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Strain assessment for the design of NSM FRP systems for the strengthening of RC members

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HIGHLIGHTS

- Effectiveness of FRP in strengthening of existing constructions is investigated.
- Bond tests on different types of near surface mounted (NSM) reinforcement are showed.
- Further results of bond tests available in literature are collected and analysed.
- A relationship to predict debonding strain of the FRP NSM strengthening is calibrated.
- The calibration is in accordance with the "design by testing approach" suggested by Eurocodes.

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ABSTRACT

Recently, experimental results of bond tests performed by several researchers to measure the performance of Fibre-Reinforced Polymer (FRP) applied according to near-surface mounted (NSM) strengthening techniques have indicated that the mechanical properties of materials and the surface properties of FRP reinforcement as well as the groove geometry and the test setup can affect the bond behaviour of this strengthening system. Experimental tests also show that the NSM technique could represent a sound alternative to FRP Externally-Bonded Reinforcement (EBR) systems because it allows the FRP tensile strength to be better exploited. Herein, the results of bond tests of different types of NSM FRP reinforcement carried out by the authors and other results available in the literature are collected and analysed in terms of the maximum bond shear stress and maximum strain at failure. The results are analysed to provide an experimentally calibrated relation aimed at predicting both the average and characteristic values of the maximum strain of NSM FRP reinforcements in the case of bond failure, according to the design assisted by testing approach.

1. Introduction

Currently, the use of FRP systems to strengthen existing reinforced concrete (RC) structures can be classified in two main categories: Externally-Bonded Reinforcement in the form of plates or sheets (EBR technique) or bars or strips applied in superficial grooves (near-surface-mounted technique, NSM). The first technique is well known and widely used in practical applications because many experimental results are now available and because several key aspects related to bond have been well interpreted by theoretical models. In contrast, the greater novelty of the near-surface mounted technique in conjunction with a wider range of strengthening systems available on the market, makes models and design formulations to date lacking (ACI 440.08) [1]. One reason for this is that research on the bond behaviour of the NSM strengthening technique, both from the numerical and experimental points of view, is less consolidated compared to the EBR technique, the latter being used in practical applications at an increasingly greater rate.

Indeed, considerable research has only been recently directed towards characterising the use of FRP bars and strips as (NSM) reinforcement as an alternative to the EBR technique to mitigate the risk of premature debonding failure [9]. Unlike EBR FRP systems, poor design provisions are currently available for the NSM strengthening technique. The effectiveness of this system is strictly related to the type of failure (at the epoxy–reinforcement interface, at the epoxy–concrete interface, in the concrete or through splitting in the epoxy cover), which depends on a large number of

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parameters affecting the local bond-slip behaviour: the mechanical properties of the materials (concrete and FRP), surface treatment of the reinforcement and of the grooves, geometry of the strengthening system (bars or strips), dimensions of the grooves and depth of the FRP reinforcement in the groove [17,9,19,20]. The test setup used to characterise the bond behaviour can also affect both the bond-slip relation and the debonding load [14].

In Bilotta et al. [2], the results of 24 pull–pull Single Shear Tests (SSTs, Series I) aimed at investigating the bond behaviour of different types of FRP bars and strips (carbon, basalt and glass bars and carbon strips) externally applied with the NSM technique for strengthening reinforced concrete (RC) members were presented. Such an experimental program was developed in the framework of a round robin initiative involving several research laboratories [15]. The findings confirmed that the NSM technique could represent a sound alternative to EBR systems because it allows debonding to be delayed. Therefore, to add further information about the influence of surface treatment and groove dimensions on the bonding of the NSM strengthening system, additional 12 SSTs (Series II) were carried out by the authors on specimens cast in the same batch as Series I.

In the following sections, the results of Series I are briefly summarised because they have been already discussed in detail [2–4], and the results of the new Series II are presented. The experimental results of Series I and II, directly carried out by the authors, have been joined with results collected from the scientific literature with the aim of developing an experimentally based formulation for calculating the maximum debonding strain in FRP NSM reinforcements.

2. Experimental program

The main geometrical and mechanical parameters of all the FRP NSM systems tested by the authors are summarised in Table 1: the bar diameter d or the strip dimensions t_f and b_f; the average values of the Young's modulus E_f, which were computed at stresses in the range of 20–60% (ACI 440.2R); the axial stiffness of the FRP reinforcement, $E_f A_f$; the average values of the tensile strength f_{fu}. The average values were obtained from five experimental tensile tests. The corresponding *CoV* values are also reported in brackets.

The shape ratio k is also listed in Table 1 and is defined as b_g/d for the round and square bars and as b_{g2}/b_f for the strips, b_f being the width of the strip and b_{g2} being the side of the groove where the bond transfer develops (see Table 2). The values of k are greater than 1.5 in each case, which is the minimum value suggested to avoid splitting failure of the epoxy [9].

In Table 2, a synthesis of the experimental program is reported. The notation of the specimens is A-x-B-d-n, where A refers to the reinforcement material (‘‘B’’, ‘‘G’’, or ‘‘C’’ for basalt, glass or carbon bars or strips), x identifies the bar diameter or the strip thickness and width (‘‘6’’ or ‘‘8’’ for round bars, ‘‘10 × 10’’ for the square bar, and ‘‘1.4 × 10’’ or ‘‘2.5 × 15’’ for the two types of strips), B denotes the surface treatment (‘‘SC’’ for a sand-coated surface, ‘‘S’’ for a smooth surface, ‘‘SW’’ for a spirally wound surface, ‘‘RB’’ for a ribbed surface, and ‘‘R’’ for a roughened surface), d indicates the dimension of the grooves (10 × 10, 14 × 14, 15 × 15, and 20 × 20 for bars and 3 × 15 and 5 × 20 for strips), and n distinguishes the ordinal number of the tests (‘‘1’’, ‘‘2’’ or ‘‘3’’). Three identical specimens were tested for each type of NSM system/groove dimension investigated.

The first 24 specimens, indicated as ‘Series I’, were realised in the framework of a round robin initiative involving several research laboratories [15] and aimed to test the bond strength of the same FRP materials according to different test setups carried out in different laboratories.

A total of 12 additional concrete specimens, indicated as ‘Series II’, were prepared by the authors using concrete prisms with the same dimensions (width b_c = 160 mm, height h_c = 200 mm and length l_c = 400 mm) and cast in the same batch as the specimens of Series I (average cylindrical compressive strength f_{cm} = 19 MPa, Young's modulus E_c = 18.6 GPa, and tensile strength f_{ctm} = 2.5 MPa, as obtained by experimental compressive and Brazilian tests on concrete coupons; see [2] for additional details). Two extra types of bars were tested (10 mm sand-coated basalt bars and 8 mm spirally wound carbon bars) in addition to the NSM systems tested in Series I, and grooves with larger dimensions were used for the 8 mm and 10 mm basalt bars (20 × 20 mm instead of 15 × 15 mm). As for the specimens in Series I, the grooves were longitudinally cut in the concrete cover (Fig. 1a) using a saw, and no specific surface treatment was adopted. In Table 2, the groove dimensions are depicted for the Series I and II tests.

The bond tests were carried out using a servo-hydraulic testing machine; steel pipes were installed at the end of the FRP bar or strip to ensure an adequate clamping of the grips of the testing machine. The test setup is asymmetrical because each bonded side of the concrete specimen is individually tested (see Fig. 1b). The specimen was blocked at the lower base of the testing machine by two steel bars embedded in the concrete prism and bolted to a system of steel plates fixed in the lower grips. Based on this setup, the concrete block was also loaded in tension (pull–pull Single Shear Test). All the tests were performed using displacement control with a speed of 0.003 mm/s. Five strain gauges were applied along the FRP reinforcements to measure axial strains along the bonded length, which was equal to l_b = 300 mm as in Series I.

3. Experimental results

In Table 3, the experimental maximum loads $P_{\max}$ and the mean values $\overline{P_{\max}}$ together with the *CoV*, the maximum tensile stress in the reinforcement f_{fd}, and the efficiency factor, which is defined as $\eta = \frac{f_{fd}}{f_{fu}}$, are reported for all specimens tested by the authors in both Series I and II. The average shear stress $\overline{\tau_{\max}}$ is also listed; it is computed by dividing the mean failure load $\overline{P_{\max}}$ by the groove surface, assuming a uniform distribution of stress along the bonded length of 300 mm.

In Fig. 2, a synthesis of the results of the whole experimental program (Series I and II) is reported in terms of the mean failure load plotted versus the axial stiffness $E_f A_f$ of each NSM system. Due to the low concrete strength, the debonding failure occurred at the epoxy–concrete interface within the concrete substrate in most cases independent of the variability of the material, geometry and surface treatment. Thus, the axial stiffness is assumed to be the main parameter influencing the debonding load. The graph of Fig. 2 confirms the increase in the maximum load as the axial stiffness increases until approximately 7500 kN; after such a value, the maximum load becomes invariant with further increases in stiffness. An epoxy–bar failure occurred only for the G-8-SW-14×14 bars due to the bad curing of the resin used to fix the external spirally wound treatment. Moreover, the tensile rupture of the fibres was observed for the thinner carbon strips (C-1.4×10-S-3×15), thus evidencing a high efficiency.

Table 1
FRP geometrical and mechanical properties (NSM).

Type	Label	$E_{f\ (CoV)}$ (GPa)	d (mm)	$t_f \vert b_f$ (mm)	$E_f A_f$ (kN)	$f_{fu\ (CoV)}$ (MPa)	k	Adhesive type
Basalt bar	B-6-SC	$46_{(3\%)}$	6	–	1300	$1282_{(8\%)}$	1.67	Sika dur 30 normal
Basalt bar	B-8-SC	$46_{(3\%)}$	8	–	2311	$1272_{(7\%)}$	1.75	Sika dur 30 normal
Basalt bar	B-10-SC	$42_{(4\%)}$	10	–	3297	$1204_{(4\%)}$	1.5	Sika dur 30 normal
Glass bar	G-8-SW	$51_{(5\%)}$	8	–	2562	$1250_{(5\%)}$	1.75	MBRACE BASF
Glass bar	G-8-RB	$59_{(7\%)}$	8	–	2964	$1333_{(4\%)}$	1.75	Sika dur 30 normal
Carbon bar	C-8-S	$155_{(2\%)}$	8	–	7787	$2495_{(3\%)}$	1.75	Sika dur 30 normal
Carbon bar	C-8-SW	$100_{(10\%)}$	8	–	5024	$1040_{(13\%)}$	1.75	Sika dur 30 normal
Carbon bar	C-10×10-S	$159_{(6\%)}$	10	–	15,900	$1397_{(7\%)}$	1.50	Stopox 452 EP + Stopox SK 41
Carbon strip	C-1.4×10-S	$177_{(3\%)}$	–	1.4|10	2695	$2221_{(9\%)}$	1.50	S&P Resin 220
Carbon strip	C-2.5×15-S	$182_{(1\%)}$	–	2.5|15	6825	$2863_{(5\%)}$	1.67	Sika dur 30 normal