# FLEXURAL STRENGTHENING OF RC SLABS WITH PRESTRESSED CFRP STRIPS USING DIFFERENT ANCHORAGE SYSTEMS

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**ABSTRACT:** In the field of flexural strengthening of concrete structures the Externally Bonded Reinforcement (EBR) technique using carbon fiber-reinforced polymers (CFRP) is commonly used. This technique offers several structural advantages when the CFRP material is prestressed. One of the critical aspects of a prestressing technique is the type of end anchorage. Two systems are investigated in the present paper: the metallic anchorage elements fixed to the ends of the FRP reinforcement and the gradient anchorage. In order to assess the performance of these two systems, an experimental program was carried out. In addition to the anchorage systems, the cross-section geometry of the CFRP strip was also included in this study. Eight slabs were monotonically tested under displacement control up to failure by using a four-point bending test configuration. The observed performance of the tested slabs is critically analyzed.

## 1. Introduction

Externally bonded reinforcement (EBR) is the common strengthening technique adopted for improving the flexural carrying capacity of existing reinforced concrete (RC) structures. EBR with prestressed fiber reinforced polymer (FRP) materials combines the benefits of the EBR technique with the ones provided by the external prestressing. Literature (e.g El-Hacha *et al.* 2001, Michels *et al.* 2013) reports several benefits 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 success of the prestressing technique directly depends on the type of end anchorage. In spite of the several end anchorage systems being available (Michels *et al.* 2013), in the ambit of the present work two commercial systems from *S&P Clever Reinforcement Company* are investigated in the present paper: the mechanical anchorage (MA) system with metallic elements fixed to the ends of the FRP reinforcement and the gradient anchorage (GA). In order to assess the performance of GA and MA systems, an experimental program was carried out. The experimental program was composed by eight slabs, for which the following parameters were studied: the strengthening system (prestressed and non-prestressed), the prestressing system (GA and MA), and 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 was composed of 8 RC slabs (see Table 1). Two slabs were used as reference specimens (REF1 and REF2). The slab SL50x1.4_EBR was strengthened with one CFRP laminate strip according to the externally bonded reinforcement (EBR) technique. The other five slabs were strengthened with one EBR prestressed CFRP laminate strip, two by using the gradient anchorage (GA) system and three with the mechanical anchorage (MA) system. Three distinct types of CFRP laminate strips were used: 50×1.4 $mm^2$, 50×1.2 $mm^2$ and 80×1.2 $mm^2$.

**Table 1 – Experimental program**

| **Specimen** | **Laminate** | **Anchorage** | $\varepsilon_{fp}$ [$10^{-3}$] | $f_{cm}$ [MPa] | $E_{cm}$ [GPa] |
|---|---|---|---|---|---|
| REF1 | - | - | - | 53.4 (4.3%) | 32.2 (7.5%) |
| REF2 | - | - | - | 57.4 (3.0%) | 32.6 (0.1%) |
| SL50x1.4_EBR | 50×1.4 $mm^2$ | - | - | 53.4 (4.3%) | 32.2 (7.5%) |
| SL50x1.4_GA | 50×1.4 $mm^2$ | GA | 4.05 | 53.4 (4.3%) | 32.2 (7.5%) |
| SL50x1.4_MA | 50×1.4 $mm^2$ | MA | 3.98 | 53.4 (4.3%) | 32.2 (7.5%) |
| SL50x1.2_MA | 50×1.2 $mm^2$ | MA | 4.19 | 49.5 (3.1%) | n.a. |
| SL80x1.2_GA | 80×1.2 $mm^2$ | GA | 4.06 | 57.4 (3.0%) | 32.6 (0.1%) |
| SL80x1.2_MA | 80×1.2 $mm^2$ | MA | 3.99 | 57.4 (3.0%) | 32.6 (0.1%) |

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

Fig. 1 presents the geometry and test configuration of the experimental program. Each slab is 2600 mm long, 600 mm wide and 120 mm thick, and reinforced with 5 bars of 8 mm of diameter (5Ø8) at the bottom and 3Ø6 at the top in the longitudinal direction. To avoid shear failure, stirrups of Ø6 at 300 mm spacing were adopted. All the slabs were strengthened with laminates of 2400 mm of length. The instrumentation included several LVTDs (according to the arrangement included in Fig. 1) to measure the slab displacement along the longitudinal axis, one load cell to register the applied force and one strain gauge at the slab mid-span to record the CFRP strain. A servo-controlled machine was used to perform the tests, under displacement control at a rate of 20 µm/s.

## 2.2. Material characterization

Three batches were used to cast the RC slabs. Six cylindrical concrete specimens with 150 mm of diameter and 300 mm of height of each concrete batch were used to evaluate the modulus of elasticity and compressive strength through the LNEC E397-1993:1993 and NP EN 12390-3:2011 recommendations, respectively. These tests were performed at the same age of the tests with the RC slabs. From the results obtained (see Table 1) an average compressive strength of about 53.4 MPa was obtained.

The tensile properties of steel reinforcement were evaluated with the NP EN ISO 6892-1:2012 standard. For that purposed, 3 specimens were used, being the 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, respectively.

The CRFP tensile properties were also assessed throughout ISO 527-5:1997 recommendations. For the laminate 50×1.4 $mm^2$ 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%) were obtained; for the 50×1.2 $mm^2$ the $E_f$=167.69 GPa (CoV=2.9%) and

$f_f$=2943.5 MPa (CoV=1.6%), whereas for the laminate 80x1.2 mm$^2$ the $E_f$=164.59 GPa (CoV=0.2%) and $f_f$=2455.3 MPa (CoV=5.0%).

In the ambit of the present work the epoxy adhesive was not characterized. However, in another experimental program made by the authors, after 7 days of curing at 22ºC, a Young modulus of 7.7 GPa (CoV=3.1%) and a tensile strength of 20.7 MPa (CoV=9.9%) were obtained (Sena-Cruz *et al.* 2012).

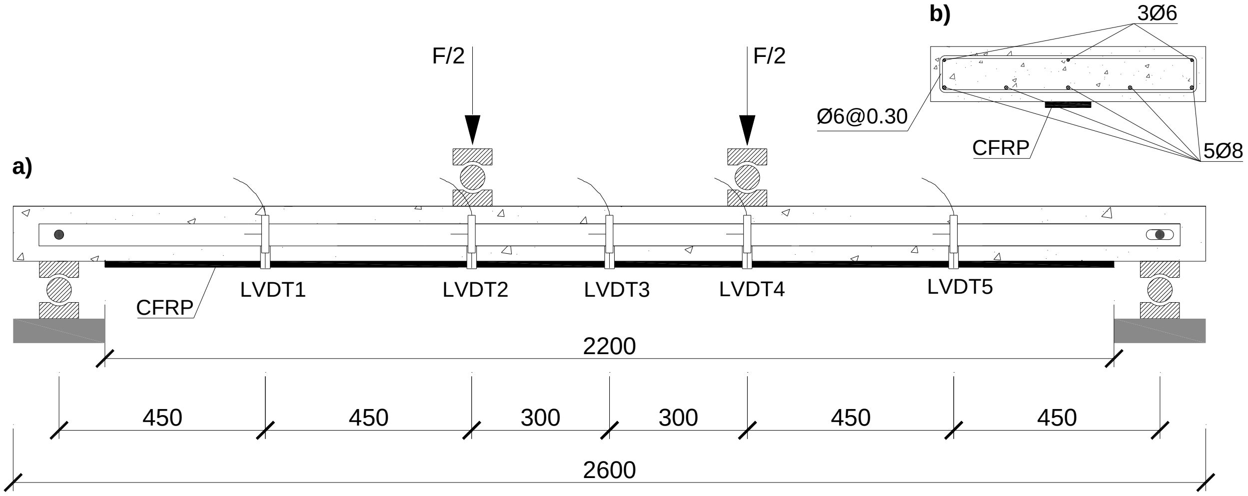


**Fig. 1 – (a) Geometry and test configuration; (b) Cross-section. Note: all units in [mm]**

## 2.3. Specimen preparation

The strengthening of the specimens included several steps. Initially the concrete surface was grinded in region where the laminate was applied. Then the typical procedures for the application of the GA (Michels *et al.* 2013) and the MA (S&P 2010) were followed. Fig. 2 and Fig. 3 present the main steps. Both systems use common components, e.g. base angles, clamps, aluminum frames, manometer and valves, and hydraulic jacks. The main difference between both methods is the use of heating device and corresponding procedures for the case of the GA, and the metallic plates in the case of the MA. Additional details can be found in the literature (Michels *et al.* 2013, S&P 2010).

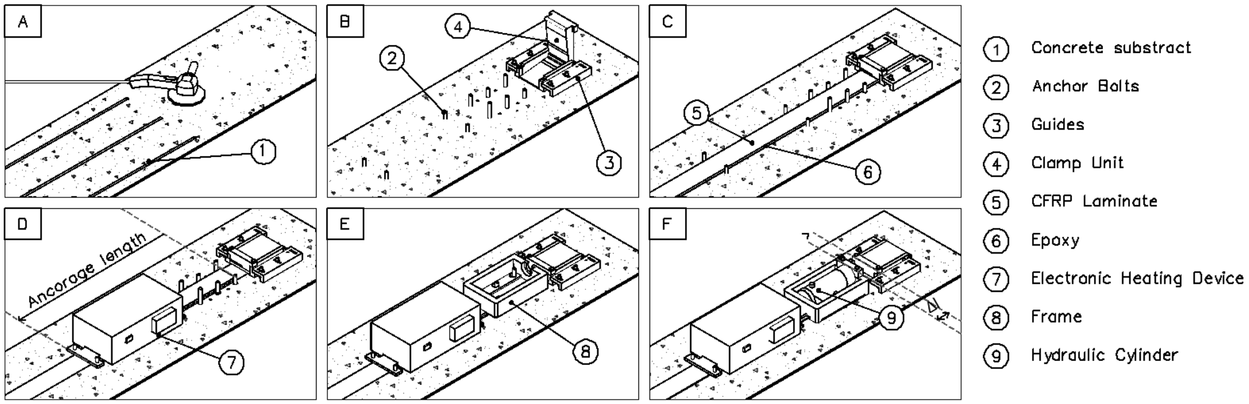


**Fig. 2 – Application procedures with the GA system**

A prestrain ($\varepsilon_{fp}$) of 0.4% was applied to the CFRP laminate strips. This value is in range of suggested values from the existing literature. Table 1 includes the values of $\varepsilon_{fp}$ registered from the strain gauge placed at the midspan of the laminate, during and after the strengthening. After the strengthening the specimens were kept in lab environment at least one month before testing.

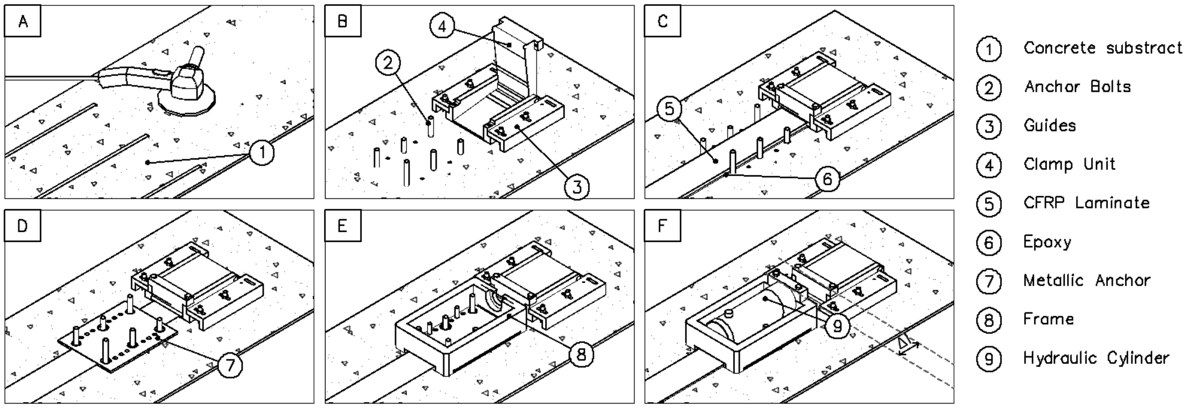


**Fig. 3 – Application procedures with the MA system**

## 3. Results

Fig. 4 (a) and (b) present the applied load *versus* midspan deflection and the applied load *versus* midspan CFRP strain, respectively, of all the tested slabs specimens. Table 2 summarizes the main results obtained. Finally, Fig. 5 presents typical failure modes observed in the tests performed.

As expected, when the strengthened slabs (EBR, GA and MA specimens) are compared with the reference ones (REF1 and REF2), it is clear that the cracking (CR), yielding (Y) and ultimate load (MAX) increased, in spite of losing ductility.

### Failure modes

It seemed that all the strengthened the slabs failed by laminate end debonding. The failure always starts from one of the extremities and shifted to the middle of the slab. For the GA and MA series in the anchorage zone (GA – heated zone; MA – region where the metallic plate are located) an interfacial failure at epoxy adhesive/CFRP laminate occurred. In the remaining regions a mix failure mode composed of an interfacial failure epoxy adhesive/CFRP laminate and cohesive failure in the concrete was observed. In some cases a significant layer of concrete was detached from the RC slab. In the SL50x1.4_EBR slab an interfacial failure epoxy adhesive/CFRP laminate was observed.

### Prestressed *versus* non-prestressed

As expected, the use of prestress improved the overall behavior of the slabs, including cracking and yielding initiation, stiffness and load carrying capacity. Although the initial stiffness was similar in the uncracked stage, mainly due to the low level of strengthening, the cracking load is significantly higher (at about 55% for the 50x1.4 $mm^2$ laminate). Similar observations can be made for the cracked stage (before the yielding initiation). The ultimate load increased in between 60% and 107%. Finally, it should be also referred that prestressing also explores better the CFRP material. In fact, in the prestressed slabs the CFRP strain at the ultimate load ($\varepsilon_{fmax}$) was at least the double of the one obtained for the EBR slab (see Table 2 and Fig. 4b).

### GA *versus* MA systems

Up to yielding initiation, GA and MA systems exhibited similar behavior. From this point on, contribution provided by the steel reinforcement is limited, being the CFRP material responsible to carry the additional loads. 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 – Fig. 4b). For all MA slabs two drop points can be observed in curves just after the yielding initiation. These two drops are related to the debonding initiation at the both extremities (in between the metallic plate anchors). After this point the slab still continues to carry load due to the existence of the metallic anchors that avoided the premature debonding of the CFRP laminate strip. For this reason the slabs of

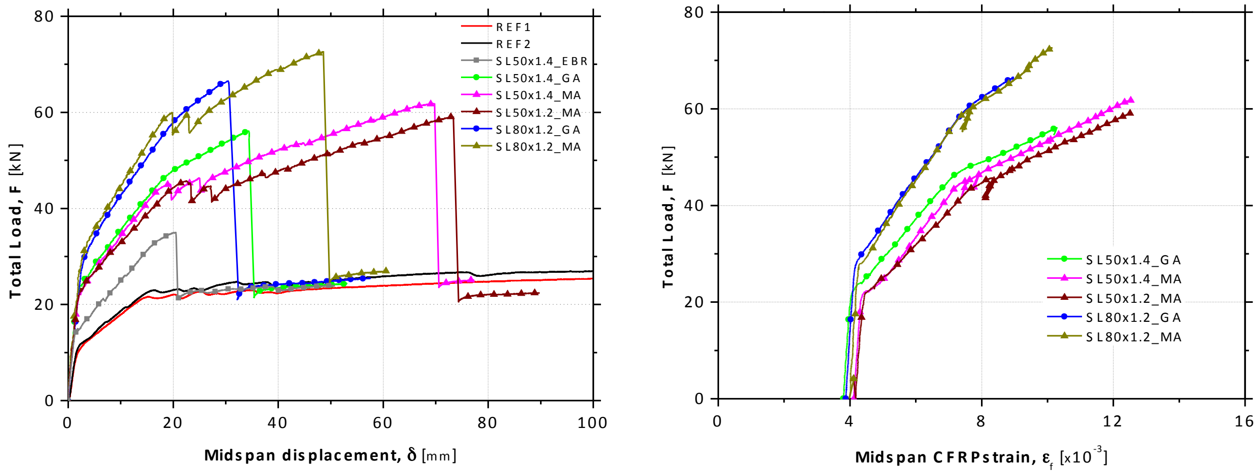
MA series present a better performance in terms of ultimate load (about 10%) when compared with the GA series.

## Influence of FRP thickness

SL50x1.4_MA and SL50x1.2_MA slabs presented a similar behavior. This observation can be explained by the fact that both slabs failed by laminate end debonding at the metallic anchor. This failure is indeed governed by the maximum shear stresses that this region can attain. Since both laminates have the same width, the maximum force that the CFRP laminate can support should be approximately the same. Remark 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 Fig. 3). The thickness effect on the EBR performance reported by literature may have negligible significance for the level of confinement applied (at about 24.9 MPa).

## Influence of FRP width

When the slabs SL50x1.2_MA and SL80x1.2_MA are compared, in general the latter presents better behavior. In spite of that, the maximum average shear stress in the CFRP laminate strip at the metallic anchor zone for SL50x1.2_MA and SL80x1.2_MA was equal 9.14 MPa and 7.40 MPa, respectively. This result indicates that the shear stress is not constant in the metallic anchor region, being better explored by laminates with smaller widths. Remark that for both slabs (SL50x1.2_MA and SL80x1.2_MA) equal metallic anchors were used (270 mm × 200 mm), with the same torque per bolt (150 N×m), yielding to different confinement pressure levels (SL50x1.2_MA – 24.9 MPa and SL80x1.2_MA – 15.6 MPa).



(a) (b)

**Fig. 4 – Experimental results: (a) total load versus mid-span displacement; (b) total load versus mid-span CFRP strain**

**Table 2 – Main results obtained**

| **Specimens** | **Crack initiation** | | **Yielding** | | **Ultimate** | | $\varepsilon_{fmax}$ [x10$^{-3}$] | **FM** |
|---|---|---|---|---|---|---|---|---|
| | $\delta_{cr}$ [mm] | $F_{cr}$ [kN] | $\delta_y$ [mm] | $F_y$ [kN] | $\delta_{max}$ [mm] | $F_{max}$ [kN] | | |
| REF1 | 2.47 | 11.04 | 15.74 | 21.50 | - | - | - | - |
| REF2 | 2.49 | 11.12 | 15.96 | 22.90 | - | - | - | - |
| SL50x1.4_EBR | 1.64 | 14.73 | 17.00 | 33.30 | 20.47 | 35.06 | 4.64 | ED |
| SL50x1.4_GA | 2.25 | 23.84 | 18.86 | 48.35 | 34.39 | 56.02 | 10.29 | ED |
| SL50x1.4_MA | 2.25 | 22.07 | 17.80 | 44.32 | 69.84 | 61.76 | 11.97 | ED |
| SL50x1.2_MA | 2.53 | 22.81 | 20.57 | 44.89 | 73.23 | 59.09 | 12.53 | ED |
| SL80x1.2_GA | 2.88 | 28.56 | 20.31 | 58.31 | 30.61 | 66.21 | 8.96 | ED |
| SL80x1.2_MA | 2.51 | 28.71 | 18.43 | 58.67 | 48.62 | 72.58 | 10.13 | ED |

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

## 4. Conclusions

An experimental program was carried out to assess the performance 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 obtained results the following conclusions can be pointed out: (i) both techniques present similar response, in spite of MA yielded to slightly higher values in terms of ultimate load; (ii) it seemed that all the slabs failed by laminate end debonding; (iii) in general high values of CFRP strain were attained, when the laminate is prestressed; (iv) similar performance was observed for laminates with different thickness.

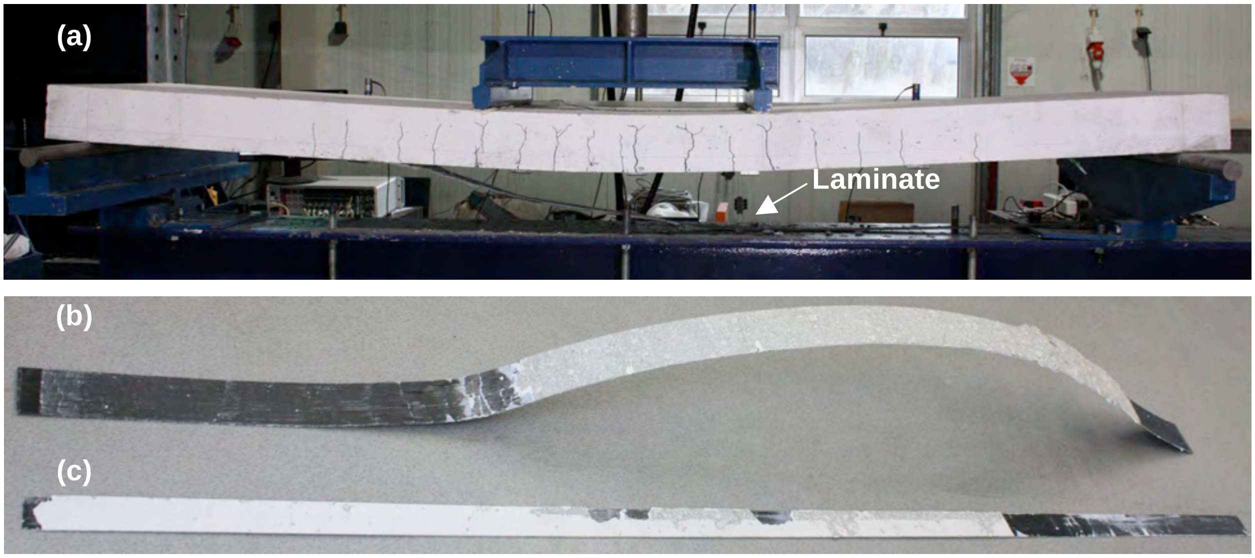


**Fig. 5 – Failure mode observed in: (a) SL50x1.4_MA, (b) SL80x1.2_GA and (c) SL50x1.4_EBR**

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