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Three dimensional mechanical model to simulate the NSM FRP strips shear strength contribution to a RC beam: Parametric studies

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ABSTRACT

This paper presents the results of a parametric study carried out by means of a mechanical model recently developed to simulate the shear strength contribution provided by a system of Near Surface Mounted (NSM) Fiber Reinforced Polymer (FRP) strips to a Reinforced Concrete (RC) beam throughout its loading process. That model, developed fulfilling equilibrium, kinematic compatibility and constitutive laws of both materials, concrete and FRP, and local bond between themselves, takes into consideration the possibility that the NSM strips may fail due to: loss of bond (debonding), concrete semi-conical tensile fracture or strip tensile rupture. It also takes into consideration: (a) interaction between progressive force transferred by bond to the surrounding concrete and its tensile fracture and (b) bi-directional interaction among adjacent strips placed on the two sides of the strengthened beam cross-section web. In the first part of the paper attention is focused on the bond-based behavior of a single NSM FRP strip mounted on a concrete prism. The influence of each geometrical–mechanical parameter on the peak force transferable through bond stresses to the surrounding concrete, excluding the possibility of either concrete fracture and strip rupture, is analyzed. In the second part of the paper attention is focused on the comprehensive behavior of a single NSM FRP strip mounted on a concrete prism. The influence of each geometrical–mechanical parameter on the peak force transferable to the surrounding concrete, also including the possibility of both concrete fracture and strip rupture, is analyzed. The third part of the paper aims at assessing the influence of each geometrical–mechanical parameter on the maximum shear strength contribution provided by a system of NSM FRP strips to a RC beam. The results of these studies are presented along with the main findings.

1. Introduction

Shear strengthening of RC beams by NSM technique consists in gluing FRP strips by an adhesive into thin shallow slits cut onto the concrete cover of the beam web lateral faces. It is a technique that has been extensively investigated in recent years (*e.g.* [12–14,9,10,1,2,7,8,11]). A three dimensional mechanical model was recently developed to simulate the NSM FRP strips shear strength contribution to a RC beam [3–5]. That model was developed fulfilling equilibrium, kinematic compatibility and constitutive laws of both materials – FRP and concrete – and bond between themselves. From a physical point of view that model assumes that, during the loading process of a RC beam strengthened in shear by the NSM technique, the strips effectively crossing the Critical Diagonal Crack (CDC) oppose its widening by anchoring to the surrounding concrete to which they transfer, through bond stresses, the force originating at their intersection with the CDC. The relative movement of the two parts into which the CDC divides the beam web, imposes on the strips' available resisting bond lengths an increasing end slip [4]. As function of the relative mechanical and geometrical properties characterizing the specific case at hand, the ultimate configuration assumed by each strip can be one of the following: (a) complete extraction of the NSM FRP strip due to loss of bond throughout the strip available resisting bond length, in case concrete mechanical properties are very high, which is indeed a very limit situation (*debonding*), (b) concrete semi-conical fracture that reaches the strip free extremity (*concrete semi-conical failure*), (c) concrete semi-conical fracture that stops progressing midway between loaded and free end, with consequent debonding of the remaining portion of the available bond length (*mixed-semi-cone-plus-debonding*) and (d) rupture of the strip independently of an initial concrete fracture (*strip rupture*). Note that the last three failure modes are brittle, while the first is more ductile [4]. The mechanical model herein applied to carry out parametric studies, takes also into account the possibility that strips placed on the two sides of the beam web can

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interact with each other. The analytical details of the mechanical model are herein omitted, for the sake of brevity, but they can be found elsewhere [3–5]. That model was also appraised on the basis of a large amount of experimental results [3].

In the first part of the paper, the model is applied to evaluate the influence of each geometrical/mechanical parameter on the peak force that a strip, near surface mounted on a concrete prism and subjected to an increasing imposed end slip, can transfer through bond stresses to the surrounding concrete. To that aim, the deformability of the concrete prism is accounted for while the possibilities of either concrete fracture or strip rupture are excluded by assuming the tensile strength of both materials, concrete and FRP, infinitely large.

In the second part of the paper, the model is applied to evaluate the influence of each geometrical/mechanical parameter on the ultimate load that a single strip, near surface mounted on a concrete prism and subjected to an increasing imposed end slip, can comprehensively transfer to the surrounding concrete. For this purpose, the possibilities of occurrence of either concrete semi-conical tensile fracture or strip tensile rupture are accounted for.

In the third part of the paper, the model is applied to evaluate the influence of each geometrical–mechanical parameter on the peak shear strength contribution provided by a system of NSM FRP strips to a RC beam.

2. Bond-based behavior of a single NSM FRP strip subject to an imposed end slip

2.1. Bond-based constitutive law of a single NSM FRP strip

Applying the model to the case of a single NSM FRP strip mounted on the surface of a concrete prism (Fig. 1), and neglecting the possibilities of both concrete semi-conical tensile fracture and strip rupture, it is possible to determine the bond-based constitutive law of the strip $V_{fi}^{bd}(L_{Rfi};\delta_{Li})$. This latter is the curve providing the bond-based force V_{fi}^{bd} that the generic ith strip, with resisting bond length L_{Rfi}, can transfer, through bond stresses, to the surrounding concrete as function of the value of the increasing imposed end slip δ_{Li} (Fig. 1a and b). The bond-based constitutive law $V_{fi}^{bd}(L_{Rfi};\delta_{Li})$ of a given NSM FRP strip depends on the following parameters [4,5] (Fig. 1d and e): strip cross section thickness a_f and width b_f; strip resisting bond length L_{Rfi}; concrete prism cross section thickness a_c and width b_c; concrete deformability E_f (which is function of the concrete compressive strength f_{cm}); strip's Young's Modulus E_f and values of bond stress (τ_0,τ_1,τ_2) and slip $(\delta_1,\delta_2,\delta_3)$ defining the local bond stress–slip relationship (Fig. 1e). The analytical details necessary to evaluate the constitutive law of a given NSM FRP strip are herein omitted, for the sake of brevity, but they can be found elsewhere [4,5]. The constitutive laws $V_{fi}^{bd}(L_{Rfi};\delta_{Li})$ of NSM FRP strips of different values of L_{Rfi} can be plotted both in a bi-dimensional $\left(V_{fi}^{bd};\delta_{Li}\right)$ and in a three-dimensional $\left(V_{fi}^{bd};L_{Rfi};\delta_{Li}\right)$ orthogonal reference system. The peak bond-transferred force $V_{fi}^{bd,\max}$ increases, by increasing the value of L_{Rfi}, up to the value $V_{fi}^{bd,\max}(L_{Rfe})$ corresponding to the effective resisting bond length L_{Rfe}, which is the value of L_{Rfi} beyond which any further increase of the resisting bond length L_{Rfi} does not yield any further peak load gain. In a bi-dimensional representation (Fig. 1a), the point $\left(V_{fi}^{bd};\delta_{Li}\right)$ representative of the state of the NSM strip of resisting bond length L_{Rfi} moves, for increasing values of δ_{Li}, on the same branch, non-linear ascending or linear horizontal for values of $L_{Rfi} \leqslant L_{Rfe}$ or $L_{Rfi} > L_{Rfe}$ respectively, common for each value of L_{Rfi}, as long as L_{Rfi} is larger or equal to the value of the *necessary bond transfer length* $L_{tr}^{bd}(\delta_{Li})$ [4,5]. Where $L_{tr}^{bd}(\delta_{Li})$, function of δ_{Li} only, is the bond length that would be necessary to entirely transfer to the surrounding concrete a force equal to the one originating in the strip loaded end, due to the imposition of

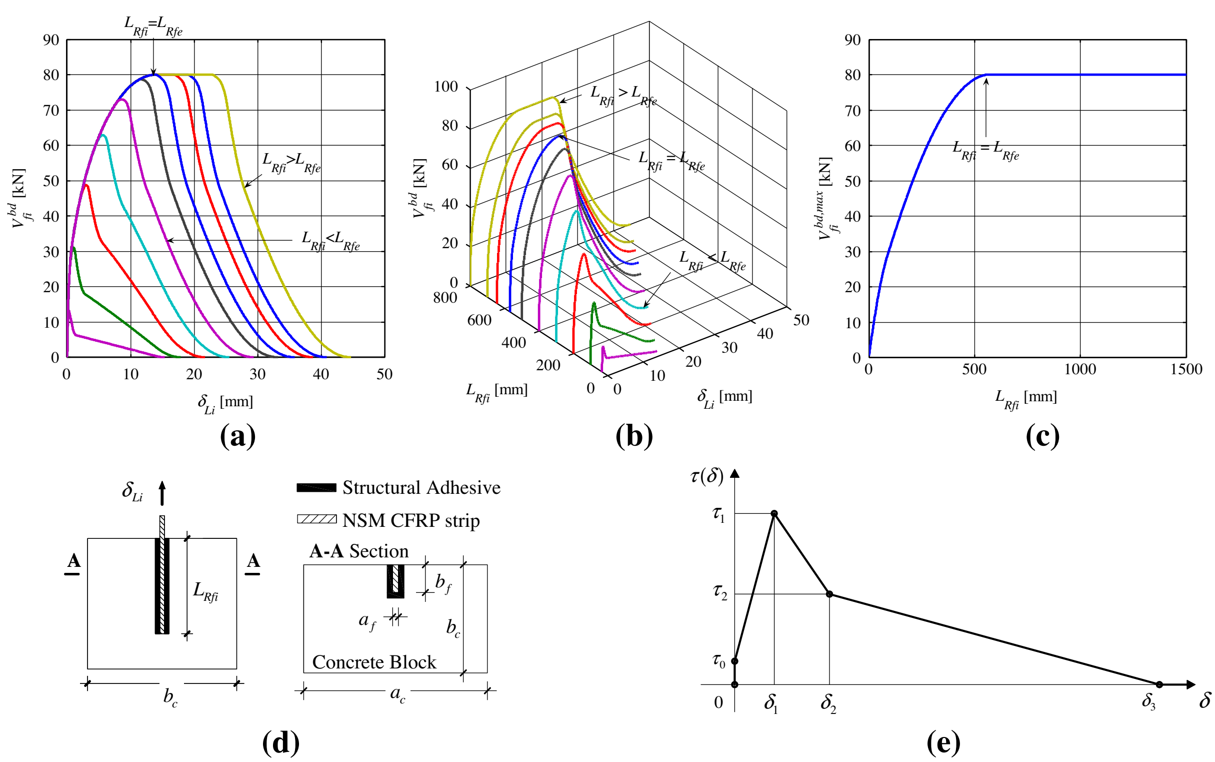

Fig. 1. Bond-based behavior of a single Near Surface Mounted (NSM) FRP strip on a concrete prism: (a and b) constitutive law $V_{fi}^{bd}(L_{Rfi};\delta_{li})$ both in a bi-dimensional and in a three dimensional representation; (c) dependence of the maximum bond-transferred force $V_{fi}^{bd,\max}$ on the resisting bond length L_{Rfi}; (d) concrete prism with a single NSM FRP strip and (e) adopted local bond stress–slip relationship.