Bond behavior of EBR CFRP systems in concrete: influence of surface preparation

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Abstract

The EBR strengthening technique has been used to improve existing reinforced concrete (RC) structures. In many cases CFRP laminates are used as reinforcing material, whereas epoxy adhesives are used as the bonding agent. In the last decades several investigations have been carried out in order to predict the bond strength of EBR CFRP systems in concrete and, as consequence of that, many analytical expressions can be found out in the literature, including in standards. However, these expressions do not account for the influence of the type of surface preparation, which is a mandatory and critical task in the strengthening application. The present work gives contributions for this lake of knowledge. For this purpose an experimental program composed of single shear lap bond tests was carried out. The main parameters studied were the type of surface preparation and the bond length. The instrumentation included sensors to measure the pullout force and the loaded and free end slips. This paper details the experimental program, presents and analyzes the obtained results. As expected, the results revealed that the bond strength depends on the type of surface preparation. Finally, existing expressions in the literature were upgraded in order to account for the type of surface preparation in the estimation of the bond strength.

1. Introduction

The externally bonded reinforcement (EBR) technique is one the most used techniques to strengthen reinforced concrete (RC) structures, through the application of fiber reinforced polymers (FRP) as reinforcing material, such as carbon FRP (CFRP) strips or sheets. The effectiveness of EBR CFRP systems in concrete is intrinsically dependent on the bond performance between FRP and concrete substrate, due to the brittle failure mechanism associated with debonding (loss of adhesion), which occurred very sudden without any warning [1]. Among other factors, such as mechanical properties of involved materials, the roughness of the concrete surface is recognized by the scientific community as a factor with a great influence on the performance of EBR FRP strengthening system [2, 3]. However, in terms of design, the existing formulations for the bond strength prediction do not include the effect of surface roughness of concrete provided by different surface treatment methodologies. With the aim of improving the knowledge on this relevant topic, experimental research composed of single shear lap bond tests was carried out. Based on experimental results, an upgraded version of analytical formulation proposed by the Italian Guideline CNR [4] for the prediction of maximum pullout force of EBR FRP systems in concrete was proposed.

2. Experimental Program

An experimental program with single shear lap bond tests was carried out in order to study the influence of surface preparation on the bond between concrete and EB CFRP laminates. The program was composed of 24 tests divided into two main groups according to the surface preparation methodology used: (i) GR - grinding and (ii) SB - sand blasting. In each group three different bond lengths (L_b) were considered: (i) 150 mm, (ii) 200 mm and (iii) 250 mm. Consequently, 6 series were adopted, each one composed of 4 specimens.

After surface preparation, the roughness of the surface was measured using a laser sensor. With this strategy it was possible to obtain for each single specimen a profile of roughness and, consequently, to obtain several statistical indicators characterizing the surface roughness, such as the mean roughness coefficient (R_m). Figure 1 shows typical roughness profiles for the case of GR and SB, highlighting the different levels of treatment.

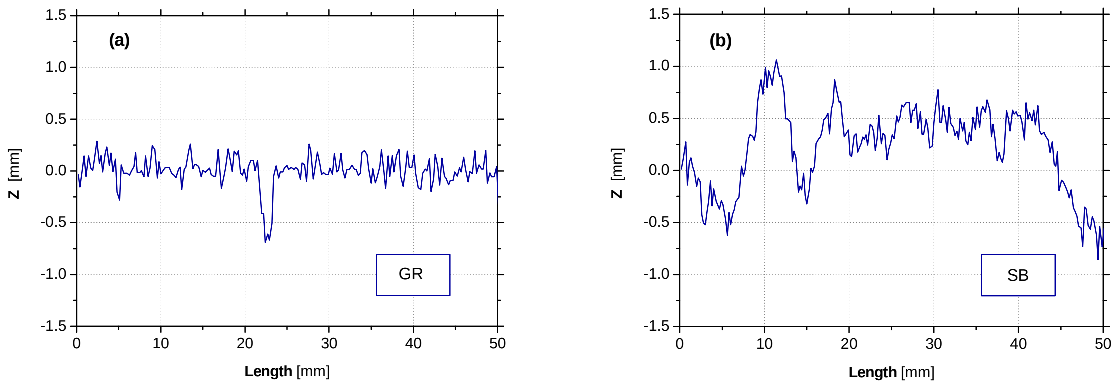


Figure 1. Roughness profile when different surface preparation methods were applied: (a) GR; (b) SB.

2.1 Materials

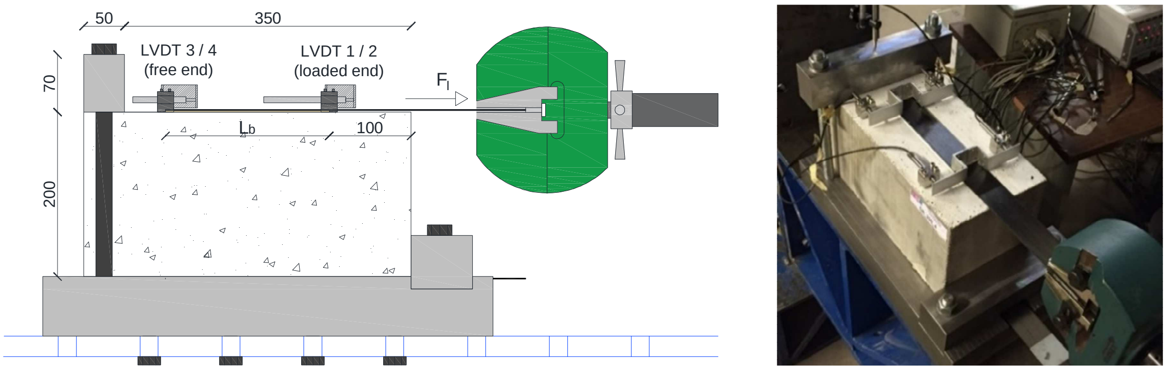
All involved materials were characterized. The average Young's modulus (E_{cm}) and average compressive strengthen (f_{cm}) of concrete were assessed using five cylinders 150mm/300mm and following the recommendations NP EN 12390-13:2014 and NP EN 12390-3:2011, respectively, at 28-days of concrete age. From the tests the E_{cm}=30.8 GPa (Coefficient of Variation, CoV=2.8%) and f_{cm}=33.4 MPa (CoV=4.3%) were attained.

The pultruded CFRP laminate strips (Type: *S&P Laminates CFK*), with 50 mm of width and 1.2 mm of thickness, were used in the experimental work. The tensile mechanical properties were assessed according to the ISO 527-5:2009. From the tests carried out using 5 samples an average Young's modulus of E_{fm} =176.4 GPa (CoV=2.0%) and an average tensile strength of f_{fu} =2222.4 MPa (CoV=4.7%), were obtained.

Finally, the epoxy adhesive (Type: *S&P Resin 220 epoxy adhesive*) was used to bond the CFRP laminates to concrete. Tensile mechanical properties were assessed using the standard ISO 527-2:2012. From 6 samples tested, an average Young's modulus of E_{am}=7.2 GPa (CoV=3.7%) and an average tensile strength of f_{am}=22 MPa (CoV=4.5%), were obtained.

2.2 Geometry, experimental set-up and instrumentation

Figure 2 depicts the test setup adopted for the present experimental program. Concrete blocks of 400×200×200 mm^3 were used. The bonded lengths start 100 mm apart from the extremity. The applied force was measured with a load cell of 200 kN (0.05% F.S.) maximum capacity. The relative displacement between the CFRP and the concrete (slip) at the loaded end section was assessed by the average of displacements measured by LVDTs 1 and 2 with a stroke of ±5 mm (0.24% F.S.). Similarly free end slip was assessed by the average of displacements measured by LVDTs 3 and 4 with a stroke of ±2.5 mm (0.24% F.S.). LVDT2 was used to control the test at 2 μm/s.



(a) (b)

Figure 2. Experimental set-up and instrumentation: (a) scheme; (b) photo.

3. Results and Discussion

Table 1 summarizes the main results obtained from the experimental program, while Figure 3(a) shows the average curves of the pullout force *versus* loaded end slip (F_l–s_l). In this table: $F_{l,max}$=maximum pullout force; $s_{l,max}$=loaded end slip at $F_{l,max}$; $s_{f,max}$=free end slip at $F_{l,max}$; τ_{max}=average bond strength; G_f=fracture energy up to 0.3 mm of s_l; f_{fd}=CFRP normal stress at $F_{l,max}$; f_{fd}/f_{fu}=efficiency parameter of the system; FM=Failure mode. From these results the following main conclusions can be pointed out:

- In all tests cohesive debonding at the concrete failure mode was observed, in spite of the thickness of the concrete layer attached to the CFRP laminate being higher for the case of SB specimens;
- The type of surface preparation clearly influenced the bond response of the EBR CFRP system: SB preparation allowed higher $F_{l,max}$ up to 27% (for the case of Lb200 series), in addition to higher values for the case of the other parameters;
- As expected, with the increase of L_b, $F_{l,max}$, $s_{f,max}$ and G_f increased, in addition to the efficiency (f_{fd}/f_{fu});
- In the F_l–s_l curves two distinct phases can be observed: an almost linear response, followed by a significant stiffness degradation up to the maximum pullout force due to debonding process;
- The F_l–s_l curves also revealed the influence of the type of surface preparation: SB series have shown higher stiffness, strength and ductility.

Table 1. Results obtained for each group series (average values).

Series	$F_{l,max}$ [kN]	$s_{l,max}$ [mm]	$s_{f,max}$ [mm]	τ_{max} [MPa]	G_f [kN.mm]	f_{fd} [MPa]	f_{fd} / f_{fu} [%]	FM
GR_Lb150	23.8 (6.9%)	0.34 (11.7%)	0.01 (38.3%)	3.2	5.08 (5.4%)	396.5	17.8	D [4]
GR_Lb200	23.8 (4.7%)	0.34 (18.0%)	0.01 (57.3%)	2.4	5.37 (6.6%)	396.3	17.8	D [4]
GR_Lb250	26.8 (7.9%)	0.35 (19.2%)	n.a.	2.1	5.89 (6.2%)	446.8	20.1	D [4]
SB_Lb150	27.2 (6.7%)	0.31 (12.5%)	0.01 (44.2%)	3.6	5.79 (3.0%)	453.1	20.4	D [4]
SB_Lb200	30.2 (9.7%)	0.41 (8.2%)	0.01 (39.9%)	3.0	5.92 (3.7%)	503.3	22.6	D [4]
SB_Lb250	31.3 (5.7%)	0.52 (24.0%)	n.a.	2.5	6.07 (2.9%)	522.0	23.5	D [4]

Notes: the values between parentheses are the corresponding coefficients of variation; FM: D=cohesive debonding at the concrete; the values between brackets is the no. of specimens with the specified FM.

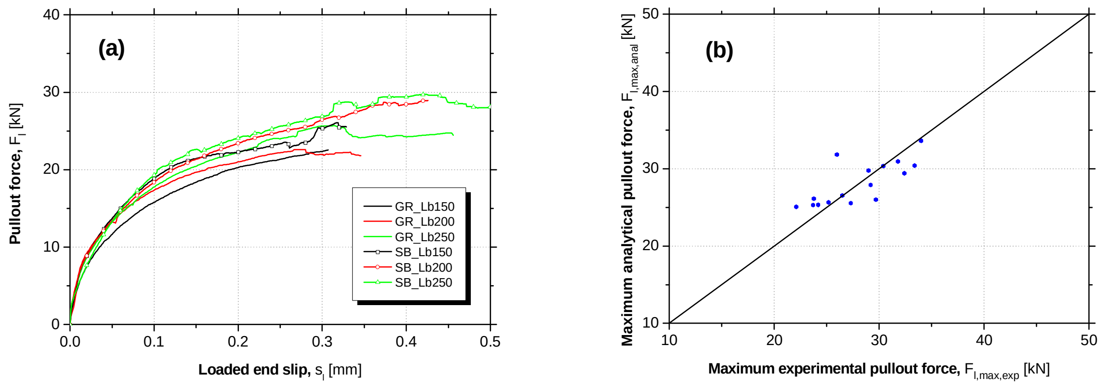


Figure 3. (a) Average curves of the pullout force *versus* loaded end slip; (b) Effect of roughness on the bond behavior - accuracy of the proposed analytical model.

4. Effect of roughness on bond behavior – analytical approach

Base on obtained experimental results, the formulation proposed by the Italian Guideline CNR [4] for the prediction of maximum pullout force of EBR FRP systems in concrete was updated/recalibrated, since the actual formula does not account for the effect of surface roughness of concrete. Applying the predictive law (Eq. 1) to the bond tests carried out in this work, the guideline prediction for maximum pullout force ($F_{\max}$) is 27.1 kN. In Eq. 1 b_f, t_f and E_f, are the width, thickness and Young's modulus of the CFRP material, whereas Γ_{Fm} is the fracture energy, estimated using Eq. 2; f_{cm} and f_{ctm} are the average compressive and tensile strength of concrete; k_{b} is a geometrical corrective factor and k_{G} is an experimental corrective factor. It should be stressed, that according to CNR, for the present case the effective length is equal to 200 mm. By comparing the prediction of $F_{\max}$ with the values included in Table 1 it is clear that improvements are needed.

$$F_{\max} = b_f . \sqrt{2. E_f . t_f . \Gamma_{\mathrm{Fm}}} \tag{1}$$

$$\Gamma_{\mathrm{Fm}} = k_{\mathrm{b}} . k_{\mathrm{G}} . \sqrt{f_{\mathrm{cm}} . f_{\mathrm{ctm}}} \tag{2}$$

By recognizing the influence of surface roughness on the bond behavior, a new parameter (k_{R}) was included in the CNR formulation. Hence, an analytical formulation capable of predicting $F_{\max}$ in function of this parameter (level of surface roughness) was proposed. To this purpose, the following procedure was adopted: (i) using the Eq. (1) and considering the $F_{\max}$ value equal to the maximum pullout force obtained from experimental tests, the average experimental values of fracture energy (Γ_{Fm}) were calculated; then, (ii) using the values of Γ_{Fm} inside Eq. (2) and all the other known parameters, the values of k_{G} were obtained, which, according to CNR guideline, for the case of pre-cured FRP systems the average value of k_{G} is 0.063 mm. The values of k_{G} were estimated as a function of the corresponding mean roughness coefficients (R_{m}).

In order to improve the formula $F_{\max}$, maintaining the value of k_{G} suggested by CNR, a new parameter (k_{R} – roughness coefficient) was introduced in the calculation of the average fracture energy of the interface, which is defined as a function of R_{m} coefficients, as demonstrated by the Eqs. (3) and (4):

$$k_{\mathrm{R}} = \frac{0.07R_{\mathrm{m}} + 0.05}{0.063} = 1.1\, R_{\mathrm{m}} + 0.8 \tag{3}$$

$$\Gamma_{\mathrm{Fm}} = k_b . k_G . k_R \sqrt{f_{cm} . f_{ctm}} \tag{4}$$

In order to assess the accuracy of proposed analytical formulation, the values of maximum pullout force for each specimen, obtained from the analytical model and from the tests are compared in Figure 3(b). From this figure, it is possible to verify the high accuracy of proposed analytical model based on existing CNR formulation for predicting the F_{max}, through the inclusion of the roughness coefficient of the concrete surface. The obtained errors (the difference between analytical and experimental results) was around 5%.

5. Conclusions

This paper summarized the obtained results from an experimental program composed of 24 single shear lap bond tests in prismatic concrete specimens strengthened with CFRP laminates according to the EBR technique. The aim of this work was to study the influence of some parameters on the bond behavior between concrete and CFRP laminate, namely: (i) type of concrete surface preparation (grinding and sand blasting); and (ii) different bond lengths (150, 200 and 250mm). From the bond pullout tests, the following main conclusions can be highlighted:

- The results showed that the surface preparation with sand blasting provided higher level of roughness on the concrete surface. Thus, the debonding failure in the tested specimens where this surface treatment methodology was applied occurred for higher values of pullout force when compared to grinding preparation. Besides to the improvements in terms of bond strength, the use of sand blasting instead of grinding allowed to increase the values of fracture energy (G_{f}) and the efficiency parameter (f_{fd}/f_{fu});
- Based on the obtained results from the experimental program, the influence of surface roughness was included in the analytical formulation for predicting the maximum pullout force proposed by CNR (2013) [4], through the inclusion of k_{R} parameter defined as a function of the mean surface roughness (R_{m}). The proposed analytical model proved to be able to accurately predict the bond strength of the EBR FRP system taking into account the level of roughness of the concrete surface where the CFRP laminate will be installed.

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References

[1] M.A. Aiello and M. Leone. Interface analysis between FRP EBR system and concrete. *Composites Part B: Engineering*, 39, 618-626, 2008.
[2] M. Savoia, C. Mazzotti and B. Ferracuti. Mode II fracture energy and interface law for FRP – concrete bonding with different concrete surface preparations. *FRAMCOS-6 Conference Proceedings, Catania, Italy*, 2007.
[3] I. Iovinella, A. Prota and C. Mazzotti. Influence of surface roughness on the bond of FRP laminates to concrete. *Construction and Building Materials*, 40, 533-542, 2013.
[4] Nacional Research Council. CNR-DT 200/2013, Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures. *Technical Guideline*, 2013.