BOND BETWEEN MULTIDIRECTIONAL LAMINATES OF CFRP AND CONCRETE

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Abstract

The Mechanically Fastened and Externally Bonded Reinforcement (MF-EBR) technique has been proposed for the strengthening of reinforced concrete (RC) structures. This retrofit system uses multidirectional carbon fibre reinforced polymer (CFRP) laminates fixed to concrete with epoxy adhesive and metallic anchors. With the aim of studying the bond behaviour of the MF-EBR system and compare with some existing ones, mainly the Mechanically Fastened-FRP (MF-FRP) and Externally Bonded Reinforcement (EBR), an experimental program composed by direct pullout tests was carried. The instrumentation includes the measurement of the applied pullout force and the loaded end slip. The strengthening effectiveness of the analyzed techniques (EBR, MF-FRP and MF-EBR) was investigated, as well as the influence on the bond performance of the bond length, diameter of the anchors and level of applied prestress to the anchors. The present work describes the carried-out tests and presents and analyzes the most significant obtained results.

Keywords: MF-EBR, MF-FRP and EBR strengthening techniques; direct pullout test; bond behaviour.

1. Introduction

The FRP’s that are being used in the structural strengthening of concrete elements are practically limited to unidirectional-fibre systems applied according to the following techniques [1]: (i) application of fabrics (in situ cured systems) or laminates glued externally on the surface of the element to strengthen (EBR – Externally Bonded Reinforcement); (ii) insertion of laminates (or rods) into slits opened on the concrete cover (NSM – Near-Surface

Mounted). In these two techniques the bond between the FRP and the element to be strengthened is usually assured by epoxy type adhesives. Consequently, the strengthening performance depends significantly of the superficial concrete resistance and, generally, the full mechanical capacity of the FRPs is not mobilized.

To avoid premature debonding failure of FRP reinforcement, some FRP-based alternative systems for structural strengthening have been proposed using either multidirectional laminates of glass and carbon fibres that are anchored to concrete elements [2], or multidirectional laminates of carbon fibres (MDL-CFRP) simultaneously glued and anchored to concrete [3]. The former strengthening technique is called the Mechanically Fastened Reinforcement FRP (MF-FRP), whereas the latter is named Mechanically Fastened and Externally Bonded Reinforcement (MF-EBR).

The MF-FRP technique has already been used for the strengthening of reinforced concrete, wood and masonry structures, and several benefits have been pointed out, namely, quick installation with relatively simple hand tools, no need of special labour skills, theoretically no surface preparation required, and the strengthened structure can be immediately used after the installation of the FRP. Additionally, the occurrence of a more ductile failure mode for the FRP system is referred [2]. However, some notable disadvantages of this technique have been reported, including crack formation induced by the impact of fasteners in high-strength concrete, and less-effective stress transfer between the FRP and concrete due to the discrete attachment points [4].

The efficiency of NSM, EBR and MF-EBR techniques was recently compared by means of four-point bending tests with RC beams submitted to monotonic and fatigue loading [5]. When compared with the EBR strengthening technique, the MF-EBR has shown a significant increase of carrying capacity (of about 40%) and deflection performance at failure (of about 140%).

This paper presents and discusses the results of the experimental program carried out for the evaluation of the bond behaviour between multi-directional CFRP laminates and concrete prisms strengthened by the MF-EBR technique, using direct pullout tests. The effectiveness of this technique was compared to those of MF-FRP and EBR.

2. Experimental Program

2.1 Specimens and Test Configuration

The experimental program comprises three different strengthening techniques: MF-EBR, MF-FRP and EBR (see Tables 1, 2 and 3). Each series was composed by three specimens. The code names given to the test series consist on alphanumeric characters, where the first string indicates the diameter of the anchors in millimetres (M8 and M10) and the second string indicates the number of anchors (F1, F2 or F3). Two distinct prestress levels were applied to the anchors, corresponding to a torque of 0 N·m (T0) and 40 N·m (T1). Finally, for the series MF-EBR a string was adopted for specifying the strengthening procedure (S1 and S2). Each series was composed by three specimens. A total of sixty pullout specimens were tested.

Figure 1a shows the specimen geometry and the configuration of pullout tests. The specimen consists of a prismatic concrete block of $150\times150\times600$ mm^3 dimensions, in which the CFRP is applied. To avoid flexural and shear failure of the prismatic concrete block, longitudinal rebars of 12 mm diameter (one in each corner of the cross-section) and steel stirrups of 6 mm diameter spaced at 100 mm were used. The concrete cover is equal to 18 mm.

Tests were performed using a servo-controlled hydraulic equipment, under displacement control with a velocity of 4 μm/s, 16.7 μm/s and 1 μm/s imposed with a displacement transducer attached to the actuator for the series MF-EBR, MF-FRP and EBR, respectively. The applied load was measured using a load cell with a static load carrying capacity of 200 kN. The relative displacement between concrete and laminate fixed to the specimen (loaded end slip) was measured with the linear variable differential transducer, LVDT (see Figure 1a). Figure 1b includes an overview picture of the pullout test configuration.

Table 1. Series MF-EBR.

Denomination	**Anchors**		**Strengthening procedure**	**Torque** [N·m]	**Bond region**	
	Diameter [mm]	**Number**			**Width** [mm]	**Length** [mm]
M8F3S1T0	8	3	S1	0	30	300
M8F3S2T0			S2	0		
M10F3S1T0	10	3	S1	0	40	
M10F3S2T0			S2	0		
M8F1S2T0	8	1	S2	0	30	100
M8F1S2T1			S2	40		
M8F2S2T0		2	S2	0		200
M8F2S2T1			S2	40		
M8F3S2T1		3	S2	40		300
M10F1S2T0	10	1	S2	0	40	100
M10F1S2T1			S2	40		
M10F2S2T0		2	S2	0		200
M10F2S2T1			S2	40		
M10F3S2T1		3	S2	40		300

Table 2. Series MF-FRP.

Denomination	**Anchors**		**Torque** [N·m]	**Bond region**	
	Diameter [mm]	**Number**		**Width** [mm]	**Length** [mm]
M8F1T0	8	1	0	30	100
M8F1T1			40		
M8F2T0		2	0		200
M8F2T1			40		
M8F3T1		3	40		300

Table 3. Series EBR.

Denomination	**Bond region**	
	Width [mm]	**Length** [mm]
EBR	30	300

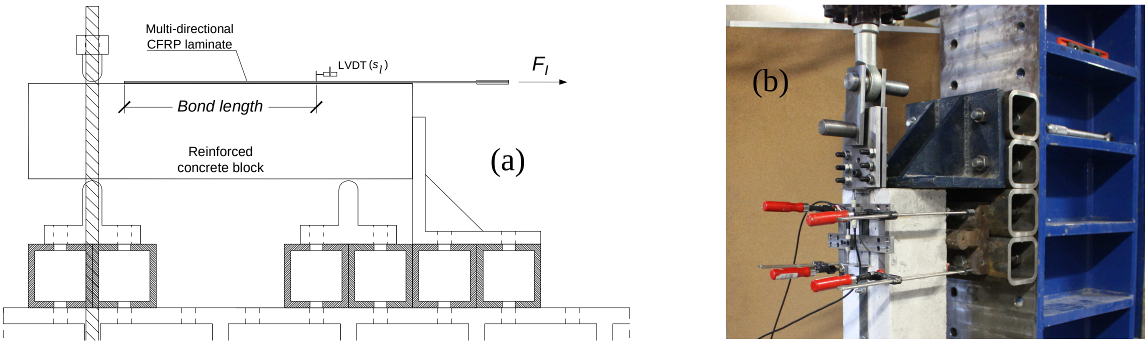

Figure 1. Direct pullout tests: (a) specimen geometry and test configuration; (b) overview.

2.2 Material characterization

The mechanical characterization of the concrete was assessed by means of compression tests. Cylindrical concrete specimens were tested at the time of the pullout tests to evaluate the compressive strength according to the NP EN 12390-3:2009 standard. An average compressive strength (f_{cm}) value of 41.54 MPa, with a coefficient of variation (CoV) of 0.2% were obtained for series M8F3S1T0, M8F3S2T0, M10F3S1T0, M10F3S2T0, while for the remaining series the corresponding values were determined: f_{cm}=56.05 MPa (CoV=8.9%).

The steel of the longitudinal bars and stirrups has a denomination of A400 NR SD according to the NP EN 1992-1-1:2010 and its properties can be consulted in this document.

The multidirectional laminate of CFRP (MDL-CFRP), with 2.07 mm thick, has 69% of fibers oriented at 0º (in the applied load direction) and 31% of fibers orientated at ±45º. The stacking sequence of this MDL-CFRP is [-45/+45/0/+45/-45]. Tensile and bearing tests of the MDL-CFRP were performed with the load direction at 0º [3], having been obtained a tensile strength of 1866.2 MPa (CoV=5.1%), a modulus of elasticity of 118.1 GPa (CoV=2.8%) and an ultimate strain of 1.58% (CoV=5.1%) [3]. From the performed bearing tests, a bearing strength of 316.4 MPa (CoV=11.8%) and 604.4 MPa (CoV=5.8%) was obtained for the unclamped and clamped tests, respectively [3].

The S&P Resin 220 epoxy adhesive© was used to glue the laminates to the concrete. From the experimental characterization of this adhesive, a tensile strength of 33.03 MPa (CoV=8.52%), an ultimate strain of 0.48% (CoV=11.80%) and a modulus of elasticity of 7.47 GPa (CoV=4.28%) were obtained [5]. According to the supplier, this epoxy resin has a compressive strength and a concrete/laminate bond strength of 90 MPa and 3 MPa, respectively.

A Hilti© chemical anchors system was adopted to fix mechanically the MDL-CFRP laminate to concrete. This system is composed by resin HIT-HY 150 max, HIT-V M8 and M10 8.8 threaded anchors and DIN 9021 washers.

2.3 Preparation of Specimens

The preparation of the specimens required several steps. For MF-FRP and EBR series, the strengthening procedures are quite well documented in the literature, e.g. [2] and [7], respectively. In the case of the MF-EBR beam, its strengthening involved the main procedures described in the following paragraph.

As previous referred, for the case of MF-EBR series two strengthening procedures were investigated, S1 and S2. The first step was the casting and cure of the concrete prisms. For the S1 procedure the following steps were executed: (i) holes of 10 mm and 12 mm diameter were drilled for the series M8 and M10, respectively, both with a depth of 100 mm; (ii) a rough concrete surface was created by using a rotary hammer with a needle adapter; (iii) the holes and the final glued surface were cleaned by using compressed-air and a steel brush; (iv) then, the holes were filled with the chemical adhesive, and the fasteners were inserted up to a depth of 100 mm; (v) the position of the fasteners was marked with a transparent acrylic strip and, then, the holes in the laminates were drilled using this auxiliary acrylic strip; (vi) the epoxy adhesive was applied on the treated area of the concrete surface and on the previously cleaned laminate surface that will be in contact with the concrete; (vii) the laminate was placed on the concrete surface by pressing it against to concrete in order to create an uniform thickness of 1 to 2 mm of adhesive layer; (viii) the adhesive in excess was removed. The S2 procedure was composed by the following steps: (ii); (iii – excluding the holes); (vi), (vii); (viii); (i); the holes were cleaned by using compressed-air and a steel brush; and, (iv). From a practical point of view, the holes in the MDL-CFRP should be done after it has been glued to the concrete. This strategy was followed in S2 procedure.

The tests were performed, at least, 7 days after the application of the adhesive used to glue the laminate to concrete. For the T1 series, the prestress was applied in two phases: one day before the test, a torque moment of 40 N·m was applied to the anchors; in the day of the test, the same torque level was again adjusted.

3. Results and Discussion

Table 4, 5 and 6 include the main results obtained in terms of maximum pullout force (F_{max}), loaded end slip (s_{l}) and failure modes for the MF-EBR, MF-FRP and EBR series, respectively. Figure 2 and 3 depict typical relationships of the pullout force *versus* loaded end slip of the tested specimens.

Table 4. Main results obtained in the MF-EBR series (average values).

Series	F_{max} [kN]	s_{l} [mm]	**Failure mode**
M8F3S1T0	34.14 (12.18%)	3.55 (16.03%)	IC+ID+BF(3)*
M8F3S2T0	32.89 (8.33%)	5.28 (25.81%)	IC+ID+BF(3)*
M10F3S1T0	48.99 (5.77%)	3.67 (24.49%)	IC+E(1)*; IC+ID+E(1)*
M10F3S2T0	48.31 (7.83%)	4.66 (14.22%)	IC+ID+BF(3)*
M8F1S2T0	15.00 (13.27%)	0.36 (20.88%)	IC+ID+BF(3)*
M8F1S2T1	20.95 (3.56%)	0.47 (19.30%)	IL+BF(3)*
M8F2S2T0	23.48 (15.28%)	0.76 (33.44%)	IC+ID+BF(3)*
M8F2S2T1	37.01 (6.03%)	1.07 (14.05%)	IC+ID+BF(1)*; D+E(2)*
M8F3S2T1	48.35 (6.66%)	1.59 (4.18%)	ID+BF(3)*
M10F1S2T0	23.12 (2.66%)	0.45 (24.94%)	IC+D+BF(2)*; IL+BF(1)*
M10F1S2T1	27.32 (3.62%)	0.40 (41.88%)	IL+BF(3)*
M10F2S2T0	28.29 (14.85%)	0.82 (10.68%)	IC+ID+BF(3)*
M10F2S2T1	40.38 (9.04%)	0.93 (10.73%)	IL+ID+BF(3)*
M10F3S2T1	57.76 (2.81%)	1.29 (12.76%)	ID+BF(3)*

Notes: the values between parentheses are the corresponding coefficients of variation; failure modes: IC=Debonding at the concrete/adhesive interface; IL=Debonding at the laminate/adhesive interface; ID=MDL-CFRP inter-delamination; BF=Bearing failure; *the value between parenthesis is the number of specimens with that type of failure mode.

Table 5. Main results obtained in the MF-FRP series (average values).

Series	F_{max} [kN]	s_{l} [mm]	**Failure mode**
M8F1T0	7.20 (7.66%)	4.63 (11.75%)	BF (2)*
M8F1T1	14.74 (2.55%)	3.91 (18.19%)	ID+BF (3)*
M8F2T0	15.39 (4.82%)	8.67 (36.98%)	ID+BF (3)*
M8F2T1	25.38 (8.92%)	6.39 (33.67%)	ID+BF (3)*
M8F3T1	36.69 (9.38%)	4.63 (63.08%)	ID+BF (3)*

Notes: the values between parentheses are the corresponding coefficients of variation; failure modes: ID=MDL-CFRP inter-delamination; BF=Bearing failure; *the value between parenthesis is the number of specimens with that type of failure mode.

Table 6. Main results obtained in the EBR series (average values).

Series	F_{max} [kN]	s_{l} [mm]	**Failure mode**
EBR	19.62 (2.55%)	0.75 (36.72%)	IC (3)*

Notes: the values between parentheses are the corresponding coefficients of variation; failure modes: IC=Debonding at the concrete/adhesive interface; *the value between parenthesis is the number of specimens with that type of failure mode.

3.1.1 MF-EBR Series

The effect of the strengthening procedure S1 and S2 of the MF-EBR technique on the bond performance was assessed by the series M8F3S1T0, M8F3S2T0, M10F3S1T0 and

M10F3S2T0. Remark that from a practical point of view, the strengthening procedure S2 should be followed (see Section 2.3). When these series are compared in terms of maximum load, a marginal difference of 3.7% and 1.4% were obtained for the M8 and M10 anchors, respectively. In addition of that, similar failure modes were observed in the almost all the specimens analysed. These failure modes include a mix of three components: debonding at the concrete/adhesive and laminate/adhesive interfaces, and bearing failure at the laminate.

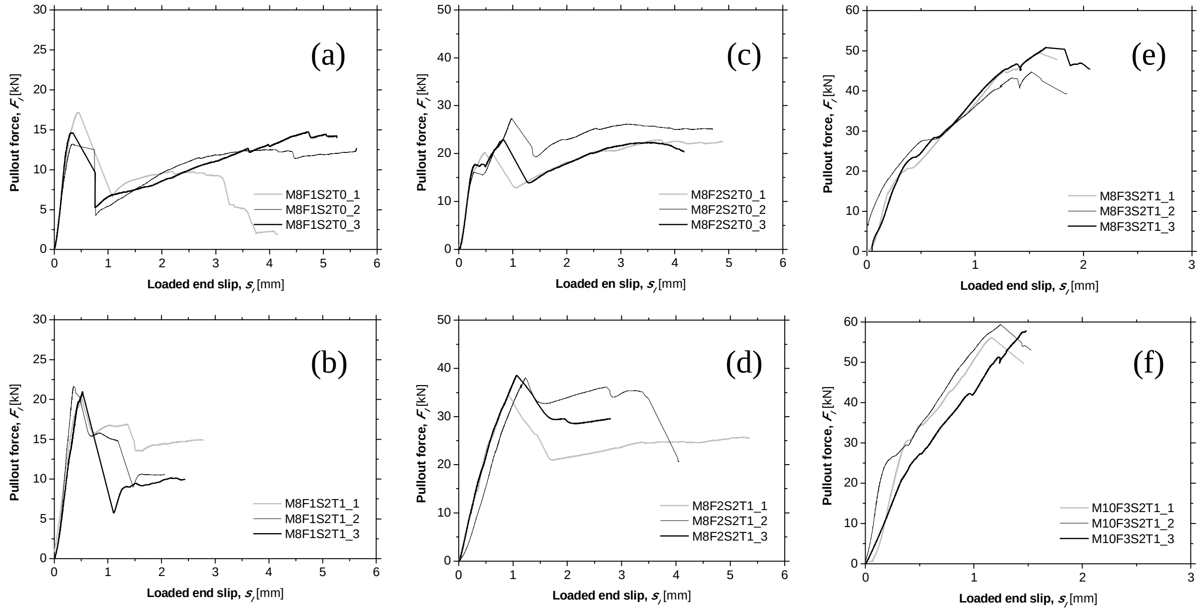

Figure 2. Pullout force *versus* loaded end slip for the series MF-EBR: (a) M8F1S2T0; (b) M8F1S2T1; (c) M8F2S2T0; (d) M8F2S2T1; (e) M8F3S2T1; (f) M10F3S2T1.

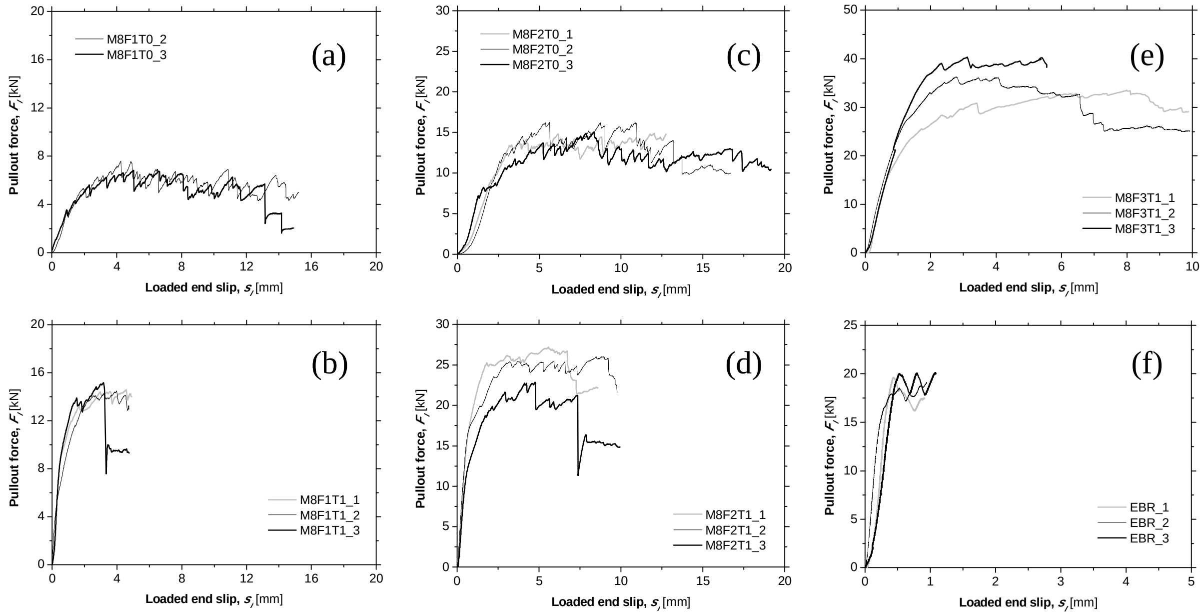

Figure 3. Pullout force *versus* loaded end slip for the series MF-FRP and EBR: (a) M8F1T0; (b) M8F1T1; (c) M8F2T0; (d) M8F2T1; (e) M8F3T1; (f) EBR.

As expected, the maximum pullout force increases with the number of anchors. This effect is, however, more clear for the T1 series where the prestress is applied to the anchors. In fact, when the F2 and F1 series are compared, the variation of $F_{\max}$ for (M8F2T0, M8F1T0) and (M8F2T1, M8F1T1) was 56.5% and 76.6%, respectively, whereas for the case of (M10F2T0, M10F1T0) and (M10F2T1, M10F1T1) was 22.4% and 47.8%, respectively. This performance may be justified by the fact that the confinement in the vicinity of the anchors, provided by the prestress, allowed superior frictional angle at the concrete/adhesive and laminate/adhesive interfaces.

When the effect of the diameter of the anchors is analysed, i.e. M8 and M10 series are compared, it is observed that $F_{\max}$ is higher in M10. This behaviour is justified by the failure mode obtained. In fact, for the majority of the series, bearing failure occurred at the laminate in the vicinity of the anchors. Since the bearing failure of the M10 involved a superior contact area, a higher strength was expected. Other interesting observation is the fact that the increase in terms of $F_{\max}$ for the prestressed series (T1) was higher for the case of M8 instead of M10. In fact for M8F1S2T1 and M8F2S2T1 series the increase due to the application of the prestress was 39.7% and 57.6%, respectively, whereas for the case of M10F1S2T1 and M10F2S2T1 series was 18.2% and 42.7%, respectively. Since the same level of prestress was applied for M8 and M10 and the bearing strength of M10 was higher that M8, this behaviour was expected.

For the F1 series the pullout force *versus* loaded end slip (F_l-s_l) relationships, up to the peak load, are very similar (see Figure 2a and b). In fact, an almost linear trend for both prestressed and non prestressed series was observed. However, as expected, the T1 series presented higher stiffness and strength. The peak load coincides with the full debonding of the concrete/adhesive interface.

The presence of the two anchors (F2 series) is clearly identified by the “two peaks” in the up to peak load (see Figure 2c). This behaviour was no longer observed in the series with prestressed anchors (see Figure 2d). Indeed, the stress state provided by the prestress led to a smoother response.

The relationships F_l-s_l of F3 series (see Fig. 2e and f) for the case of M8 and M10 are quite similar up to the peak load. However, higher strength can be observed for the case of M10.

Debonding at the concrete/adhesive (IC) and laminate/adhesive (IL) interfaces, MDL-CFRP inter-delamination (ID) and bearing failure at the laminate (BF) were the observed failure modes. The IC+ID+BF is the most observed failure mode. The IC is a failure mode currently observed with the EBR strengthening technique, whereas BF failure mode is observed in the MF-FRP one. Since the MF-EBR is a hybrid strengthening technique, a “hybrid” failure mode is expected.

3.1.2 MF-FRP Series

Like in the MF-EBR system, in the MF-FRP one the maximum pullout force has increased with the number and diameter of anchors, and the prestressed applied to the anchors. When the M8F3T1 and M8F2T1 series are compared with the M8F1T1 in terms of pullout force variation divided by the total number of anchors, a ratio of 0.86 and 0.83 was obtained, respectively. This indicates that an interaction between anchors exists. As expected, when the MF-FRP series is compared with the corresponding MF-EBR series in terms of F_l, higher values were found in the latter. In fact, for the MF-EBR series, in addition of the anchor, the multidirectional CFRP laminate is bonded to concrete with epoxy adhesive. However, when the F_l-s_l is analyzed, a “more” ductile response can be found in the MF-FRP series. In fact, after the complete debondig of the laminate at the concrete/adhesive interface, in the MF-EBR systems, a sudden decay of the pullout force occurs aborting the test.

3.1.3 EBR Series

As expected, when the EBR series is compared with the MF-EBR one, the former corresponds to a lower bound and showed similar behaviour, as reported in the literature, including the type of failure mode, i.e. deboding at the concrete/adhesive interface [1].

4. Conclusions

In the present work, a description was given about the main aspects of an experimental program carried out to assess the bond behaviour between CFRP laminates and concrete elements when the MF-EBR, MF-FRP and EBR strengthening systems are used. In this experimental program, by executing pullout tests, the influence of the diameter (M8 and M10) and number of anchors (F1, F2 and F3), the applied prestress level on them (T0 and T1), the strengthening procedure (S1 and S2) and the type of strengthening technique (MF-EBR, MF-FRP and EBR) were investigated.

The most effective strengthening technique was the MF-EBR, since it provided the higher maximum pullout force, $F_{\max}$.

Both strengthening procedures analyzed in the MF-EBR system yielded to similar results. This aspect should be highlighted since from practical point of view the S2 procedure is significantly simpler to be applied.

As expected, the maximum pullout force, $F_{\max}$, increased with the number and diameter of the anchors. Applying a prestress due to a torque moment of 40 N·m, the $F_{\max}$ has increased in about 57%, when compared with similar solutions without prestress.

Pullout force *versus* slip responses were non-linear up to peak. For the case of prestressed anchors a more “uniform” response was obtained. Mixed failure modes have occurred, by debonding at the interfaces concrete/adhesive and adhesive/concrete, bearing at the MDL-CFRP and inter-delamination of the laminate for the case of MF-EBR and MF-FRP.

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