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Bond between concrete and multi-directional CFRP laminates

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Abstract Recently, laminates of multi-directional carbon fiber reinforced polymers (MDL-CFRP) have been developed for Civil Engineering applications. A MDL-CFRP laminate has fibers in distinct directions that can be arranged in order to optimize stiffness and/or strength requisites. These laminates can be conceived in order to be fixed to structural elements with anchors, resulting high effective strengthening systems. To evaluate the strengthening potentialities of this type of laminates, pullout tests were carried out. The influence of the number of anchors, their geometric location and the applied pre-stress are analyzed. The present work describes the carried-out tests and presents and analyzes the most significant obtained results.

Keywords: multi-directional CFRP laminates; pullout tests; bond behavior.

Introduction

The use of fiber reinforced polymers (FRP) in the structural rehabilitation and/or strengthening has had a sustainable increase since their first use in the structural strengthening. For that contributed their light weight, high stiffness/weight ratio, corrosion immunity and also the decrease of their production costs lately seen, consequence of the growing search for those types of materials.

The application of FRPs on the structural elements to strengthen is practically limited to unidirectional FRPs and has been used, mainly, by: (i) application of fabrics (*in situ* cured systems) glued externally on the surface of the element to strengthen (EBR – *Externally Bonded Reinforcement*); (ii) insertion of laminates (or rods) glued into the cover concrete (*NSM – Near-Surface Mounted*). In these two techniques the bond between the FRP and the element to be strengthened is usually assured by the glue performance of epoxy type adhesives.

In consequence, the strengthening performance depends significantly of the superficial concrete resistance and, generally, the full mechanical capacity of the FRPs is not mobilized. In order to avoid premature failure of FRP reinforcement, complements have been applied to the aforementioned strengthening techniques, such as, application of anchor systems, made of steel plates, bolted in the ends of the FRP or strapping with FRP fabric. This kind of localized intervention requires differentiated and time consuming tasks that lead to a stress concentration in the element to strengthen.

Recently, some FRP-based alternatives for structural strengthening have been proposed. They are composed by hybrid multi-directional laminates of glass and carbon fibers that are anchored to the concrete elements (Bank e Arora 2007, Elsayed et al. 2009). This technique was called *Mechanically Fastened Reinforcement* (MF).

The proposal suggested in this work intends to go further in the present state-of-the art in this area: first the technique uses laminates simultaneously glued (EBR) and anchored to concrete (MF) and, on the other hand, a new type and cost competitive multi-directional laminate is developed, made only with carbon fibers, and presenting mechanical properties superior to those of existent multi-directional laminates.

This paper presents the results of the tests performed to characterize the MDL-CFRP developed and also the experimental program conducted in order to evaluate the behavior of the bond between these multi-directional laminates and concrete.

Experimental program

In the context of the present work, the main parameters analyzed were the geometric configurations of the anchors and the level of the pre-stress applied to the anchors, as well as the type of the strengthening technique. Table 1 describes the experimental program carried out. Cubic concrete blocks of 200 mm edge were used and strengthened according to the externally bonded reinforcement technique (EBR) and according to the mechanically fastened and bonded reinforcement technique (MF+EBR) – see Fig. 1. The anchors used in the present program have 10 mm of diameter (M10). A constant bond length of 200 mm was adopted for the specimens. The tests were performed using a servo-control hydraulic equipment, under displacement control with a velocity of 1 μm/s imposed with a displacement transducer attached to the actuator. The applied load was measured using a load cell with a static load carrying capacity of 300 kN. The relative displacement between concrete and the laminate fixed to the specimen was measure through linear variable differential transducers (LVDT). In each specimen the loaded and free end slips were measured through LVDT1 and LVDT2, respectively (Fig. 1). In addition, for the MF1 and MF2 series, slips in the vicinity of the anchors were registered using LVDT3 and LVDT4 (Fig. 1b,c). A torque of 20 N×mm was used for the case of the pre-stressed anchors.

Table 1: Experimental program

Denomination	*Type of strengthening*	*N. of anchors*	*Torque [N×mm]*	*N. of specimens*
EBR	EBR	0	-	2
MF1-T0	MF+EBR	1	0	3
MF1-T20		1	20	3
MF2-T0		2	0	1
MF2-T20		2	20	1

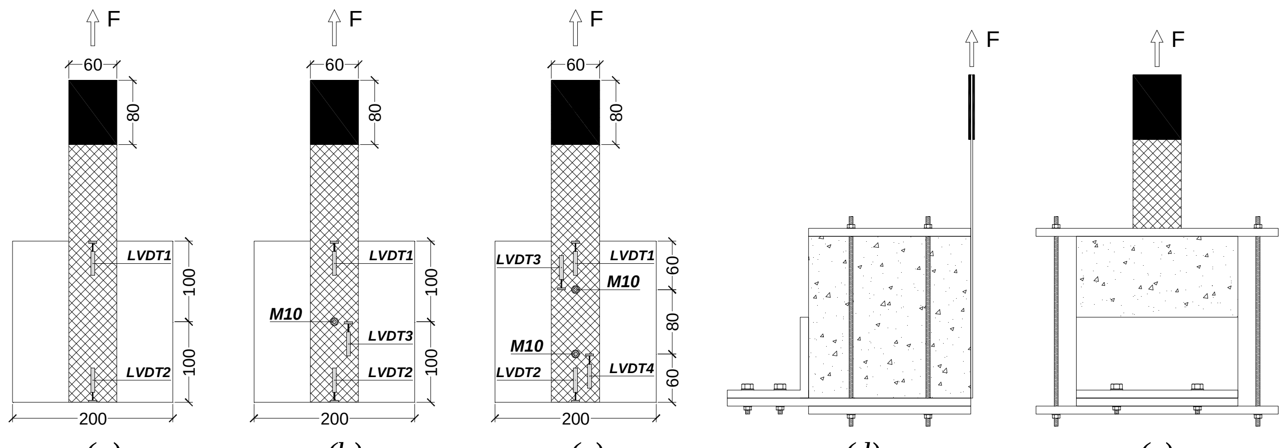
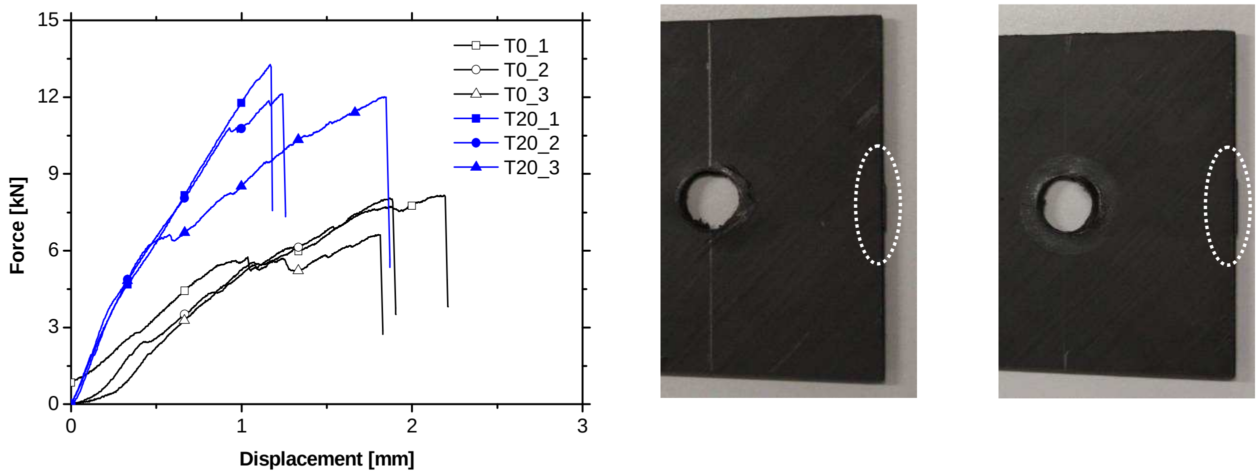


Figure 1: (a) EBR series; (b) MF1 series; (c) MF2 series; (d) support configuration (side view); (e) back view

Material characterization

The MDL-CFRP laminates used in the present work were designed and produced for a research project that intends to explore their possibilities in structural strengthening. The MDL-CFRP is composed by a unidirectional pre-cured CFRP laminate with the trademark CFK® 150/2000 (CFK). The main direction of the fibers of the CFK laminate was 0º with the applied load direction. In each face, the CFK laminate has a layer of a unidirectional carbon pre-preg with fibers orientated at ±45º. This pre-preg material has the trademark TEXIPREG® HS 160 REM (HS). According to the manufacture, the CFK has 1.4 mm of thickness, and a tensile strength and a Young modulus of 2000 MPa and 165 GPa, respectively. On the other hand, the HS has 0.15 mm of thickness, a tensile strength of 1700 MPa and a longitudinal modulus of elasticity of 150 GPa. Autoclave equipment was used for the production of the MDL-CFRP, namely for the cure of the HS.

After the production of the MDL-CFRP, geometrical and mechanical characterizations were performed. The MDL-CFRP has 2.07 mm of thickness (69% of this value is from the CFK). The mechanical characterization involved the determination of tensile, flexural and bearing properties, according to the standards ISO 527-4:1997, ASTM D790–03 and ASTM D5961/D5961M–05, respectively. These properties were only evaluated for the main direction, i.e. 0º. From the performed tests, a tensile strength of 1866.2 MPa (5.1%), a Young modulus of 118.1 GPa (2.8%) and 1.58% of ultimate strain (5.1%) were obtained from the tensile characterization. From the flexural tests a flexural tensile strength of 865.6 MPa (1.4%) was obtained. Two distinct bearing tests were performed with the MDL-CFRP laminate: without (T0) and with (T20) pre-stress. For the case of pre-stressed specimens, DIN 9021 washers were used. A torque moment of 20 N×m was adopted. From the performed bearing tests, a bearing strength of 316.4 MPa (11.8%) and 604.4 MPa (5.8%) were obtained for the case of series T0 and T20, respectively. The values in brackets are the respective coefficients of variation. Figure 2(a) includes the obtained results in terms of force *versus* displacement relationship for the T0 series (specimens T0_1 to T0_3), and for the T20 series (specimens T20_1 to T20_3); the typical failure mode of the T0 series (see Figure 2(b)); the typical failure mode of the T20 series (see Figure 2(c)). From Figure 2(a) a distinct behavior for the series T0 and T20 can be pointed, not only in terms of stiffness, but also in terms of strength. In fact, the T20 series presented a lesser ductile behavior. A hybrid failure mode was observed in all the specimens (shear-out + bearing). Nevertheless, for the case of the T20 series the region where the shear-out and bearing occurred was higher than the one of the T0 series, justifying the superior behavior of the pre-stressed series.



(a) *(b)* *(c)*

Figure 2: (a) Displacement versus force relationship; (b) failure mode of the series without pre-stress; (c) failure mode of the series with pre-stress.

In the context of the direct pullout tests, a medium-strength concrete class (C20/25) was selected to manufacture the cubes. The compressive strength and the Young modulus were evaluated at 28 days according to the NP EN 12390-3:2009 and LNEC E397-1993 (1993), respectively. From the tests an average compressive strength value of 28.4 MPa (5.6%), and an average value of 29.8 GPa (1.0%) for the Young modulus were obtained. The values in brackets are the correspondent coefficients of variation. At the age of the pullout tests, the compressive strength was evaluated using the expressions (3.1) and (3.2) included in the EN 1992-1-1:2004. The obtained value was 32.8 MPa.

To bond the laminates to the concrete an epoxy adhesive was used. For this purpose, the S&P Resin 220 epoxy adhesive® was selected. According to technical sheet of the product, this epoxy has a flexural tensile strength, a compressive strength and a bond concrete/laminate strength equal to 30 MPa, 90 MPa e 3 MPa, respectively.

Hilti® chemical anchors were selected to fix mechanically the laminate. With this intention, the resin HIT-HY 150, the 5.8 M10 threaded anchor and the DIN 9021 washers were used. According to technical sheet of the product, with this anchorage system a maximum torque of 28 N×m (characteristic value) can be applied.

Specimen preparation

In the following paragraphs the main steps involving specimen preparation are briefly presented. The first step was the casting and cure of the concrete blocks. The next step was the preparation of the concrete surface and the multi-directional laminates, using the following main tasks:

- A roughness concrete surface was made using a rotary hammer with a needle adapter. Compressed-air was used to clean the final surface;
- Drilled holes were performed in all the specimens with anchors. Compressed-air and a steel brush were used to clean the holes;
- The holes in the laminates with anchors were performed with a current drill bit. From a visual inspection to the holes performed, no damage was observed;
- All the laminates were cleaned with a solvent (e.g. acetone).

The third main step for the MF1 and MF2 series was the anchorage M10 threaded anchor to the concrete blocks. This step was done according to the technical sheet of the supplier. To glue the laminate to the concrete, the epoxy adhesive was prepared according to the instructions of the technical sheet. A special care was taken to assure a layer of adhesive of a thickness of about 1 to 2 mm. All remaining adhesive was removed. The tests were performed, at least, one month after the application of the adhesive.

For the T20 series, the pre-stress was applied in two phases: one day before the test a torque moment of 20 N×mm was applied to the anchors; in the day of the test, the same torque was again adjusted. For this purpose, a torque wrench with a range of 10 to 110 N×mm was used.

Results

Table 2 includes the main results obtained from the pullout tests. For each test, the maximum pullout load, F_{max}, the ratio (F_{max}/F_r), where F_r is the residual pullout load (after peak load), and the failure modes are included. As expected, the inclusion of the anchors increases the load carrying capacity of the system, as well as the residual strength. The average increments, when compared with the EBR technique, are 35%, 39% and 80% for the case of the series MF1_T0, MF1_T20 and MF2, respectively.

From these results, the use of pre-stressed anchors is not convincing, since a marginal increment was observed using this strategy. One main reason can be ascribed to the difficulty in applying, with high accuracy, the torque moment. On the other side, from visual inspection of the specimens after the tests, a non-uniform distribution of the epoxy adhesive was found.

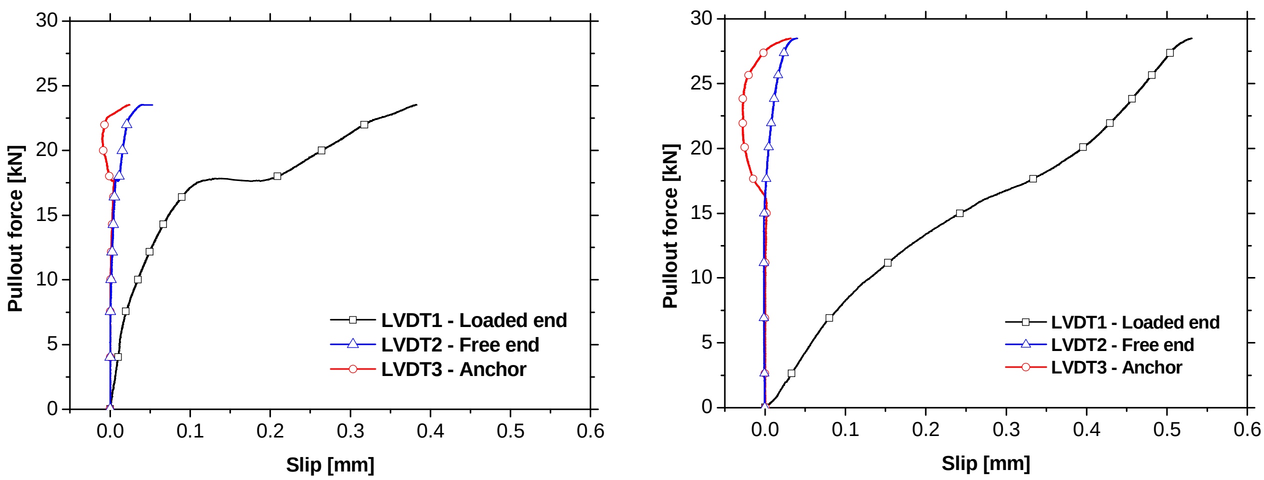
Table 2: Main results from the pullout tests

Specimen	F_{max} *[kN]*	F_r/F_{max} *[%]*	*Failure mode*
EBR_1	17,55	0,0	D
EBR_2	20,84	0,0	D
MF1-T0_1	26,08	5,8	D+B
MF1-T0_2	23,56	18,1	D+B
MF1-T0_3	28,36	15,9	D+B
MF1-T20_1	28,50	59,8	D+B
MF1-T20_2	27,76	26,8	D+B
MF1-T20_3	23,57	53,6	D+B
MF2-T0	35,76	72,0	D+B
MF2-T20	33,51	85,5	D+B

Notes: F_{max}=maximum pullout force; F_r=residual force (after peak pullout); *D*=debonding at the interface adhesive/concrete; *B*=bearing at the multi-directional laminate in the vicinity of the anchorages.

Figure 3 shows the typical relationship between pullout force and slip for the case of MF1_T0 and MF1_T20 series. From these graphs the following main conclusions can be pointed out:

- Up to peak load, both series exhibit a non-linear response. This non-linear behavior is more visible in the series without pre-stressed anchors;
- Until the effective bonded zone reaches the location of the anchors, the slips at the anchor region and at the free end are marginal;
- Since the laminate is multi-directional, a negative slip at the vicinity of the anchor was observed at the initial phase, followed be a positive slip.



(a) *(b)*

Figure 3: Pullout force vs. slip relationship for the specimen (a) MF1_T0_2 and (b) MF2_T20_1

Conclusions

In the present work, a description of the main aspects of an experimental program carried out to assess the strengthening effectiveness of multi-directional CFRP laminates that can be anchored and bonded to concrete elements. In this experimental program, by executing pullout test, the influence of the geometric location of the anchors and the applied pre-stress were analyzed.

When compared with the EBR technique, the use of anchors increased the load carrying capacity in about 35% and 80% for one and two anchors, respectively. The use of pre-stressed anchors did not yield to significant increments in terms of maximum pullout load, when compared with non pre-stressed anchors. However, a significant residual strength was observed for the case of pre-stressed anchors.

The pullout force *versus* slip responses of all series is non-linear up to peak. For the case of pre-stressed anchors a more "uniform" response was obtained. In all the specimens tested a mixed debonding at the interface adhesive/concrete and bearing at the MDL-CFRP failure modes were observed.

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