained (the coefficient of variation was 7%).

14 Considering the results of the Table 5 and Figure 13 it can be concluded that for relatively high T cross section RC
15 beams the formulation proposed by Dias and Barros [11] provided more realistic predictions for the shear capacity
16 contributed by the CFRP (V_f). For the better performance of the formulation of Dias and Barros [11], it contributed the
17 fact that this formulation considers parameters that are related to the performance of RC beams shear strengthened with
18 NSM technique using CFRP laminates, whose evaluation was based on the obtained experimental results, namely:
19 concrete strength, percentage of existing steel stirrups, percentage and orientation of the CFRP.

20

21 5. CONCLUSIONS

22 To appraise the possibility of the application of NSM CFRP laminates for the shear strengthening of relatively high
23 T cross section RC beams having a certain percentage of existing steel stirrups, an experimental program was carried
24 out. The height of the T cross section of the tested RC beams was 600 mm.

25 From the obtained experimental results, it can be concluded that NSM shear strengthening technique with CFRP
26 laminates is very effective in RC beams of relatively high cross section, not only in terms of increasing the overall

1 behavior of the beams, but also in assuring higher mobilization of the tensile capacity of the CFRP. The NSM CFRP
2 shear strengthening configurations provided an increase in terms of maximum load (F_{max}) that ranged between 21%
3 ($\rho_f=0.044\%$) and 83% ($\rho_f=0.113\%$) of the maximum load of the reference beam. In general, the values of the deflection
4 at the loaded section in correspondence to F_{max} of the strengthened beams were higher than those occurred in the
5 reference beam. Inclined laminates were more effective than vertical laminates, and the shear resistance of the beams
6 increased with the percentage of laminates. The maximum tensile strain recorded in the NSM CFRP laminates up to the
7 maximum load ranged from 54% to 81% of its ultimate tensile strain, indicating that this strengthening technique can
8 mobilize high stress levels in the CFRP. A very important aspect of the effectiveness of the NSM technique, regarding
9 the analyzed beams, is its capacity to mobilize the yield stress of the stirrups before the maximum load of the
10 strengthened beams has been attained.

11 Considering available experimental results obtained with the same test setup but using RC beams of lower T cross
12 section ($h = 400$ mm instead of $h = 600$ mm), it was verified that the shear strengthening effectiveness of the NSM
13 technique has increased with the height of the cross section.

14 In general, the formulation proposed by Dias and Barros [11] provided safe and acceptable estimates for the
15 contribution of the NSM shear strengthening systems (the predicted values of the CFRP contribution for the shear
16 resistance were 67% of the results registered experimentally). The formulation proposed by Nanni *et al.* [13] provided
17 very conservative predictions when the NSM CFRP laminates were applied on relatively high T cross section RC beams
18 (the predicted values of the CFRP contribution for the shear resistance were 51% of the results registered
19 experimentally). Furthermore, the scatter of the results in terms of the $V_f^{Exp.} / V_{fd}^{Ana}$ ratio for the Dias and Barros [11]
20 formulation was also quite low (the coefficient of variation was 7% and 18% for the formulations provided by Dias and
21 Barros [11] and Nanni *et al.* [13], respectively).

22 23 **ACKNOWLEDGEMENTS**

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- 1 **List of Tables:**
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17 and Barros.

18 **Fig. 11** - Graphical representation of variables used in the formulation proposed by Nanni *et al.* (for this example

19
$$\sum_i L_i = L_2 + L_3 + L_4).$$

20 **Fig. 12** - Graphical representation of l_{max} .

21 **Fig. 13** - a) Comparison between the experimental and analytical values of the NSM CFRP contribution for the shear
22 resistance, V_f , and b) $(V_{f, Exp} / V_{f, Ana})$ vs. percentage of CFRP (ρ_f). [Note: VL - vertical laminates; IL - inclined
23 laminates].

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Table 1 - General information about the series of the tested RC beams.

Beam	ρ_{sl} (%) ⁽¹⁾	ρ_{sw} (%) ⁽²⁾	a/d	NSM CFRP laminates	θ_f (°)	s_f (mm)	ρ_f (%) ⁽³⁾
3S-R	2.0	0.09	2.5	-	-	-	-
3S-4LV				2×4	90	350	0.044
3S-7LV				2×7	90	175	0.089
3S-4LI				2×4	52	350	0.056
3S-9LI				2×9	52	175	0.113

(1) The percentage of the longitudinal tensile reinforcement was obtained from $\rho_{sl} = (A_{sl} / (b_w \times d)) \times 100$, where A_{sl} is the cross sectional area of the longitudinal tensile steel reinforcement (see Fig. 1), $b_w = 180$ mm is the width of the beam's web and d is the distance from extreme compression fiber to the centroid of tensile reinforcement. (2) The percentage of the vertical steel stirrups was obtained from $\rho_{sw} = (A_{sw} / (b_w \times s_w)) \times 100$, where A_{sw} is the cross sectional of the two vertical arms of a steel stirrup, and s_w is the spacing of the stirrups. (3) The CFRP percentage was obtained from $\rho_f = ((2 \times a_f \times b_f) / (b_w \times s_f \times \sin \theta_f)) \times 100$, where a_f and b_f are the dimensions of the laminate cross section, and s_f is the CFRP spacing.

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Table 2 - Average values of the properties of the steel.

Diameter (mm)	φ6	φ12	φ16	φ32
Yield stress [f_{sym}] (MPa)	555	562	560	734
Tensile strength [f_{sun}] (MPa)	683	662	675	885

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Table 3 - Experimental results of the tested RC beams.

Beam	F_{max} (kN)	$\Delta F_{max} / F_{max}^{3S-R}$ (%)	F_{max} / F_{max}^{3S-R}	$u_{F_{max}}$ (mm)
3S-R	331.4	0	1.00	10.68
3S-4LV	401.8	21.2	1.21	11.78
3S-7LV	472.1	42.5	1.42	10.58
3S-4LI	491.7	48.4	1.48	13.35
3S-9LI	605.0	82.6	1.83	18.21

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Table 4 - Strain values in the CFRP laminates.

Beam	Monitored laminate ⁽¹⁾	ϵ_{CFRP}^{SG-L1} (‰)	ϵ_{CFRP}^{SG-L2} (‰)	ϵ_{CFRP}^{SG-L3} (‰)	ϵ_{CFRP}^{SG-L4} (‰)	ϵ_{CFRP}^{max} (‰)
3S-4LV	2	2.96 (7.64)	2.50	9.84	4.34	12.47
	3	0.54	11.60	12.47	11.33 (11.58)	
3S-7LV	3	4.79	9.57	0.95	2.00	9.57
	5	0.14 (0.15)	NA ⁽²⁾	1.09 (5.56)	5.48 (5.52)	
3S-4LI	2	12.16	10.31	9.48	2.97 (3.28)	13.49
	3	NA ⁽²⁾	8.41	13.49	5.64	
3S-9LI	4	13.84	10.82	14.39	7.90	14.39
	6	0.26 (0.29)	7.22	7.68 (8.08)	3.70 (5.92)	

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Table 5 - Experimental vs. analytical results.

Beam	Experimental	Analytical formulation			
		Nanni <i>et al.</i> [13]		Dias and Barros [11]	
	V_f^{Exp} (kN)	V_f^{Ana} (kN)	$V_f^{Exp.} / V_f^{Ana}$	V_f^{Ana} (kN)	$V_f^{Exp.} / V_f^{Ana}$
3S-4LV	46.9	28.0	1.68	34.2	1.37
3S-7LV	93.8	55.9	1.68	60.2	1.56
3S-4LI	106.9	44.1	2.42	72.5	1.47
3S-9LI	182.4	88.1	2.07	111.8	1.63

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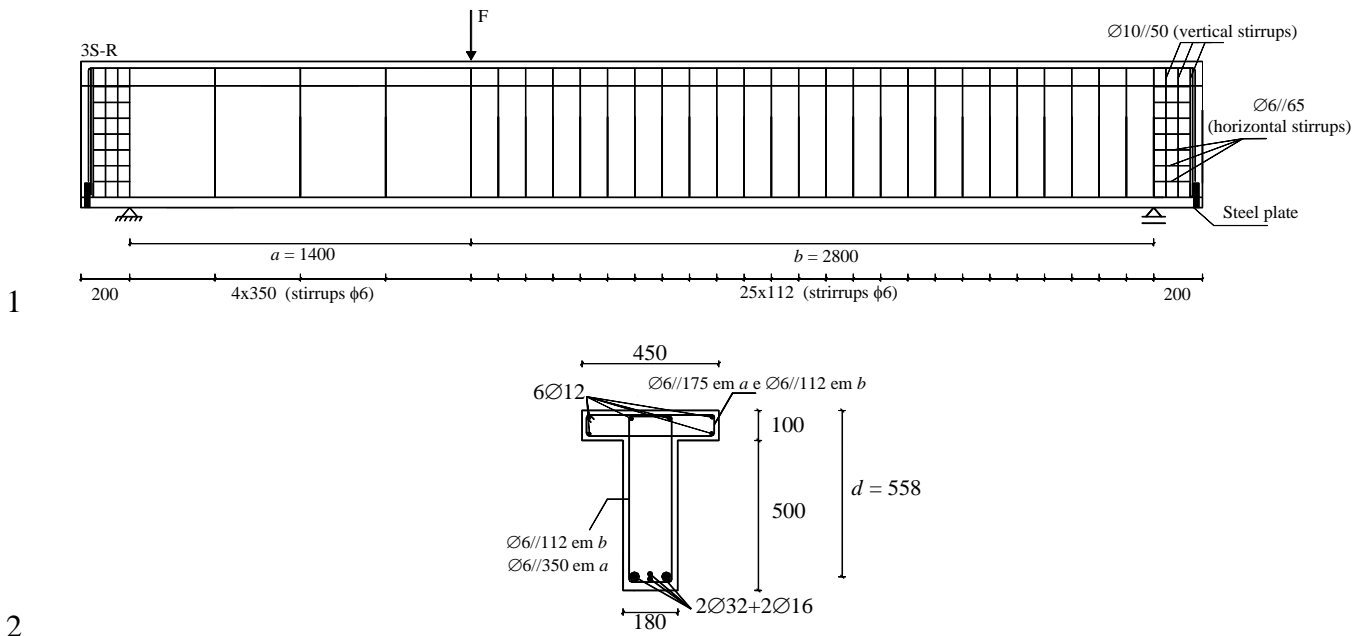
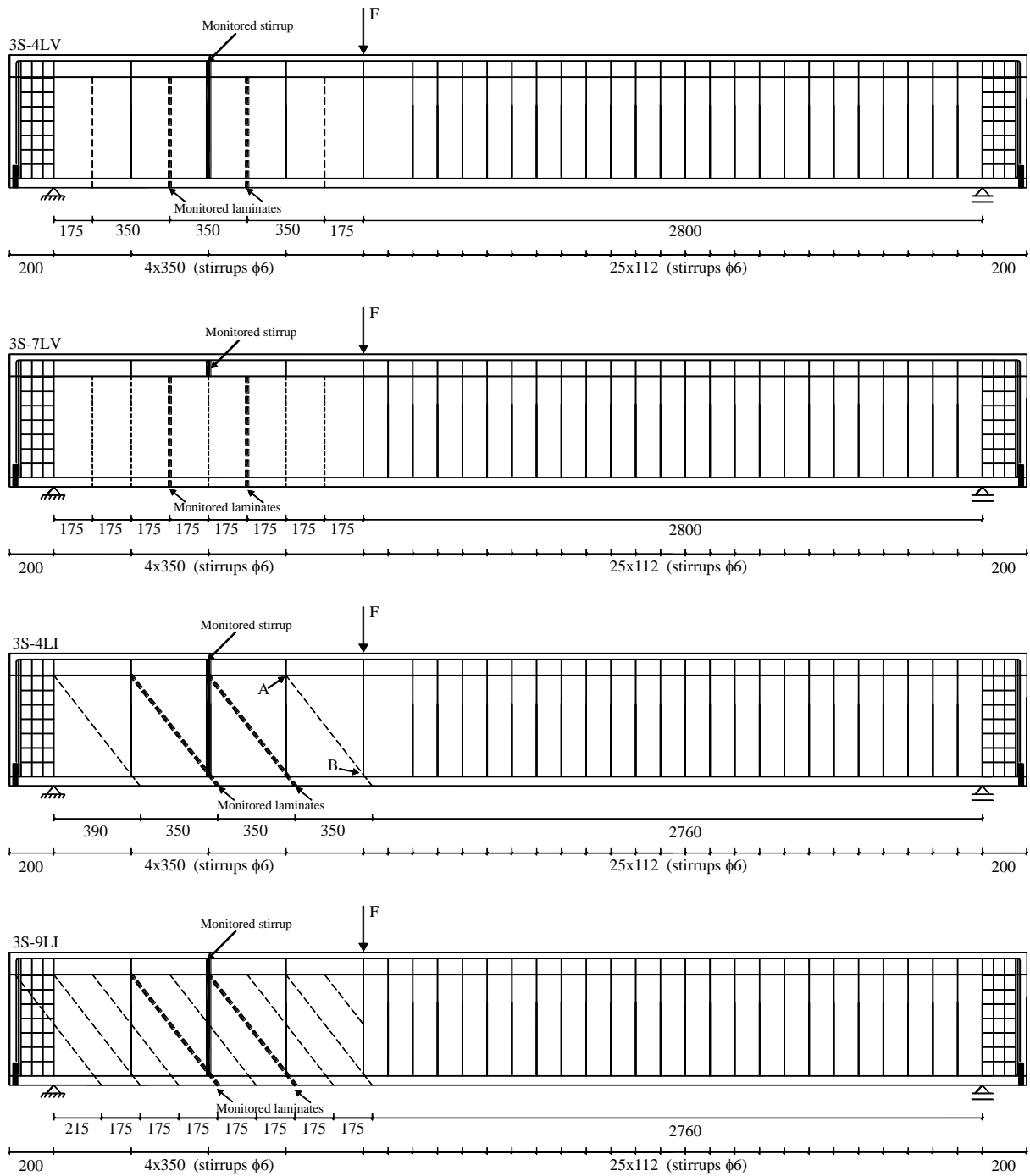


Fig. 1 - Geometry of the reference beam, steel reinforcements common to all of the tested beams, support and load conditions (dimensions in mm).



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Fig. 2 - NSM CFRP shear strengthening configurations (laminates at dashed lines) and localization of the monitored laminates and steel stirrups in the tested beams (dimensions in mm).



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b)



c)

Fig. 3 - a) and b) NSM CFRP laminates shear strengthening technique; c) test setup.

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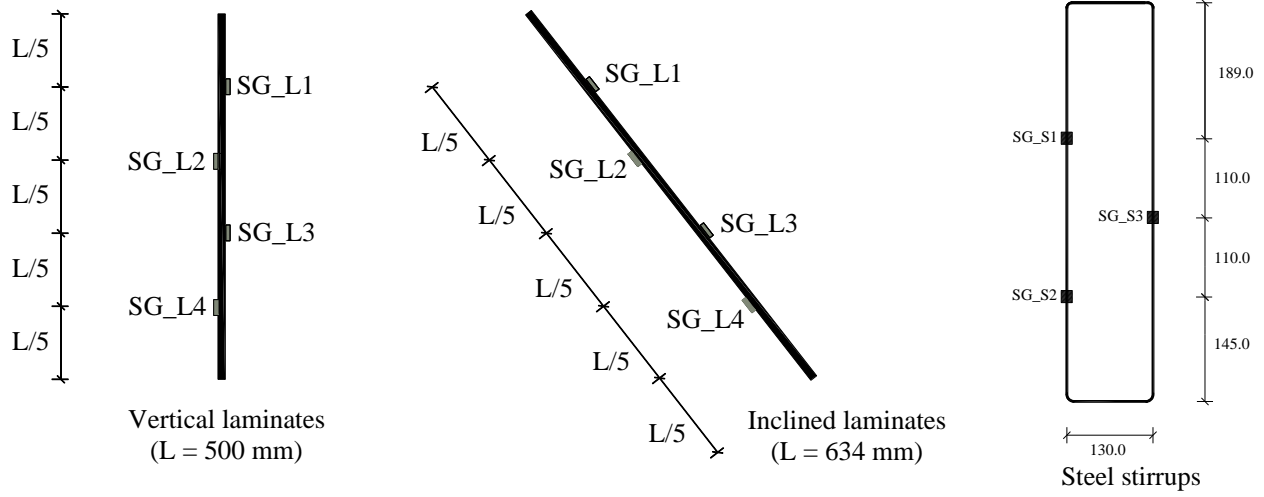


Fig. 4 - Position of the strain gauges in the monitored CFRP laminates and in the monitored steel stirrups (dimensions in mm).

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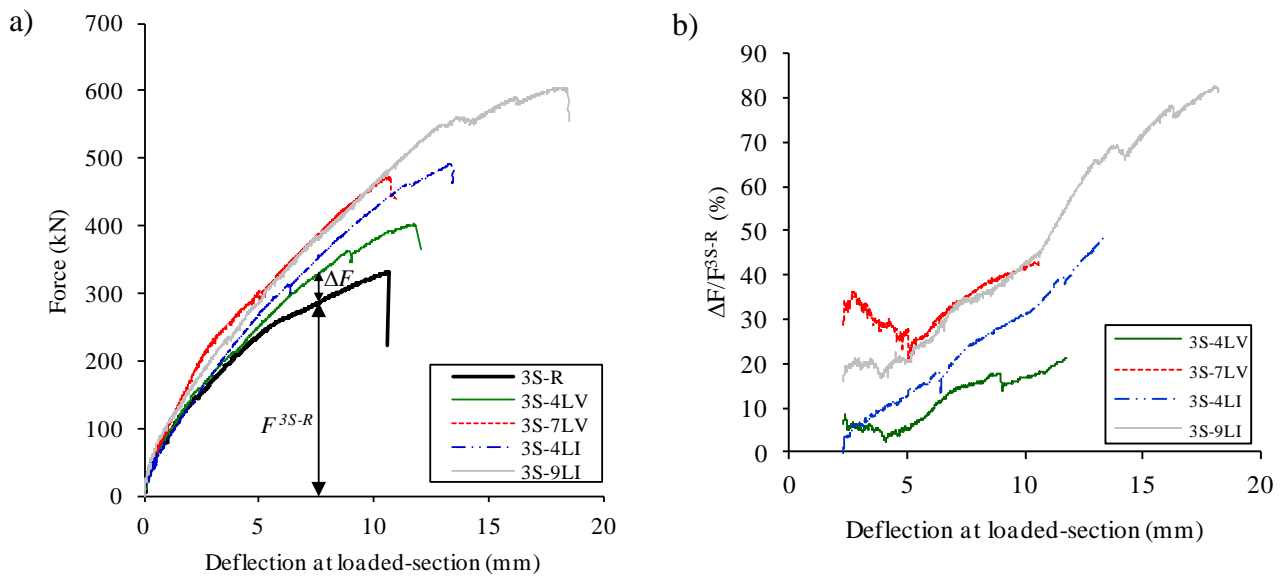
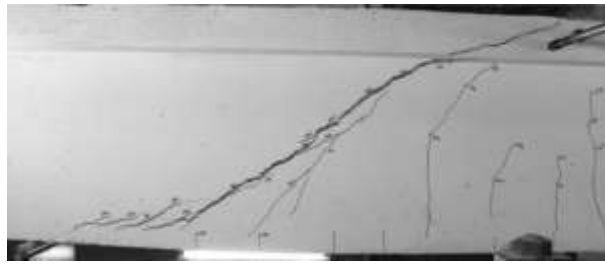
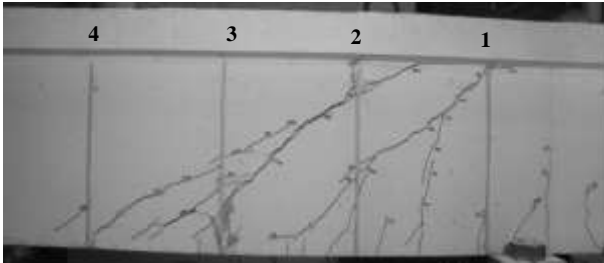


Fig. 5 - a) Force vs. deflection at loaded section of the tested beams and b) $\Delta F/F^{3S-R}$ vs. deflection at loaded section of the NCM CFRP tested beams.

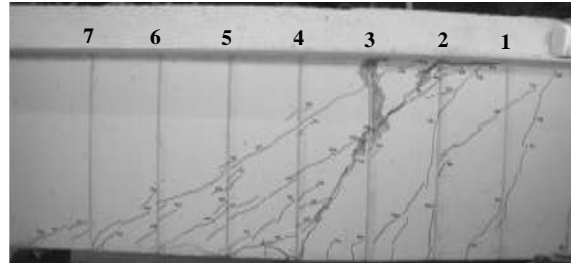
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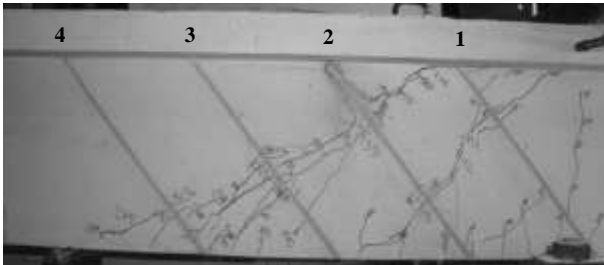
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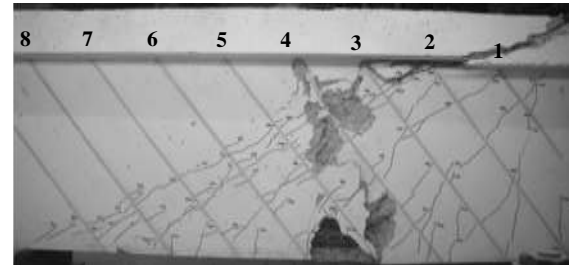
b) Beam 3S-4LV



c) Beam 3S-7LV



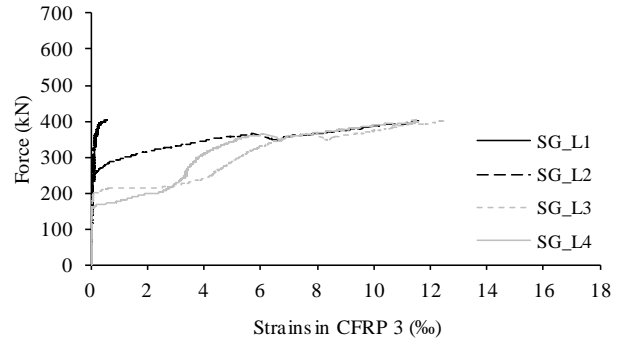
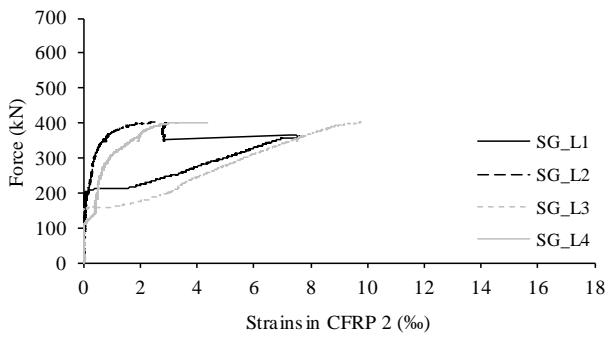
d) Beam 3S-4LI



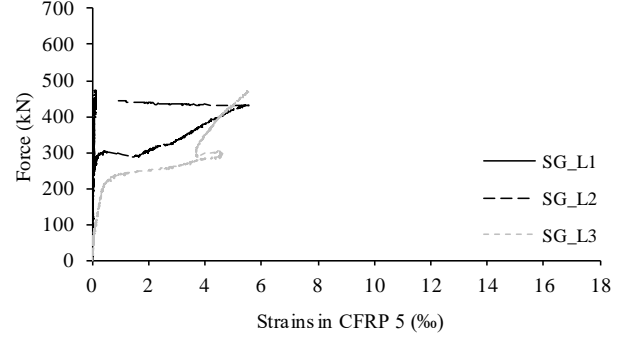
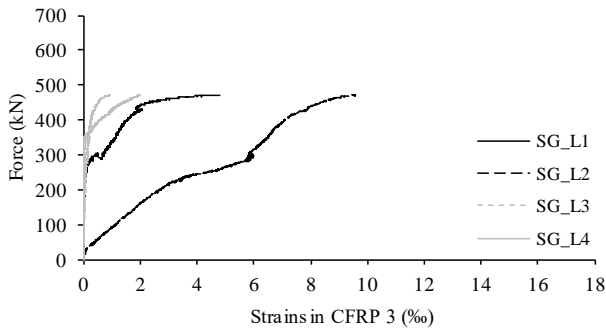
e) Beam 3S-9LI

Fig. 6 - Crack patterns of the tested beams at failure.

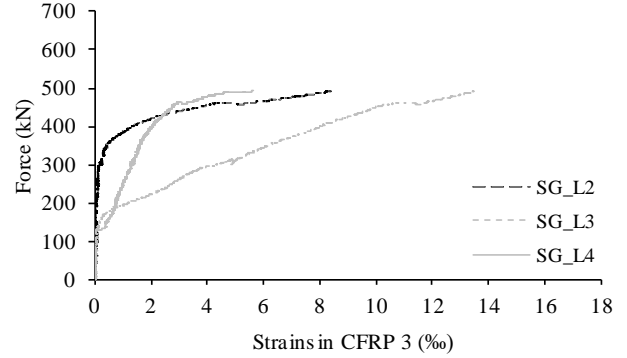
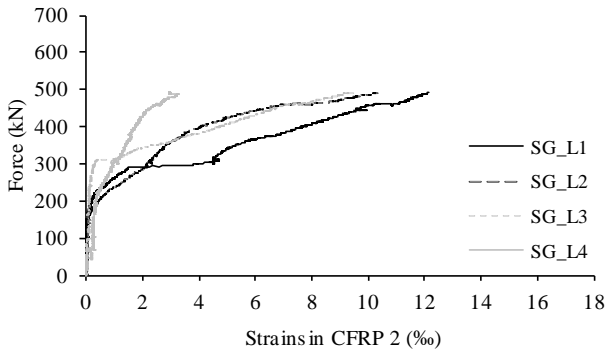
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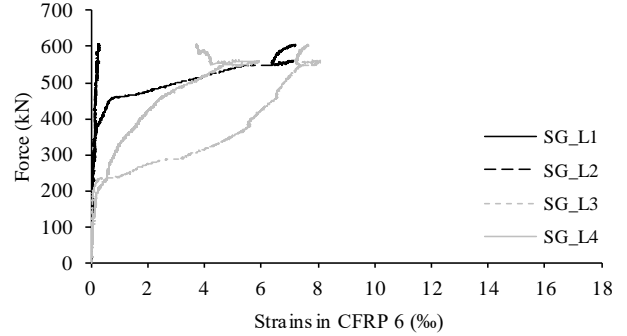
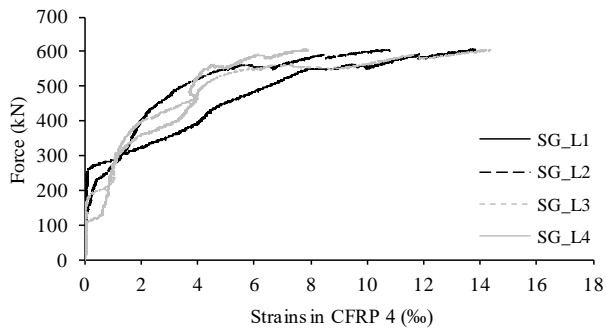
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b) Beam 3S-7LV



c) Beam 3S-4LI

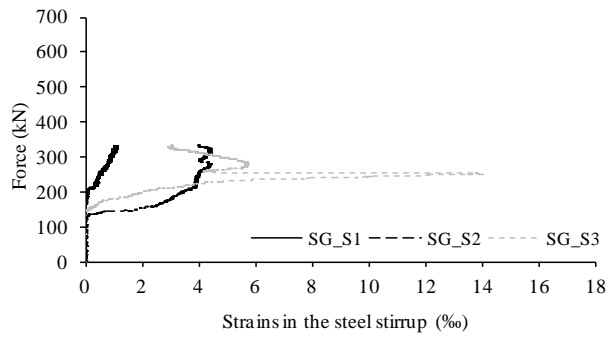


d) Beam 3S-9LI

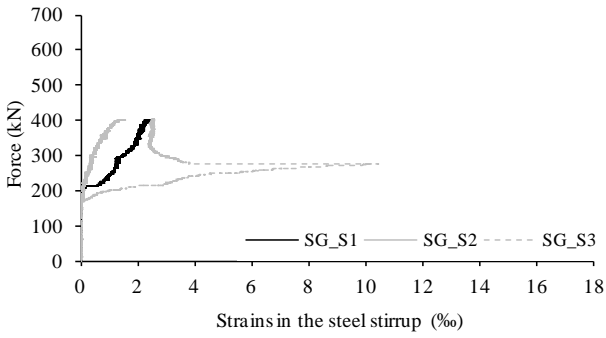
Fig. 7 - Variation of strains in the monitored CFRP laminates of the tested beams.

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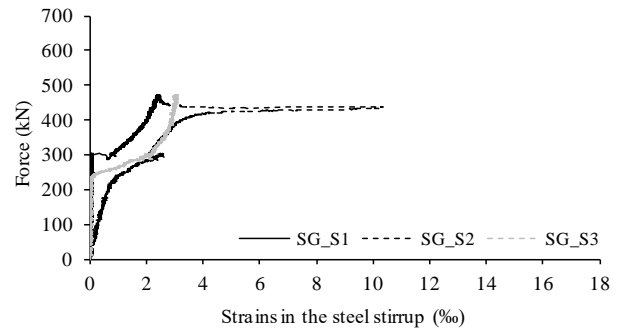
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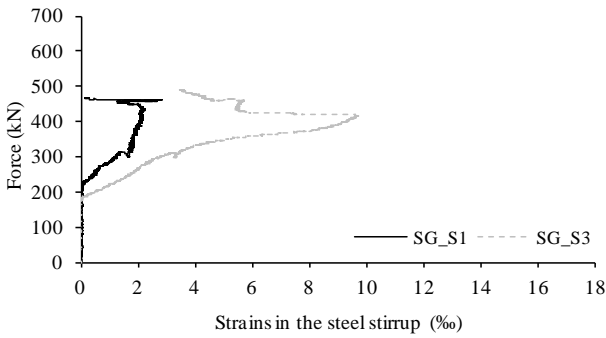
a) Beam 3S-R



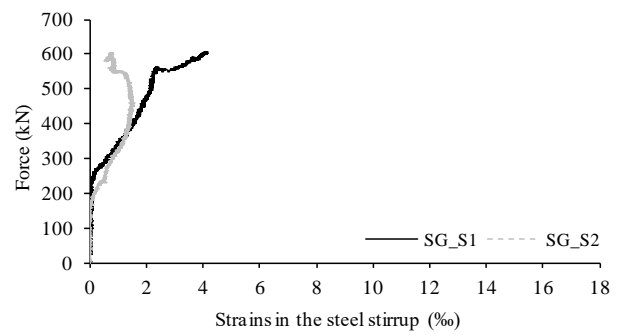
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c) Beam 3S-7LV



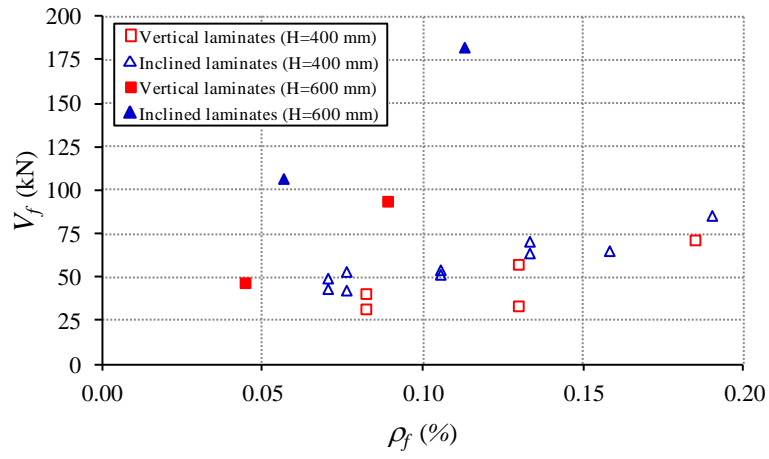
d) Beam 3S-4LI



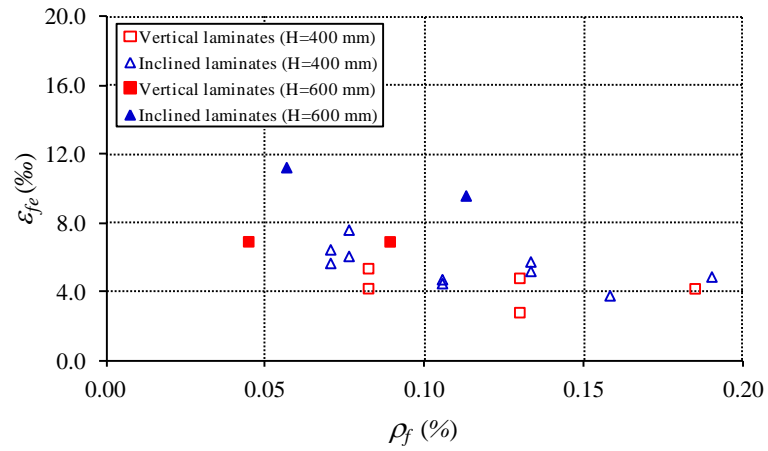
e) Beam 3S-9LI

Fig. 8 - Variation of strains in the monitored steel stirrups of the tested beams.

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Fig. 9 - Comparison of the shear strengthening effectiveness of the NSM technique with CFRP laminates in terms of: a)

V_f and b) ϵ_{fe} .

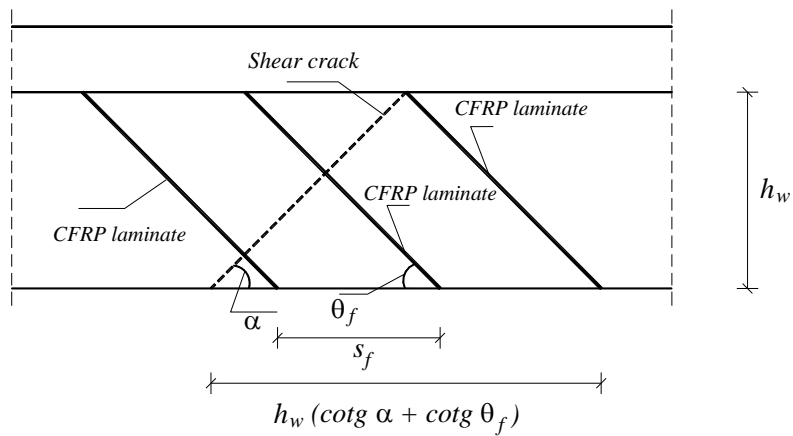


Fig. 10 - Geometric representation of the data for the analytical definition of the effective strain of the CFRP used in the formulation proposed by Dias and Barros.

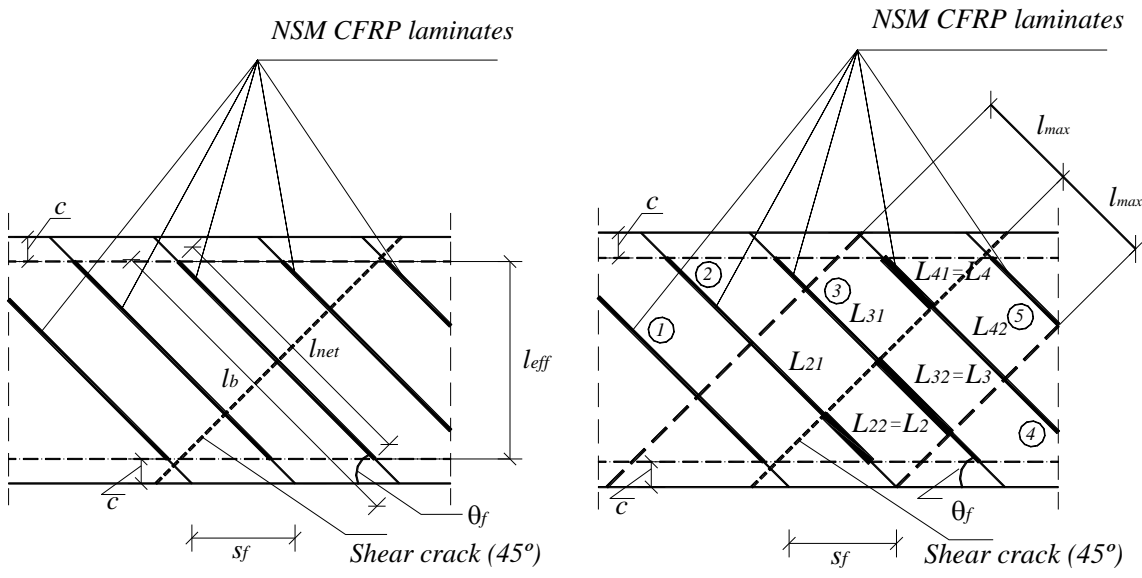


Fig. 11 - Graphical representation of variables used in the formulation proposed by Nanni *et al.* (for this example

$$\sum_i L_i = L_2 + L_3 + L_4).$$

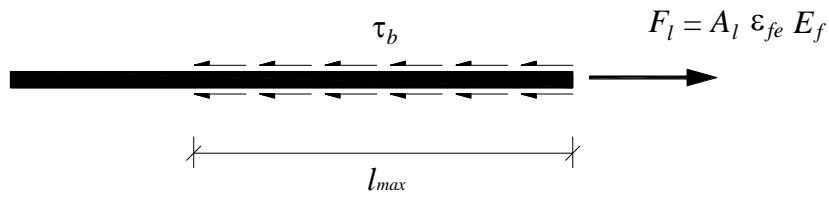
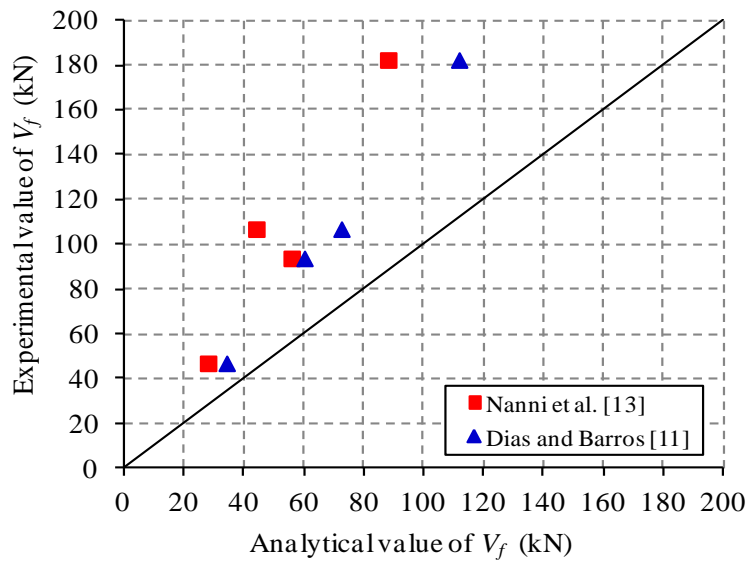
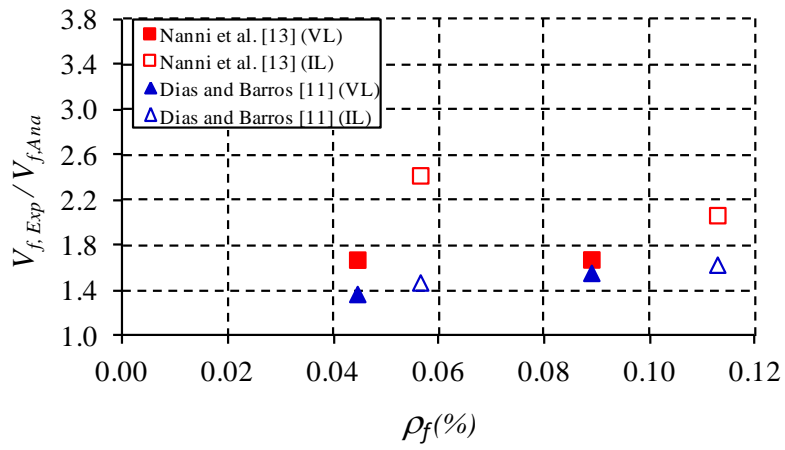


Fig. 12 - Graphical representation of l_{max} .



a)



b)

Fig. 13 - a) Comparison between the experimental and analytical values of the NSM CFRP contribution for the shear resistance, V_f , and b) $(V_{f,Exp} / V_{f,Ana})$ vs. percentage of CFRP (ρ_f). [Note: VL - vertical laminates; IL - inclined laminates].