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Mechanical Model to simulate the NSM FRP strips shear strength contribution to RC beams

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ABSTRACT: A three dimensional mechanical model has been recently developed to simulate the Near Surface Mounted (NSM) Fibre Reinforced Polymer (FRP) strips shear strength contribution to Reinforced Concrete (RC) beams throughout the entire loading process, as function of the Critical Diagonal Crack (CDC) opening angle. It was developed by fulfilling equilibrium, kinematic compatibility and constitutive laws of both intervening materials and bond between them. It takes into consideration all of possible failure modes that can affect the behaviour, at ultimate, of a single NSM strip, namely: loss of bond (debonding), semi-conical concrete tensile fracture, rupture of the strip itself and a mixed shallow-semi-cone-plus-debonding failure. Besides, it allows the interaction among adjacent strips to be accounted for. The numerical results, in terms of both shear strength contribution and predicted cracking scenario are presented and compared with experimental evidence regarding some of the most recent experimental programs. From that comparison, a satisfactory level of prediction accuracy, regardless of the main parameters such as concrete mechanical properties, amount and inclination of strips, arises. The main findings, as well as the influence of some of the main intervening parameters, are shown.

1 INTRODUCTION

A model developed in Bianco (2008) and Bianco et. al (2009) is presented that predicts the NSM FRP strips contribution to the shear strength of an underdisegned RC beam. It assumes that each NSM strip may fail due to (Fig. 1a): debonding, tensile rupture of the strip, concrete semi-conical fracture or mixed shallow semi-cone-plus-debonding. Phases undergone by bond by imposing an increasing end slip and representing the phenomena that occur, in sequence, within the adhesive layer, are plotted in Figure 1b. The beam is schematized as a prism divided in two parts by the Critical Diagonal Crack (CDC) that can be, in turn, thought as a plane (Fig. 1c). After the insurgence of the CDC, the two parts of the web start moving apart by pivoting around the CDC tip (point E in Fig. 1d) and the crossing strips oppose the crack widening by anchoring to the surrounding concrete where the force originating in the loaded section is transferred through bond. When the principal stresses transferred to the concrete exceed its mean tensile strength, it fractures along co-axial and successive semi-conical surfaces. When the spacing between adjacent strips is reduced, the fracture surfaces pertaining to each strip overlap (Fig. 1e). The concrete fracture capacity is evaluated taking into account this detrimental group effect. Moreover, when the spacing between adjacent strips is very small, the components of concrete mean tensile strength parallel to the CDC and orthogonal to the web faces, are balanced only from an overall point of view, but not locally on each web face, thus justifying the concrete cover spalling observed experimentally (Fig. 3f).

2 SIMULATIONS OF EXPERIEMENTAL TESTS AND PARAMETRIC STUDIES

The model proposed was applied to the RC beams tested by Dias et al. (2007) and by Dias and Barros (2008). The beams tested in those experimental programs were T-cross-section RC beams characterized by the same test set-up, the same amount of longitudinal reinforcement, the same kind of CFRP strips and epoxy adhesive and they differed for the mechanical properties of concrete. In fact, the former experimental program was characterized by a concrete mean compressive strength f_{cm} of 18.6 MPa while the latter by 31.1 MPa. Both series presented different configurations of NSM strips, in terms of both inclination β and spacing s_f and the former program also included beams characterized by a different amount of existing steel stirrups. Those beams are characterized by the following common geometrical and mechanical parameters: $b_w = 180\,mm$; $h_w = 300\,mm$; $f_{fu} = 2952\,MPa$; $E_f = 166\,GPa$; $a_f = 1.4\,mm$; $b_f = 10.0\,mm$ ($a_f\,; b_f$ =strip cross section dimensions). The parameters characterizing the adopted local bond stress-slip relationship, being the average values of those obtained in a previous investigation (Bianco 2008) are: $\tau_0 = 2.0\,MPa$; $\tau_1 = 20.1\,MPa$; $\tau_2 = 9.0\,MPa$; $\delta_1 = 0.07\,mm$; $\delta_2 = 0.83\,mm$; $\delta_3 = 14.1\,mm$.

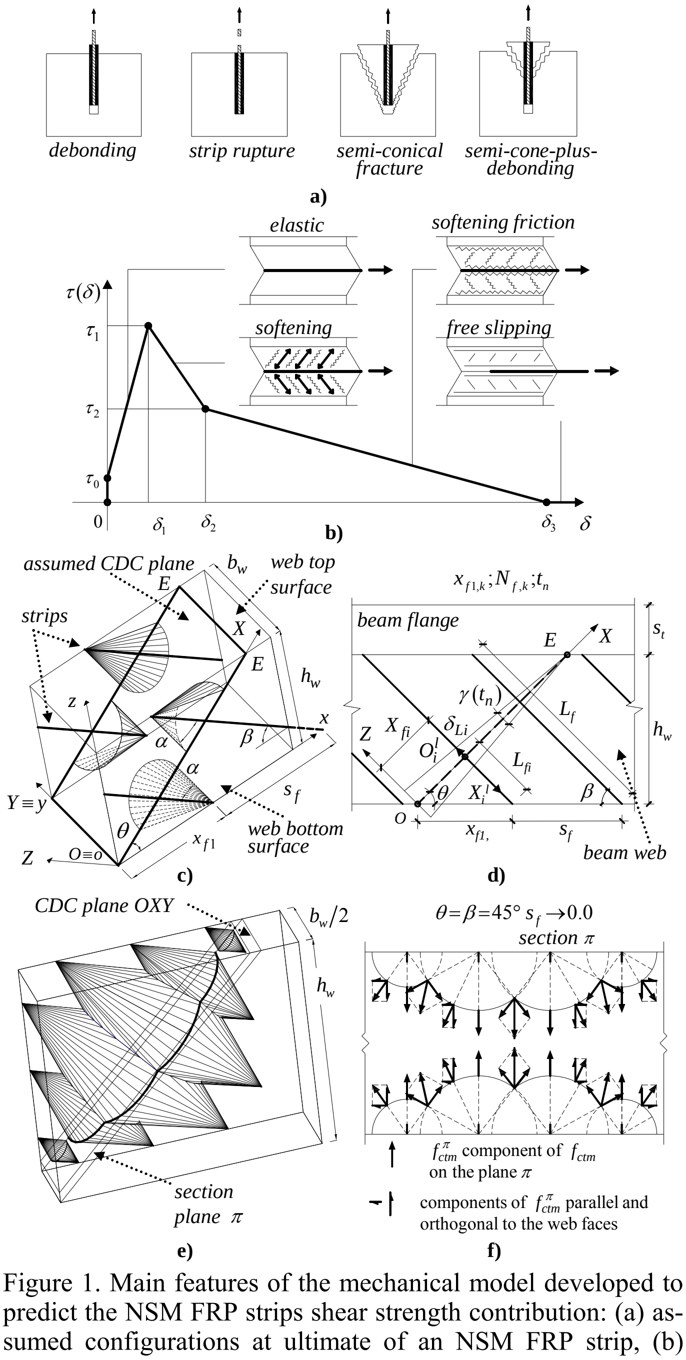

Figure 1. Main features of the mechanical model developed to predict the NSM FRP strips shear strength contribution: (a) assumed configurations at ultimate of an NSM FRP strip, (b) adopted local bond stress-slip relationship, (c) strengthened beam web and CDC occurred, (d) loading process of a shear strengthened beam, (e) interaction among adjacent strips, (f) section of the web by a plane parallel to the CDC plane.

The CDC inclination angle θ adopted in the simulations plotted in Figure 2 is the one experimentally observed (Bianco 2009). The angle α was assumed equal to 28.5°, being the average of values obtained in a previous investigation (Bianco 2008) by back analysis of experimental data. The two parameters characterizing the loading process are: $\dot{\gamma} = 0.01°$ and $\gamma_{\max} = 1.0°$ (Fig. 1d). Concrete average tensile strength f_{ctm} was calculated from the average compressive strength by means of the formulae present in the CEB Fib Model Code 1990 resulting in 1.45 MPa and 2.45 MPa for the former and latter series of beams, respectively. Comparison between the numerical results and experimental recordings are plotted in Figure 2.

From that comparison, a satisfactory data-fitting performance of the proposed model, in terms of prediction of the peak NSM shear strength contribution $V_{f,k}^{\max}$ arises, regardless of the different concrete mechanical properties, inclination of the strips, their spacing along the beam axis and amount of existing steel stirrups. It should be outlined that the difference between the peak value of V_f, obtained for the three different configurations, and consequently the dispersion of the numerical predictions with respect to the experimental recording, increases by reducing the spacing between adjacent strips (see Fig. 2).

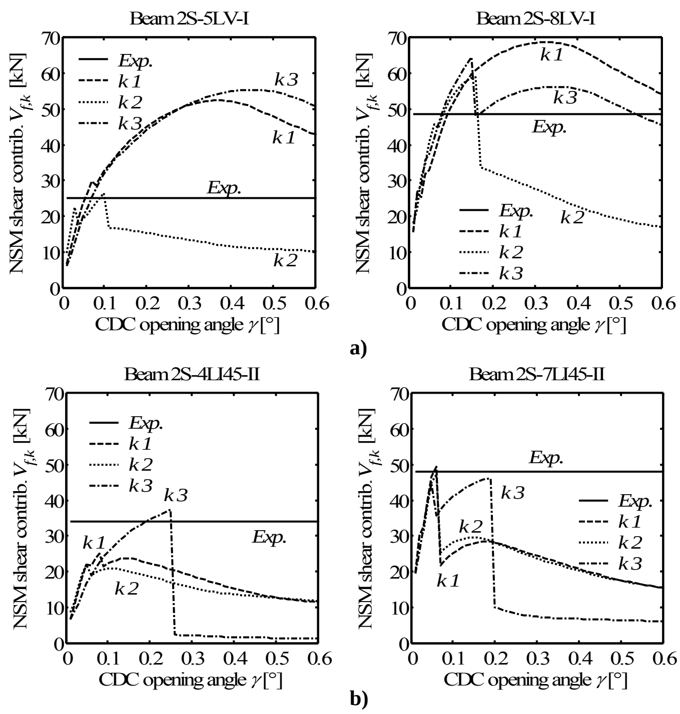

Figure 2. Comparison between numerical predictions and experimental recordings for: a) some of the beams tested by Dias and Barros (2008) and b) some of the beams tested by Dias et al. (2007).

The typical graph of shear strength contribution as function of the CDC opening angle $V_f\,[\gamma(t_n)]$ is characterized by abrupt decays corresponding to the strips' failure. The peculiar behavior of a RC beam strengthened in shear by NSM technique can be easily explained referring to one of those beams as for instance the beam labeled 2S-7LI45-II (with 2 existing steel stirrups, 7 strips at 45º) whose cracking scenario, both numerically predicted and experimentally recorded, is reported in Figure 3.

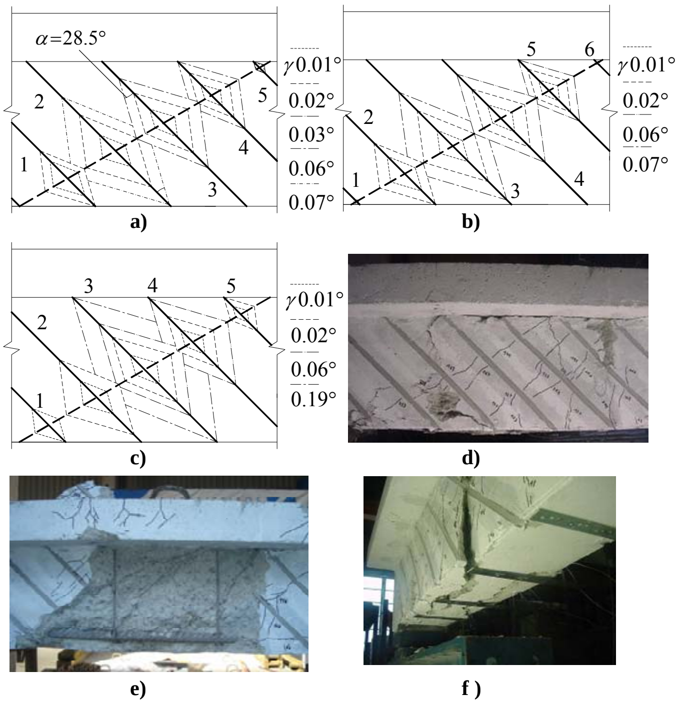

Figure 3. Cracking scenario regarding beam 2S-7LI45-II: numerical results for (a) the first $k=1$, (b) second $k=2$, and (c) third $k=3$ geometrical configuration and (d-f) experimental post-test pictures.

The first strips to fail are those characterized by shorter available bond lengths that generally fail in the first stages of the loading process, like for instance: the 1st ($\gamma = 0.02°$) and the 5th ($\gamma = 0.03°$) of the 1st configuration (Fig. 3a); the 1st and 6th ($\gamma = 0.01°$) and the 2nd ($\gamma = 0.02°$) of the 2nd configuration (Fig. 3b). Those failures are not so evident in the corresponding graph (Fig. 2) since, in the first load steps, the contribution provided by the strips with larger available bond length is increasing and relatively much higher. When a strip fails at a higher stage of the loading process, the corresponding decay in the load carrying capacity is much more evident, like it happens, for instance: for the 2nd strip of the 1st configuration at $\gamma = 0.07°$, the 3rd of the 2nd configuration at $\gamma = 0.07°$ or the 3rd strip of the 3rd configuration at $\gamma = 0.19°$. The first two are mixed shallow-semi-cone-plus-debonding failures and the third is characterized by a semi-conical concrete fracture that reaches the inner tip. After those failures, the corresponding graphs present a different trend: in the first two cases, a maximum relative follows while, in the third, the shear carrying capacity goes on diminishing in a smooth way. The former behavior is due to the fact that, when the last fracture occurs, that is the mixed failure of the 2nd and 3rd strip respectively, the remaining strips still have a resisting bond length higher than the required transfer length and their contribution can still increase before gradual complete debonding follows. The latter is due to the fact that, when the 3rd central strip fails, the 2nd and the 4th had already failed by mixed failure so that the overall carrying capacity goes on diminishing until complete debonding of their left resisting bond lengths.

The numerical modeling strategy herein proposed also allows to carry out parametric studies to assess the influence of all of the involved parameters on the NSM shear strength contribution. Hereafter, for the sake of brevity, only a short parametric study is presented (Fig. 4a-b) that aims at singling out, even by means of the comparison between numerical predictions and experimental recordings, the influence of the spacing for beams with strips at 60° and with two different concrete types. It arises that, as expected, the higher the concrete mechanical properties, the higher the shear carrying capacity, for the same value of spacing between adjacent strips.

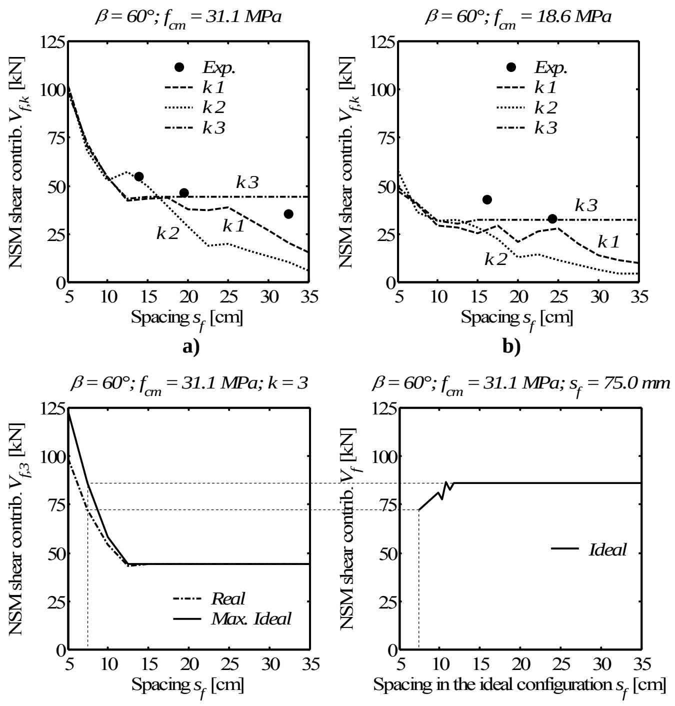

Figure 4. Comparison between numerical and experimental results: as function of the spacing between adjacent strips at 60° for concrete fcm 31.1 MPa (a) and fcm 18.6 MPa (b); group effect for the 3rd configuration (concrete fcm 31.1 MPa and β 60°) (c) and ideal shear strength contribution for a system of NSM with spacing 75 mm (d).

It can also be gathered that, by reducing the spacing between adjacent strips, due to the increase of the number of strips effectively crossing the CDC, the shear strength contribution increases even if, as highlighted in Figure 4c for the 3rd configuration only (with $\beta = 60°; f_{cm} = 31.1\, MPa$), the smaller the spacing, the higher the group effect. This latter can be defined as the decrease of shear strength contribution with respect to an ideal situation where the same system of strips, characterized by the real value of the spacing s_f, the same available bond lengths and the same imposed end slips, are instead spaced out, along the CDC, at such an extent that they do not interact any longer between each other. The corresponding increase in shear strength contribution increases up to a maximum ideal value, beyond which any further increase of the ideal spacing between adjacent strips does not produce any further increase in carrying capacity. That can be also gathered from Figure 4d, in which the ideal trend is plotted as function of the ideal spacing for the real configuration of strips at $s_f = 75\, mm$.

The detrimental group effect increases by reducing the spacing between strips (Fig. 4c).

3 CONCLUSIONS

The need to provide a rational explanation to the observed peculiar failure mode affecting the behavior, at ultimate, of RC beam strengthened in shear by the NSM technique led to the development of a comprehensive numerical model to simulate the NSM shear strength contribution throughout the loading process whose main features were herein presented. The comparison between the numerical predictions and the experimental recordings showed the high level of accuracy of the proposed model especially if one considers that: the model neglects the softening behavior of concrete in tension, the high scatter affecting concrete tensile strength and, on the contrary, the simplified and indirect way in which it was herein calculated.

The application of that model also let some complex phenomena to be pinpointed, such as the group effect between adjacent strips. Despite its relative complexity, the proposed model can be usefully applied to obtain useful information for designers interested in applying such innovative technique. At the same time, it can be conveniently summarized into a simplified closed-form design formula for practitioners.

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