A pullout test for the near surface mounted CFRP-concrete bond characterization

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Abstract. To characterize the bond behavior between concrete and CFRP strips, a pullout test is proposed. The developed test setup was used in an experimental program to evaluate the influence of the bond length and the width of slits on the bond behavior. The present work describes the pullout test setup, the carried-out tests and presents and analyzes the most significant obtained results.

Introduction

In the last years, the scientific and technical communities interested in the structural rehabilitation of the built patrimony have shown a growing interest in the study and application of the near surface mounted (NSM) strengthening technique. The NSM technique consists on bonding FRP reinforcements to concrete substrate into saw cuts opened in the concrete cover of the elements to strengthen. If FRP's of circular cross section are used, they are installed into grooves of rectangular shape, while slits are executed in case of selecting FRP bars of rectangular cross section (designated currently as strips).

Under the framework of the finite element analysis of a structure strengthened according to the NSM technique, the knowledge of the tangential stiffness used to model the slip mode of the interface finite elements applied to model the CFRP-concrete bond behavior can be decisive to assure high accuracies in the analysis. Furthermore, practical aspects of the design of a strengthening solution require the determination of the anchorage force and anchorage length. These aspects can only be accurately treated when a local bond stress-slip relationship is known, which can be obtained from experiments.

Direct and beam pullouts are the most common tests to characterize the FRP-concrete bond behavior. In the present work, a new pullout test is proposed that has some advantages when compared to the available ones [1-4]. The influences of the bond length, L_b, and the width of the slits, w, on the CFRP-concrete bond behavior are investigated testing specimens with $L_b = 100$ and 200 mm and $w = 4$, 5 and 6 mm. Each series is composed of three specimens, forming an experimental program of eighteen specimens. From the experimental data a bond stress-slip law is obtained.

Pullout test setup and test program

Prismatic concrete blocks with dimensions of $150 \times 150 \times 600$ mm^3 were adopted in the pullout tests. To avoid flexural failure of the specimens, 2Ø10 rebars at the bottom and top surfaces were used, with a concrete cover of 18 mm deep. Fig. 1 depicts the configuration adopted in the pullout tests. The bond test region was located in the left side of the specimen, and several bond lengths, L_b, were analyzed. The depth of the slit where the CFRP strip was inserted was 15 mm, while different slit widths were studied.

The displacement transducer LVDT1 was used to measure the slip at the loaded end, s_l, while the LVDT2 was applied to measure the slip at the free end, s_f. Strain gages glued to the CFRP were used to estimate the strain variation in the bonded region. The applied force F was registered with a load cell placed between the specimen and the actuator. The tests were performed using

servo-controlled equipment, under displacement control, with an average slip rate of 5 μm/s. For this purpose, the internal transducer of the actuator was used. Fig. 2 shows the setup of the proposed pullout test.
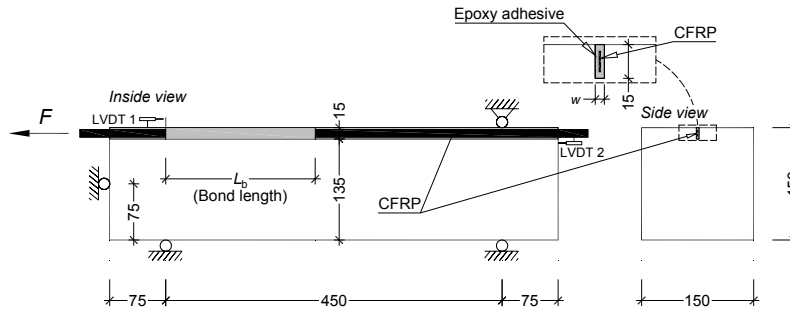

Fig. 1 - Reinforced concrete specimen. Note: all dimensions are in millimeters.
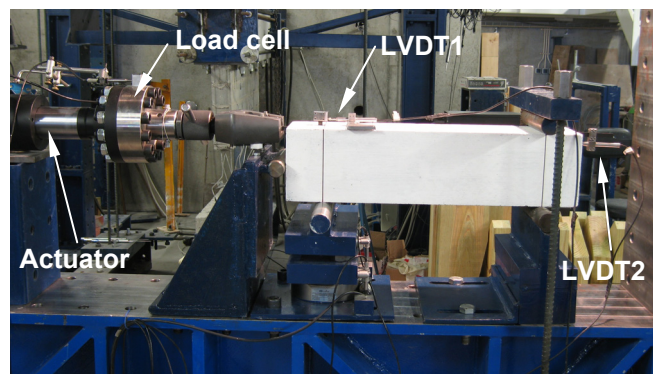

Fig. 2 - Pullout test configuration.

To assess the influence of the bond length and the width of the slit on the bond performance, an experimental program was carried out in the context of the present work. The generic denomination of a series is LbX_WZ, where X and Z are the CFRP bond length (100 or 200 mm) and the width of the slit (4, 5 or 6 mm), respectively. The experimental program is composed by six series, each one consisting of three specimens. In the first specimen (B1) of series with 100 mm and 200 mm of bond length three and four strain gauges, respectively, were installed in the CFRP along the bond length.

Materials characterization

Concrete. A C30/37 concrete strength class was used. Three cylinder specimens with a diameter of 150 mm and a height of 300 mm were used to evaluate the concrete compressive strength. The compression tests were carried out in a universal test machine, under load control, at a rate of 0.5 MPa/s. The average compressive strength of 39.9 MPa, with a coefficient of variation of 1.09%, was obtained at the age of 28 days. According to the Model Code 1990 [5], the concrete compressive strength is about 50 MPa at the age of the pullout tests.

CFRP strips. The S&P® CFRP strips were provided in rolls, and were composed of unidirectional carbon fibers, agglutinated with an epoxy adhesive. The properties indicated by the supplier and obtained from carried out tests are included in Table 1. Further details related to the laboratory characterization of the CFRP strips can be found elsewhere [6]. The values within parentheses are the coefficients of variation of the corresponding properties.

Epoxy adhesive. The low viscosity epoxy adhesive used to bond the CFRP strips to concrete, produced by Degussa®, had the trademark MBrace Epoxikleber 220. This adhesive is composed of two components and, according to the supplier, its properties are those indicated in Table 2. Some

results obtained in experimental tests are also included in this table [6]. The values within parentheses are the coefficients of variation of the corresponding properties.

Table 1 - CFRP properties.

Property	Supplier	Laboratory [6]
Width [mm]	10	9.56 (0.60%)
Thickness [mm]	1.4	1.45 (0.72%)
Tensile strength [MPa]	> 2000	2879 (2%)
Young's modulus [GPa]	> 150	156.1 (1.6%)
Ultimate strain [%]	1.4	1.85 (3.5%)

Table 2 - Epoxy adhesive properties.

Property	Supplier	Laboratory [6]
Tensile strength [MPa]	7	33.0 (8.5%)
Young's modulus [GPa]	7	7.5 (4.3%)
Pot life at 20 ºC [min]	60	-
Time of cure [days]	3	-
Mixing ratio (Comp. I to Comp. II)	3.805 to 1.195 by weight	-

Specimen Preparation

A saw fixed on a table was used to open the slits in the concrete specimens. Then, these slits were cleaned with compressed water to eliminate the remaining dust induced by the sawing process. Afterwards, the specimens were air dried in the laboratory environment. Just before bonding the CFRP, the slits were cleaned with a jet of compressed air. To avoid the flow of epoxy adhesive to undesirable zones of the slit, a masking procedure was adopted.

The preparation of the CFRP strip involved the following steps: to restrict the bonding to the desired length, its vicinity was masked with tape; strains gauges were glued to the CFRP; and, finally, the CFRP was cleaned with acetone.

In the bond region, the slit was completely filled with epoxy adhesive. The lateral surfaces of the CFRP corresponding to the bond length were covered with a thin layer of epoxy adhesive. Afterwards, the strip was forcibly inserted into the slit, the adhesive in excess was removed and the surface was leveled. The specimens were kept, at least, one week in the laboratory environment before being tested.

Results

Fig. 3 includes the typical relationships between the pullout force and slip at the loaded and free ends (F_l-s_l and F_l-s_f) for the Lb100 series. The analysis of the curves of Fig. 3(a) shows that the response is nonlinear up to peak load. After peak load, sudden load decay occurred, followed by a smooth decrease of the pullout force with the increase of the slip. Residual pullout forces, which are quite significant, indicate that frictional mechanisms in the CFRP-adhesive-concrete interfaces are mobilized. From the curves of Fig. 3(b) it can be concluded that the free end slip is almost null up to peak load. In all series, the first specimen (beam B1) exhibited a lower peak and residual force when compared to the other specimens of the same series. The main reason is related to the existence of strain gauges in the bond zone. In fact, the installation of strain gauges reduced the bonded zone in about 15% and 10% for the Lb100 and Lb200 series, respectively.

Fig. 4 shows the pullout force versus loaded end slip of the specimen B1_Lb200_W5 of the Lb200 series. Since the CFRP have ruptured, the post-peak response does not exist. This chart also depicts the relationship between the strains recorded in the strain gauges and the loaded end slip. Strain gauge 1 (SG1) and 4 (SG4) were placed at 25 mm of the loaded and free ends, respectively, while strain gauges 2 (SG2) and 3 (SG3) were glued to the CFRP at 50 mm and 100 mm from SG1.

Strain gauges SG1 and SG3 were placed in the same side of the CFRP and SG2 and SG4 were placed on the other side. From the obtained results it can be concluded that high strains were registered in the CFRP, and the local bond stress reach the post-peak phase in the SG1, SG2 and SG3 (see also the section analytical simulation).
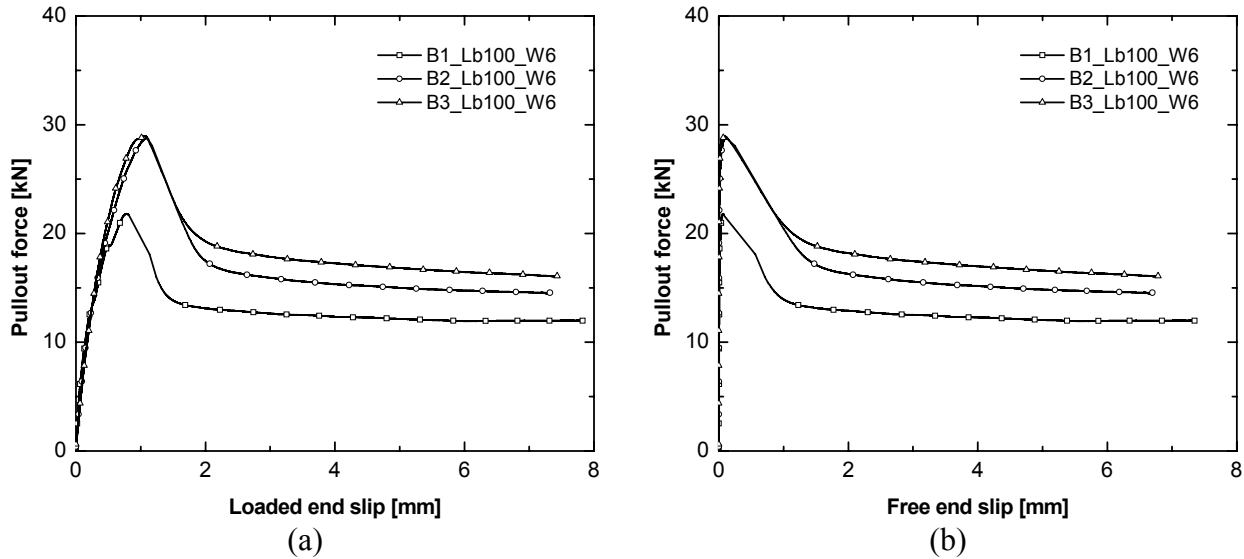

Fig. 3 - Pullout force *vs*. loaded end slip (a) and *vs*. free end slip (b), of the Lb100_W6 series.

Table 3 includes the main results obtained from the performed tests. For the Lb100 series the maximum pullout force, F_{lmax}, and the corresponding loaded end slip, s_{lmax}, were calculated using B2 and B3 of each corresponding series, while in the Lb200 series, all specimens were used for this evaluation. Two distinct types of failure were observed: the pullout of the CFRP (in the Lb100 series) and the failure of the CFRP strip (in the Lb200 series). The exceptions occurred in the B3_Lb100_W5 (CFRP failure) and B1_Lb200_W4 specimens (Pullout). The failure of the CFRP ranged between 33 kN and 34 kN and, for the range values of the width of the adhesive bond layer considered, this parameter seems do not have influence on both peak load and its corresponding slip.

Table 3 - Main results obtained from the experimental program (average values).

Series	F_{lmax} [kN]	s_{lmax} [mm]	Failure Mode
Lb100_W4	29.4 (3.8%)	1.22 (n.a.)	Pullout
Lb100_W5	30.7 (17.4%)	1.19 (7.3%)	Pullout/ CFRP failure
Lb100_W6	28.9 (0.5%)	1.08 (1.8%)	Pullout
Lb200_W4	34.5 (4.3%)	n.a.	Pullout/ CFRP failure
Lb200_W5	33.5 (6.9%)	n.a.	CFRP failure
Lb200_W6	35.0 (1.2%)	n.a.	CFRP failure

Analytical Simulation

The following differential equation can be used to simulate the strip-concrete bond behavior, as shown elsewhere [7]:

$$\frac{d^2s}{dx^2} = \frac{2}{t_f E_f} \tau\big(s(x)\big)$$ (1)

where t_f and E_f are the thickness and the Young's modulus of the CFRP strip, respectively, *s* is the slip, i.e., the relative displacement between the strip and concrete and τ is the local bond stress-slip

relationship. Using a numerical strategy [7], the second order differential equation (1) can be solved with a specific local bond stress-slip relationship. A tri-linear local bond stress-slip relationship was used composed by the following points which define the limits of each branch: Point 1 (0 mm, 0 MPa); Point 2 (0.35 mm, 16.2 MPa); Point 3 (1.7 mm, 9 MPa); Point 4 (10 mm, 7.1 MPa). Fig. 4(b) includes the experimental and analytical responses in terms of pullout force versus loaded and slip. From this chart a good agreement can be observed between the experimental results and the numerical analysis.
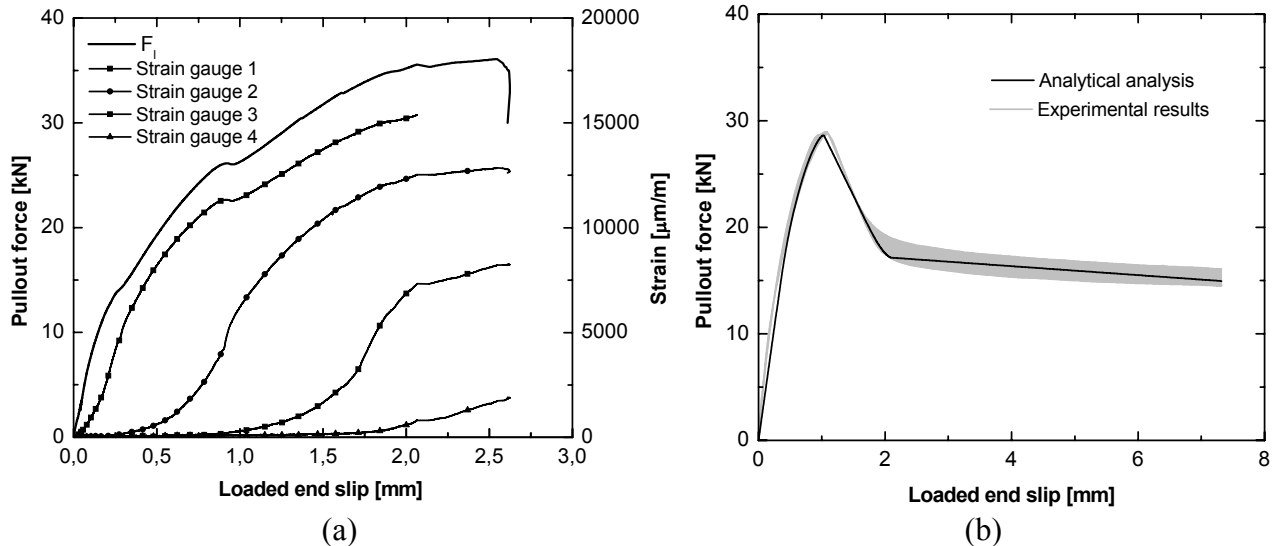

(a)   (b)

Fig. 4 - (a) Response of the specimen B1_Lb200_W5. (b) Analytical simulation of the Lb100_W6 series.

Conclusion

Direct pullout tests were carried out to evaluate the influence of the bond length and the width of slits on the bond behavior of NSM CFRP strips-concrete. From the obtained results the following observations can be pointed out: a bond length of about 200 mm mobilizes the tensile strength of the used CFRP strips; the bond behavior is not influenced by the width of the adhesive layer, when it ranges from 1.25 mm to 2.25 mm; NSM provides a significant residual pullout force; the application of strain gauges in the bond length to measure the strain field should be avoided since it disturbs considerably the CFRP-concrete bond conditions.

Acknowledgements

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