Abstract of Paper No: 127

Experimental and numerical study of distinct techniques to strengthen beams failing in bending under monotonic loading

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The use of fiber reinforced polymers (FRP's) in the context of strengthening Civil Engineering structures has grown in the last decades. Properties such as light weight, high stiffness/weight ratio, corrosion immunity and wide variety of sizes and shapes available are some of the reasons that justify the growing use of this type of materials. They have been applied mostly by two strengthening techniques: Externally Bonded Reinforcement (EBR) and Near-Surface Mounted (NSM).

The efficiency of these techniques depends, mainly, on the performance of the bond. This type of reinforcement is applied on the cover concrete, which is normally the weakest region of the element to be strengthened. Consequently, the most common problem is the premature failure of FRP reinforcement, which happens more frequently in the EBR technique.

In an attempt of overcoming this problem, other techniques have been proposed. The present one uses multi-directional carbon fiber laminates, simultaneously glued and anchored to concrete. In addition the anchors can be pre-stressed. This technique was called MF-EBR – Mechanically Fastened and Externally Bonded Reinforcement.

This paper presents the results of the experimental tests carried out with reinforced concrete beams strengthened with the three techniques previously referred in order to assess the efficiency of each one. An additional beam was casted and was used as the reference beam. For this purpose four reinforced concrete beams of 200×300×2200 mm^3 were used submitted to four-point bending tests.

The present work describes the carried-out tests and presents and analyzes the most significant obtained results, as well as the numerical simulations performed.

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Experimental and numerical study of distinct techniques to strengthen beams failing in bending under monotonic loading

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ABSTRACT: With the purpose of study three distinct techniques to strengthen beams failing in bending under monotonic loading, an experimental program was carried out. Three techniques are analyzed: Externally Bonded Reinforcement (EBR), Near-Surface Mounted (NSM) and Mechanically Fastened and Externally Bonded Reinforcement (MF-EBR). Unidirectional CFRP laminates were used for the case of the EBR and NSM techniques, whereas multi-directional CFRP laminates were used with the MF-EBR system. In this work the tests are described in detail, and the obtained results are presented and discussed. Numerical simulations of the tests are presented to evaluate the ability of current FEM tools in the simulation of these strengthening techniques.

1 INTRODUCTION

The strengthening technique named Mechanically Fastened and Externally Bonded Reinforcement (MF-EBR) has been recently proposed. In this strengthening technique multi-directional laminates of carbon fiber reinforced polymer (MDL-CFRP) are simultaneously glued and mechanically fixed with anchors. In addition the anchors are pre-stressed. To analyze the performance of this system when compared with Externally Bonded Reinforcement (EBR) and Near-Surface Mounted (NSM) techniques, an experimental program was carried out with reinforced concrete beams. In this paper are presented the main results from the tests performed in beams flexural strengthened with the EBR, NSM and MF-EBR techniques. Numerical simulations of the monotonic tests are presented to evaluate the ability of current FEM tools in the simulation of these strengthened structures.

2 EXPERIMENTAL PROGRAM

To appraise the effectiveness of the MF-EBR technique, an experimental program was carried out involving a reference beam (REF) and three more beams strengthened according to the following techniques: Externally Bonded Reinforcement (EBR), Near-Surface Mounted (NSM) and Mechanically Fastened and Externally Bonded Reinforcement (MF-EBR). These four reinforced concrete (RC) beams have been produced with same geometry, reinforcement arrangement of longitudinal and transversal steel bars, and concrete strength class. The RC beams have a cross section of 200 mm wide, 300 mm height and 2200 mm long being 2000 mm the distance between supports. All the beams have three longitudinal steel bars of 10 mm diameter (3Ø10) at the bottom, and 2Ø10 at the top (see Fig. 1). The transverse reinforcement is composed by stirrups Ø6 with a constant spacing of 100 mm. Fig. 2 includes the cross section of the strengthened beams.

Table 1 presents the main properties of the beams. In this table t_f, L_f and w_f are the thickness, the length and the width of the laminates, respectively, and $\rho_{s,eq}$ is the equivalent longitudinal steel reinforcement ratio defined by the following Eq. 1,

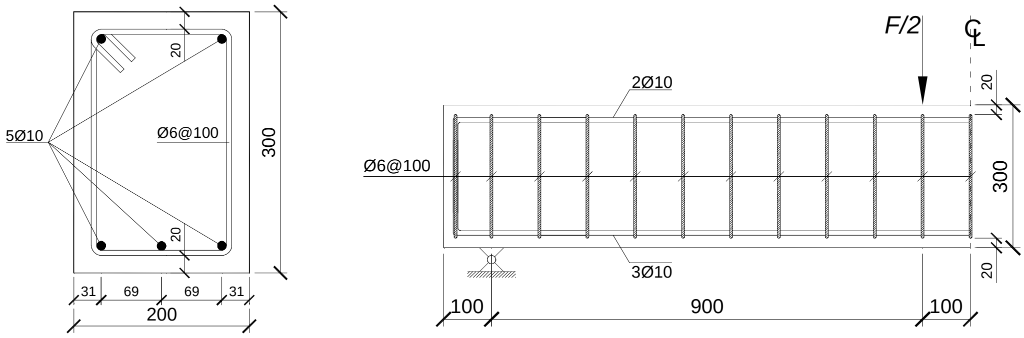
$$\rho_{s,eq} = \frac{A_s}{bd_s} + \frac{E_f}{E_s} \cdot \frac{A_f}{bd_f} \tag{1}$$

where b is the width of the beam, A_s and A_f are the cross sectional area of the tensile longitudinal steel bars and FRP systems, respectively, E_s and E_f are the modulus of elasticity of steel and FRP, respectively, and d_s and d_f are the distance from the top concrete compression fiber to the centroid of the steel bars and FRP systems, respectively.

A four-point bending test configuration was adopted in the present experimental study (Fig. 3a). The tests were performed under displacement control, with a deflection rate of 20 μm/s using, for this purpose, the linear variable differential transducer (LVDT) located at the midspan of the beam (LVDT3 in Fig. 3). The load was applied through a servo-controlled hydraulic actuator equipped with a load cell of 500 kN.

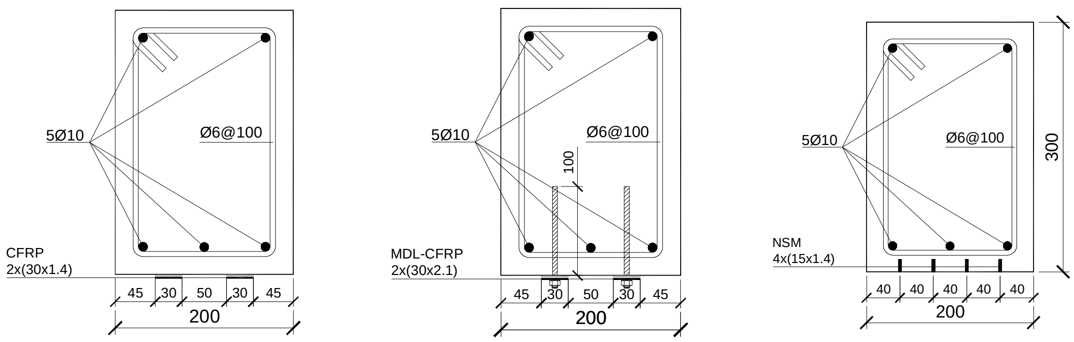
As seen in Fig. 3 four additional LVDTs were used to measure the deflections in the loaded sections (LVDT2 and LVDT4) and at the sections coinciding with the free ends of the FRP systems (LVDT1 and LVDT5). In addition, strain gauges (SG) were used to measure the strains in the tensile longitudinal steel bars (SGs1 and SGs2) and in the FRP systems (SGf1 to SGf8). The location of this instrumentation is also included in Fig. 3.

Preparation of the strengthened beams required several procedures. Those are described in Sena-Cruz et al. (2010).



(a) (b)

Figure 1. RC beams: (a) Cross section; (b) Longitudinal view. Note: all units in [mm].



(a) (b) (b)

Figure 2. Strengthened beams cross section: (a) EBR; (b) MF-EBR; (c) NSM. Note: all units in [mm].

Table 1. Properties of the beams.

Beam	Type of laminate	N.º of laminates	t_f (mm)	L_f (mm)	w_f (mm)	$\rho_{s,eq}$ (%)
REF	-	-	-	-	-	0.439
EBR	Unidirectional	2	1.41	1400	30	0.550
MF-EBR	Multidirectional	2	2.07	1400	30	0.553
NSM	Unidirectional	4	1.41	1400	15	0.561

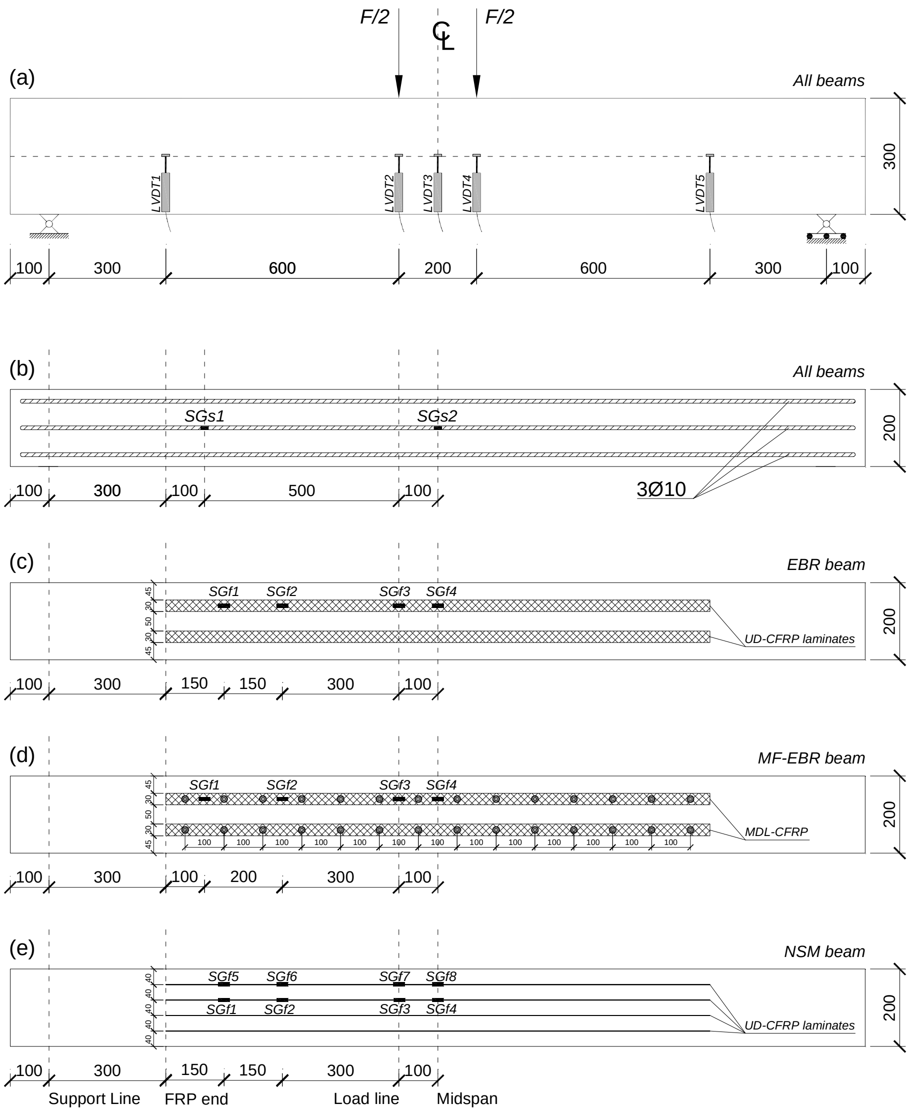


Figure 3. Instrumentation adopted: (a) vertical deflection; (b) strains in the reinforcement; (c) strains on the laminate of the EBR beam; (d) strains on the laminate of the MF-EBR beam; (e) strains on the laminates of the NSM beam. Note: all units in [mm].

3 MATERIAL CHARACTERIZATION

The mechanical characterization of concrete was assessed by means of compression tests. For this purpose six cylindrical concrete specimens were tested to evaluate the compressive strength and the modulus of elasticity according to the NP EN 12390-3:2009 and LNEC E397-1993, respectively. From the compression tests, an average compressive strength value of 53.08 MPa, with a coefficient of variation (CoV) 4.0%, and an average value of 31.17 GPa (CoV=4.4%) for the modulus of elasticity, were obtained.

The multi-directional laminate of CFRP (MDL-CFRP) used in the MF-EBR beam was designed and produced for a research project that intends to explore the possibilities of their use in structural strengthening. The MDL-CFRP core 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 of the CFK laminate, two layers of a unidirectional carbon pre-preg with fibers orientated at ±45º were glued. This pre-preg material has the trademark TEXIPREG® HS 160 REM (HS). Autoclave equipment was used for the production of the MDL-CFRP, namely for the cure of the HS. The procedures for the production of the laminate are described in Coelho (2010). After production, the multi-directional laminate had a thickness of 2.07 mm and a length of 1400 mm. For the other two beams (EBR and NSM) a unidirectional CFK® 150/2000 was used.

Tensile tests were performed according to the ISO 527-4:1997 for both laminates (CFK and MDL-CFRP) to assess their tensile properties. From these tests was obtained a tensile strength, a modulus of elasticity and an ultimate strain of 1866 MPa, 118 GPa and 1.58% for MDL-CFRP, and 2435 MPa, 158 GPa and 1.50% for CFK, respectively (Coelho, 2010).

The evaluation of the bearing strength of the MDL-CFRP was performed according to ASTM D5961/D5961M–05. These tests were made in two series, one without pre-stress in the fastener and the other with a pre-stress applied by a torque of 20 N×m. From the performed bearing tests, a bearing strength of 316.4 MPa (CoV=11.8%) and 604.4 MPa (CoV=5.8%) were obtained for the cases of series without and with pre-stress, respectively (Coelho, 2010).

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

The Hilti® chemical anchors system was adopted to fix mechanically the laminate to the concrete in the MF-EBR beam. This system is composed by the resin HIT-HY 150 max, the M8 8.8 threaded anchors and the DIN 9021 washers. According to the technical sheet of the product, with this fastener system a maximum torque of 20 N×m (characteristic value) can be applied. This value is too conservative because it takes into account large safety coefficients. In this context, tests were made in additional specimens in order to assess the highest torque that can be applied to this anchoring system. From those tests an average value of 40 N×m was adopted for the MF-EBR beam.

4 RESULTS

Table 2 resumes the main results obtained from the performed tests, while Fig. 4a depicts the relationship between force and displacement at mid-span during the tests. In this table the meaning of the symbols is the following one:

- δ_{cr} = deflection at concrete crack load initiation;
- F_{cr} = load at concrete crack initiation;
- δ_{y} = deflection at the yield initiation of the steel bars;
- F_{y} = load at the yield initiation of the steel bars;
- δ_{max} = deflection at the maximum load;
- F_{max} = maximum load;
- ε_{fu} = ultimate strain in the FRP according to the results obtained in tensile tests;
- ε_{fy} = maximum strain in the FRP at F_{y};
- ε_{fmax} = maximum strain in the FRP at F_{max}.

From this table and figure it can be concluded that the most effective strengthening technique was the MF-EBR, not only due to the maximum load reached (F_{max}=148.2 kN), but also in terms of deflection at failure and maximum/failure strain ratio.

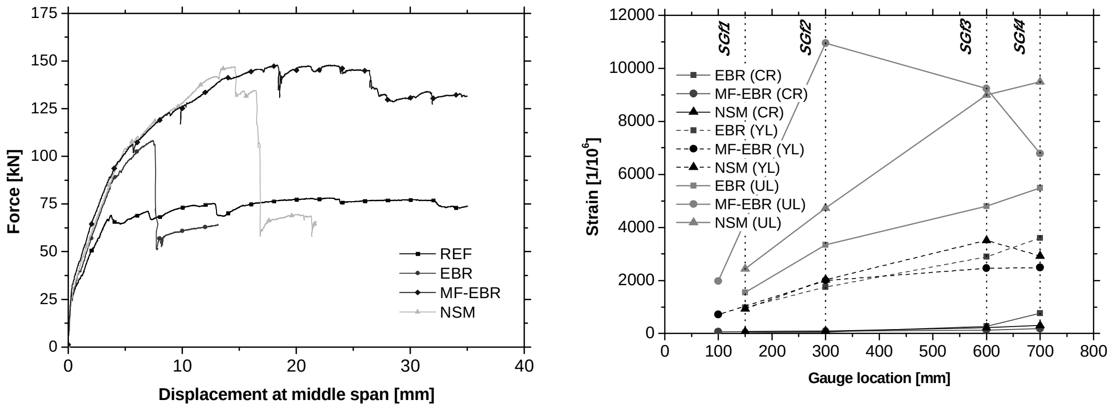
When compared with the EBR, the MF-EBR system had an increase of the load carrying capacity of about 37%. This superior behaviour cannot be explained by the higher axial stiffness, $E_f A_f$, of the laminate since the ratio between the $E_f A_f$ of the MDL-CFRP and $E_f A_f$ of the CFK (used in the EBR beam) is only equal to 1.08. The pre-stressed anchors have contributed for this higher strengthening effectiveness of MF-EBR technique. In fact, while the EBR system failed by peeling (Fig. 5a), and NSM FRP systems by rip-off (detachment of the concrete cover that includes the CFRP strips, Fig. 5b), the MF-EBR FRP laminates failed by bearing (Fig. 5c). The presence of the anchors avoided the "premature" debonding (peeling) of the laminates, as well as the detachment of the concrete cover (rip-off).

Table 2. Main results obtained.

Beam	Crack initiation		Yielding		Ultimate		δ_{max}/δ_y (-)	$\varepsilon_{fy}/\varepsilon_{fu}$ (%)	$\varepsilon_{fmax}/\varepsilon_{fu}$ (%)	FRP Failure mode
	δ_{cr} (mm)	F_{cr} (kN)	δ_y (mm)	F_y (kN)	F_{max} (kN)	δ_{max} (mm)				
REF	0.36	29	3.8	70	22.6	79.3	5.95	-	-	-
EBR	0.27	25	4.1	90	7.4	108.4 (37%)*	1.80	24.0	36.6	Peeling
MF-EBR	0.38	32	4.2	96	18.3	148.2 (87%)*	4.35	15.8	69.3	Bearing
NSM	0.40	29	4.9	104	14.6	147.3 (86%)*	2.98	23.4	63.3	Rip-off

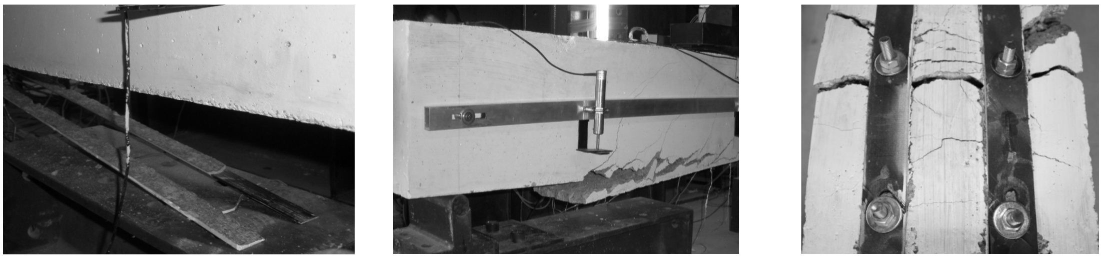
* $(F_{max} - F_{max,REF}) / F_{max,REF}$ where $F_{max,REF}$ is the maximum load of the reference beam.

Apparently, in the MF-EBR beam, the force corresponding to the crack initiation, F_{cr}, is higher than the F_{cr} of the other beams. This behaviour can be explained by the existence of pre-stress. In fact the pre-stress provided by the anchors may induce a compressive stress state on the concrete cover which delays crack initiation. This phenomenon could also explain the higher stiffness between the concrete crack initiation and the steel yield initiation of the MF-EBR beam. After the yielding of the longitudinal reinforcement, a slightly higher stiffness can be observed in the NSM beam, when compared with the MF-EBR beam. This behaviour can be justified by the efficiency of the NSM technique, since the laminates are fully embedded into the concrete.



(a) (b)

Figure 4. (a) Force *versus* displacement relationship of the beams; (b) Strain variation in the FRP's.



(a) (b) (c)

Figure 5. Failure modes: (a) EBR beam; (b) NSM beam; (c) MF-EBR beam.

In Fig. 4b is represented the strains in the CFRP laminates for three distinct load levels: at crack initiation (CR), at yielding initiation of the steel bars (YL), and at the maximum load (UL). In this graph, the location of the SG is referred to the left extremity of the laminates. As expected, from the extremity of the laminate up to the point load (left shear span length), the strain variation along the laminate increased almost linearly up to the load level corresponding to the yield initiation of the steel bars, which reflects the variation of the applied bending moment. The minimum strains observed in the MF-EBR laminates up to the yield initiation is justified by the high strain concentration around the fasteners, leading to minimum values in the intermediate zones between consecutive fasteners, where SGf are installed. However, the presence of the fasteners has allowed the development of the highest strain field in the shear span length, which justifies the largest load carrying capacity, and ductility of MF-EBR beam.

5 NUMERICAL SIMULATION

The tests were numerically simulated with the purpose of evaluating the accuracy of the available FEM tools in the simulation of RC beams strengthened with the considered techniques. All the simulations were performed in the FEMIX computer code (Sena-Cruz et al., 2007). These tested beams were modeled as a plane stress problem. To simulate the concrete part of the specimens, 4-node Serendipity plane stress elements with 2×2 Gauss-Legendre integration scheme are used.

An elasto-plastic multi-fixed smeared crack model is adopted for simulating the nonlinear material behavior of concrete (Sena-Cruz, 2004). Two different yield surfaces were used: the Rankine criterion for concrete under traction and the Owen and Figueiras (1983) yield surface for the concrete under compression. An isotropic hardening rule was adopted in the elasto-plastic model, with a strain hardening flow rule. The assumed hardening/softening diagram can be found elsewhere (Sena-Cruz, 2004). The crack evolution in fracture mode I is simulated using the Cornellisen et al. (1986) tension softening diagram. The following concrete properties are used in the numerical simulations: density, ρ=25 N/mm^3; Poisson's ratio, ν_c=0.2; initial Young's modulus, E_{ci}=31.17 GPa; compressive strength, f_c= 53.08 MPa; tensile strength, f_{ct}=2.9 MPa; fracture energy, G_c=0.09 N/mm; crack band width, l_b=square root of the area of the integration point (IP); threshold angle, α=89º; maximum number of cracks per integration point, n_{cr}=2.

The longitudinal and transverse steel reinforcements, as well as the FRP's, are simulated with 2-node linear cable elements with two Gauss-Legendre integration points. Perfect bond between the concrete and steel reinforcements was assumed. Bi-linear stress-strain relationships up to the ultimate load are assumed for the simulation of steel reinforcements. A linear stress-strain relationship, up to the tensile strength, is adopted for the case of unidirectional laminate (EBR and NSM beams). A bi-linear stress-strain relationship is assumed for the simulation of multi-directional CFRP laminate (MF-EBR beam). The properties adopted in the simulations of the steel reinforcements and FRP's can be found in Sena-Cruz et al. (2010). Remark that all the adopted values for the properties of the distinct materials used in the simulations were estimated taking into account the mechanical material characterization performed on the concrete, steel and FRP's.

Perfect bond between concrete and FRP was assumed for the simulation of the NSM beam, while for the cases of EBR and MF-EBR beams slip was allowed. To model slip at the CFRP-concrete interface, in the simulations of EBR and MF-EBR beams 4-node interface finite elements with two Gauss-Lobatto integration points are used. In the present numerical analysis the following relationship in terms of bond stress *versus* slip (τ–s) is adopted to simulate the nonlinear behavior of the CFRP-concrete interface:

$$\tau(s)=\begin{cases}\tau_{\mathrm{m}}\left(s/s_{\mathrm{m}}\right)^{\alpha} & \text{if } s\le s_{\mathrm{m}}\\ \tau_{\mathrm{m}}\left(s/s_{\mathrm{m}}\right)^{\alpha'} & \text{if } s> s_{\mathrm{m}}\end{cases} \tag{2}$$

where τ_{m} and s_{m} are the bond strength and the corresponding slip, respectively; α and α' define the shape of the τ–s law in the pre and post-peak phases, respectively. Assuming that the normal stiffness of the interface elements has a marginal effect on the bonding behavior, a constant value of 10^7 N/mm^3 is attributed. The evaluation of the τ_{m} was based on the information included in the technical sheet of the adhesive, whereas the other parameters where adjusted to fit the experimental response. Thus, τ_{m}=3.0 MPa, s_{m}=0.17 mm, α=0.9 and α'=-2.0 were assumed for the simulation of the EBR beam, and τ_{m}=3.0 MPa, s_{m}=0.05 mm, α=0.9 and α'=10.0 for the simulation of the MF-EBR beam. To simulate the anchors in the MF-EBR beam, 2-D linear elastic frame elements were used with perfect bond to concrete.

A uniform temperature variation of -146ºC was applied to the frame elements, in order to simulate the pre-stress in anchors (40 N×m torque).

Fig. 6 depicts the load *versus* deflection at mid-span obtained experimentally and numerically for the REF, EBR and MF-EBR beams. From the analysis of these curves, the main aspects observed in the experimental tests, such as crack initiation, yield initiation and load carrying capacity are well simulated.

Two distinct simulations were performed for the case of NSM beam, since it failed by concrete cover rip-off that includes the CFRP strips. In the first simulation (Num. 1) concrete properties were assumed equal for all the finite elements, whereas in the second simulation (Num. 2) the mechanical properties for the concrete region between the longitudinal reinforcement and the CFRP strips were reduced to numerically simulate the concrete cover rip-off behavior (Fig. 6). This figure shows the relationships between load and deflection at mid-span obtained experimentally and numerically for the NSM beam. Despite the numerical simulation 2 has almost predicted the ultimate load, simulation 1 has initially predicted better the initial behavior.

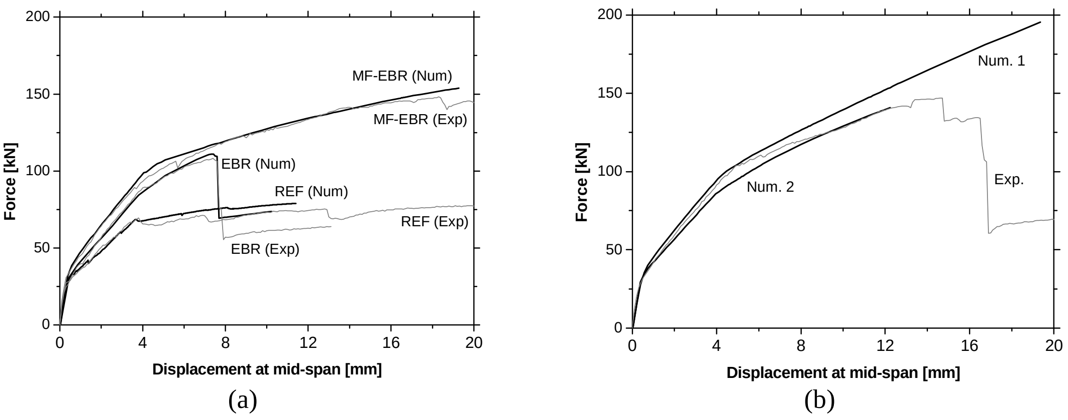


Figure 6. Load *versus* deflection at mid-span obtained experimentally and numerically: (a) REF, EBR and MF-EBR beams and (b) NSM beam.

6 CONCLUSIONS

In this paper the flexural strengthening technique named Mechanically Fastened and Externally Bonded Reinforcement (MF-EBR) is analyzed. This technique combines the fasteners from the MF technique and the epoxy bond-based performance from the EBR technique. In addition, all the fasteners are pre-stressed. This new system uses multi-directional laminates exclusively made with carbon fibers reinforced polymers, developed in the scope of the present research project.

To assess to the efficiency of the MF-EBR when compared with other existent techniques (EBR and NSM), an experimental program was carried out, composed by four beams: a reference beam (REF) and the other three were strengthened one with each of the three strengthening techniques analyzed: EBR, MF-EBR and NSM. The beams were submitted to a four-point bending tests. When compared to the reference beam, an increase on the loading carrying capacity of 37%, 87% and 86%, was obtained for the EBR, MF-EBR and NSM systems, respectively. When compared to the EBR beam, an increase on the loading carrying capacity of 37% for MF-EBR technique was obtained. The most favorable aspect of the MF-EBR technique was, however, the level of ductility (4.35) which was much higher than the one registered in the other two strengthened beams, the EBR (1.80) and NSM (2.98) beams.

Numerical simulations of the monotonic tests demonstrated that current FEM tools can simulate with high accuracy all the principal aspects observed in the tests such as crack initiation, stiffness degradation, yielding initiation in steel bars, load carrying capacity and crack patterns.

7 ACKNOWLEDGEMENTS

The present work is part of a research project (PTDC/ECM/74337/2006) supported by the programs COMPETE and FEDER, from the Portuguese Science and Technology Foundation (FCT). The authors acknowledge the materials generously supplied by Hilti, S&P Clever Reinforcement and SECIL, and TSwaterjet, Lda. for the cutting of the laminates using the water-jet technology.

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