A NEW APPROACH FOR MODELLING THE NSM SHEAR STRENGTHENING CONTRIBUTION IN REINFORCED CONCRETE BEAMS

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1 INTRODUCTION

The gluing of carbon fiber reinforced polymer (CFRP) bars to concrete by a structural adhesive into thin slits opened in the concrete cover of the beam lateral faces, for the shear strengthening of RC beams, was explored, some years ago, in the pioneering work by De Lorenzis and Nanni [1]. This technique, internationally designated as Near Surface Mounted (NSM), originally contemplated the employment of round section CFRP bars glued into the slits by means of an epoxy adhesive. More recently, other authors verified the higher effectiveness attainable by using quadrilateral cross section bars instead of round rods [2].

Barros and Dias [3] designed and carried out tests on rectangular cross section beams to assess the effectiveness of rectangular cross-section NSM CFRP laminates for the shear strengthening of RC beams. From the experimental research carried out within their work, those authors verified that the NSM technique provided higher shear resistance and deformability at the failure of the beams than the externally bonded reinforcement (EBR) technique. They also analyzed the observed failure modes, reporting about a failure mode different than debonding, constituted by the separation, from the underlying core of the beam, of two concrete layers, nearly as thick as the cover of the beam lateral faces. This type of failure mode was also recently reported by De Lorenzis and Rizzo [4].

In the work by Barros and Dias the contribution by the CFRP strengthening systems for the shear resistance of RC beams was simulated using the formulation by Nanni *et al.* [5]. However, in order to take into account the peculiarities related to the employment of rectangular cross section bars, as opposed to rods, new values for the parameters of that formulation were used, based on the results obtained from the pull-out bending tests carried out by Sena-Cruz and Barros [6]. By applying that formulation, they obtained satisfactory results in terms of safety coefficient of the predicted values.

The promising results obtained in that preliminary work, encouraged Dias and Barros to arrange another experimental program [7], mainly devoted to appraise the potentialities of the NSM in the more realistic case of quasi-real scale T-cross-section beams. This latter experimental program confirmed the NSM high effectiveness to increase the load carrying capacity of beams failing in shear. The shear strengthening arrangements with laminates placed at 45° and 60° resulted as the most effective. At the same time, further analysis of the failure modes confirmed the occurrence, especially for high strengthening ratio of laminates, of the detachment of the concrete cover containing the glued laminates. The failure could be ascribed to debonding only for CFRP shear strengthening configurations of very low ratio, regardless of their inclination and even in those cases, pure debonding never occurred since some concrete was always bonded to the pulled-out length of the laminates.

The only formulation available to date to simulate the NSM contribution is the one by Nanni *et al.* [5], which is based on the assumption that debonding is the only possible failure mechanism.

The potentiality of a new approach, which assumes as commanding failure mechanism the concrete tensile fracture, is herein appraised. This approach rationally explains the main features of the physical behavior observed experimentally and provides the possibility to take into account the interaction between adjacent laminates.

2 EXISTING MODELS

In the most recent Codes of Practice and Guidelines available worldwide on the use of FRP materials for the concrete structural strengthening, a clear and comprehensive analytical formulation to predict the shear strength contribution provided by NSM CFRP laminates is still lacking. Some proposals for a design formula can be found in the relevant scientific literature. The first proposal, in this respect, has to be ascribed to De Lorenzis [8]. More recently, Nanni *et al.* [5] proposed an upgraded version of that formulation. Both of the above formulae rely on the assumption that the NSM laminates fail by debonding. The term "debonding" envisages failure occurring at the laminate/adhesive or adhesive/concrete interfaces, as well as within the adhesive [6]. Debonding can be also regarded as a failure occurring along a surface parallel to the laminate, a few millimeters inside the surrounding concrete, since a thin layer of concrete in contact with the adhesive has higher strength due to the adhesive penetration into the concrete micro-structure. Anyway, the laminate pullout tests currently underway show that debonding failure might be characterized by the simultaneous occurrence of more than one of those mechanisms. The formulation by Nanni *et al.* [5] is the following:

$$V_f = 4\left(a_f + b_f\right)\tau_b L_{tot,\min} = 4\left(a_f + b_f\right)\tau_b \sum_{i=1}^{N_f} L_{fi} \tag{1}$$

with: a_f and b_f being, respectively, the width and thickness of the laminates' cross section; τ_b the average bond strength; N_f the number of laminates crossing the shear crack on one side of the web; $L_{tot,\min}$ the minimum possible value assumed by the sum of the effective bond length of each laminate, L_{fi}, *i.e.* shorter part of the i-th laminate on either side of the crack.

The conservative value of the total length $L_{tot,\min}$ is determined by means of several assumptions (see Fig. 1):

- The length of the laminates is reduced by twice the projection of the concrete cover thickness (*c* in Fig. 1);
- The position of the first laminate x_{f1}, with respect to the crack origin, *i.e.* the intersection of the crack line with the intrados of the beam web is assumed equal to the laminates' spacing s_f:

$$x_{f1} = s_f \tag{2}$$

- To preserve the resisting contribution by concrete aggregate interlock, the value of the effective bond length of each laminate is limited by $l_{\max}$, *i.e.* the value corresponding to the attainment of the maximum effective strain of 4 ‰, as follows:

$$L_{fi} = \min\left[L_{fi1}; L_{fi2}; l_{\max}\right] \tag{3}$$

where L_{fi1} and L_{fi2} are the values of the length of the two parts into which the i-th laminate is divided by the crack and $l_{\max}$ is calculated as follows:

$$l_{\max} = \frac{0.004}{2}\frac{a_f b_f}{a_f + b_f}\frac{E_f}{\tau_b} \tag{4}$$

where E_f is the FRP elasticity modulus.

In the work by Nanni *et al.,* a value of 6.9 *MPa* was assumed for the average bond strength and a crack inclination angle (θ in Fig. 1) of 45° was considered.

Barros and Dias [3] outlined that this formulation provided, for their experimental recordings, too conservative estimates. By using the values of 5.9 ‰ for the maximum effective strain and 16.1 *MPa* for the average bond strength, they obtained analytical values for V_f resulting about 72 % of those recorded experimentally, which is satisfactory, from a safe design standpoint.

As regards the average bond strength, it arises, from the most recent results available worldwide, that it is length-dependent and decreases by increasing the bond length, as Fig. 2 shows. Further details can be found elsewhere [6, 10, 11, 12].

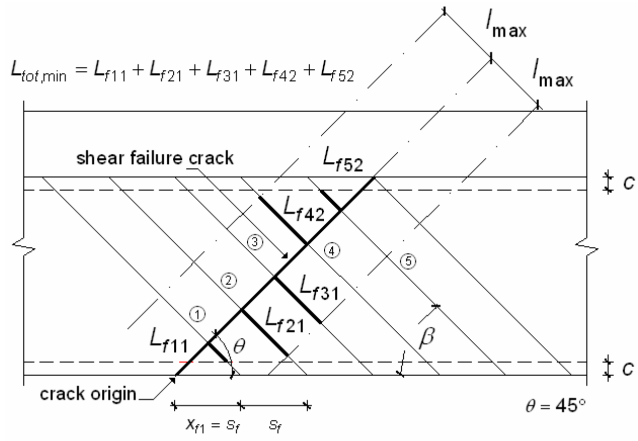


Fig. 1 Concept of $L_{tot,\min}$.

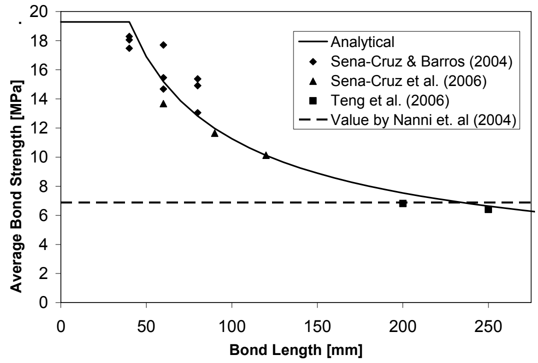


Fig. 2 Length dependence on the average bond strength.

3 PROPOSED MODEL

The extensive analysis of the available experimental results by Barros and Dias [3] and by Dias and Barros [7] outlined the possibility that, for low values of the spacing between subsequent laminates, a failure mode different than debonding might occur. In fact, those authors observed the progressive detachment of the concrete cover, containing the laminates, from the core of the beam, which was also recently reported by De Lorenzis and Rizzo [4].

By extensively searching the technical literature available to date, the analogy arises between the employment of NSM laminates glued into slits opened in the concrete cover and the fastening technology to concrete by means of bonded anchors. In fact, this latter consists in fixing threaded rods into holes drilled in the concrete soffit of RC elements by means of different kinds of adhesives. The stress transfer, as for the NSM, relies on the bond characteristics. In those cases, [13,14], besides the debonding failure mode, another failure mode was observed, designated as "concrete cone failure". It is characterized by a cone-shaped spalling of the concrete surrounding the anchor and originating from along the embedded length of the anchor and propagating towards the external surface of the concrete (see Fig. 3). This failure occurs when the applied force is such as to induce, in the surrounding concrete, principal stresses exceeding its tensile strength. The resulting concrete fracture conical surface, envelope of the tension isostatics, presents, at its vertex, an angle of about 45° with the axis of the anchor.

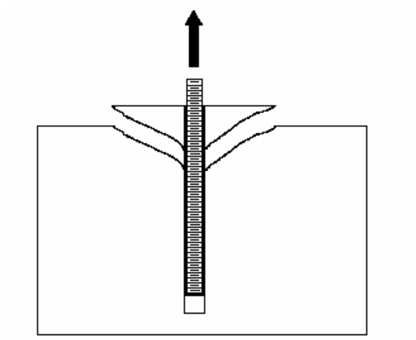


Fig. 3 Typical conical tensile fracture observed for the technology of adhesive fastenings.

In the case of NSM laminates, the critical shear failure crack can be schematized like an inclined plane dividing the web of the beam into two portions sewn together by the crossing laminates that can be seen like fastenings (see Fig. 4a). The contribution of the laminates is limited by concrete tensile fracture along their available bond length, *i.e.* the shorter of the two parts on either side of the crack plane. In the case of shear strengthening of RC beams by NSM, due to the different geometrical features, the concrete crack surface for each laminate, envelope of the principal tensile stresses, is assumed as having a semi-conical configuration (see Fig. 4). In the case of the application of fastenings, since they are generally located far from the edges of the soffit of the RC element in which they are embedded, they can be thought as embedded in a semi-space of concrete. On the contrary, in the case of the NSM technology, the laminates crossing the crack plane are embedded in the two portions of the beam and in correspondence of their edges. Thus, due to the different and asymmetric geometrical shape of the concrete in which the laminate is embedded, with respect to the case of the anchor, it is more likely that the relevant fracture surface starts propagating from the inner tip of the available bond length of the laminate (see Fig. 4). This assumption was adopted in the present work.

The angle between the axis and the generatrices of the semi-conical surface, calibrated on the basis of the critical interpretation of some experimental results available to date [11,12], ranges between 20° and 30° and shows to be dependent on the available bond length of the laminate, with a tendency to decrease with the increase of the bond length. However, in that respect, due to the shortage of available results, further investigations are required.

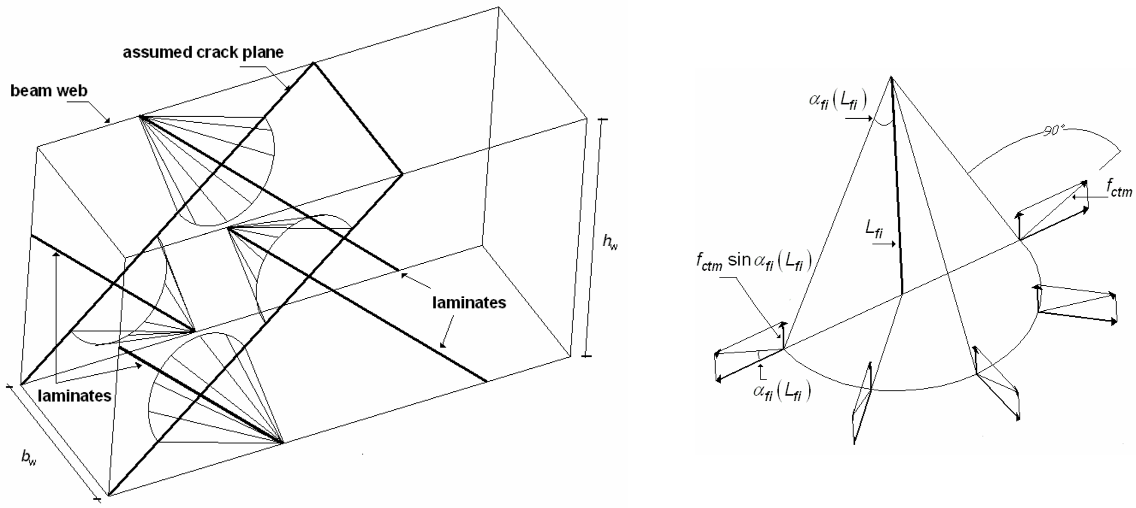
The maximum contribution provided by the NSM system to the shear resistance of the strengthened beam can be calculated by (see Fig. 4b): distributing the component of the concrete average tensile strength parallel to the laminate, *i.e.*, $f_{ctm}\sin\alpha_{fi}$, throughout each of the resulting semi-conical surfaces, integrating and projecting the resulting force orthogonally to the beam axis, according to the following formula [11]:

$$V_f = 2\, sin\beta \sum_{i=1}^{N_f} \int_{C_{fi}\left(L_{fi};\alpha_{fi}\right)} \left(f_{ctm}\sin\alpha_{fi}\right) dC_{fi} \tag{5}$$

where: f_{ctm} is the average concrete tensile strength; β is the inclination of the laminates (see Fig. 1); N_f is the number of laminates crossing the shear failure crack; the term $C_{fi}\left(L_{fi};\alpha_{fi}\right)$ schematically indicates the semi-conical surface ascribed to the i^{-th} laminate and $\alpha_{fi} = \alpha\left(L_{fi}\right)$ the length dependent angle between the generatrices and the axis of the semi-cone associated to the i^{-th} laminate. The $\alpha_{fi} = \alpha\left(L_{fi}\right)$ relationship hereinafter assumed, is the following [11]:

$$\alpha_{fi} = \begin{cases} 32.31 & \text{for} \quad 0 \le L_{fi} \le 30 \\ 33.973 - 0.0587\,.\,L_{fi} & \quad 30 < L_{fi} \le 150 \\ 25.17 & \quad L_{fi} > 150 \end{cases} \tag{6}$$

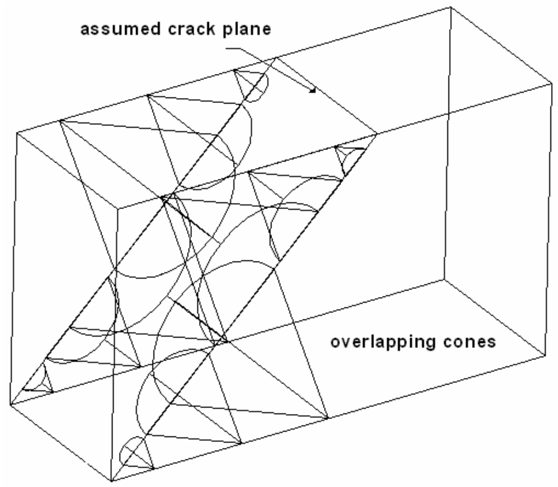
For the sake of brevity, the analytical details of the proposed model are omitted in the present work, but they can be found elsewhere [11].



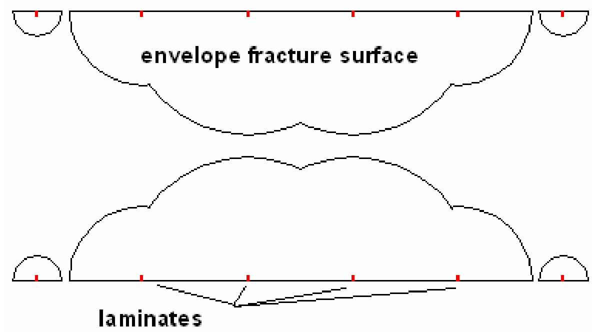
(a) (b)

Fig. 4 Main features of the proposed model: (a) crack plane crossed by laminates and their semi-conical fracture surfaces; (b) detail of the semi-conical surface and the distribution of the average tensile strength.

Reducing the spacing between laminates, their semi-conical surfaces overlap each other and the resulting envelope area of all of their fracture surfaces progressively becomes smaller than the mere summation of each of them (see Fig. 5). This allows the interaction between laminates to be easily accounted for by calculating the resulting overall fracture surface accordingly. For very short values of the spacing, the resulting concrete failure surface is almost parallel to the web face of the beam. This 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 Fig. 6a).



(a)

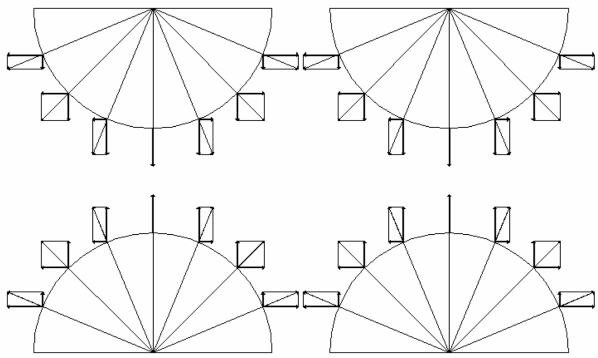


(b)

Fig. 5 Interaction between laminates: (a) semi-conical surfaces overlapping; (b) section parallel to the crack plane.

Since the position of the semi-conical surfaces is symmetric with respect to the vertical plane passing through the beam axis (equal strengthening arrangement is assumed in both beam lateral faces), the horizontal outward components of the tensile strength vectors distributed throughout their surface and lying on a plane parallel to the crack plane, are balanced only from an overall standpoint and not locally, see Fig. 6b. This local unbalance of the horizontal tensile stress component orthogonal to the web face justifies the outward expulsion of the concrete cover in both the uppermost and lowermost parts of the strengthened sides of the web. The post-test photographic documentation clearly spotlights this local occurrence [7].

(a)



(b)

Fig. 6 Outward expulsion of the strengthened concrete cover: a) reported outward expulsion of the cover (beam 2S_8LI45); b) Local unbalance of the components of the concrete tensile strength orthogonal to the web faces and lying on a plane parallel to the crack.

4 MODEL APPRAISAL

The Predictive Model herein proposed was appraised based on the experimental results available to date [3, 7]. In the experimental programs considered: the laminate cross section was 1.4 x 10 mm^2, the average value of the elasticity modulus of the CFRP ranged from 166.0 to 166.6 *GPa* and the tensile strength from 2286 to 2952 *MPa*, while the average concrete compressive strength, at the date of the tests varied from 31.1 to 56.2 *MPa*. The first series [3] of beams was composed of rectangular cross section beams of 150 x 150 mm^2 (designated by a label starting with B) and of 150 x 300 mm^2 (whose label's initial is A), both without existing stirrups. The second series [7] was composed of T beams, whose web had dimensions 180 × 300 mm^2, all of which with existing steel stirrups.

The value of the mean concrete tensile strength was deduced from the average compressive strength measured at the date of the tests, and by means of the formulae available in the CEB-FIP Model Code 1990 [15] from which the following expression was deduced:

$$f_{ctm}\left[MPa\right] = 1.40\left(\frac{f_{cm}-8}{10}\right)^{2/3} \tag{7}$$

This indirect way of evaluating the average concrete tensile strength is not rigorous. In fact, the concrete tensile strength is a quantity intrinsically affected by a high scatter that can be controlled, in statistical terms, when it is measured directly. When f_{ctm} is deduced from another quantity already affected by scatter like the compressive strength, the scatter increases and gets difficult to control. Moreover, the tensile strength of the concrete cover of the beam lateral faces can present different mechanical properties with respect to the concrete of the core. Thus, a direct measurement of the concrete tensile strength, better if across the concrete cover of the beam lateral faces, would be preferable.

The Proposed predictive Model (PM) was applied, for each of the beams examined, for three different possible positions of the first laminate with respect to the crack origin, (*i.e.* three different values of x_{f1}, see Fig. 1) in order to obtain a range of possible analytical predictions (for further analytical details see [11]). Moreover, for the crack inclination, a value of 45° was assumed. The obtained results are listed in Tables 1-2 and plotted in Figures 7-8.

The obtained values were compared with those provided by the formulation by Nanni *et al.* even if this latter is explicitly a design formula, *i.e.* it provides the value of the NSM shear strength contribution that can be relied upon from a design standpoint. Conversely, the predictive model provides the analytical value fitting the experimental measure that is obtained loading the beam until its ultimate state.

The formulation by Nanni *et al.*, in order to provide the expected NSM contribution to the ultimate shear strength of a given beam, instead of the reduced conservative value useful for a safe design, should be applied by removing the safety factor. This latter cannot be clearly identified in that formulation since several assumptions concur to accomplish that function, *i.e.*: the use of the value $\tau_b = 6.9\,MPa$ for the average bond strength; the limitation of the bond length of each laminate to the value corresponding to the attainment of a maximum effective strain of 4‰; the reduction of the length of the laminates by twice the projection of the concrete cover. The first limitation is extremely conservative with respect to the experimental evidence, whose average value is about 12.2 *MPa*, as already pointed out in paragraph 2 of the present paper. Moreover, the second limitation provides a great reduction on the available bond length of each laminate and, for the geometrical dimensions of the cases herein examined, it always resulted predominant, strongly limiting the NSM shear contribution, V_f^{Nanni}.

For some of the beams taken into consideration, the shortfall and disagreement with the general trend shown by the relevant experimental value of the NSM shear contribution, prompted the authors to further analyses. Since it was verified that in the reference beam the shear failure crack was crossed by a couple of stirrups, while in the aforementioned beams one only stirrup effectively contributed to the ultimate strength, the NSM contribution was re-calculated accordingly (values in parentheses in Table 2).

Notwithstanding the above outlined drawbacks, from the obtained values, the following observations can be drawn.

For each of the examined beams, the following ratios were determined:

- The ratio of the difference between the lower bound of the range of the predicted values and the corresponding experimental value divided by this latter *i.e.*:

$$\left(V_{f,\min}^{PM} - V_f^{\exp}\right) / V_f^{\exp} = \Delta V_{\min}^{PM} / V_f^{\exp} \quad (8)$$

- The ratio of the difference between the upper bound of the range of the predicted values and the corresponding experimental value divided by this latter *i.e.*:

$$\left(V_{f,\max}^{PM} - V_f^{\exp}\right) / V_f^{\exp} = \Delta V_{\max}^{PM} / V_f^{\exp} \quad (9)$$

- The ratio of the difference between the value obtained by Nanni *et al.*'s formulation and the corresponding experimental value divided by this latter *i.e.*:

$$\left(V_f^{Nanni} - V_f^{\exp}\right) / V_f^{\exp} = \Delta V^{Nanni} / V_f^{\exp} \quad (10)$$

The values of the above ratios are listed in Tables 1 and 2. The average values of the first two above ratios, obtained by taking into consideration the beams belonging to both of the two series and substituting the values $V_f^{\exp}$ that were not deemed completely in accordance with the general trend with the re-calculated ones (values in parentheses in Tables 2), are equal, respectively, to 2.64%, and 62.97%. It arises that the minimum values provided by the PM slightly overestimate the corresponding experimental recordings, while these latter are lower than the maximum analytical ones. The values provided by the formulation by Nanni *et. al* underestimate the experimental recordings.

When only the beams belonging to the first series of beams (without existing steel stirrups) are taken into consideration, the average value of $\Delta V_{\min}^{PM} / V_f^{\exp}$ is equal to 5.81% and the average value of $\Delta V_{\max}^{PM} / V_f^{\exp}$ is equal to 60.28%. For the beams belonging to the second series, the average value of the ratio $\Delta V_{\min}^{PM} / V_f^{\exp}$ is equal to -0.53 % and the average value of $\Delta V_{\max}^{PM} / V_f^{\exp}$ is equal to 65.67%. From the above values and from Figs. 7 and 8, it arises that, on average, the experimental recordings lie within the analytical range even if for the beams of the second series the data fitting results to be slightly better since the average value of the ratio $\Delta V_{\min}^{PM} / V_f^{\exp}$ is negative meaning that $V_{f,\min}^{PM}$ is, on average, slightly lower than $V_f^{\exp}$. There seems not to be much difference in terms of data fitting between beams with and without existing steel stirrups but, in this respect, a larger amount of experimental data is required.

As expected, based on the reasons pointed out earlier, the formulation by Nanni *et al.* underestimates the experimental recordings and this underestimation ranges from −31.65% to −33.10% for the two series of beams. These values are very close to the value of −30.00% obtained by Barros & Dias [3] as already mentioned earlier in this paper, even if they used a value of 16.1 *MPa* for the average bond strength that is 2.3 times as large as the original value proposed by Nanni *et al.* and herein adopted. This spotlights the predominance of the limitation on the effective strain represented by equation (4).

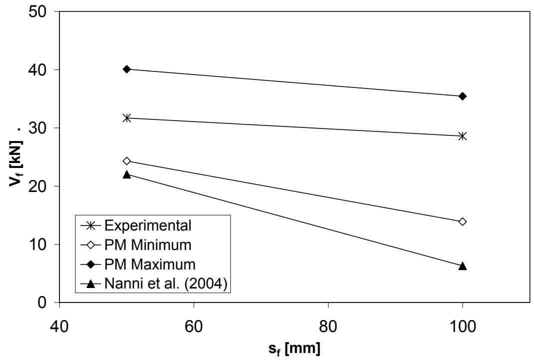
Table 1 Appraisal of the Proposed Model (PM) for the first series by Barros & Dias [3].

beam	β	f_{ctm}	s_f	$V_f^{\exp}$	$V_{f,\min}^{PM}$	$V_{f,\max}^{PM}$	V_f^{Nanni}	$\frac{\Delta V_{\min}^{PM}}{V_f^{\exp}}$	$\frac{\Delta V_{\max}^{PM}}{V_f^{\exp}}$	$\frac{\Delta V^{Nanni}}{V_f^{\exp}}$
	[°]	[MPa]	[mm]	[kN]	[kN]	[kN]	[kN]	[%]	[%]	[%]
A10_VL	90	3.60	200	29.10	40.19	80.25	18.66	38.12	175.76	-35.88
A10_IL	45	3.60	300	28.80	49.79	68.16	18.66	72.89	136.67	-35.21
A12_VL	90	3.60	100	59.30	62.53	96.94	37.32	5.44	63.48	-37.07
A12_IL	45	3.60	150	72.90	97.42	99.46	55.98	33.64	36.44	-23.21
B10_VL	90	3.99	100	28.60	13.90	35.43	6.29	-51.41	23.89	-78.01
B10_IL	45	3.99	150	23.20	17.80	27.59	18.66	-23.27	18.94	-19.57
B12_VL	90	3.99	50	31.70	24.31	40.09	22.02	-23.32	26.48	-30.54
B12_IL	45	3.99	75	36.40	34.35	36.62	38.68	-5.63	0.60	6.26
							average	5.81	60.28	-31.65

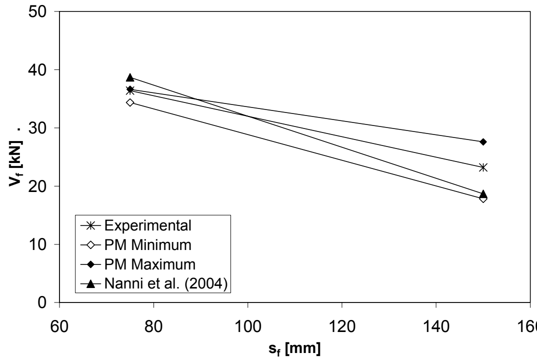
Table 2 Appraisal of the Proposed Model (PM) for the second series by Dias & Barros [7]

beam	β	f_{ctm}	s_f	V_f^{exp}	$V_{f,\min}^{PM}$	$V_{f,\max}^{PM}$	V_f^{Nanni}	$\frac{\Delta V_{\min}^{PM}}{V_f^{exp}}$	$\frac{\Delta V_{\max}^{PM}}{V_f^{exp}}$	$\frac{\Delta V^{Nanni}}{V_f^{exp}}$
	[°]	[MPa]	[mm]	[kN]	[kN]	[kN]	[kN]	[%]	[%]	[%]
2S_3LV	90	2.45	267	0.60 (22.20)	4.36	60.24	0.00	626.67 (-80.36)	9940.00 (171.35)	-100.00 (-100.00)
2S_5LV	90	2.45	160	25.20	45.75	60.24	18.66	81.54	139.05	-25.95
2S_7LV	90	2.45	100	48.60	48.69	74.51	36.28	0.18	53.31	-25.35
2S_3LI45	45	2.45	367	7.80 (29.40)	22.96	49.83	18.66	194.36 (-21.90)	538.85 (69.49)	139.22 (-36.53)
2S_5LI45	45	2.45	220	41.40	47.11	62.06	34.68	13.79	49.90	-16.23
2S_8LI45	45	2.45	138	40.20	68.83	73.07	55.98	71.22	81.77	39.24
2S_3LI60	60	2.45	325	35.40	14.97	46.76	18.15	-57.71	32.09	-48.72
2S_5LI60	60	2.45	195	46.20	41.48	51.83	21.84	-10.21	12.19	-52.73
2S_7LI60	60	2.45	139	54.60	53.88	68.22	37.32	-1.32	24.95	-31.65
							average	102.06 (-0.53)	1208.01 (65.67)	-13.58 (-33.10)

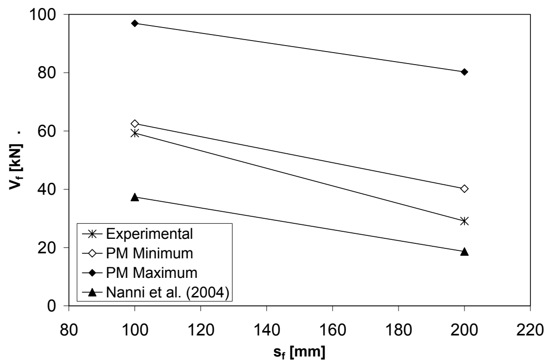
Note: the values in parentheses were re-calculated since the resisting force provided by stirrups resulted to be a half of the one provided by the reference beam.



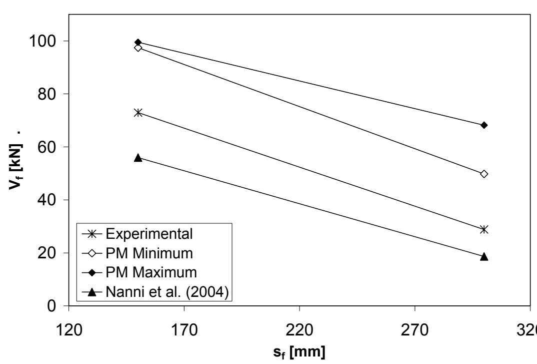
(a) Beams B10_VL and B12_VL



(b) Beams B10_IL and B12_IL

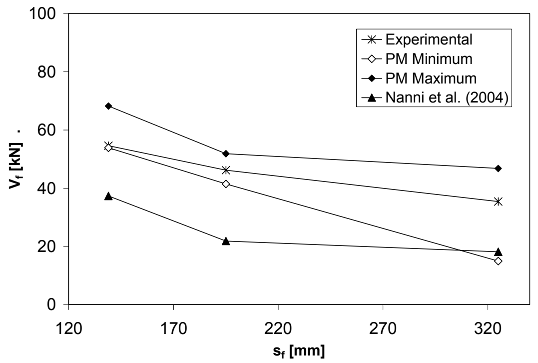


(c) Beams A10_VL and A12_VL

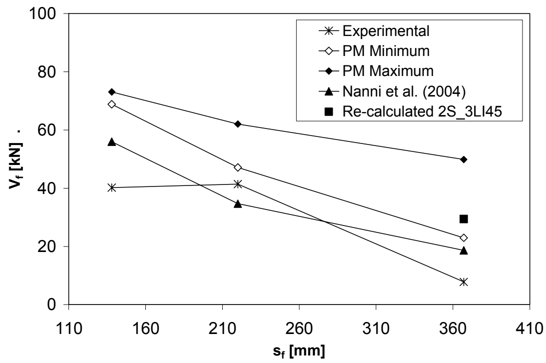


(d) Beams A10_IL and A12_IL

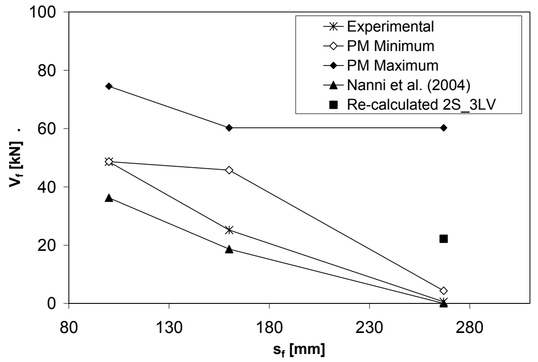
Fig. 7 Appraisal of the Proposed Model (PM) for the beams of the first series by Barros & Dias [3].



(a) Beams 2S_3LI60; 2S_5LI60; 2S_7LI60



(b) Beams 2S_3LI45; 2S_5LI45; 2S_8LI45



(c) Beams 2S_3LV; 2S_5LV; 2S_7LV

Fig. 8 Appraisal of the PM for the beams of the second series by Dias & Barros [7].

5 CONCLUSIONS

For the time being, most of the efforts carried out by the academic community interested in the NSM strengthening technique for RC structures are mainly devoted to quantifying values for the parameters related to the debonding failure mechanism of the NSM CFRP laminates. Furthermore, the only available formulation to date, by Nanni *et al.*, for the prediction of the contribution of NSM systems to the shear resistance of RC beams is also based on the assumption that debonding is the commanding failure mode of the laminates.

On the contrary, from the experimental evidence, it emerges that debonding rarely, if ever, occurs. Meanwhile, a failure mode, consisting in the separation of the concrete cover containing the glued laminates, is always more frequently reported in the relevant scientific publications.

A new Predictive Model, originated from the need for a rational explanation of the features of the above failure mechanism affecting the behaviour at ultimate of RC beams shear strengthened by NSM CFRP laminates, is presented in its preliminary idea and appraised on the basis of some of the experimental results available to date. This model assumes as commanding failure mechanism the concrete tensile fracture and allows for the interaction between adjacent laminates.

Given the conceptual difference between predictive models and design formulae, the values provided by the proposed model are compared with those obtained applying the formulation by Nanni *et al.* for a preliminary appraisal of the idea.

The formulation by Nanni *et al.* provides satisfactory predictions in terms of conservativeness even if it relies on, from an analytical standpoint, the concurrence of some limitations, not always showing consistency with experimental evidence.

The data fitting performance of the Proposed Model is satisfactory since, on average, for the cases herein examined, the experimentally recorded value lies within the corresponding range of analytical predictions.

Moreover, for the time being, both formulations lack the possibility to take into account the interaction with the existing stirrups, but the analytical formulation of the Proposed Model can, in a rational way, take into account this interaction. The authors of the present paper are currently working in this area.

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