FLEXURAL STRENGTHENING OF RC SLABS WITH PRESTRESSED CFRP STRIPS: SERVICEABILITY AND ULTIMATE LOAD STATE BEHAVIOR

Sena-Cruz, José[1], Correia, Luís[2], Teixeira, Tiago[3] and Michels, Julien[4]

[1] ISISE, University of Minho, Associate Professor, e-mail: jsena@civil.uminho.pt
[2] ISISE, University of Minho, PhD Student, e-mail: lcorreia@civil.uminho.pt
[3] ISISE, University of Minho, PhD Student, e-mail: tiago.teixeira@civil.uminho.pt
[4] Empa, Project Leader, e-mail: julien.michels@empa.ch

RESUMO

O presente trabalho pretende contribuir para o conhecimento da técnica EBR (Externally Bonded Reinforcement) usando laminados de CFRP (Carbon Fiber-Reinforced Polymer) pré-esforçados no reforço à flexão de estruturas de betão, sob condições de serviço (SLS) e estado limite último (ULS). Para tal, foi desenvolvido um programa experimental composto por 8 lajes ensaiadas até à rotura. Duas lajes foram usadas como de referência; 5 reforçadas com laminados de EBR/CFRP pré-esforçados; finalmente, 1 laje reforçada com um laminado EBR/CFRP. Dois sistemas distintos de ancoragem foram estudados: MA (Mechanical Anchorage) e GA (Gradient Anchorage). O efeito da largura e espessura do laminado foi também estudado. A performance dos protótipos é criticamente analisada ao nível dos SLS e ULS.

ABSTRACT

The present work intends to contribute to the knowledge of Externally Bonded Reinforcement (EBR) technique using prestressed Carbon Fiber-Reinforced Polymer laminates (CFRP) to strengthen concrete structures in flexure, at both serviceability (SLS) and ultimate load levels (ULS). For that purpose, an experimental program was carried out with 8 slabs monotonically tested under displacement control up to failure. Two slabs were used as reference specimens (unstrengthened); 5 slabs were strengthened with prestressed EBR CFRP laminates; finally, 1 slab was strengthened EBR CFRP laminates without being prestressed. To fix the ends of the prestressed CFRP laminates two different anchorage systems were used: Mechanical Anchorage (MA) and Gradient Anchorage (GA). The effect of the width and thickness of the CFRP laminate were also studied. The observed performance of the tested slabs is critically analyzed in terms of SLS and ULS aspects.

Keywords: Structural Strengthening; EBR technique; Prestressed CFRP laminates; SLS and ULS limit states.

1. INTRODUCTION

Extensive research has been developed on the strengthening of reinforced concrete (RC) structures with fiber reinforced polymer (FRP) materials. The most common strategy for improving the flexural carrying capacity of RC structures is the externally bonded reinforcement (EBR) technique. The use of prestressed FRP combines the benefits of the EBR technique with the advantages associated with external prestressing. Literature (El-Hacha, Wight, & Green, 2001; Michels et al., 2013) reports several positive aspects when the combination of these two techniques is used, mainly deflection and crack width reduction, delay in the onset of cracking and yielding initiation, more efficient use of concrete and FRP materials, reduction of premature debonding failure, and increase the load carrying capacity (flexural and shear).

The end anchorage system plays a key role in the success of the prestressing technique. In fact the very high shear stresses developed at the interface concrete/FRP strip ends is a problem associated to the use of prestressing techniques (Kotynia et al., 2011), which can be mitigated by the use of end anchorage systems. In spite of the several end anchorage systems being available (Michels et al., 2013), two commercially systems from S&P Clever Reinforcement Company are investigated in the context of the present work: the Mechanical Anchorage (MA) system with metallic plate elements fixed to the ends of the FRP reinforcement and the Gradient Anchorage (GA).

To assess to the serviceability and ultimate performance of MA and GA systems, an experimental program was carried out. For that purpose, the experimental campaign was composed of eight slabs (two reference specimens and six strengthened specimens) and the following parameters were studied: (i) the strengthening system (prestressed and non-prestressed), (ii) the anchorage system (MA and GA), and (iii) the geometry of the laminate (thickness and width). The tests are described and the obtained results are critically analyzed.

2. EXPERIMENTAL PROGRAM

2.1 Specimens and test configuration

The experimental program comprises a total of 8 RC slabs (see Table 1): (i) two slabs were used as control specimens (REF1 and REF2); (ii) one specimen was strengthened with a single CFRP laminate according to the externally bonded reinforcement (EBR) technique; (iii) the other five specimens were strengthened with one EBR prestressed CFRP laminate. As mentioned before, two types of anchorage systems were used to fix the prestressed CFRP laminate to the ends: the gradient anchorage (GA) system (2 specimens) and the mechanical anchorage (MA) system (3 specimens). Three distinct types of CFRP strips were used with the following cross-section geometry: 50×1.4 mm^2, 50×1.2 mm^2 and 80×1.2 mm^2.

Table 1: Experimental program

Specimen	Laminate [mm^2]	Anchorage	ε_{fp} [$\times 10^{-3}$]	f_{cm} [MPa]	E_{cm} [GPa]
REF1	-	-	-	53.4 (4.3%)	32.2 (7.5%)
SL50×1.4_GA	50×1.4	GA	4.05		
SL50×1.4_PA	50×1.4	MA	3.98		
SL50×1.4_EBR	50×1.4	-	-		
SL50×1.2_PA	50×1.2	MA	4.19	49.5 (3.1%)	n.a.
REF2	-	-	-	57.4 (3.0%)	32.6 (0.1%)
SL80×1.2_GA	80×1.2	GA	4.06		
SL80×1.2_PA	80×1.2	MA	3.99		

Note: f_{cm}=average compressive strength on cylinder 150mm/300mm of concrete at slab testing day; E_{cm}=average modulus of elasticity of concrete at slab testing day; the values between parentheses are the corresponding coefficients of variation (CoV).

The geometry and test configuration of the experimental program is depicted in Figure 1. Each slab is 2600 mm long, 600 mm wide and 120 mm thick. The reinforcement is composed of 5 bars of 8 mm of diameter (5Ø8) at the bottom and 3Ø6 at the top in the longitudinal direction. Stirrups of Ø6 at 300 mm spacing were adopted to avoid shear failure in all specimens. The strengthening was composed by CFRP strips with 2200 mm of length.

The instrumentation included 5 linear variable differential transducers (LVDTs), three in the pure bending zone with a range of ±75 mm and a linearity error of ±0.1%, and two more LVDTs in between the applied loads and supports with a range of ±25 mm and the same maximum linearity error. The aim is to record the deflection along the longitudinal axis of the slabs. One load cell with 200 kN of maximum measuring capacity and a linear error of ±0.05% was used to measure the applied load and one strain gauge (TML – Type BFLA-5-3) glued on the CFRP strip at the mid-span was installed to record the CFRP strain in tension. All tests were carried out with a servo-controlled machine under displacement control at a rate of 20 μm/s.

During the tests (up to pre-defined applied load) the evolution of the cracks width were monitored through a handheld USB microscope. This microscope is a VEHO VMS-004D, with a native capturing resolution of 640×480 pixels and a maximum magnification power of 400×. In the present study a magnification factor of 20× was used.

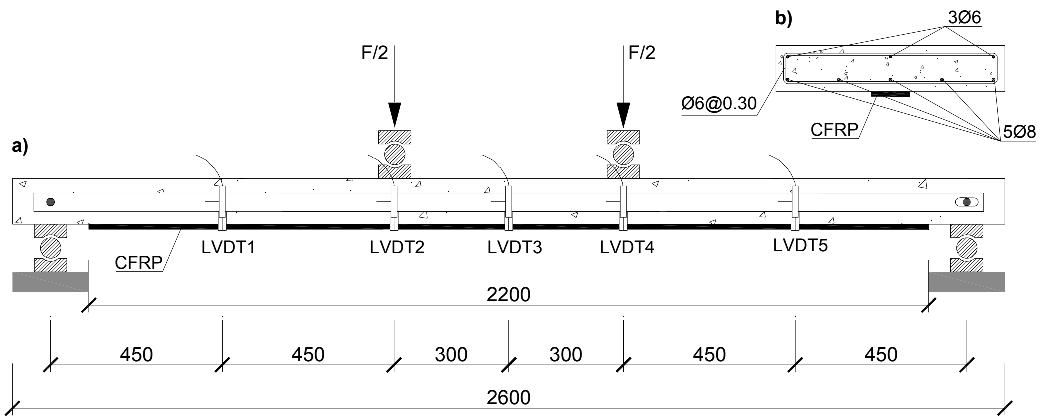


Figure 1: (a) Geometry and test configuration; (b) Cross-section. Note: all units in [mm].

2.2 Material characterization

Concrete

Three batches were used to cast the RC slabs. In order to evaluate the mechanical properties of concrete compression tests were carried out. For that purpose six cylindrical specimens with 150 mm of diameter and 300 mm of height were casted for each concrete batch. The modulus of elasticity and the compressive strength were evaluated according to the LNEC E397-1993:1993 and NP EN 12390-3:2011 recommendations, respectively. These tests were carried out at the same age of the tests with the RC slabs. Table 1 includes the obtained results. In general low coefficients of variation were observed for both modulus of elasticity and the compressive strength. An average compressive strength of about 53.4 MPa was obtained.

Steel

The tensile properties of steel reinforcement were assessed through the NP EN ISO 6892-1:2012 standard. Three specimens were used for each bar type (Ø6 and Ø8). From the tests performed a Young modulus, yield and ultimate strengths equal to 209.5 GPa (CoV=8.5%), 579.3 MPa (CoV=3.3%) and 669.7 MPa (CoV=1.7%) for the bar Ø6 and 212.8 GPa (CoV=9.7%), 501.4 MPa (CoV=5.9%) and 593.9 MPa (CoV=3.9%) for the bar Ø8, were obtained, respectively.

CFRP laminate

All the CFRP strips used in the present experimental work were produced by S&P Clever Reinforcement Ibérica Lda. From the tensile tests carried out according to the ISO 527-

5:1997, the following properties were obtained: (i) 50×1.4 mm^2 strip had a Young modulus (E_f) of 154.8 GPa (CoV=4.6%) and a tensile strength (f_f) of 2457.1 MPa (CoV=1.2%); (ii) the 50×1.2 mm^2 strip had the E_f=167.69 GPa (CoV=2.9%) and f_f=2943.5 MPa (CoV=1.6%); (iii) the strip 80x1.2 mm^2 had the E_f=164.59 GPa (CoV=0.2%) and f_f=2455.3 MPa (CoV=5.0%).

Epoxy adhesive

The "S&P 220 Resin" epoxy adhesive from the same company that produced the laminates was used to bond the strips to concrete. The tensile properties of the epoxy adhesive were assessed throughout the ISO 527-2:1993 standards. For that purpose six epoxy specimens were casted and cured under the same conditions than for the strengthened slabs. An elastic modulus of 6.3 GPa (CoV=4.7%) and a tensile strength of 24.4 MPa (CoV=1.8%) were obtained from the experimental characterization.

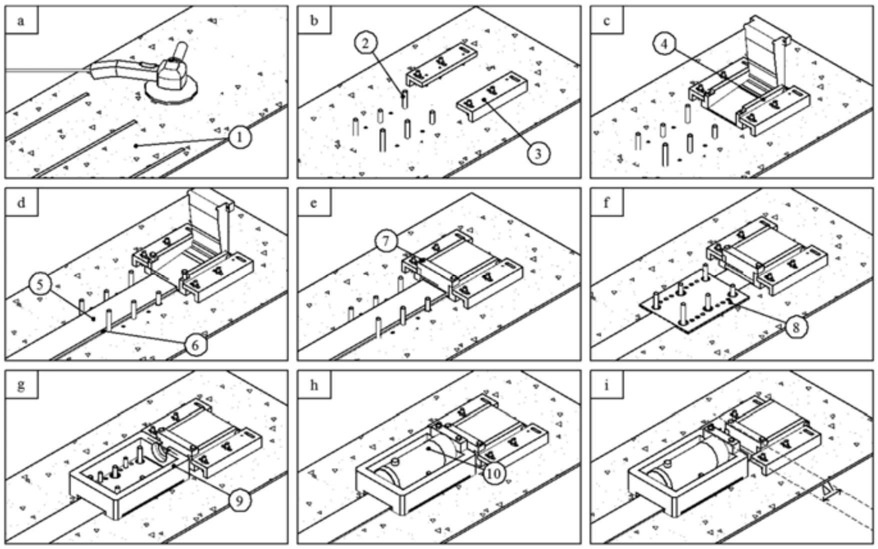
2.3 Specimen preparation

The application of the MA and GA is composed of several steps. These two systems have several common procedures and equipment. The main steps are described in the following paragraphs:

- **i.** The first step consists in grinding the region of the concrete surface where the strip was applied (Figures 2a and 3a). Afterwards, compressed air is used to clean the slab;
- **ii.** Several holes are drilled to accommodate temporary (GA system) and temporary and permanent (MA system) bolt anchors. After fixing the referred bolts, aluminum guides are placed in the right position to guide and fix the clamp units (Figures 2b and 3b);
- **iii.** The clamp units are placed in between the guides at each extremity of the slab (Figures 2c and 3c);
- **iv.** The epoxy adhesive is prepared according to the requirements included in the datasheet of the product, while the laminate is cleaned with a solvent. Epoxy adhesive is applied on surface of the CFRP laminate, as well as on the concrete surface region in contact with the laminate. Then, the CFRP laminate is placed on its final position and slightly pressed against the concrete surface (Figures 2d and 3d);
- **v.** The clamp units are closed (Figures 2e and 3e) and the metallic anchors plates and heating devices are placed on their predefined locations for the case of MA and GA systems, respectively (Figures 2f and 3f);

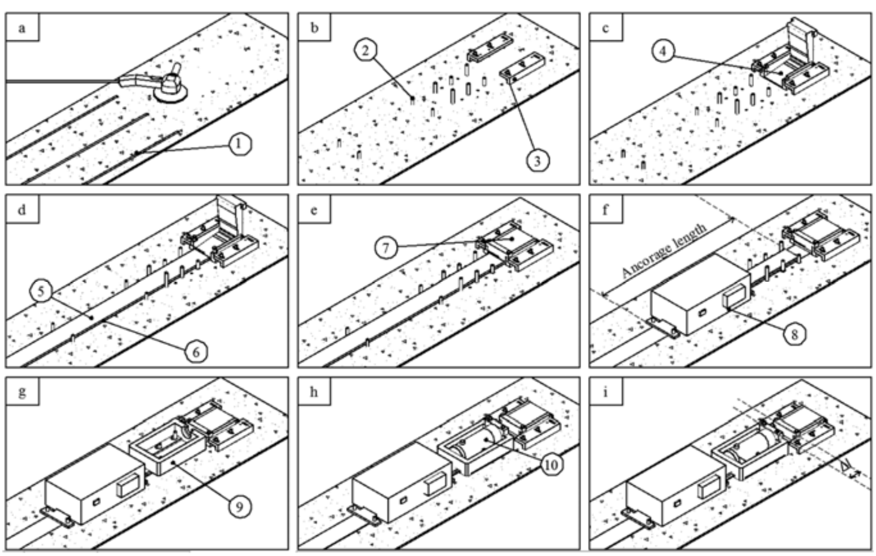
vi. The aluminum frames are placed on their predefined locations and fixed against the concrete with the anchors (Figures 2g and 3g) in order to accommodate the hydraulic cylinders (Figures 2h and 3h);

vii. Finally, the prestress is applied with a manual hydraulic pump (Figures 2i and 3i).



Legend: 1 – Concrete substract; 2 – Anchor bolts; 3 – Guides; 4 – Clamp unit; 5 – CFRP laminate; 6 – Epoxy adhesive; 7 – Clamp unit closed; 8 – Metallic anchor; 9 – Aluminum frame; 10 – Hydraulic cylinder.

Figure 2: Application procedures with the MA system.



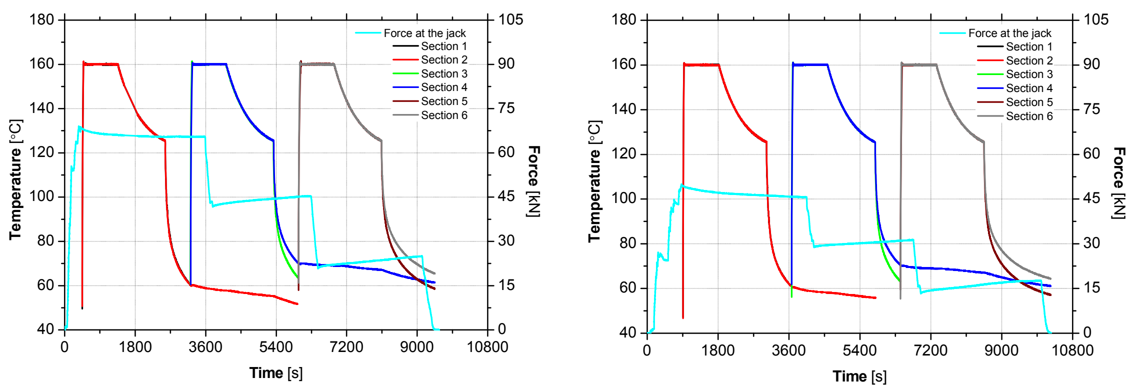
Legend: 1 – Concrete substract; 2 – Anchor bolts; 3 – Guides; 4 – Clamp unit; 5 – CFRP laminate; 6 – Epoxy adhesive; 7 – Clamp unit closed; 8 – Heating device; 9 – Aluminum frame; 10 – Hydraulic cylinder.

Figure 3: Application procedures with the GA system.

After the CFRP being presstressed distinct procedures are followed for the case of the MA and GA systems. Additional details can be found in (S&P, 2010) for the MA system and in (Michels et al. 2013) for the GA system. The strengthening application is concluded after 3 hours (GA) or one day (MA). It should be stressed out that, according to the supplier of the epoxy adhesive, 3 days are generally required to obtain a sufficient cure of the epoxy in normal curing conditions.

In the prestressed specimens, the CFRP strip was prestressed up to a prestrain (ε_{fp}) of nearly 0.4%, which is in range of suggested values from the existing literature. Table 1 includes the last values of ε_{fp} registered from the strain gauge placed at the mid-span of the laminate during the strengthening. The specimens were kept in lab environment after the strengthening at least one month before testing.

During the application of the GA method, all specimens were monitored in terms of applied force by the hydraulic cylinders to the CFRP strips and the temperature at the distinct sectors composing the heating devices. Figure 4 presents the registered values for the SL50×1.4_GA and SL80×1.2_GA specimens. In the present study an anchorage length of 600 mm was adopted for the specimens with GA method. Since the heating device is composed of several sectors (heating plates) each one with a geometry of 100×100 mm^2, 3 subsectors, each one with 200 mm of length, were adopted. In these graphs it is possible to see the evolution of the temperature in the heating plates with time: an initial plateau of 160ºC during 15 minutes, followed by an exponential decrease during 20 minutes, and finally the cooling phase. The releasing force in each step was equal to 1/3 of the total applied force. The release occurred 15 minutes after the initiation of the cooling phase.



(a) (b)

Figure 4: Heating (Temperature of the heating elements from the heating equipment) and jack releasing steps for the gradient anchorage (GA): (a) SL50×1.4_GA; (b) SL80×1.2_GA.

3. RESULTS

3.1 Serviceability aspects

Deflections

Figure 9 includes the relationship between the applied load and the deflection at mid-span, whereas Table 2 summarizes the key results. As expected, the strengthening decreased the deflection for a specific load level, since the stiffness of the composite system RC slab/CFRP strip was increased. Prestressing did not significantly change the stiffness of the elastic phase. However, a significant increment in terms of cracking (δ_{cr}, F_{cr}) and yielding (δ_y, F_y) initiations were observed for the MA and GA series, when compared the EBR and reference specimens. In general, both prestressing systems presented similar performance in terms of serviceability loads/deflections up to the yielding initiation.

Crack width

The crack width of each slab was monitored with the microscope previously referred (*cf.* §2.1). For that purpose three cracks were selected in the pure bending region (see Figure 1): two close to the point loads and one at mid-span. For each picture taken with the microscope, three measurements were done in order to obtain the average crack width (see Figure 5). Figure 6 plots the evolution of the average width with the applied load.

As expected, the strengthened specimens exhibited lower crack widths when compared with the reference specimen (REF2). The results are not clearly conclusive when the MA and GA are compared. However similar results were expected since identical responses in terms of the force-deflection behavior were observed (see Figure 9).

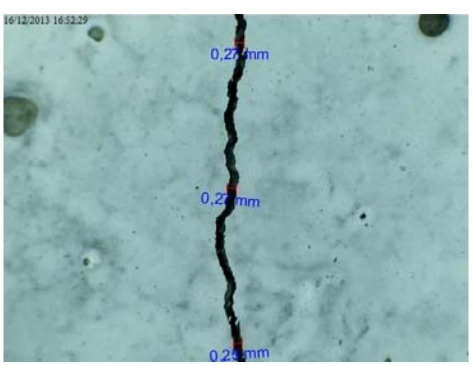


Figure 5: Crack width measurements.

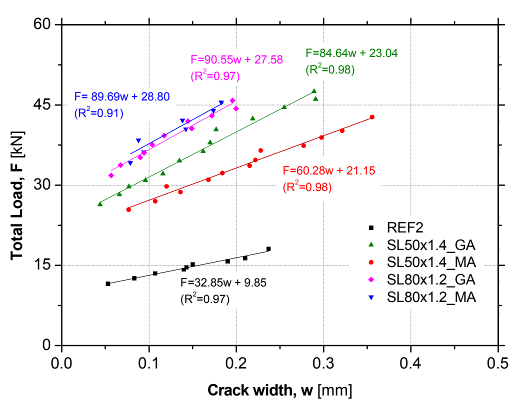
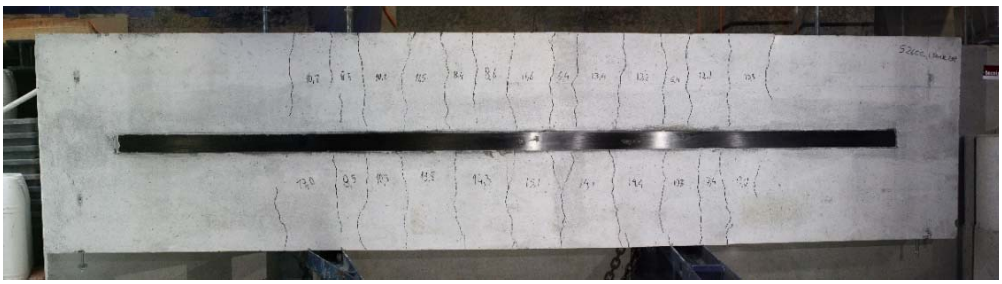


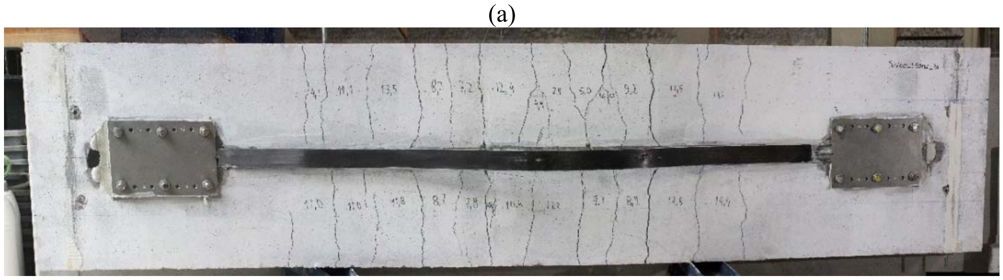
Figure 6: Total load *versus* crack width.

Crack spacing

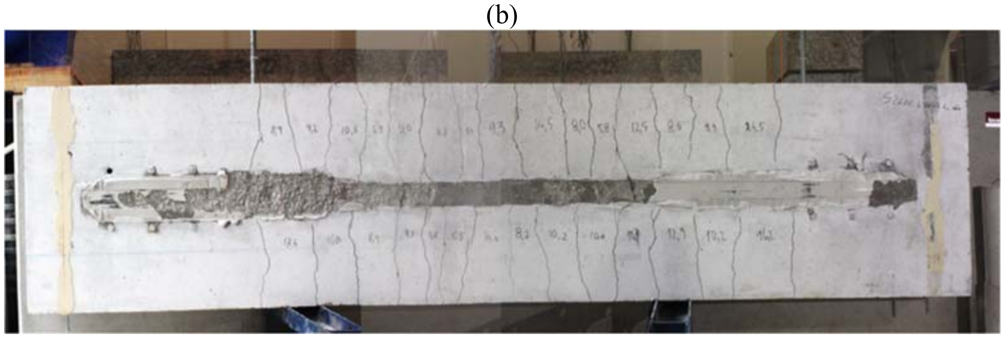
The crack spacing was also evaluated at the end of each test, as shown in Figure 7. Figure 8 presents the values obtained in terms of average crack spacing. In spite of the reduced number of specimens, the crack spacing was reduced with the use of prestressed laminates. In fact in present work, a marginal reduction of the crack spacing was observed for the SL50×1.4_EBR. A marginal crack spacing reduction was observed for this specimen. No rational explanation justifies this behavior.



(a)



(b)



(c)

Figure 7: Crack pattern of the specimens: (a) SL50×1.4_EBR; (b) SL50×1.4_MA; (c) SL50×1.4_GA.

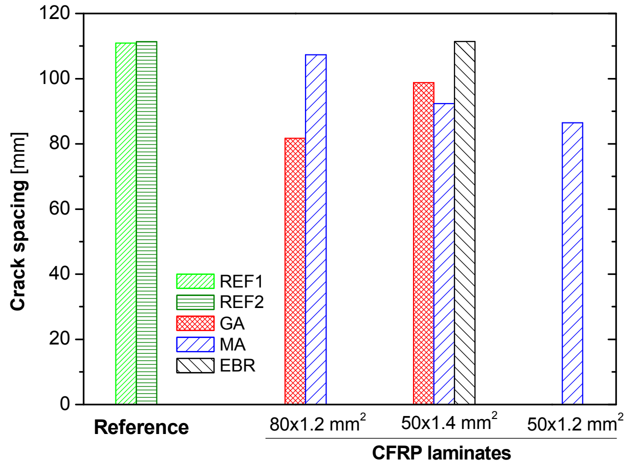
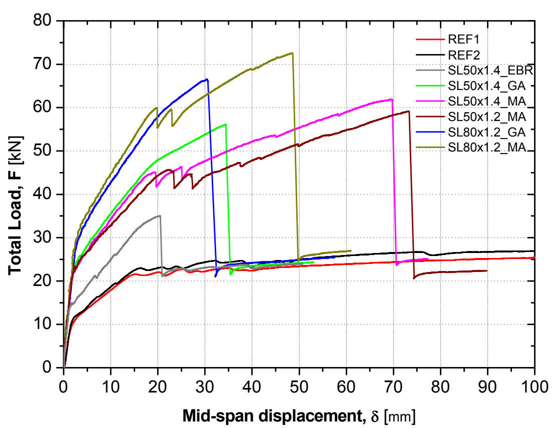


Figure 8: Distance between cracks observed on the specimens.



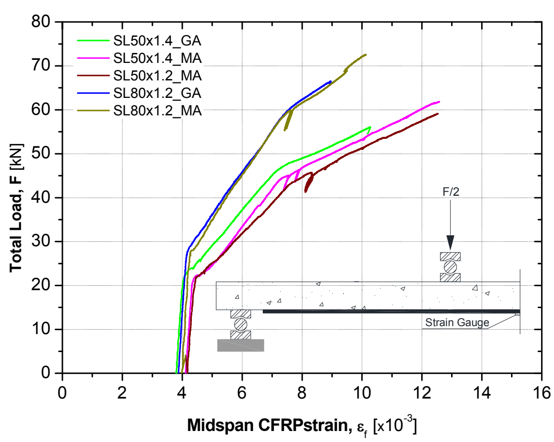


Figure 9: Total load *versus* mid-span displacement.

Figure 10: Total load *versus* mid-span CFRP strain.

Table 2: Main results obtained from the experimental program

Specimen	Crack initiation		Yielding		Ultimate		ε_{fmax} [$\times10^{-3}$]	FM
	δ_{cr} [mm]	F_{cr} [kN]	δ_y [mm]	F_y [kN]	δ_{max} [mm]	F_{max} [kN]		
REF1	2.47	11.04	15.74	21.50	-	-	-	-
SL50×1.4_GA	2.25	23.84	18.86	48.35	34.39	56.02	10.29	ED
SL50×1.4_MA	2.25	22.07	17.80	44.32	69.84	61.76	11.97	ED
SL50×1.4_EBR	1.64	14.73	17.00	33.30	20.47	35.06	4.64	ED
SL50×1.2_MA	2.53	22.81	20.57	44.89	73.23	59.09	12.53	ED
REF2	2.49	11.12	15.96	22.90	-	-	-	-
SL80×1.2_GA	2.88	28.56	20.31	58.31	30.61	66.21	8.96	ED
SL80×1.2_MA	2.51	28.71	18.43	58.67	48.62	72.58	10.13	ED

Note: FM – failure mode; ED – laminate end debonding

3.2 Ultimate limit state

Failures modes

All the strengthened the slabs seemed to fail by strip end debonding. The failure started from one of the extremities and then shifted to the middle of the slab. In the anchorage zone for the GA and MA specimens, an interfacial failure at epoxy adhesive/CFRP laminate was observed. In the remaining CFRP strip region a mix failure mode composed of an interfacial failure epoxy adhesive/CFRP strip and cohesive failure in the concrete was detected. In some tested specimens a layer of concrete was detached from the RC slabs. Finally, in the SL50×1.4_EBR slab an interfacial failure between epoxy adhesive and CFRP strip was observed.

Prestressed *versus* unprestressed specimens

As expected, the overall behavior of the prestressed slabs was better than the unprestressed ones. An improvement in several aspects, such as the cracking and yielding initiation, stiffness and load carrying capacity was observed. Even though the initial stiffness at the uncracked stage was similar mainly due to the low level of strengthening used, the cracking load is significantly higher (about 55% for the specimens with CFRP laminates with 50×1.4 mm^2). Similar observations can be made for the cracked stage (before the yielding initiation). The ultimate load increased in between 60% and 107% when compared with the unprestressed specimen. Finally, it should be also referred that prestressing implicated a better CFRP material exploitation: it was observed that in the prestressed slabs, the CFRP strain at the ultimate load (ε_{fmax}) was at least the double of the one obtained for the EBR slab (see Figure 10).

GA *versus* MA systems

For both systems, a very similar behavior until steel yielding is observed. In the next test phase, the CFRP material is responsible to carry the additional loads since the contribution provided by the internal steel reinforcement is limited (this reinforcement exhibits a quite small hardening modulus of elasticity). For this reason, the force increment carried by CFRP material increases significantly at the onset of the yielding initiation (see the slope variation from second to third braches of total load *versus* strain – Figure 10).

After the initiation of the yielding two drop points on the F-δ curves of the slabs with the MA system could be noticed. This behavior is related to the debonding initiation that occurred between the metallic plate anchors. The metallic anchors delayed the failure by debonding of the CFRP strip, allowing the slab to continue to carry load after that point. For this reason the

MA slabs' performance showed a better behavior in terms of ultimate load (about 10%) when compared with the GA series.

Influence of FRP strip thickness

For both specimens, an identical behavior was observed (SL50×1.4_MA and SL50×1.2_MA). This resemblance is due to the fact that both specimens failed by laminate end debonding at the metallic anchor. This failure is indeed governed by the maximum shear stresses that this region can attain, the maximum force that the CFRP laminate can support should be approximately the same. It should be remarked that the laminate at the metallic anchor zone is confined by the pressure of this device due to the torque (150 N×m) applied in the six bolts (see Figure 2). The thickness effect on the EBR performance reported by literature may have negligible significance due to the level of confinement applied (at about 24.9 MPa).

Influence of FRP strip width

In the present experimental campaign the laminate width was evaluated by comparing the performance of SL80×1.2_MA with the SL50×1.2_MA, and it was clear that the slab with the wider laminate had a better behavior. In spite of that, the maximum average shear stress in the CFRP laminate strip at the metallic anchor zone for SL50×1.2_MA and SL80×1.2_MA was equal 9.14 MPa and 7.40 MPa, respectively. This outcome indicates that in the metallic anchor region the shear stress is not constant and that laminates with smaller widths have a better performance at this matter. Notice that in all the MA slabs the same metallic anchors were used (270 mm × 200 mm), with the same torque per bolt (150 N×m), yielding to different confinement pressure levels (SL50×1.2_MA – 24.9 MPa and SL80×1.2_MA – 15.6 MPa).

4. CONCLUSIONS

This work presented an experimental program in which the main objective was to assess the service and ultimate states of two different anchorage systems in the context of the use of prestressed CFRP laminates strips with the EBR technique: mechanical anchorage (MA) and gradient anchorage (GA). From the tests carried out it was possible to point out the following main conclusions: (i) in general it was observed that at the service level the strengthening clearly improved the slab's performance with lower deflections, crack width delay and lower crack spacing; (ii) both anchorage techniques presented similar response, in spite of MA yielded to slightly higher values in terms of maximum load; (iii) all the slabs failed by strip end debonding; (iv) when the laminate is prestressed high values of CFRP strain were attained; (v) similar performance was observed for strip with different thickness.

5. ACKNOWLEDGEMENTS

This work is supported by FEDER funds through the Operational Program for Competitiveness Factors - COMPETE and National Funds through FCT - Portuguese Foundation for Science and Technology under the project FRPreDur - PTDC/ECM-EST/2424/2012. The authors also like to thank all the companies that have been involved supporting and contributing for the development of this study, mainly: S&P Clever Reinforcement Ibérica Lda, S&P Clever Reinforcement Company (Switzerland), Tecnipor - Gomes & Taveira Lda., Vialam – Indústrias Metalúrgicas e Metalomecânicas, Lda., Hilti Portugal-Produtos e Serviços, Lda. The second and third authors wish also to acknowledge the grants SFRH/BD/98309/2013 and SFRH/BD/94850/2013, respectively, provided by FCT.

6. REFERENCES

EL-HACHA, R., WIGHT, R., & GREEN, **Prestressed fibre-reinforced polymer laminates for strengthening structures**. Progress in Structural Engineering and Materials, 3(2), 111–121, 2001.

ISO 527-2:1993. **Plastics — Determination of tensile properties — Part 2: Test conditions for moulding and extrusión plastics**. ISO - International Organization for Standardization, Genève, 8 pp.

ISO 527-5:1997. **Plastics — Determination of tensile properties — Part 5: Test conditions for unidirectional fibre-reinforced plastic composites**. ISO - International Organization for Standardization, Genève, 11 pp.

KOTYNIA, R., WALENDZIAK, R., STOECKLIN, I., & MEIER, U. **RC Slabs Strengthened with Prestressed and Gradually Anchored CFRP Strips under Monotonic and Cyclic Loading**. Journal of Composites for Construction, 15(2)(Special Issue in Honor of Professor Urs Meier), 168–180, 2011.

LNEC E397-1993:1993. **Concrete - Determination of the elasticity Young modulus under compression.** Portuguese specification from LNEC.

MICHELS, J., CZADERSKI, C., EL-HACHA, R., BRÖNNIMANN, R., & MOTAVALLI, M. **Temporary bond strength of partly cured epoxy adhesive for anchoring prestressed CFRP strips on concrete**. Composite Structures, 94(9), 2667-2676, 2012. doi: http://dx.doi.org/10.1016/j.compstruct.2012.03.037

MICHELS, J., SENA-CRUZ, J., CZADERSKI, C., & MOTAVALLI, M. **Structural Strengthening with Prestressed CFRP Strips with Gradient Anchorage**. Journal of Composites for Construction, 17(5), 651-661, 2013. doi: 10.1061/(asce)cc.1943-5614.0000372

NP ISO 6892-1:2009. **Metallic materials — Tensile testing — Part 1: Method of test at room temperatura.** IPQ - Instituto Português da Qualidade, Caparica.

NP EN 12390-3:2011. **Testing hardened concrete. Part 3: Compressive strength of test specimens.** IPQ - Instituto Português da Qualidade, Caparica.

S&P. (2010). **Pre-stressed S&P Laminates CFK. Manual for applicators.** Technical Report HüM/03.04.2011, 20 pp.

S&P. **Pre-stressed S&P Laminates CFK. Manual for applicators**. Technical Report, 2010. HüM/03.04.2011, 20.