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# Bond of FRP rods in damaged RC beams strengthened with NSM technique

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**Abstract**

In strengthening reinforced concrete (RC) elements with composite materials, the role of adherence between concrete and FRP assumes great importance as it guarantees the effectiveness of the consolidation method. In this paper the bond mechanisms between FRP rods and concrete second the Near Surface Mounted (NSM) technique have been analyzed by experimental results of investigation and a theoretical linear model. The experimental investigation consists of direct pull-out tests on RC elements with circular GFRP and CFRP rods inserted into a groove. Through pull-out tests main parameters of bond have been presented. The experimental results are compared with those obtained by the theoretical model.



*Keywords:* NSM techinque; CFRP/GFRP rods; RC specimens; adhesion bond; pull-out test

## 1. Introduction

The so-called Near Surface Mounted (NSM) is a strengthening technique for reinforced concrete (RC) beams. It consists of creating special grooves in the concrete cover, where Fiber Reinforced Polymers (FRPs) of different sections are placed and normally fixed by epoxy resins or special mortars (Szabò et al. (2007), El-Hacha et al. (2004), Capozucca (2009), Capozucca et al. (2020), Sabau et al. (2018)). The NSM technique provides a strengthening alternative to externally bonded (EB) method, that is based on the adhesion of FRP sheets on the surfaces of RC beams

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(Bilotta et al. (2011)). The effectiveness of the NSM strengthening technique can be assessed by dynamic tests and vibration response analysis (Capozucca (2013), Capozucca (2018)).

The NSM technique offers several advantages over EB method (De Lorenzis et al. (2007), Kotynia (2012)), for example: easier installation; higher bonding efficiency; less exposure to mechanical and thermal impacts thanks to the concrete cover. However, current knowledge on adhesion problems of NSM method with FRP is limited.

The main problem is the preservation of bond between the FRP bars and the concrete beam through the resin as filler (Capozucca (2013), Capozucca (2011), Focacci et al. (2000), Lees (2009), Hassan et al. (2004), Perera et al. 2009), Hassan et al. (2003)). NSM technique may be indeed an efficient method of strengthening if the bond between FRP rods inserted into groove is maintained until failure of the strengthened element. Some constructive parameters that can influence adhesion and therefore structural behavior may be the rod section dimensions (nominal diameter $d_b$ for rods with circular section), bond length $l_b$, type of FRP material used, rods surface configuration, thickness of concrete cover, amount of longitudinal steel reinforcement (Cosenza et al. (1997), Kotynia et al. (2021), Barros et al. (2006)). Adhesion bond diagrams, shear stress $\tau$ vs slip $s$, represent a focus of much research (Bianco et al. (2009), Ceroni et al. (2012), Yuan et al. (2012)). Adhesion bond laws were deduced through experimental tests for different types of circular cross-section rods (De Lorenzis (2004)) and for NSM sheets (Sena Cruz et al. (2006)).

Experimental results of pull-out tests conducted by Sharaky et al. (2013) have shown that filler properties greatly influence adhesion behavior. The most common and best performing groove filler is an epoxy two-component. Experimental results (De Lorenzis et al. (2007)) have shown that the tensile strength values of epoxy resin vary between 13.8 and 42.6 MPa, while those of cement mortar vary between 6.3 and 9 MPa. Furthermore, it has been observed (Sharaky et al. (2013)) that the delamination load increases with increasing groove width $w_g$, regardless of the properties and surface treatment of FRP rods. For rods with circular section, De Lorenzis et al. (2002), based on the results of the adhesion tests on elements with square grooves, defining $k=w_g/d_b$, proposed a minimum value of $k$=1.5 for smooth or slightly sandblasted rods and a minimum value of $k$=2.0 for ribbed rods.

Based on the above considerations, this paper presents the results of pull-out tests on RC specimens with circular GFRP and CFRP rods inserted according to the NSM technique. Subsequently, with an analytical model based on linear behavior, the experimental data are compared.

**Nomenclature**

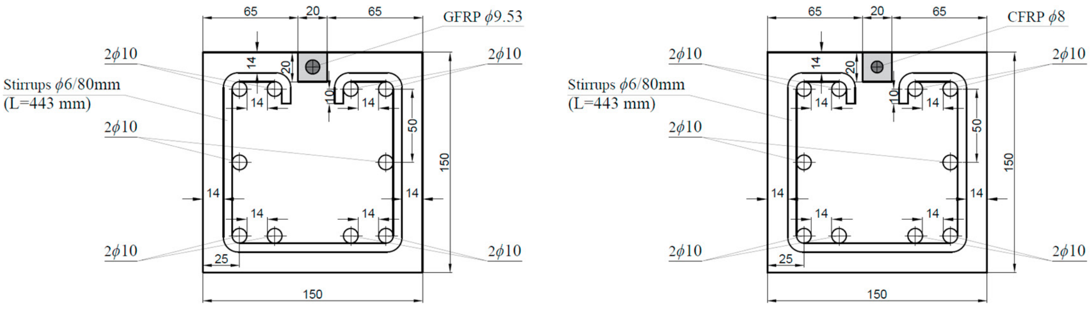
| | |
|---|---|
| $d_b$ | nominal diameter of circular FRP rod |
| $l_b$ | bond length |
| $\tau$ | shear adhesion stress |
| $s$ | slip between FRP rod and concrete |
| $w_g$ | groove width |
| $E_b$ | elastic modulus of FRP rods |
| $f_b$ | tensile strength of FRP rods |
| $z$ | coordinate along the bond length |
| $G_f$ | fracture energy |
| $\varepsilon$ | strain of FRP rod |
| $A_b$ | FRP rod area |
| $F$ | pull-out force |
| $G_e$ | shear modulus of resin |
| $K_e$ | stiffness of resin |

## 2. Experimental pull-out tests

Pull-out tests were performed to investigate the adhesion behavior of the different types of FRP rods on RC specimens, varying the bond length. Two series of pull-out tests were performed on RC specimens strengthened by a different type of FRP rod according to the NSM technique: the first series with GFRP (Glass Fiber Reinforced

Polymers) rods (Fig. 1a) the second series with CFRP (Carbon Fiber Reinforced Polymers) rods (Fig. 1b). Each of these series consists of three pull-out tests with three different bond lengths $l_b$: 200 mm, 250 mm, and 300 mm.

GFRP rods are characterized by a nominal diameter $d_b$ of 9.53 mm, tensile elastic modulus $E_b$ of 40800 MPa and tensile strength $f_b$ equal to 760 MPa. The epoxy resin is a two-component thixotropic epoxy adhesive, characterized by an elastic modulus equal to 6000 MPa.

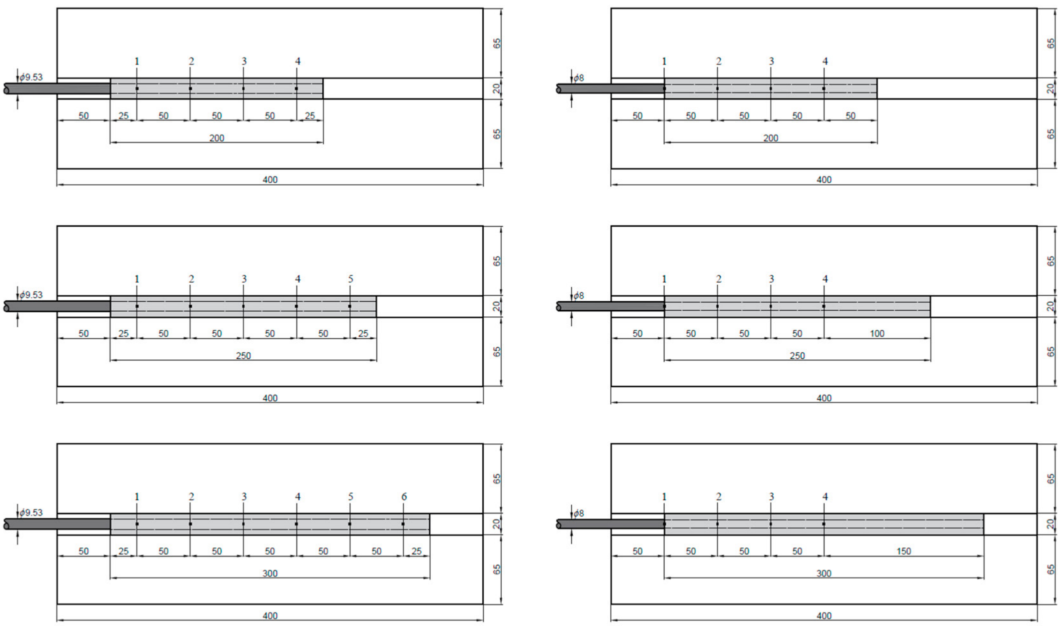



(a) (b)

Fig. 1. Cross section of specimens:(a) first series with GFRP rods; (b) second series with CFRP rods.

CFRP rods, with helical winding of carbon wire and surface sandblasting, are characterized by a nominal diameter $d_b$ of 8 mm, tensile elastic modulus $E_b$ of $130 \cdot 10^3$ MPa, tensile strength $f_b$ of 1800 MPa. The epoxy resin is a thixotropic adhesive characterized by an elastic modulus equal to 9500 MPa. The properties of all the FRP bars and epoxy resin have been provided by the manufacturer.

Strain gauges were placed along the FRP rods, at intervals $z$=50 mm to measure rod strains. A 50 mm long section was left free at the loaded end, to avoid a cone break in the concrete (Fig. 2).



(a) (b)

Fig. 2. Three tests with different bond lengths: (a) first series (GFRP bar); (b) second series (CFRP bar).

### 2.1. Experimental results

From analysis of experimental data, it is possible to deduce different information. About the first series in all three tests, no delamination phenomena occurred. The crisis happened due to the achievement of tensile strength of the GFRP rod. The adhesion bond diagrams, $\tau$-$s$, are all almost linear (Fig. 3a).

Regarding the second series, the crisis occurred by delamination. Adhesion bond diagrams $\tau$-$s$ generally present a branch increasing to a well-defined peak, followed by a descending branch of softening (Fig. 3b)

For each pull-out test, the most significant adhesion bond diagram ($\tau$-$s$), i.e., the one relating to the greatest fracture energy, $G_f$, was selected. For each diagram, the peak adhesion stress, $\tau_m$, and associated slip, $s_m$, were identified.

Table 1 summarizes the peak adhesion stress $\tau_m$, the associated slip $s_m$ and fracture energy, $G_f$, for the two series of pull-out tests.

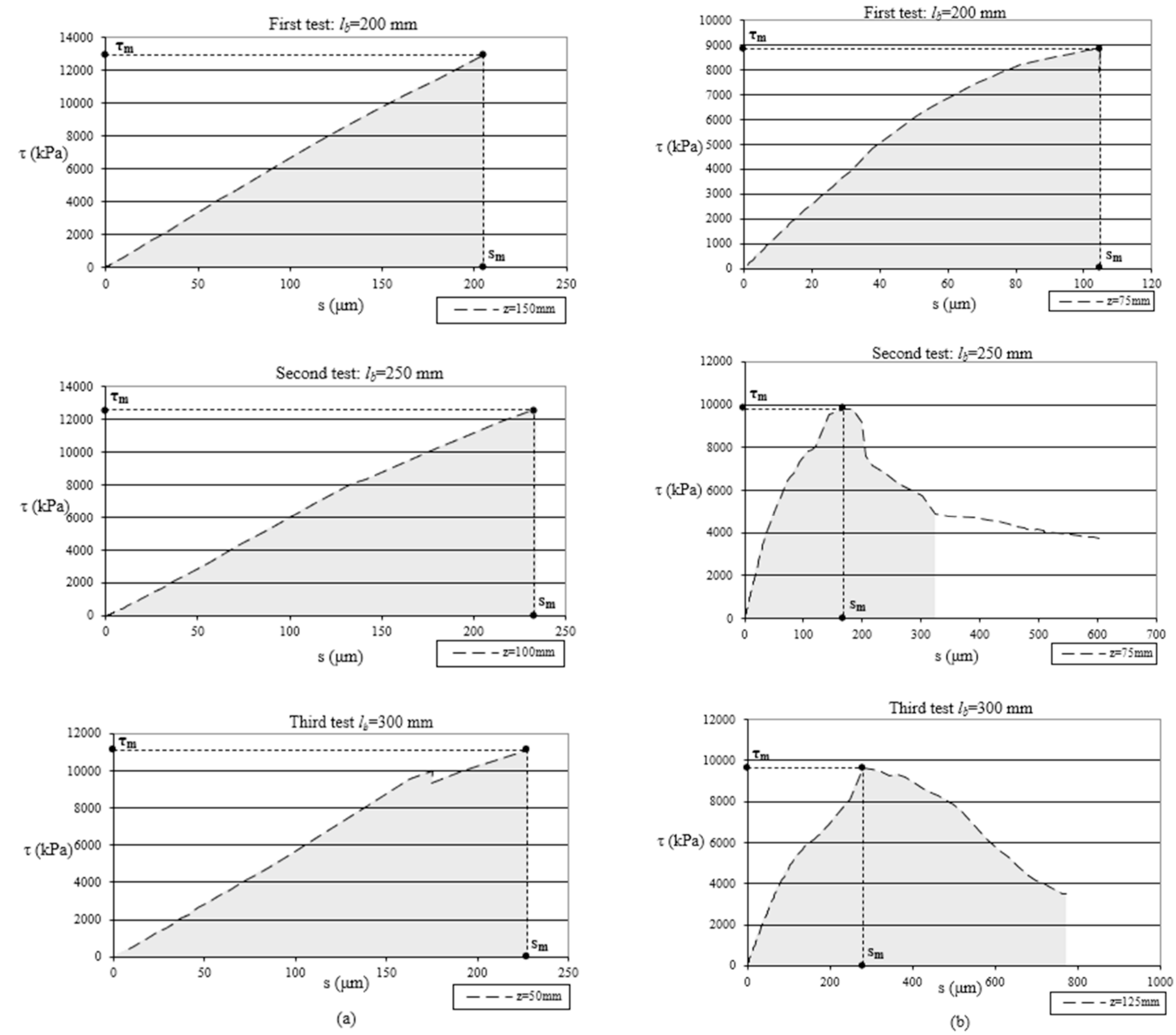



Fig. 3. Most significant adhesion bond diagrams, $\tau$-$s$, for each pull-out test: (a) first series; (b) second series.

Table 1. Values of relevant parameters of adhesion bond $\tau$-$s$.

| Series | $G_f$ (N/mm) | $\tau_m$ (N/mm$^2$) | $s_m$ (mm·10$^{-3}$) |
|---|---|---|---|
| First series (GFRP rod) | 1.37÷1.56 | 11÷13 | 205÷233 |
| Second series (CFRP rod) | 0.59÷4.91 | 8.84÷9.62 | 104÷280 |

The values reported of the two series must be compared with each other with due caution. In the first series, the crisis occurred by reaching the tensile strength of the GFRP rod and not by delamination, so the values of $\tau_m$ are not really the peak values. About the second series, the crisis occurred by delamination, so $\tau_m$ is the adhesion stress at which the delamination process begins and $\varepsilon_{max}$ is the maximum associated strain.

The maximum strain values $\varepsilon_{max}$ recorded by the various measuring points were reported in Table 2.

Table 2. Maximum strain values $\varepsilon_{max}$ recorded along the bond length $z$.

| | Maximum strain $\varepsilon_{max}$ (‰) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| First series (GFRP) | - | $z$=25 | - | $z$=75 | - | $z$=125 | - | $z$=175 | $z$=225 | $z$=275 |
| First test | | 5.3 | | 4.5 | | 7.4 | | 0.8 | - | - |
| Second test | | 6.4 | | 7.4 | | 6.8 | | 3.1 | 0.2 | - |
| Third test | | 6.8 | | 6.5 | | 6.1 | | 2.6 | 0.2 | 0.03 |
| Second series (CFRP) | $z$=0 | - | $z$=50 | - | $z$=100 | - | $z$=150 | - | - | - |
| First test | 3.6 | | 2.4 | | 2.1 | | 1.8 | | | |
| Second test | 3.4 | | 4.8 | | 4.1 | | 2.8 | | | |
| Third test | 7.1 | | 5.3 | | 5.6 | | 4.9 | | | |

## 3. Linear elastic model

The adhesion mechanisms between the FRP rod and the RC element are related to the adhesion stress and slip at the interface of the material.

The model proposed by Capozucca (2013) intends to describe the adhesion behavior of FRP rods, in elements reinforced according to the NSM technique. This model considers, therefore, a RC specimen, reinforced with FRP rod, according to the NSM technique, subjected to a pull-out test.

The theoretical distribution of deformations along the FRP rod is:

$$\varepsilon(z) = \frac{F}{E_b \cdot A_b} \cdot \frac{\sinh(\xi \cdot z)}{\sinh(\xi \cdot l_b)} \tag{1}$$

where $F$ is the applied pull-out force and $A_b$ the FRP rod area. The parameter $\xi$ of Eq. 1 is:

$$\xi = \sqrt{\frac{K_e}{E_b \cdot A_b}} \tag{2}$$

The Eq. 2 is a function of the stiffness of the epoxy resin $K_e$, which, for FRP rods with circular cross-section, is:

$$K_e = \frac{3}{2} \cdot \pi \cdot \frac{w_g}{w_g - d_b} \cdot G_e$$

where $G_e$ is the shear modulus of resin.

Figs. 4a and 4b show, respectively, the comparison between experimental and theoretical results, obtained with the linear elastic model, for the first series and second series of pull-out tests.

Load levels $F$ at which delamination has not yet occurred have been considered. Therefore, for each load level, the measured strain values $\varepsilon_{exp}$ were compared with the theoretical ones $\varepsilon_{theor}$.

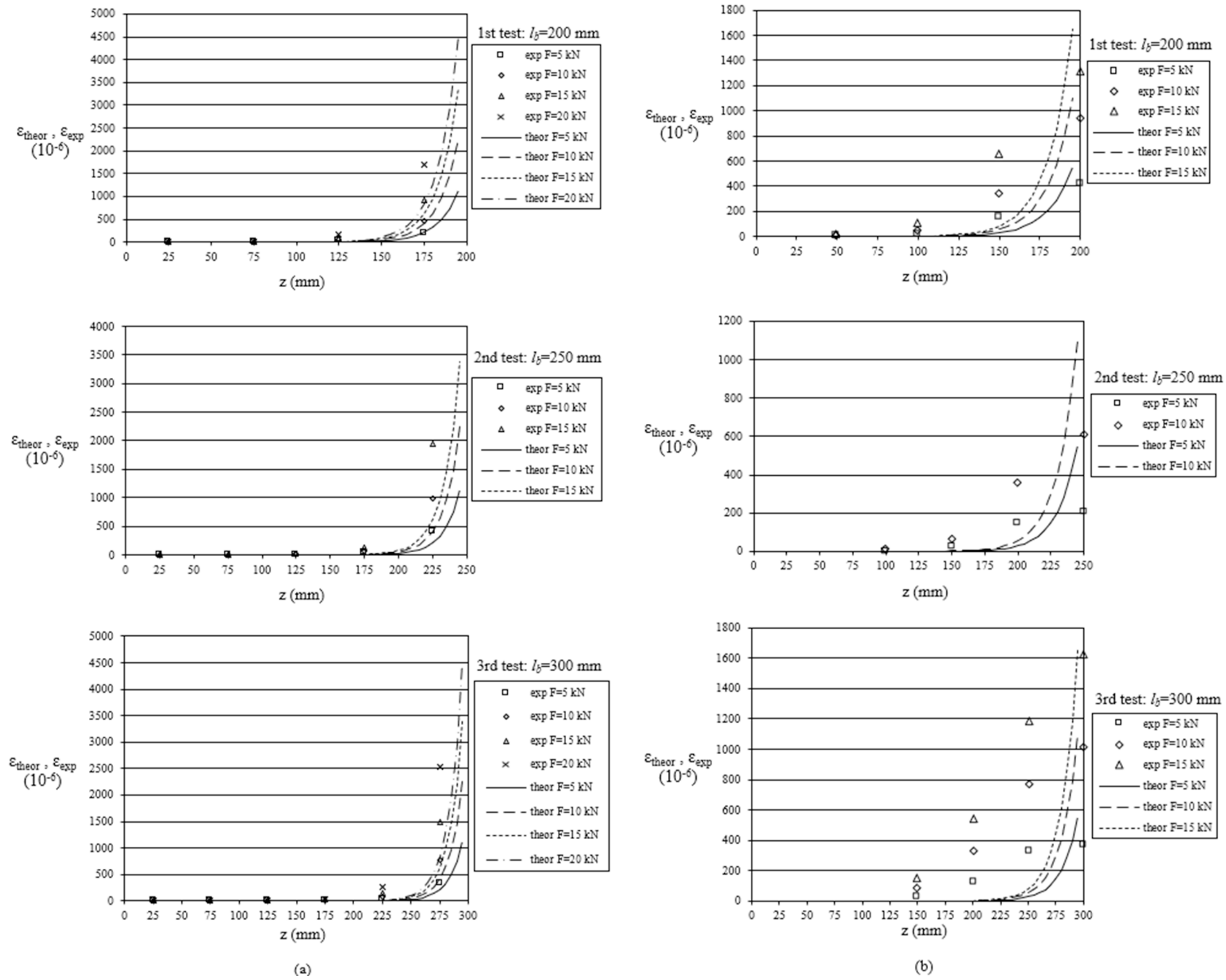



Fig. 4. Comparison between theoretical and experimental strain values $\varepsilon$ along the anchor length $z$: (a) first series; (b) second series.

The first series, being related to tests in which the crisis does not occur by delamination, is the most suitable for a comparison with the theoretical model of linear elastic type. It shows rather encouraging results, with low percentage error values.

## 4. Conclusions

Based on the $\tau$-s diagrams, it appears that the bond between GFRP-resin-concrete rods is maintained until the rod failure with shear stress values greater than 11 MPa. The fracture energy grows considerably in the case of CFRP rods with increasing of bond length, due to higher slip values. However, the comparison between the results of the two series of tests must consider that the crisis occurred for different reasons: reaching the tensile strength of the GFRP rod in the first series and delamination in the second series.

The comparison between the theoretical and experimental results of the first series in terms of strain rods along the anchor length shows a good correspondence, since no delamination phenomena occurred.

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