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

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ABSTRACT

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

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

1. INTRODUCTION

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

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structures. For the shear strengthening, CFRP can be applied according to the followings two main techniques:

1. Externally Bonded Reinforcement (EBR) where the CFRP (wet lay-up sheets or laminates) is bonded to the external faces of the elements to be strengthened, by full wrapping the cross section, or applying in a U configuration, or in the lateral faces of the beam [1-4];

2. Near Surface Mounted (NSM) where CFRP bars (circular, square or rectangular cross section) are introduced into pre-cut slits opened on the concrete cover of the elements to strengthen [5-8]. Due to the largest bond area and higher confinement provided by the surrounding concrete, narrow strips of CFRP laminates of rectangular cross section, installed into thin slits and bonded to concrete by an epoxy adhesive, are the most effective CFRP strengthening elements for the NSM technique [9].

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

The effectiveness of NSM shear strengthening technique with CFRP laminates applied for T cross section RC beams with a certain percentage of steel stirrups was assessed by an extensive experimental research carried out by Dias and Barros [11]. In this context, the influence of the following parameters was appraised: concrete strength; percentage of existing steel stirrups; percentage and inclination of the CFRP laminates; existence of shear cracks when the RC beams are shear strengthened with NSM CFRP laminates. The tested RC beams with a T cross section of 400 mm height, had percentages of steel stirrups ($\rho_{sw}$) ranging between 0.10% and 0.17%. In terms of concrete strength, three types were basically used: low strength ($f_{cm} = 18.6$ MPa, where $f_{cm}$ is the average concrete compressive strength at the age of the beams tests), medium strength ($f_{cm} = 31.1$ to 39.7 MPa), and high strength ($f_{cm} = 59.4$ MPa). Three orientations of the laminates with respect to the beam’s axis were tested ($\theta = 90^\circ$ - vertical laminates; $\theta = 45^\circ$ - laminates at 45°; $\theta = 60^\circ$ - laminates at 60°), and the levels of the CFRP percentage ($\rho_f$) analyzed ranged between 0.06% and 0.19%. Regardless of the percentage of CFRP, percentage of existing steel stirrups and concrete strength, inclined laminates were more effective than vertical laminates. It was also verified that the beam’s shear capacity increased with $\rho_f$, while the NSM shear strengthening effectiveness decreased with the increase of the percentage of existing steel stirrups. The main difference of the behavior of NSM CFRP beams with and without pre-cracks resided in an expected loss of initial stiffness in the pre-cracked beams. However, the pre-cracking had not affected the efficacy of the NSM shear
strengthening technique in terms of load carrying capacity and ultimate deflection. The contribution of the NSM CFRP laminates for the beam shear resistance was limited by the concrete tensile strength. In fact, this technique was more effective when applied to RC beams of high-strength concrete, not only in terms of increasing the load carrying capacity of the beams, but also in assuring higher mobilization of the tensile capacity of the CFRP. This can be justified by the physical interpretation of the types of failure modes developed during the shear crack propagation bridged by NSM CFRP laminates described elsewhere [12]. However, considering the results of Dias and Barros [11], the shear strengthening can still be significant in RC beams of relatively low concrete strength if a convenient bond length for the CFRP laminates is assured.

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

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

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

2. EXPERIMENTAL PROGRAM

2.1 Beam prototypes

The experimental program was composed of five T cross section RC beams: a reference beam (Fig. 1) and four NSM CFRP shear strengthened beams (Fig. 2). The beams were 4600 mm long and the T cross section had overall dimensions of 450 mm (width of flange) by 600 mm (total depth). The width of the web and the thickness of the flange were 180 mm and 100 mm, respectively. Fig. 1 shows the T cross section geometry and the steel reinforcement details.
for the series of beams, as well as the loading configuration and support conditions. The adopted reinforcement was designed to assure shear failure mode for all the tested beams. To localize the shear failure in only one of the beam shear spans, a three point loading configuration with a distinct length for the beam shear spans was selected, as shown 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 according to the available research [14], this is the minimum value that assures a negligible arch effect. To avoid shear failure in the beam span, steel stirrups of 6 mm diameter at a spacing of 112 mm (ϕ6@112 mm) were applied in this span. To prevent brittle spalling of the concrete cover at the supports, the beam’s ends were strengthened by confining the concrete with a two-directional cage of ϕ6@65 mm horizontal stirrups and ϕ10@50 mm vertical stirrups (Fig. 1). To overcome the difficulties of bending the ϕ32 mm longitudinal tensile bars, their ends were welded to a steel plate.

The differences between the tested beams were restricted to the CFRP shear reinforcement in the a beam span. The reference beam without CFRP was designated as “3S-R” (three steel stirrups in the a shear span leading a steel shear reinforcing ratio, ρsw, of 0.09%), while the following NSM strengthening configurations, with CFRP laminates of 1.4×10 mm² cross section, were adopted for the other four beams that also included three steel stirrups in the a shear span (Fig. 2 and Table 1): 3S-4LV beam with four CFRP laminates per face installed in vertical slits (θf = 90°) with 350 mm of spacing; 3S-7LV beam with seven CFRP laminates per face installed in vertical slits (θf = 90°) with 175 mm of spacing; 3S-4LI beam with four CFRP laminates per face with 350 mm of spacing and inclined at 52 degrees with respect to the longitudinal axis of the beam (θf = 52° - the same orientation of the line AB present in the beam 3S-4LI of the Fig. 2); 3S-9LI beam with nine CFRP laminates per face with 175 mm of spacing and inclined at 52 degrees with respect to the longitudinal axis of the beam (θf = 52°).

The CFRP laminates were installed in slits executed from the bottom surface of the flange to the bottom tensile surface of the beam’s web, i.e., bridging the total lateral surfaces of the beam’s web (Fig. 3a). In fact, each CFRP 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 lateral surfaces (the laminates were not anchored to the beam flange; they were restricted to the beam web). The configuration adopted for the CFRP laminates avoided any type of injury in the steel reinforcements during the execution of the slits (the concrete cover of the lateral faces of the beam’s web was about 22 mm thickness). After opening the slits, the NSM strengthening technique is composed of the following procedures: 1) the slits were cleaned by compressed air; 2) the laminates were cleaned with acetone; 3) the epoxy adhesive was produced according to supplier recommendations; 4) the slits were filled with the adhesive; 5) the adhesive was applied on the faces of the laminates; and 6) the laminates were inserted into the slits (Fig. 3b) and adhesive in excess was removed. To guarantee a proper curing of the adhesive, at least one week passed between the beam strengthening operations and the beam test.
The details of the shear strengthening configurations are indicated in Table 1. This table shows that the tested beams had a percentage of longitudinal tensile bars ($\rho_{sl}$) of 2%, a percentage of steel stirrups ($\rho_{sw}$) of 0.09%, and a percentage of NSM CFRP laminates ($\rho_f$) ranging from 0.044% to 0.113%.

### 2.2 Material properties

The concrete compressive strength was evaluated when the beam tests were realized. In order to do it, direct compression tests were carried out with cylinders of 150 mm diameter and 300 mm height, according to EN 206-1 [15]. 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 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 properties of the high bond steel bars used in the tested beams (Table 2) were obtained from uniaxial tensile tests performed according to the recommendations of EN 10002-1[16]. CFK 150/2000 S&P laminates were used in the present experimental research and the tensile properties were evaluated following the recommendations of ISO 527-5 [17]. The average value of the tensile strength ($f_{tu}$), elasticity modulus ($E$), and ultimate strain ($\varepsilon_{tu}$) of CFRP laminate was, respectively, 3009.3 MPa, 169.2 GPa and 17.8‰.

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

### 2.3 Test setup and monitoring system

Three point beam bending tests (Fig. 3c) 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. With the purpose to obtain the strain variation along two laminates 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 each laminate as shown in Fig. 4. Adopting the same principle, one steel stirrup was monitored with three strain gauges (SG_S) installed according to the configuration represented in Fig. 4. The location of the monitored laminates and stirrups in the tested beams is indicated in Fig. 2.
3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Load carrying capacity of the tested beams

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

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

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

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

### 3.2 Failure modes

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

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

In the 3S-4LI beam, at a load level of about 462 kN the 4th laminate from the loaded section debonded at its bottom part (laminate 4 in Fig. 6d), with a formation of a concrete volume surrounding the laminate. This was followed by a decay of the load carrying capacity of this beam (Fig. 5a). The load was transferred, mainly, to the second and third laminates from the loaded section (laminates 2 and 3 in Fig. 6d), the ones crossing the critical shear crack, and the load was again increased up to the moment ($F_{\max} = 491.7$ kN) when occurred the debonding of the top part of the laminate 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 from the loaded section debonded at its top part (laminate 3 in Fig. 6e), with a formation of a concrete volume surrounding the laminate. This was followed by a decay of the load carrying capacity of this beam (Fig. 5a). The load was transferred, mainly, to the 4th laminate from the loaded section (laminate 4 in Fig. 6e), and the load was again...
increased up to the moment \( F_{\text{max}} = 605 \text{ kN} \) when occurred the debonding of the top part of this laminate (Fig. 6e), followed by a sudden and abrupt load decay.

### 3.3 Strains in the CFRP laminates and steel stirrups

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

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

### 3.4 Comparison of the shear strengthening effectiveness

The shear capacity contributed by the CFRP \( (V_f) \) was obtained by subtracting the shear resistance of the reference beam \( (V_{\text{ref}}) \) from the shear resistance of the strengthened beam \( (V) \):

\[
V_i = V_{\text{ref}} + V_f
\]  

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

By comparing the \( V_f \) values of the beams of the present experimental program (46.9 kN, 93.8 kN, 106.9 kN and 182.4 kN for the beams 3S-4LV, 3S-7LV, 3S-4LI and 3S-9LI, respectively) to those determined in NSM shear strengthened RC beams [11] with the same kind of concrete \( (f_{\text{cm}} = 39.7 \text{ MPa}) \) and the same test setup, but with RC
beams of smaller height of the cross section, 400 mm, (Fig. 9a), it can be concluded that the effectiveness of the NSM technique with CFRP laminates increases with the height of the cross section.

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

$$
\varepsilon_{fe} = V_f \left( \frac{h_w \times A_{f_c}}{s_f} \times E_f \times \left( \cot \gamma + \cot \alpha \theta_f \right) \times \sin \theta_f \right)
$$

where $h_w$ is the height of the beam’s web, $A_{f_c}$ is the cross sectional area of a “laminate stirrup” that is formed by two lateral laminates ($A_{f_c} = 2 \times a_f \times b_f$), $s_f$ is the spacing of laminates, $E_f$ is the elastic modulus of the laminate, $\alpha$ is the orientation of the shear failure crack (considered as 45°), and $\theta_f$ is the inclination of the laminates with respect to the beam axis (Fig. 10).

Fig. 9b compares the $\varepsilon_{fe}$ values obtained in the present experimental program (6.9‰ for the beams with vertical laminates; 11.3‰ and 9.6‰ for the beams 3S-4LI and 3S-9LI, respectively) with those obtained in Dias and Barros [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 400 mm. In Fig. 9b is again visible that the effectiveness of the NSM technique with CFRP laminates increases with the height of the cross section.

4. APPRAISAL OF THE PREDICTIVE PERFORMANCE OF ANALYTICAL FORMULATIONS

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

4.1 Formulation by Nanni et al. [13]

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

$$
V_f = 4 \alpha (a_f + b_f) \tau_{b} \cdot L_{tot \min} \sin \theta_f
$$

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

$$
L_{tot \ min} = \sum_i L_i
$$
where \( L_i \) represents the length of each single NSM laminate crossed by a 45-degree shear crack, determined from,

\[
L_i = \begin{cases} 
\min \left( \frac{s_f}{\cos \theta_f + \sin \theta_f} i; \ l_{\max} \right) & i = 1, \ldots, \frac{N}{2} \\
\min \left( \frac{s_f}{\cos \theta_f + \sin \theta_f} i; \ l_{\max} \right) & i = \frac{N}{2} + 1, \ldots, N
\end{cases}
\]

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

\[
l_{\text{net}} = l_b \cdot \frac{2c}{\sin \theta_f}
\]

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

The first limitation of (5) 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 \( N \),

\[
N = \frac{l_{\text{eff}} \left( 1 + \cot \theta_f \right)}{s_f}
\]

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

\[
l_{\text{eff}} = l_b \sin \theta_f - 2c
\]

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

\[
l_{\text{max}} = \frac{\varepsilon_{fe} \cdot a_f \cdot b_f \cdot E_f}{2 \cdot a_f + b_f \cdot \tau_b}
\]

Considering for \( \varepsilon_{fe} \) and \( \tau_b \) the values recommended by Barros and Dias [7], respectively, 0.59% and 16.1 MPa, and assuming for the elastic modulus of the laminate the average value recorded in the experimental program of the present work (169.2 GPa), the values of the contribution of the NSM laminates for the shear strengthening of the tested beams (\( V_f^{Ana} \)), included in Table 5, were compared to those registered experimentally (\( V_f^{Exp} \)). The values of the \( V_f^{Exp} / V_f^{Ana} \) 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 coefficient of variation was 18%). These values show that the formulation proposed by Nanni et al. [13] is very conservative when the NSM CFRP laminates are installed into the slits of relatively high T cross section RC beams.
4.2 Formulation by Dias and Barros [11]

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

\[
V_f = h_w \times \frac{A_{fe}}{S_f} \times e_{fe} \times E_f \times \left( \cot g \, \alpha + \cot g \, \theta_f \right) \times \sin \theta_f
\]  

(10)

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

\[
e_{fe} = \left[ 3.76888 \times e^{\left( \frac{-0.11502610 \, f_f + 0.00104370 \, f_f^2}{f_f} \right)} \times \left( E_f \, \rho_f + E_{st} \, \rho_{sw} \right) \left( f_{cm} \, 2^{1/3} \right)^{-0.466796} \times \left( 0.0351999 f_f - 0.00034310 f_f^2 \right) \right]^{-1} / f_f
\]  

(11)

In equation (11), \( \rho_f \) and \( \rho_{sw} \) are introduced like a ratio and not in percentage (values obtained with the equations in the footnote of Table 1, but eliminating the term 100), \( f_{cm} \) is the average concrete compressive strength in cylinders (in MPa), \( E_s \) is the elasticity modulus of the steel stirrups (in MPa, the same units should be used for the elasticity modulus of the laminate \( E_{st} \)) and \( \gamma_f \) is an uncertainty factor equal to 1.3. The meaning of the others parameters of equations (10) and (11) was described in the section 3.4 (see also Fig. 10).

Adopting the formulation proposed by Dias and Barros [11], the obtained values of the contribution of the NSM laminates for the shear strengthening of the tested beams \( V_f^{Ana} \) are included in Table 5 and were compared to those 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 value of about 1.51 for \( V_f^{Exp} / V_f^{Ana} \) was obtained (the coefficient of variation was 7%).

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

5. CONCLUSIONS

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

From the obtained experimental results, it can be concluded that NSM shear strengthening technique with CFRP laminates is very effective in RC beams of relatively high cross section, not only in terms of increasing the overall
behavior of the beams, but also in assuring higher mobilization of the tensile capacity of the CFRP. The NSM CFRP shear strengthening configurations provided an increase in terms of maximum load ($F_{\text{max}}$) that ranged between 21% ($\rho_f=0.044\%$) and 83% ($\rho_f=0.113\%$) of the maximum load of the reference beam. In general, the values of the deflection at the loaded section in correspondence to $F_{\text{max}}$ of the strengthened beams were higher than those occurred in the reference beam. Inclined laminates were more effective than vertical laminates, and the shear resistance of the beams increased with the percentage of laminates. The maximum tensile strain recorded in the NSM CFRP laminates up to the maximum load ranged from 54% to 81% of its ultimate tensile strain, indicating that this strengthening technique can mobilize high stress levels in the CFRP. A very important aspect of the effectiveness of the NSM technique, regarding the analyzed beams, is its capacity to mobilize the yield stress of the stirrups before the maximum load of the strengthened beams has been attained.

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

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

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14 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 ($\rho$). [Note: VL - vertical laminates; IL - inclined laminates].
Table 1 - General information about the series of the tested RC beams.

<table>
<thead>
<tr>
<th>Beam</th>
<th>$\rho_{sl}$ (%) (1)</th>
<th>$\rho_{sw}$ (%) (2)</th>
<th>$a/d$</th>
<th>NSM CFRP laminates</th>
<th>$\theta_f$ (°)</th>
<th>$s_f$ (mm)</th>
<th>$\rho_f$ (%) (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3S-R</td>
<td>2.0</td>
<td>0.09</td>
<td>2.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3S-4LV</td>
<td></td>
<td></td>
<td></td>
<td>2x4</td>
<td>90</td>
<td>350</td>
<td>0.044</td>
</tr>
<tr>
<td>3S-7LV</td>
<td></td>
<td></td>
<td></td>
<td>2x7</td>
<td>90</td>
<td>175</td>
<td>0.089</td>
</tr>
<tr>
<td>3S-4LI</td>
<td></td>
<td></td>
<td></td>
<td>2x4</td>
<td>52</td>
<td>350</td>
<td>0.056</td>
</tr>
<tr>
<td>3S-9LI</td>
<td></td>
<td></td>
<td></td>
<td>2x9</td>
<td>52</td>
<td>175</td>
<td>0.113</td>
</tr>
</tbody>
</table>

(1) The percentage of the longitudinal tensile reinforcement was obtained from $\rho_{sl} = \frac{A_y}{b_w \times d} \times 100$, where $A_y$ 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 $\rho_{sw} = \frac{A_w}{b_w \times s_w} \times 100$, where $A_w$ 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 $\rho_f = \frac{2 \times a_f \times b_f \times \frac{b_w \times s_f \times \sin \theta_f}{\cos \theta_f}}{\cos \theta_f} \times 100$, where $a_f$ and $b_f$ are the dimensions of the laminate cross section, and $s_f$ is the CFRP spacing.

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

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>$\phi6$</th>
<th>$\phi12$</th>
<th>$\phi16$</th>
<th>$\phi32$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield stress [$f_{y_{sym}}$] (MPa)</td>
<td>555</td>
<td>562</td>
<td>560</td>
<td>734</td>
</tr>
<tr>
<td>Tensile strength [$f_{sum}$] (MPa)</td>
<td>683</td>
<td>662</td>
<td>675</td>
<td>885</td>
</tr>
</tbody>
</table>
Table 3 - Experimental results of the tested RC beams.

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

Table 4 - Strain values in the CFRP laminates.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Monitored laminate(1)</th>
<th>$\varepsilon_{SG,L1}^{CFRP}$ (%o)</th>
<th>$\varepsilon_{SG,L2}^{CFRP}$ (%o)</th>
<th>$\varepsilon_{SG,L3}^{CFRP}$ (%o)</th>
<th>$\varepsilon_{SG,L4}^{CFRP}$ (%o)</th>
<th>$\varepsilon_{max}^{CFRP}$ (%o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3S-4LV</td>
<td>2</td>
<td>2.96 (7.64)</td>
<td>2.50</td>
<td>9.84</td>
<td>4.34</td>
<td>12.47</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.54</td>
<td>11.60</td>
<td>12.47</td>
<td>11.33 (11.58)</td>
<td>9.57</td>
</tr>
<tr>
<td>3S-7LV</td>
<td>3</td>
<td>4.79</td>
<td>9.57</td>
<td>0.95</td>
<td>2.00</td>
<td>13.49</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.14 (0.15)</td>
<td>NA (2)</td>
<td>1.09 (5.56)</td>
<td>5.48 (5.52)</td>
<td>9.57</td>
</tr>
<tr>
<td>3S-4LI</td>
<td>2</td>
<td>12.16</td>
<td>10.31</td>
<td>9.48</td>
<td>2.97 (3.28)</td>
<td>13.49</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>NA (2)</td>
<td>8.41</td>
<td>13.49</td>
<td>5.64 (5.62)</td>
<td>13.49</td>
</tr>
<tr>
<td>3S-9LI</td>
<td>4</td>
<td>13.84</td>
<td>10.82</td>
<td>14.39</td>
<td>7.90</td>
<td>14.39</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.26 (0.29)</td>
<td>7.22</td>
<td>7.68 (8.08)</td>
<td>3.70 (5.92)</td>
<td>14.39</td>
</tr>
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</table>

(1) See Fig. 6. (2) This SG did not work. Note: The strain values in brackets are referred to the load when occurred the maximum strain in the laminates before the maximum load.

Table 5 - Experimental vs. analytical results.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Experimental $V_f^{Exp}$ (kN)</th>
<th>Analytical formulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_f^{Exp}$/$V_f^{Ana}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$V_f^{Exp}$/$V_f^{Ana}$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam</th>
<th>$V_f^{Exp}$ (kN)</th>
<th>$V_f^{Ana}$ (kN)</th>
<th>$V_f^{Exp}/V_f^{Ana}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3S-4LV</td>
<td>46.9</td>
<td>28.0</td>
<td>1.68</td>
</tr>
<tr>
<td>3S-7LV</td>
<td>93.8</td>
<td>55.9</td>
<td>1.68</td>
</tr>
<tr>
<td>3S-4LI</td>
<td>106.9</td>
<td>44.1</td>
<td>2.42</td>
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<tr>
<td>3S-9LI</td>
<td>182.4</td>
<td>88.1</td>
<td>2.07</td>
</tr>
</tbody>
</table>
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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 $l_{\text{max}}$. 

$F_i = A_i \varepsilon_{fe} E_f$
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 ($\rho_f$). [Note: VL - vertical laminates; IL - inclined laminates].