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Modeling of debonding failure for RC beams strengthened in shear with NSM FRP reinforcement

Andrea Rizzo, Laura De Lorenzis *

Department of Innovation Engineering, University of Lecce, via per Monteroni, 73100 Lecce, Italy

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ABSTRACT

The shear capacity of reinforced concrete members can be successfully increased using near-surface mounted (NSM) fiber-reinforced polymer (FRP) reinforcement. Tests conducted thus far have shown that failure is often controlled by diagonal tension associated to debonding between the NSM reinforcement and the concrete substrate. In absence of steel stirrups and/or when the spacing of the NSM reinforcement is large, debonding involves separately each of the bars crossed by the critical shear crack. In order for shear strengthening of beams with NSM reinforcement to be safely designed, an analytical model able to encompass the failure mode mentioned above must be developed. This paper presents two possible approaches, a simplified and a more sophisticated one, to predict the FRP contribution to the shear capacity. In the first approach, suitable for immediate design use, an ideally plastic bond–slip behavior of the NSM reinforcement is assumed, which implies a complete redistribution of the bond stresses along the reinforcement at ultimate. The second approach, implemented numerically, accounts for detailed bond–slip modeling of the NSM reinforcement, considering different types of local bond–slip laws calibrated during previous experimental investigations. It also takes advantage of an approach developed by previous researchers to evaluate the interaction between the contributions of steel stirrups and FRP reinforcement to the shear capacity. The paper illustrates the two models and compares their predictions, with the ultimate goal to evaluate whether the first simple model can be used expecting the same safety in predictions of the second model.

1. Introduction

One of the major applications of fiber-reinforced polymer (FRP) composites for strengthening of reinforced concrete (RC) members is their use as additional web reinforcement to increase the shear capacity of the members. Over the last few years, shear strengthening with externally bonded FRP laminates has become a well established technique upon extensive experimental verification and with the development of analytical models reflected in the relevant code provisions. A state-of-the-art review of existing research on this topic up to 2003 can be found in Ref. [1]. Further papers have been published in the past few years (see e.g. [2–8]).

A more recent and less investigated method for shear strengthening of RC members is the use of near-surface mounted (NSM) FRP reinforcement, in the form of round bars, square bars or rectangular bars with large width to thickness ratio (also briefly indicated as strips). In this paper the term "bars" is used to refer collectively to all possible types of NSM reinforcement. In the NSM method, the reinforcement is embedded in grooves cut onto the surface of the member to be strengthened and filled with an appropriate binding agent such as epoxy paste or cement grout. A review of available research on NSM strengthening of RC structures up to 2005 is reported in Ref. [9]. Further papers have been published more recently [7,10,11]. For shear strengthening with NSM reinforcement, the grooves are cut on the sides of the member at a desired angle to the beam axis.

Applications of NSM FRP reinforcement for shear strengthening of RC beams are described in Refs. [7,10–14]. De Lorenzis and Nanni [12] carried out tests on large size T-beams, most of which had no internal stirrups. Carbon FRP (CFRP) ribbed round bars in epoxy-filled grooves were used as NSM shear reinforcement. The test variables included bar spacing and inclination angle, and anchorage of the bars in the flange. The NSM reinforcement produced a shear strength increase which was as high as 106% in the absence of steel stirrups, and still significant in presence of a limited amount of internal shear reinforcement. Nanni et al. [13] reported the test results of a single full-scale PC girder taken from a bridge and shear-strengthened with NSM CFRP strips. The beam failed in flexure at a shear force close to the shear resistance predicted by the model given in Ref. [12]. Barros and co-workers [7,10,11] tested beams of different sizes and with different amounts of longitudinal steel reinforcement. Some of these beams

* Corresponding author.
E-mail addresses: andrea.rizzo@unile.it (A. Rizzo), laura.delorenzis@unile.it (L. De Lorenzis).

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were strengthened with NSM CFRP strips of different inclinations, while others were strengthened with equivalent amounts of externally bonded FRP shear reinforcement. The NSM technique proved more effective than externally bonded FRP in terms of both strength and deformation capacity. Rizzo and De Lorenzis [14] carried out tests on beams with a limited amount of internal steel stirrups strengthened with NSM round bars and strips, analyzing the effect of the spacing and inclination of the FRP strengthening, and of the type of groove-filling epoxy. The increase in shear capacity was about 16% for one beam strengthened with externally bonded U-wrapped laminate, and ranged between 22% and 44% for the beams strengthened with NSM reinforcement. The use of NSM reinforcement was thus more efficient due to early debonding of the externally bonded laminate.

Two different failure modes were identified in Ref. [12] for beams strengthened in shear with NSM ribbed bars. In absence of steel stirrups, the failure mode was debonding of the FRP bars by splitting of the epoxy cover and cracking of the surrounding concrete, associated with the diagonal tension failure of concrete. This failure mode was prevented by providing better anchorage of the NSM bars crossing the critical shear crack, by either anchoring the bars in the beam flange or the use of inclined (e.g. 45°) bars at a sufficiently close spacing to achieve a longer total bond length. Once this mechanism was prevented, separation of the concrete cover of the steel longitudinal reinforcement became the controlling failure mode. This second mode, however, may be attributed to the fact that no or very limited steel stirrups were present in the beams [12], and is unlikely in beams with a more realistic amount of steel stirrups. More recent experiments conducted by the authors [14] have shown that the presence of steel stirrups, combined with a relatively small spacing of the reinforcement, may originate a third failure mechanism in which the lateral concrete covers of the steel stirrups detach from the core of the beam with the NSM reinforcement still embedded. Thus, due to the particular failure mode, decreasing the spacing or increasing the inclination of the bars cannot benefit the shear capacity of the beam since the reduced distance between the bars accelerates the formation of a debonding failure pattern involving all the bars together. Although it has not been observed so far, tensile rupture of the NSM reinforcement is another possible failure mode.

At present, different approaches to compute the capacity of shear-strengthened beams are available in the literature, most of which are based on the generalization of the truss model usually adopted for computation of the shear capacity of RC beams. As debonding failure modes often control, and considering that the bond behavior of NSM reinforcement is markedly different from that of externally bonded reinforcement, specific models for NSM-strengthened beams are needed. The only model specific for NSM reinforcement is that by De Lorenzis and Nanni [12]. They proposed a model based on the following assumptions: inclination angle of the shear cracks constant and equal to 45°; even distribution of bond stresses along the FRP bars at ultimate; the local bond strength is reached in all the bars intersected by the critical shear crack at ultimate. The last two assumptions in turn derive from the use of an ideally plastic local bond–slip curve (with unlimited ductility) for the NSM reinforcement. In this model, the FRP contribution to the shear strength of the beam results proportional to the sum of the minimum embedment lengths of all the bars intersected by the critical shear crack, computed for the most unfavorable crack position. The same authors also proposed that the maximum strain in the bars be limited to $4000\mu\varepsilon$ in order to avoid the loss of the aggregate interlock due to a large width of the shear crack. The simple equations resulting from this model were provided for the cases of vertical bars, for ratios of bar spacing to beam effective depth ranging from 0.25 to 1.0.

The adoption of an ideally plastic local bond–slip curve in the model in [12], while yielding simple expressions for the NSM FRP contribution to the shear capacity, is a crude approximation of the real bond–slip behavior of NSM reinforcement and may easily result un-conservative. On the other hand, starting from local bond–slip relationships obtained from bond tests, it is possible to improve the accuracy of the model at the expenses of its simplicity. Moreover, the model in [12], such as virtually all models currently available on the capacity of RC beams shear-strengthened with FRP systems, computes the capacity of the strengthened beam as the sum of the contributions of steel stirrups and FRP system. This implies the assumption that the peak shear forces that can be resisted by the steel stirrups and by the FRP are reached at the same time, which is generally an un-conservative assumption. Recently, Mohamed Ali et al. [15] proposed a partial-interaction model to quantify the vertical shear interaction between transverse FRP plates and steel stirrups. The analysis of the shear-strengthened beam is conducted by gradually increasing the opening of the shear crack, and computing the corresponding slip and bond stress distributions along the NSM reinforcement. The steel stirrups are considered fully anchored at their ends, and bond between the FRP plates and concrete is analyzed by using a linear softening local bond–slip relationship.

In this paper, two models are proposed for the shear capacity of RC beams strengthened in shear with NSM reinforcement. In both models, the failure mode is assumed to be debonding of the NSM reinforcement. In particular, debonding is assumed to take place in each single NSM bar separately, with no global separation of the cover of the internal stirrups. The latter failure mode deserves a specific investigation and is not covered herein.

The first model is a generalization of the model in [12], where the assumption of perfectly plastic bond–slip behaviour is maintained but the angles formed by the critical shear crack. Moreover, by the NSM reinforcement to the beam axis are made variable. Moreover, a wide range of spacings of the NSM reinforcement is considered. The second model is based on the approach in [15], where an appropriate local bond–slip model is considered for the shear strengthening system and the possibility of a reduced effectiveness of the internal stirrups due to interaction with the external strengthening is accounted for. The local bond–slip models adopted for NSM reinforcement are taken from previously available bond test results. The purpose of the paper is to comparatively evaluate the performance of the two models. The final goal is to determine whether, and under which conditions, the first simple model can be used expecting the same safety in predictions of the second model.

2. Generalized ideally plastic (GIP) model

2.1. FRP contribution to the shear capacity

As follows, the simplified approach proposed in [12] is generalized for any value of the FRP spacing, and of the angles formed by the shear crack and by the FRP strengthening with the horizontal direction. The formulation is suitable to account for any possible debonding failure mode, provided that it involves each NSM bar separately and that it displays sufficient pseudo-ductility to make the assumption of a perfectly plastic bond–slip behavior physically reasonable. According to [12], a constant shear stress at failure τ_f at the bar-epoxy interface is assumed in all the FRP bars intersected by the shear crack at ultimate, thus the FRP shear contribution V_{FRP} can be calculated multiplying τ_f by the total lateral surface of the minimum embedment lengths of all the bars crossed by the crack. This results in the following equation:

$$V_{FRP} = 2\left(\sum_{i=1}^{n_{s,f}} l_{emb,i}\right) p\tau_f \sin\alpha = 2 l_{emb,tot} p\tau_f \sin\alpha \tag{1}$$