Long-term structural and durability performances of reinforced concrete elements strengthened in flexure with CFRP laminates: a research project

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Abstract

Over the last two decades, the use of fibre reinforced polymer (FRP) materials for strengthening existing reinforced concrete (RC) structures has been constantly increasing, and nowadays it is considered state-of-the-art and is frequently used by the construction industry. Typically, these composite materials are externally bonded (EBR technique) or near-surface-mounted (NSM technique) on the elements to be retrofitted. Although substantial research has been performed and design rules have been established, most studies focused on the short-term structural performance of the strengthened elements without considering their long-term behaviour. The FRPLongDur R&D project aims at studying the long-term structural behaviour and durability performance of RC elements strengthened in flexure with Carbon FRP (CFRP) laminates according to the EBR and NSM techniques, under various real environmental exposure and loading conditions (carbonation, moisture, chlorides, thermal and freeze-thaw cycles, initial FRP pre-strain level and sustained loading). For this purpose, several prototypes have been installed in different sites of Portugal, each one being representative of the above listed environments under investigation, currently considered as the most critical exposure conditions. Additionally, test specimens of the materials involved – CFRP laminate, epoxy adhesive and concrete – and bond specimens have been prepared and installed near the other prototypes in order to evaluate their own durability. The present paper presents the initial insights on the ongoing FRPLongDur project.

Keywords: Strengthening; CFRP laminates; durability; long-term behaviour; accelerated ageing; outdoor ageing.

1. Introduction

Nowadays, carbon fibre reinforced polymer (CFRP) materials for strengthening existing reinforced concrete (RC) structures are considered state-of-the-art. Durability of structures strengthened with CFRP has been intensively studied under laboratorial conditions using accelerated ageing protocols. However, very few studies of durability have been performed in real outdoor conditions. Moreover, the relationship between accelerated ageing tests under laboratorial conditions and real outdoor ageing conditions for assessing the durability of these systems is not fully understood [1].

Few publications on this topic can be found in literature. Some of them include both types of exposure conditions, i.e. accelerated ageing and outdoor conditions and they do an attempt to establish relationships between both [1-5]. Other publications only focused on the durability under outdoor conditions [6-9]. In general, the level of damage observed in structures exposed to accelerated ageing in laboratorial conditions is much greater than the one of outdoor conditions.

This paper presents an overview of the ongoing FRPLongDur research project, namely, a brief description of the project, preparation and installation of the specimens and some preliminary results.

2. FRPLongDur description

Figure 1 presents the flowchart of the research project. The main objective of this project is to contribute for the knowledge on long-term structural behaviour and durability performance of RC elements strengthened in flexure with CFRP laminates according to the EBR and NSM techniques under various real environments. The project involves three main components: (i) an experimental program, (ii) numerical simulations, and (iii) design recommendations. Two distinct scales are used: (i) specimens for material and bond characterization, and (ii) full scale slabs. Finally, this project involves three institutions, namely the University of Minho, the Portuguese National Laboratory of Civil Engineering (LNEC) and the Swiss Federal Laboratories for Materials Science and Technology (Empa).

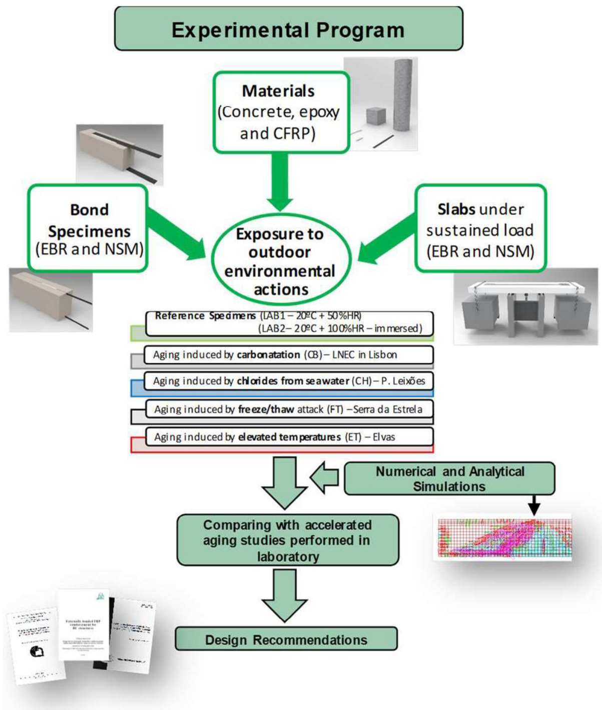

Figure 1. Research project flowchart.

2.1 Specimens

In order to evaluate the materials' durability, a set of specimens was defined including samples of (i) concrete (cylinders of 150 mm diameter and 300 mm high), (ii) epoxy adhesive (dog-boned shaped specimens according to ISO 527-2) and, (iii) CFRP laminate (specimens with different width and 250 mm of length, according to ISO 527-5).

For the assessment of the durability of bond CFRP/concrete systems for both EBR and NSM techniques: (i) EBR bond specimens materialized with concrete prisms with 200×200×400 [mm] were adopted. On their lateral surfaces (parallel to the casting direction), a CFRP laminate with a cross-section of 50×1.2 [mm] was applied over a bond length (L_b) of 220 mm in each side; (ii) NSM bond specimens consisted on a concrete cube (200 mm of edge) with a CFRP laminate (cross-section of 10×1.4 [mm] installed on their lateral surfaces, with L_b = 60 mm were adopted.

The FRPLongDur project also included the execution of full-scale RC slabs. These concrete slabs present a rectangular cross-section of 600×120 [mm] with a total length of 2600 mm. The bottom steel reinforcement was composed of 5 steel bars of 8 mm diameter (4∅8) whereas 3∅6 were used as top steel reinforcement. Steel stirrups of 6 mm diameter spaced at 300 mm were used. A concrete cover of 20 mm was set. Four distinct strengthening solutions were adopted including two non-prestressed (EBR and NSM) and two prestressed systems (MA – mechanical anchorage and GA – gradient anchorage). For the case of the EBR slabs, a CFRP with a cross-section of 100×1.2 [mm] was used. On the NSM slab, four CFRP laminates were used with a cross-section of 10×1.4 [mm]. On both pre-stressed systems (MA and GA), a CFRP laminate with a cross-section of 50×1.2 [mm] was used, with a pre-strain of 0.4%. To assess to the synergic effects of creep and the environmental action (of each selected environmental exposure condition), the slabs were submitted to a sustained load with a magnitude of about 40% of the ultimate load carrying capacity of the corresponding slab under a four-point bending test configuration.

2.2 Environmental exposure conditions

Six different environmental exposure conditions (EEC) were selected. For each one, different experimental stations (ES) were created and placed in Portugal in different sites, representing each one the EEC (see Figure 2). These EEC include: (i) two environments characterized by constant temperature and humidity and no ultraviolet (UV) radiation, LAB1 (20 °C and 55% RH) and LAB2 (specimens immerse in tap water at 20 °C) located at the Structural Laboratory (LEST) of UMinho, Guimarães; (ii) one outdoor environment inducing ageing mainly by carbonation (CB), at the National Laboratory of Civil Engineering (LNEC), Lisbon (-38.77°N, 9.13°W); (iii) one outdoor environment inducing ageing mainly by freeze-thaw cycles (FT), at Lagoa Comprida's Dam (EDP), Serra da Estrela, Seia (40.37°N, -7.65°W); (iv) one outdoor environment inducing ageing mainly by the elevated temperatures (ET), at the factory of S&P Clever and Reinforcement Company, Elvas (38.89°N, -7.15°W); and (v) one outdoor environment inducing ageing mainly by chlorides from sea water (CH), at Porto de Mar de Viana do Castelo (APDL), Viana do Castelo (41.68°N, -8.82°W). The specimens installed in LAB1 and LAB2 are used as control specimens for establishing comparisons with the other EEC's.

2.3 Monitoring and testing

The FRPLongDur project includes the collection of the specimens (material samples and bond specimens) after 1, 2, 3, 4, 6, 8 and 10 years of exposure to perform destructive tests to assess the level of degradation, from physical, chemical and mechanical points of view. For the full-scale slabs, the plan includes periodic monitoring of the following parameters: (i) mid-span displacement, (ii) crack width and depth, (iii) compressive strain on the concrete at mid-span, and, (iv) strains along the CFRP laminate.

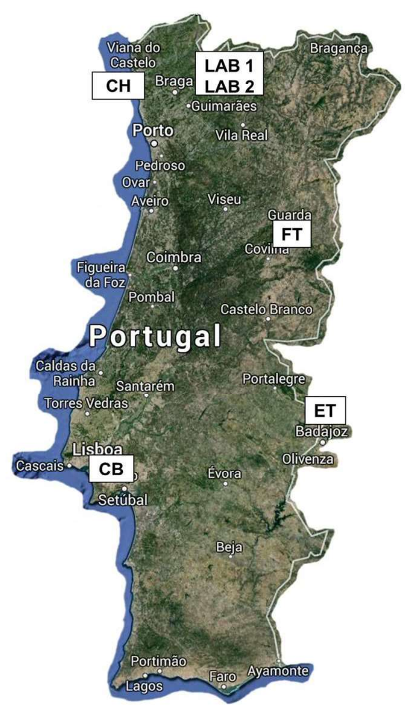

Figure 2. Geographical location of the experimental stations of the FRPLongDur project.

2.4 Numerical and analytical simulations

Based on the results obtained from the behaviour observed on the specimens subjected to the EEC, it is planned to establish numerical and analytical simulations for better understanding the phenomena observed and to extend the ageing tests in order to predict the working service life of this type of structures.

2.5 Correlations between artificial and real ageing conditions

Based on the results obtained from the work described on the previous sections and using also the information on the existing literature, it is planned to establish correlations between the effects caused in the specimens by the artificial at the lab and natural outdoor ageing conditions.

2.6 Design recommendations

The ultimate goal of this project is to establish design recommendations for application of these strengthening systems. In this task, it will be focused on the establishment of parameters able to characterize the long-term degradation of these systems in order to include these parameters in the design procedures.

3. Specimen's preparation and installation of ES

All the concrete specimens were cast from a unique concrete mixture batch (Figure 3). 12 m^3 of fresh concrete were used to cast 140 cylinders, 90 cubes, 90 prims and 30 slabs (see also Section 2.1). In the case of the slabs, prior the concreting, several gauge sensors were installed. A concrete C30/37 XC4(P) CL 0.40 dmax 12.5 S4 was adopted. Steel bars of A400 NR SD were used as reinforcement for the slabs.

Figure 3. Casting.

The installation of the CFRP laminates in the different specimen types, followed the type protocols used with the EBR, NSM, MA and GA techniques. Further information about these aspects can be found in [5, 10, 11].

Currently, the installation of the different experimental stations (ES) is already concluded, as depicted in Figure 4. Typically, *in situ* installation took one day. However, several weeks were necessary for the preparation of all the specimens used in each ES.

4. Preliminary results

4.1 Tests at T0

At the onset of the installation of the ES (T0), an experimental campaign composed of (i) direct pull-out tests on NSM specimens (DPT-NSM), (ii) single-lap shear tests on EBR specimens (SLT-EBR) and, (iii) flexural tests with RC slabs (EBR, NSM, MA and GA), were performed. In addition, tests on samples of the involved materials were also done. These tests were performed for the sake of comparison between aged and unaged specimens.

4.1.1 Bond tests

The T0 experimental campaign includes 8 specimens for assessing the bond performance of EBR and NSM techniques (4 specimens per technique). For EBR specimens, a CFRP laminate with a cross-section of 50×1.2 [mm] with a L_b = 220 mm was applied; and on NSM specimens, it was used a CFRP of 10×1.4 [mm] along a L_b = 60 mm. The specimen's geometry and test configuration adopted for the bond NSM and EBR tests is shown in Figure 5a and Figure 5b, respectively. Additional details about specimen's geometry and test setup can be found in the literature (EBR - [10], NSM - [5]).

Figure 4. Experimental stations of FRPLongDur.

4.1.2 Flexural tests with RC slabs

Details about the experimental campaign with the RC slabs are presented in Table 1. One slab was used as reference slab (SL_REF_T0). The slab SL_NSM_T0 was strengthened with four laminate strips according to the near surface mounted (NSM) technique and the slab SL_EBR_T0 was strengthened with one laminate strip according to the externally bonded technique (EBR). Finally, two slabs were strengthened with one prestressed CFRP laminate strip, using the MA (SL_MA_T0) and GA (SL_GA_T0) systems. Three distinct types of CFRP laminate geometries were used: 10×1.4 mm^2 (NSM), 50×1.2 mm^2 (MA and GA) and 100×1.2 mm^2 (EBR). All the strengthened slabs were designed to achieve approximately the same ultimate load (double the ultimate load of the slab SL_REF_T0). Figure 6 presents the geometry, instrumentation and test configuration of the RC slabs. The instrumentation included LVTDs, strain gauges and load cells. A servo-controlled machine was used to perform the tests, under displacement control at a rate of 1.2 mm/min.

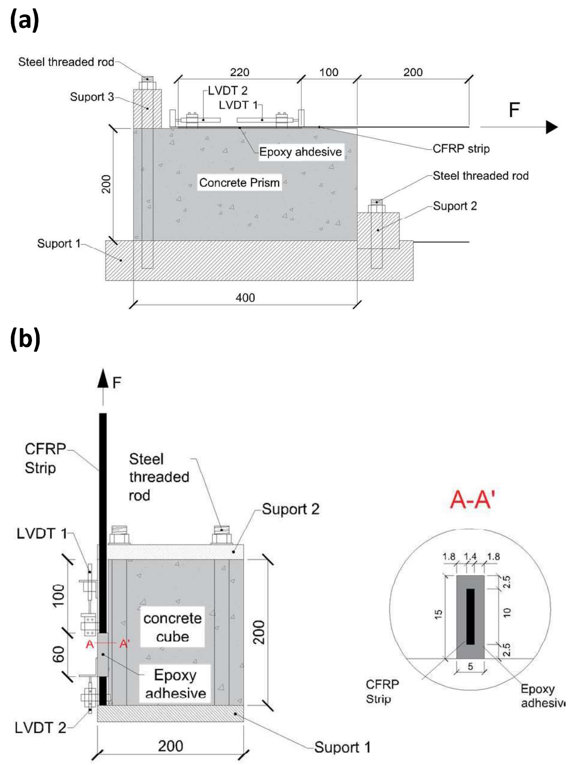

Figure 5. Specimen's geometry and test setup of bond tests of (a) EBR and (b) NSM (units in [mm]).

4.2 Materials

As referred before, all specimens were cast using a single batch. Six cylindrical concrete specimens (diameter/height = 150/300 [mm]) were used to evaluate the modulus of elasticity and compressive strength through the NP EN 12390-13:2013 and NP EN 12390-3:2011 standards, respectively. The average compressive strength and modulus of elasticity of the concrete (age of 28 days) was equal to 41.5 MPa (COV = 4.4%) and 29.1 GPa (COV = 4.7%).

Tensile properties of steel reinforcement were evaluated with the NP EN ISO 6892-1:2012 standard. Four samples with a length of 500 mm of each bar type were tested and the main results - modulus of elasticity, E_s, Yield strength, f_y, and ultimate tensile strength, f_t - are presented in Table 1.

The CFRP tensile properties were also assessed using a minimum of five specimens and the experimental procedure followed was the one described by ISO 527-5:1997. The modulus of elasticity, E_s, and ultimate strength, f_f, of the laminates used in the EBR and NSM bond specimens are equal to 184.3 GPa (2.9%), 185.0 GPa (1.5%), 2980.3 MPa (4.1%) and 2858.2 MPa (2.0%), respectively; in the case RC slab, the values are included in Table 1.

The epoxy adhesive was also characterized during this preliminary experimental campaign. Six specimens were tested according to the ISO 527-2:2012 recommendations. The average value of the modulus of elasticity, ultimate strain, and tensile strength were equal to 6.5 GPa (Cov=3.0%), 0.4% (Cov=6.2%) and 19.9 MPa (CoV=3.0%), respectively.

4.3 Results

4.3.1 Bond tests

Table 2 present the main results obtained in the EBR and NSM bond tests. In this table, F_{max} is the maximum force achieved during the test whereas s_{lmax} is the slip at the loaded end at F_{max}. Finally, FM represents the failure mode observed in the test.

The bond EBR tests present an average maximum shear force of 30.5 kN and the dominant failure mode was cohesive failure at the concrete. According to the CNR [12], the expected maximum strength before CFRP debonding is equal to 505.1 MPa, whereas the mean experimental maximum strength obtained was equal to 508.7 MPa. Therefore, a good correlation between the experimental maximum strength and the expected maximum strength was observed.

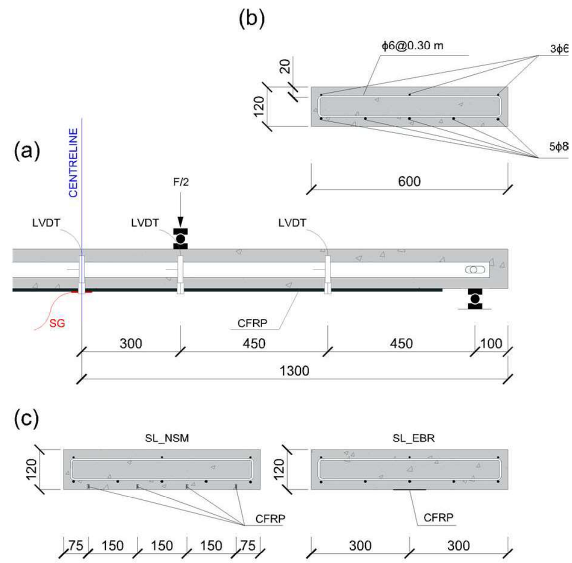

Figure 6. (a) Geometry and test configuration; cross-section for (b) reference slab; and for (c) strengthened slabs. Note: All units in [mm].

Table 1. Experimental programme of RC slabs.

SPECIMEN	CFRP STRIP [mm²]	ANCHORAGE TYPE	ε_{fp} [%]	E_s [GPA]		f_y [MPa]		f_t [MPa]		E_f [GPA]	f_f [MPa]
				Φ6	Φ8	Φ6	Φ8	Φ6	Φ8		
SL_REF_T0	--	--	--	219.9 (1.6%)	209.3 (7.7%)	543.9 (1.8%)	551.2 (0.8%)	670.0 (0.9%)	635.4 (0.5%)	--	--
SL_EBR_T0	100×1.2	--	--							187.2 (0.9%)	2895.2 (4.4%)
SL_NSM_T0	4x (10×1.4)	--	--	241.4 (5.3%)	228.1 (3.2%)	528.2 (0.7%)	581.3 (0.6%)	687.1 (0.7%)	698.3 (0.3%)	185.0 (1.5%)	2858.2 (2.0%)
SL_MA_T0	50×1.2	MA	0.4	219.9 (1.6%)	209.3 (7.7%)	543.9 (1.8%)	551.2 (0.8%)	670.0 (0.9%)	635.4 (0.5%)	184.3 (2.9%)	2980.3 (4.1%)
SL_GA_T0	50×1.2	GA	0.4								

Note: the values between parentheses are the corresponding coefficients of variation (CoV).

Table 2. Main results of EBR and NSM bond tests (average results of 4 specimens).

Series	F_{max} [kN]	s_{lmax} [mm]	FM
SLT-EBR	30.52 (11.61%)	0.53 (15.13%)	D+C[2] C[2]
DPT-NSM	28.21 (2.48%)	0.54 (5.69%)	D[4]

Notes: Values between parentheses are the corresponding coefficient of variations; D = Debonding at laminate-adhesive interface, C = Cohesive failure of concrete, values between brackets are the n. of specimens where this FM occurred.

The maximum pull-out force obtained from the bond NSM tests is close to 28.2 kN. In the CFRP strip (10×1.4 mm^2) this load corresponds to a stress level of 2014.3 MPa, which represents 70.4% of its tensile strength. In comparison to the bond EBR tests, it is clear that with a smaller bonded length (60 mm) the NSM technique can achieve higher ultimate stress levels. These observations have been also observed in other works.

4.3.2 Flexural tests with RC slabs

Table 3 presents the main results obtained from the slab tests and Figure 7 presents the relationship between force and mid-span displacement. In general, all slabs present three test phases: (i) elastic phase, (ii) cracked phase and, (iii) phase after steel yielding. Flexural stiffness K_I is similar in all slabs – 9.1 kN/mm (CoV=12%) – because all strengthened slabs present low amount of strengthening reinforcement.

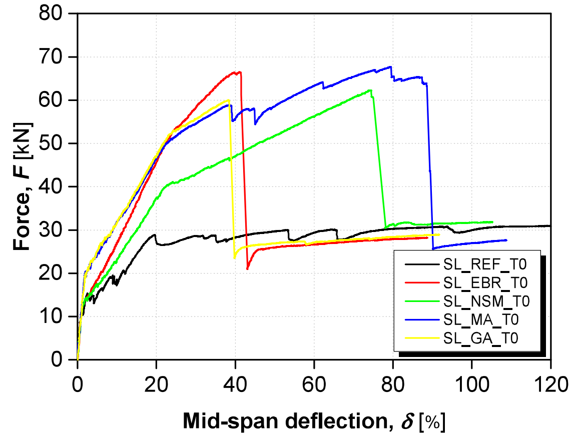

Figure 7. Force vs. mid-span displacement obtained on the slab tests.

In the following stage, the cracking of the concrete reduces the slabs' flexural stiffness K_{II}. The strenghtening, delayed the crak initiation (δ_{cr}, F_{cr}), specially on the prestressed slabs. After the yielding of the steel, the influence of the CFRP reinforceemnt is clearly noticed in the flexural stiffness, K_{III}, of each slab, as the CFRP material becomes responsible to carry the aditional load increments (steel exibits small hardening modulus). The steel yielding occurred for similar loads (F_y) and mid-span deflections (δ_y) in all the strenghtened slabs, except to the SL_NSM_T0, where the F_y was about 77% of the observed in other slabs.

Table 3. Main results of slab tests.

Specimen	Stiffness			Crack initiation		Yielding		Failure			Efficiency and ductility parameters		FM
	K_I [kN/mm]	K_{II} [kN/mm]	K_{III} [kN/mm]	δ_{cr} [mm]	F_{cr} [kN]	δ_y [mm]	F_y [kN]	δ_{max} [mm]	F_{max} [kN]	ε_{fmax} [x10^{-3}]	F_{max}/F_y [-]	δ_{max}/δ_y [-]	
SL_REF_T0	7.51	1.30	--	1.17	12.30	19.58	28.82	120.47	30.96	--	--	--	--
SL_EBR_T0	10.82	1.87	0.98	1.32	12.63	24.64	53.22	41.23	66.47	6.65	1.25	1.67	D
SL_NSM_T0	9.14	1.35	0.44	2.41	14.44	22.28	39.94	74.44	62.28	14.09	1.56	3.34	F
SL_GA_T0	9.95	1.56	0.55	2.00	20.01	23.26	52.04	38.27	59.98	7.00	1.15	1.65	D
SL_MA_T0	10.59	1.57	0.55	2.04	20.41	22.19	49.69	79.24	67.62	12.24	1.36	3.57	F

Notes: K_I, K_{II}, K_{III} = Flexural stiffness at elastic, cracking and yielding stages; F_{cr}, F_y, F_{max} = cracking, yielding and ultimate loads; δ_{cr}, δ_y, δ_{max} = mid-span displacement at F_{cr}, F_y, F_{max}; ε_{fmax} = CFRP laminate strain at F_{max}; F_{max}/F_y and δ_{max}/δ_y = ductility indexes; Failure Modes (FM): D = Detachment of CFRP laminate; F = CFRP rupture.

SL_NSM_T0 failed by CFRP rupture, for the maximum load, F_{max}, of 62.3 kN. Similarly, the prestressed slab SL_MA_T0 also failled by CFRP rutpure when F_{max} = 67.62 kN. The remaining two strengthened slabs (SL_EBR_T0 and SL_GA_T0) failed by CFRP strip debonding. The two prestressed slabs exibit a similar behaviour until steel yielding. At this test stage, the debonding of the CFRP laminate starts to occurr, however, the metalic anchor plates of in the SL_MA_T0 avoided the premature failure, whereas in the SL_GA_T0 (gradient anchorage), the initial CFRP strip debonding was rapidly transformed into the complete strip detachment.

Ultimatly, as proviously referred, each strenghtened specimen was designed to support the maximum load of 60 kN (duplicate the load carrying capacity of the reference slab). The test results confirm that the strenghtening solutions were adequate to achive the predefined goal.

5. Conclusions

The present work presented a general description and the main preliminary results of an ongoing research project whose main goal is to study the long-term structural behaviour and durability performance of RC elements strengthened in flexure with CFRP laminates according to the EBR and NSM techniques, under various real environments.

At the onset of the installation of the experimental stations, an experimental campaign composed of pull-out tests on NSM specimens, single-lap shear tests on EBR specimens, and flexural tests on RC slabs was carried out. From the obtained results the following conclusions can be pointed out: (i) good correlation between the experimental maximum strength and the expected maximum strength was observed with the single-lap shear tests on EBR specimens; (ii) the pull-out tests on NSM specimens showed a more efficient use of the CFRP material (70.4% of its tensile strength) than the EBR specimens; (iii) all the slabs were able to reach the predefined load of 60 kN; (iv) slabs SL_NSM_T0 and SL_MA_T0 presented the highest CFRP strain at failure, thus allowing more efficiency in the use of the CFRP laminate strips.

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