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# INFLUENCE OF THE CONCRETE MECHANICAL PROPERTIES ON THE EFFICACY OF THE SHEAR STRENGTHENING INTERVENTION ON RC BEAMS BY NSM TECHNIQUE

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## ABSTRACT

The occurrence of a failure mode, different from debonding, consisting on the detachment, from the beam core, of "two concrete lateral walls" containing the glued laminates, highlights the paramount importance of concrete mechanical properties on the effectiveness of NSM shear strengthening technique. A new mechanical-analytical interpretation of the phenomenon affecting the ultimate behaviour of RC beams NSM-strengthened in shear is presented along with the main findings. This approach takes into account the possibility that the shear strengthening contribution of the NSM laminates can be limited by the three following failure modes: debonding, concrete tensile fracture and laminates' tensile rupture. The interaction between laminates can be also accounted for. The proposed mechanical interpretation of the NSM laminates behaviour can be extended to NSM rods.

## KEYWORDS

CFRP, RC beams, NSM technique, concrete tensile fracture, debonding, laminates tensile rupture.

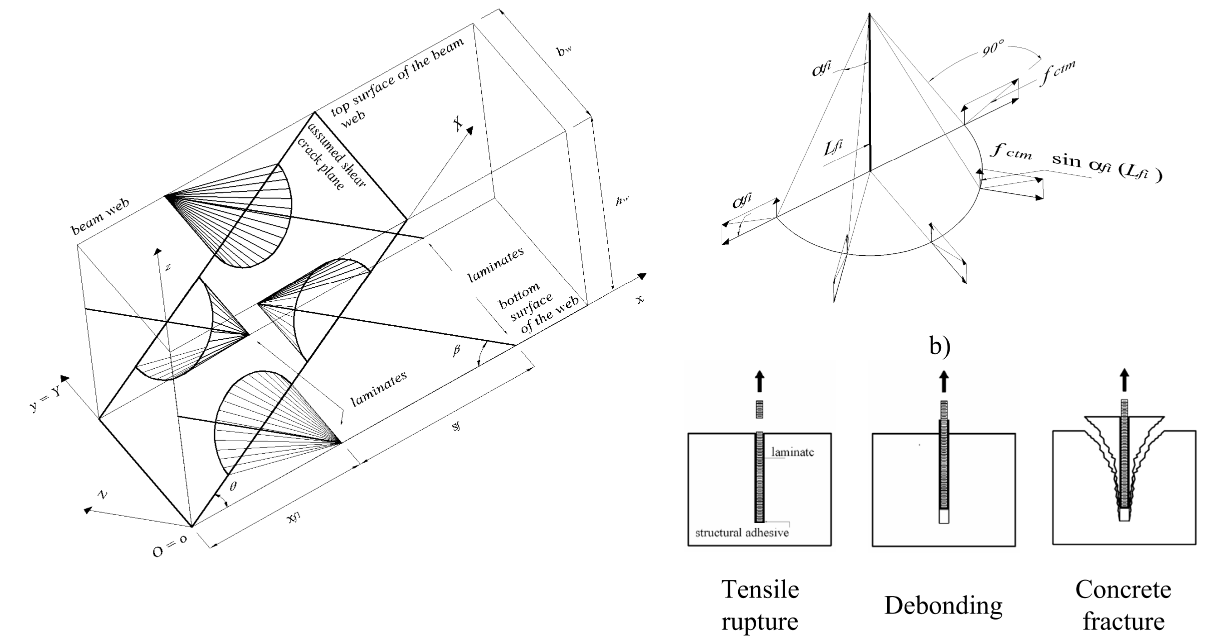
## INTRODUCTION

Some among the most recent and accredited experimental programs (De Lorenzis and Rizzo 2006, Dias and Barros 2006) have highlighted the occurrence of a singular failure mode affecting the behaviour, at ultimate, of Near Surface Mounted (NSM) shear-strengthened RC beams. The progressive detachment of the concrete cover, containing the glued laminates, from the underlying core of the beam web was reported. The occurrence of that failure mode encouraged Dias *et al.* (2007) to arrange and carry out an experimental program on low strength RC beams to further investigate the influence of concrete mechanical properties on the efficacy of the NSM shear strengthening technique. In that occasion, the previously observed failure mode resulted even more evident, thus confirming the authors' suspicions about the paramount importance of the concrete mechanical properties. The need for a rational explanation to the observed failure mode has led Bianco *et al.* (2007) to propose and verify the potentialities of a new modelling approach. Within that work, Bianco *et al.* (2006) developed a new analytical predictive model to evaluate the NSM shear strength contribution that takes into account, as possible failure modes undergone by NSM laminates: debonding, concrete tensile fracture and laminates' tensile rupture. The Proposed Model (PM) allows the interaction between laminates to be easily accounted for. The main features of the PM are shown together with its main findings. The PM is applied to predict the NSM shear strength contribution recorded in some of the most recent experimental programs regarding the employment of both CFRP laminates and rods. From the comparison with the predictions obtained from a Debonding-based Modelling strategy (DM) that contemplates debonding as the main failure mode, the higher prediction accuracy of the PM arises.

## PROPOSED PREDICTIVE MODEL

### *Physical fundamentals*

By searching the technical literature available to date, the analogy arises between the NSM technique and the fastening technology to concrete by means of adhesive anchors (Cook and Konz 2001). This latter consists in fixing anchors into holes drilled in the soffit of RC elements by different kinds of structural adhesives. As for the NSM laminates, the stress transfer of anchors strongly relies on the bond characteristics. The experimental evidence in the field of fastening technology reported three possible failure modes: tensile rupture of the anchor, debonding and another failure mode designated as "concrete cone failure" (see Figure 1c). This latter is characterized by a cone-shaped spalling of the concrete surrounding the anchor, originating at a certain point of the embedded length of the anchor and propagating towards the external surface of the concrete. This failure occurs when the applied force is such as to induce, in the surrounding concrete, principal tensile stresses exceeding the concrete tensile strength. The resulting concrete fracture conical surface, envelope of the tension isostatics, shows, at its vertex, an angle of about 45° with the anchor axis. In the case of NSM laminates, the critical diagonal crack can be schematized like a plane slicing the web of the beam in two parts sewn together by the crossing laminates that can be regarded as fastenings (see Figure 1a).




a) c)

Figure 1 – Main features of the proposed model: a) crack plane crossed by laminates and their semi-conical fracture surfaces; b) detail of the semi-conical fracture surface and the distribution of the average tensile strength; c) assumed failure modes.

The laminates may fail along their "available bond length" *i.e.* the shorter of the two parts in which the shear crack divides them, by: debonding, tensile rupture or concrete tensile fracture (see Figure 1c). The asymmetric geometrical features support the assumption that, in the case of the laminates glued into thin slits in the concrete web face, the concrete fracture surface, envelope of the principal tensile stresses induced in the surrounding concrete, has a semi-conical shape propagating from the inner tip of the laminate embedded length. The concrete average tensile strength, $f_{ctm}$, is distributed throughout each of the resulting semi-conical surfaces orthogonally to them in each point (see Figure 1b). The NSM shear strength contribution, $V_f$, can be calculated by adding the contribution ascribed to each laminate, $V_{fi}^{p}$, parallel to its orientation, and projecting the resulting force orthogonally to the beam axis, according to the following Eq. 1:

$$V_f = 2 \, . \, \sin\beta \, . \sum_{i=1}^{N_f} V_{fi}^{p} = 2 \cdot \sin\beta \cdot \sum_{i=1}^{N_f} \min\left\{V_{fi}^{p,db} ; V_{fi}^{p,tr} ; V_{fi}^{p,cf}\right\} \quad (1)$$

where $\beta$ is the inclination of the laminates and $N_f$ is the number of the laminates crossing the shear crack and where the contribution provided by each laminate, $V_{fi}^{p}$, can be assumed as the minimum among the three possible contributions ascribed, respectively, to debonding, $V_{fi}^{p,db}$, tensile rupture of the laminate, $V_{fi}^{p,tr}$, or concrete tensile fracture, $V_{fi}^{p,cf}$. Those three terms can be computed as follows (Eq. 2):

$$V_{fi}^{p,db} = 2 \, . \left(a_f + b_f\right) . \, \tau_b(L_f) \, . \, L_f \quad ; \quad V_{fi}^{p,tr} = a_f \, . \, b_f \, . \, f_{fu} \quad ; \quad V_{fi}^{p,cf} = \int_{C_{fi}\left(L_{fi};\alpha_{fi}\right)} \left(f_{ctm} \, . \sin\alpha_{fi}\right) . \, dC_{fi} \quad (2)$$

where: $a_f$ and $b_f$ are, respectively, thickness and width of the laminates' cross section, $\tau_b(L_f)$ is the length-dependent value of the average bond strength, $f_{fu}$ is the tensile strength of the adopted CFRP laminates. In Eq. 2, the concrete fracture-based term, $V_{fi}^{p,cf}$, ascribed to each laminate and parallel to its orientation, is calculated distributing the component of the concrete mean tensile strength parallel to the laminate, *i.e.*, $f_{ctm} \cdot \sin \alpha_{fi}$, throughout the resulting relevant semi-conical surface and integrating (see Figure 1b). $C_{fi}\left(L_{fi};\alpha_{fi}\right)$ concisely denotes the semi-conical surface associated to the i-th laminate and $\alpha_{fi}$ is the angle between the generatrices and the axis of the semi-cone attributed to the i-th laminate. The angle between the axis of the semi-conical surface and its generatrices, $\alpha_f$, calibrated on the basis of the interpretation of some experimental results available to date (Bianco *et al.* 2006), ranges approximately between 20° and 30° and shows a length-dependency on the available bond length, $L_f$, but, in this respect, further investigations are required. The relationship between the angle, $\alpha_{fi}$ (in degrees), and the available bond length, $L_{fi}$ (in mm), along with the relationship $\tau_b(L_f)$ (with $\tau_b$ in MPa and $L_f$ in mm) assumed in the present work are as reported hereafter (Eq. 3):

$$\alpha_{fi} = \begin{cases} 32.31 & 0 \le L_{fi} \le 30 \\ 33.973 - 0.0587 \cdot L_{fi} & 30 < L_{fi} \le 150 \\ 25.17 & L_{fi} > 150 \end{cases} \quad ; \quad \tau_b\left(L_f\right) = \begin{cases} 19.28 & 0 < L_f < 40 \\ 0.355 + 174.613 \cdot \left(L_f\right)^{-0.60233} & L_f \ge 40 \end{cases} \tag{3}$$

If attention is focused on one laminate only, in the case in which it results to be orthogonal to the crack plane and in complete absence of interaction with the contiguous ones, the shear strength contribution parallel to its orientation $V_{fi}^{p}$ can be calculated by the following Eq. 4:

$$V_{fi}^{p} = \min\left\{2 \cdot \left(a_f + b_f\right) \cdot \tau_b(L_{fi}) \cdot L_{fi};\ a_f \cdot b_f \cdot f_{fu}\ ;\ \left(\frac{\pi}{2} \cdot f_{ctm}\right) \cdot tg^2\alpha_{fi} \cdot L_{fi}^2\right\} \tag{4}$$

that, for the materials regarding the experimental programs by Dias and Barros (2006), is plotted in Figure 2.

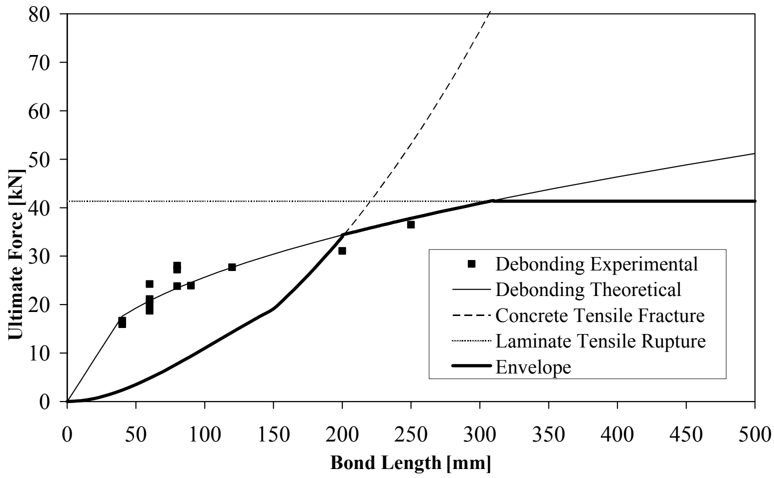
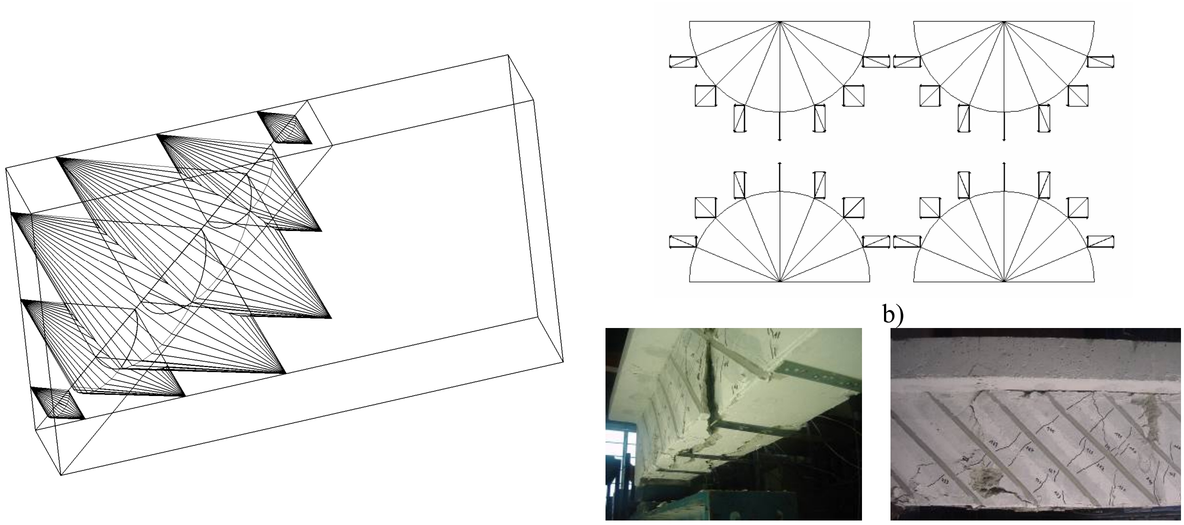



Figure 2 – Expected failure mode as function of the available bond length

It arises that: for a value of the available bond length up to 200 mm, the prevailing failure mode is the concrete semi-conical fracture; for a value between 200 and 310 mm, the failure mode is debonding, and for an available bond length higher than 310 mm, the laminates are expected to fail by tensile rupture. Due to the interaction between contiguous laminates, the curve regarding the concrete tensile fracture opens downwards (when laminates spacing decreases) thus further reducing the range of length values where debonding is expected to be the prevailing failure mode. The terms $V_{fi}^{p,tr}$ and $V_{fi}^{p,db}$, based on the phenomena of tensile rupture and debonding of the laminate, respectively, are intrinsically independent of the interaction between subsequent laminates that, on the contrary, affects the concrete fracture-based term, $V_{fi}^{p,cf}$. As the spacing between subsequent laminates is reduced, their semi-conical fracture surfaces overlap and the resulting envelope area progressively becomes smaller than the mere summation of each of them (see Figure 3a). This detrimental interaction between laminates can be easily taken into account by calculating accordingly the resulting semi-conical surface ascribed to each laminate. For very short values of the spacing, the resulting concrete failure surface is almost parallel to the web face of the beam, which is in agreement with the failure mode observed experimentally, consisting in the detachment of the concrete cover from the underlying core of the beam (see Figure 3c). Since the position of those semi-conical surfaces is symmetric with respect to the vertical plane passing through the beam axis, the horizontal outward components of the tensile strength vectors distributed throughout their surfaces are balanced only from an overall standpoint but not locally (see Figure 3b). This local unbalance of the horizontal tensile stress component orthogonal to the beam web face justifies the outward expulsion of the concrete cover in both the uppermost and lowermost parts of the strengthened sides of the web.




a) c)

Figure 3 – Outward expulsion of the strengthened concrete cover: a) inside view of the resulting fracture surface on one side of the web; b) local unbalance of the components of the concrete tensile strength orthogonal to the web faces; c) details of beam 2S-7LI45 from Dias *et al.* (2007).

***Analytical details***

The value of the $V_f$ can be calculated for three different geometrical configurations of the laminates with respect to the assumed shear crack so as to evaluate the maximum and minimum possible analytical value. Further details about the strategy adopted to evaluate the concrete semi-conical surface ascribed to each i-th laminate for the above three configurations can be found elsewhere (Bianco *et al.* 2006).

**RESULTS AND DISCUSSIONS**

The PM described in the previous sections was applied to predict the experimentally recorded shear strength contribution for the beams tested by Dias and Barros (2006) and by Dias *et al.* (2007). The beams tested within those two works, are characterized by the same test set-up, the same amount of stirrups and differ in the mechanical properties of concrete. In fact, the former experimental program was characterized by a concrete mean tensile strength of 2.45 MPa while the latter by 1.45 MPa. The concrete mean tensile strength was obtained by the mean compressive strength at the test date and according to CEB Model Code 1990. The values of NSM shear strength contribution obtained by the PM were compared with those obtained by considering debonding as the only failure mode, whose relevant values are labelled by DM, see Figure 4. The title of each graph plotted in Figure 4 reports, in sequence, the number of stirrups (2S), the laminates' inclination (L90°-45°-60°) and the concrete mean tensile strength (fctm 2.45 or 1.45 MPa). The analytical values were computed assuming a crack angle of 45°. From Figure 4 it arises that, for each placement of the laminates, varying concrete mean tensile strength from 2.45 (left) to 1.45 MPa (right), yields a decrease in the experimentally recorded NSM shear strength contribution. While the proposed modelling strategy is capable of capturing, with efficacy, such decrease, a modelling strategy based on debonding as the only possible failure mode, provides predictions that remain unchanged regardless of the changed concrete mechanical properties, thus providing a variable safety factor. The PM was also applied to predict the recorded NSM shear strength contribution for the beams tested by De Lorenzis and Rizzo (2006), see Table 1. Those authors tested rectangular cross section beams, strengthened in shear with either NSM laminates or rods, with concrete mean tensile strength of 1.80 MPa. The experimental values regarding those beams are listed in Table 1. The beams labelling is according to the following strategy: the first two letters indicate if NSM rods (NB) or laminates (NS) were adopted, the following two digits indicate the FRPs angle (in degrees) with respect to the beam axis, the other two digits indicate the FRPs spacing along the beam axis (in mm), and the last letter refers to the kind of epoxy adhesive adopted (a or b).

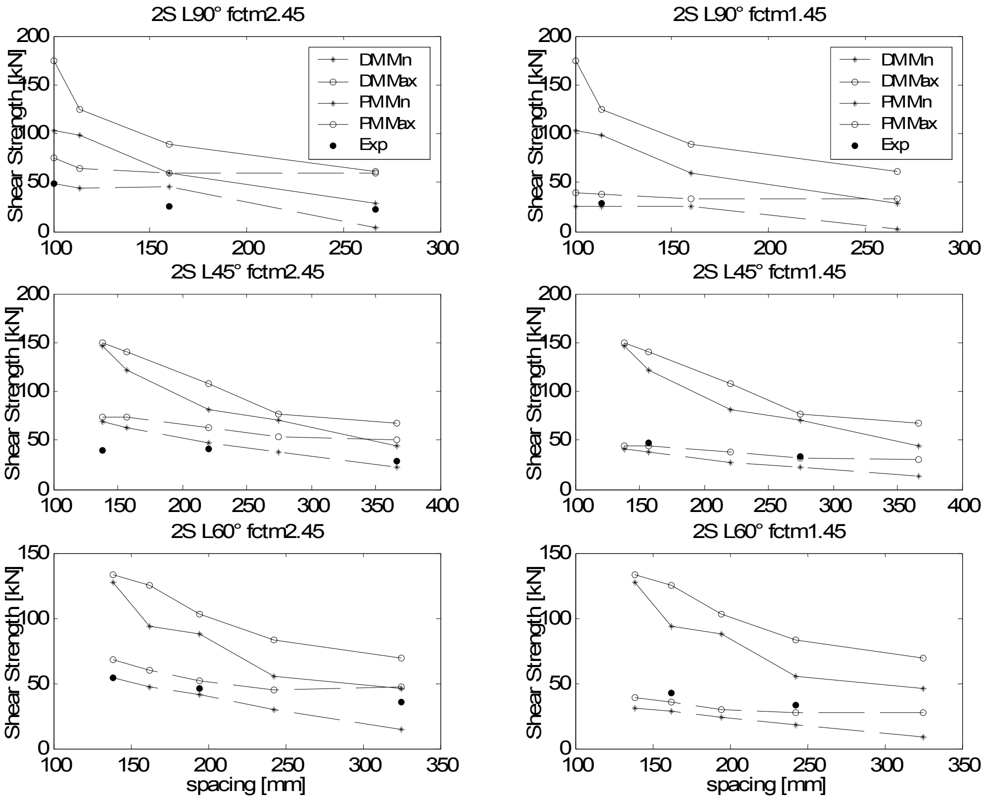



Figure 4 – Comparison between analytical (by both DM and PM) and experimental values of the NSM shear strength contribution for the beams by Dias and Barros (2006) (left) and Dias *et al.* (2007) (right)

For the case of the RC beams strengthened by NSM rods, $V_{fi}^{p}$ was computed as follows (Eq. 5):

$$V_{fi}^{p} = \min\left\{\pi \cdot d_b \cdot L_{fi} \cdot \tau_{b,rod}\left(L_{fi}\right); \pi \cdot \frac{d_b^{\ 2}}{4} \cdot f_{fu}; \left(A_i^{nlin} + A_i^{lin}\right) \cdot \sin\left(\theta + \beta\right) \cdot f_{ctm}\right\} \tag{5}$$

in which $d_b$ is the nominal diameter of the adopted rod, $\tau_{b,rod}\left(L_{fi}\right)$ is the length-dependent average bond strength for the case of rods. The relationship, $\tau_{b,rod}\left(L_{fi}\right)$, calibrated on the basis of the test results reported by De Lorenzis & Nanni (2002), is the following (Eq. 6):

$$\tau_{b,rod}\left(L_f\right) = \begin{cases} 4.99 & 0 \le L_f < 114 \\ 15.10 - 2.13 \cdot \ln L_f & 114 \le L_f \le 312 \\ 2.84 & L_f > 312 \end{cases} \tag{6}$$

Indeed, as outlined by De Lorenzis and Nanni (2002), as function of the groove dimensions and the relative mechanical properties of adhesive and surrounding concrete, rods were also observed to fail by splitting of the adhesive but, since the reported failure mode of the beams was concrete tensile fracture, that issue was not further addressed. The analytical range $\left[V_{f,\min}^{DM}; V_{f,\max}^{DM}\right]$, obtained by applying the DM, with the debonding-based relationship $\tau_{b,rod}\left(L_{fi}\right)$ is also reported. The experimental recordings ascribed to the beams labelled NB90_73_a and NS90_73_a seem to be excessively high with respect to the others. In fact, for the beam NB90_73_a, the experimental value is almost twice as large as the one regarding the NB90_73_b beam that differs from the former only for the quality of the epoxy employed. If those two values are neglected, a good agreement emerges between the value provided by the PM and the experimental recordings. At the same time, the analytical ranges provided by the DM, systematically overestimate the experimental recordings.

Table 1. Comparison between experimental and analytical (by the PM and the DM) for the beams tested by De Lorenzis and Rizzo (2006)

| Beam label | $s_f$ | $\beta$ | $V_{f,\min}^{PM}$ | $V_{f,\max}^{PM}$ | $V_{f,\min}^{DM}$ | $V_{f,\max}^{DM}$ | $V_f^{\exp}$ |
|---|---|---|---|---|---|---|---|
| | [mm] | [°] | [kN] | [kN] | [kN] | [kN] | [kN] |
| NB90_73_a | 73 | 90 | 16.99 | 28.83 | 32.33 | 39.74 | 54.20 |
| NB90_73_b | 73 | 90 | 16.99 | 28.83 | 32.33 | 39.74 | 26.40 |
| NB90_45_b | 45 | 90 | 26.70 | 31.94 | 56.44 | 59.96 | 28.60 |
| NB45_146_a | 146 | 45 | 21.72 | 25.69 | 32.22 | 36.97 | 39.10 |
| NB45_73_a | 73 | 45 | 29.93 | 30.80 | 68.69 | 69.65 | 28.00 |
| NS90_73_a | 73 | 90 | 16.99 | 31.18 | 138.46 | 171.56 | 50.50 |
| NS45_146_a | 146 | 45 | 21.72 | 25.69 | 113.04 | 150.23 | 32.70 |

## CONCLUSIONS

A new predictive model, originated from the need for a rational explanation to the features of the observed failure mechanisms affecting the behaviour at ultimate of RC beams shear strengthened by NSM CFRP laminates, was proposed. This model assumes as possible failure mechanisms: debonding, tensile rupture of the laminates and concrete tensile fracture, and allows the interaction between laminates to be accounted for. The comparisons with the debonding-based model showed that the proposed model provides a better estimation of the experimentally recorded NSM shear strength contribution, not only in the case of laminates but also in the case of rods. From the analyses carried out applying the proposed model and the comparison with experimentally recorded values, the paramount importance of concrete mechanical properties arises.

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