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Creep behavior of RC slabs strengthened NSM CFRP laminate strips under different environmental conditions

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ABSTRACT: With the aim of analyzing the long-term deformational performance of concrete elements flexurally strengthened with the near-surface mounted (NSM) technique, an experimental program has been launched using slab specimens submitted to sustained loads under the following environmental conditions: (i) 20ºC temperature and 55% relative humidity; (ii) immersed in water tank at 20ºC with 0% of chlorides; (iii) immersed in water tank at 20ºC with 2.5% of chlorides; (iv) submitted to wet/dry cycles at 20ºC with 2.5% of chlorides. The slabs are continuously monitored in terms of mid-span vertical deflection and strains (in concrete, CFRP laminate strip and steel reinforcements). The present paper summarizes the preliminary results obtained in this ongoing project.

1 INTRODUCTION

Since the beginning of XXI century the near-surface mounted (NSM) technique using fiber reinforced polymers (FRP) has been developed to increase the load carrying capacity of concrete members (De Lorenzis & Teng 2007). The NSM technique consists on introducing FRP bars into saw cut grooves opened on the concrete cover of the concrete members to be strengthened, whose cross-section can be round, square, rectangular or oval.

Due to the following main advantages, the NSM technique is becoming a real alternative to other techniques, such as the externally bonded reinforcement (EBR), (De Lorenzis & Teng 2007): less proneness to debonding; higher levels of efficacy; reduction of amount of site installation work; more protected against accidental impacts/damages, fire, and acts of vandalism; from the aesthetic point of view is virtually unchanged; and, in some cases, the ultimate strength of FRP can be reached.

When compared with the EBR, the existing knowledge on the NSM reinforcement is much more limited, being the durability and long-term performance two major topics which require significant research. Literature treating these topics is extremely limited. Only a fee works can be found, e.g. Burke (2008), Derias et al. (2008) or Sena-Cruz et a. (2012). Even though these works that have been done with a limited number of specimens, it was clear that aggressive actions such as wet-dry cycles, elevated temperature exposure or salt water spray yielded non-negligible degradation in the ultimate strength compared with reference prototypes. However, this decrease did not surpass 11%.

In the present work preliminary results on the effect of different environmental (moisture, wet-dry) and chemical (chlorides) actions on the creep behavior of RC slabs strengthened NSM CFRP laminate strips is shown. This work is part of an ongoing R&D project “CutInDur - Long-term structural and durability performance of concrete elements strengthened with the NSM technique” which aims to contribute for increasing the knowledge in this area.

2 EXPERIMENTAL PROGRAM

The creep behavior of slabs elements flexurally strengthened with NSM CFRP laminate strips under different environmental conditions have been assessed by using eight slab specimens within an experimental program summarized in Table 1. Two additional slabs were also included in the experimental program: REF (unstrengthened slab) and STR (strengthened slab tested up to the failure). Three environmental actions are considered: prototypes immersed in water tank at 20ºC with 0% of chlorides (Series S2); prototypes immersed in water tank at 20ºC with 2.5% of chlorides (Series S3); and prototypes submitted to a wet/dry cycles with water at 20ºC and 2.5% of chlorides (Series S4). Additionally, reference specimens are kept in the lab environment with an average 20ºC temperature and 55% relative humidity (Series S1). The percentage of chlorides was based on the ASTM D1141-98 (2003), which recommends 24.53 g of NaCl per liter of water. Half of the specimens will be submitted to these environmental actions during 360 days, whereas the other half will continue during more 360 days. At the end of each accelerated aging test, the specimens will be monotonically tested up to failure. The creep load level applied to each slab is about 1/3 of its corresponding ultimate load, given by the results obtained from the STR slab. The code names given to the test series consist on alphanumeric characters separated by underscores (see Table 1). The first string indicates the specimen type (BP and SL). The second string defines the environmental action (REF, PW, CW and WD). Finally, the last string indicates the number of days that the specimen will be submitted to the environmental action.

Table 1. Experimental Program

Series	Environmental Program	Slab Specimens
S0	-	REF and STR
S1	Lab environment	SL_REF360, SL_REF720
S2	Prototypes immersed in tap water at 20ºC	SL_PW360, SL_PW720
S3	Prototypes immersed in water at 20ºC with 2.5% of chlorides	SL_CW360, SL_CW720
S4	Prototypes submitted to wet/dry cycles with water at 20ºC with 2.5% of chlorides	SL_WD360, SL_WD720

2.1 Materials and material characterization

2.1.1 Concrete

Only one batch of 3.6 m^3 was used to cast all the specimens included in the R&D Project CutInDur. The supplied concrete has the following properties: concrete strength class - C25/30, according to Eurocode 2 (2004); cement strength class - CEM 42.5 (type II); maximum aggregate size - 12 mm; exposure class XC4, according to Eurocode 2 (2004). In addition to the tests performed at 28-days, compression tests at 190-days of age were conducted according to the recommendations NP EN 12390-3:2011 (2011). This age coincides with the test of the STR slab. At this time the average concrete compressive strength in cylinders was 49.64 MPa, with a coefficient of variation (CoV) of 3.6%.

2.1.2 Steel reinforcement

The slabs were reinforced with steel bars of 6 mm of diameter. Tension tests according to NP EN 10002-1:1990 (1990) were performed to assess to its mechanical characteristics. The average value of the modulus of elasticity, hardening modulus and ultimate strength were, respectively, 212.2 GPa (CoV=6.3%), 0.7 GPa (CoV=6.6%) and 733.0 MPa (CoV=1.0%).

2.1.3 CFRP laminate strips

The CFRP laminate strip used in the present experimental program has a rectangular cross-section with 10×1.4 mm^2 and is produced by S&P® Clever Reinforcement Company. Five specimens were used to assess to the Young's modulus and tensile strength of the CFRP laminated according to ISO 527-5:1997(E) (2011). A Young's modulus and tensile strength of 178 GPa (CoV=0.6%) and 2858 MPa (CoV=2.4%) were obtained, respectively.

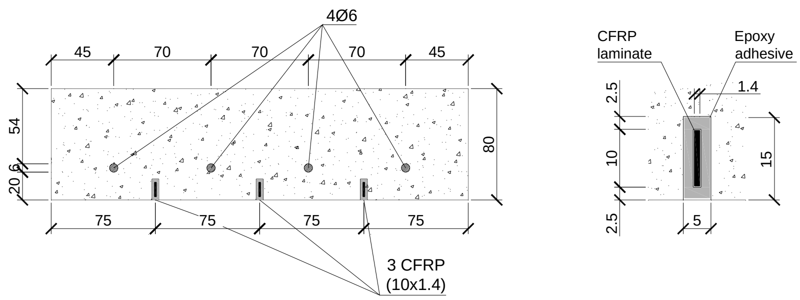
2.1.4 Epoxy adhesive

The epoxy resin produced by the same supplier was used to bond the CFRP laminate strips to concrete. This adhesive has the trademark "S&P Resin 220". Tests performed by Michels et al. (2013) with 6 specimens have revealed that this epoxy cured at room temperature, at 7-days of age, has an average Young's modulus and a tensile strength of 7.7 GPa (CoV=3.1%) and 20.7 MPa (CoV=9.9%), respectively.

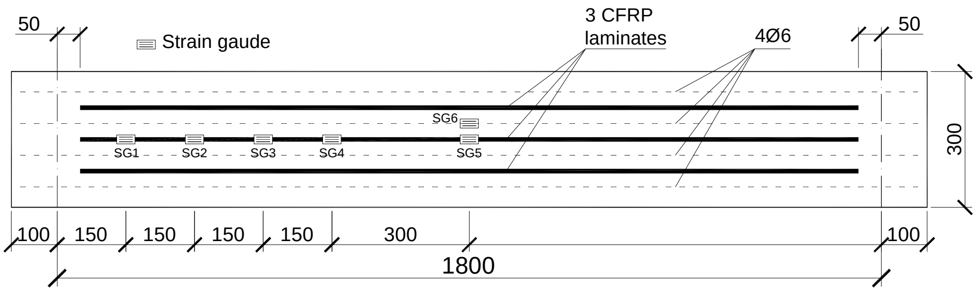
2.2 Specimens and test configuration

Figure 1 presents the cross-section geometry and reinforcement detailing, as well as the instrumentation and test configuration of the slabs. The slabs are 2000×300×80 mm^3 long. The longitudinal steel reinforcement is composed by 4Ø6, which corresponds to a longitudinal reinforcement ratio, ρ_l, equal to 0.47%. The NSM flexural strengthening solution is composed by 3 CFRP laminate strips. The corresponding equivalent longitudinal reinforcement ratio is 0.68%. LVDTs, load cell and strain gauges are used to measure distinct parameters of the slabs tested up to failure: 5 LVDTs measure the deflection along the slab's longitudinal axis; the load cell records the applied vertical force; 5 strain gauges (SG1 to SG5) are glued on the lateral surface of the intermediate CFRP to measure the strains in distinct sections; 2 additional strain gauges (not included in the drawing Figure 1) are used to record the strains in the longitudinal reinforcement and concrete at the top fiber of the cross-section mid-span. The internal displacement transducer of the servo-control equipment is used to control the test at 20 μm/s of deflection rate.

During the creep accelerated aging tests only the strains, the deflection at midspan and applied force are measured. With the aim of having a redundant system for reading the midspan deflection, the LVDT3 and one mechanical dial gage located at the opposite lateral face of the midspan slab are used.



(a)



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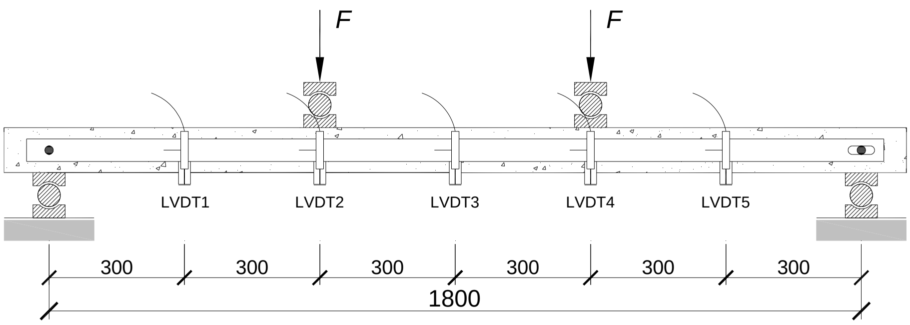


(c)

Figure 1. Slab specimens: (a) Cross-section geometry and reinforcement detailing; (b) Longitudinal geometry, reinforcement detailing and gauge instrumentation; (c) Test configuration. Note: all units in [mm].

2.3 Preparation of specimens

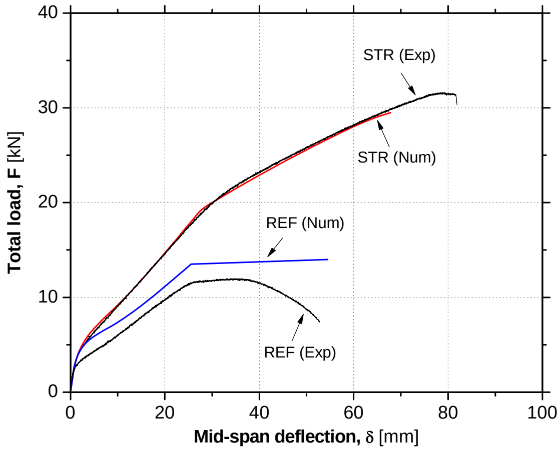
The preparation of the strengthened specimens required several steps. These steps are quite well detailed in the literature, e.g. De Lorenzis & Teng (2007). The strengthening of the specimens occurred at about 75 days after concreting. At this moment the opened grooves were completely dry and clean. The strengthening was performed in the interior of the lab with an average temperature of about 25ºC and 42% of relative humidity. All the tests have been done at the Structural lab of the University of Minho.

3 RESULTS

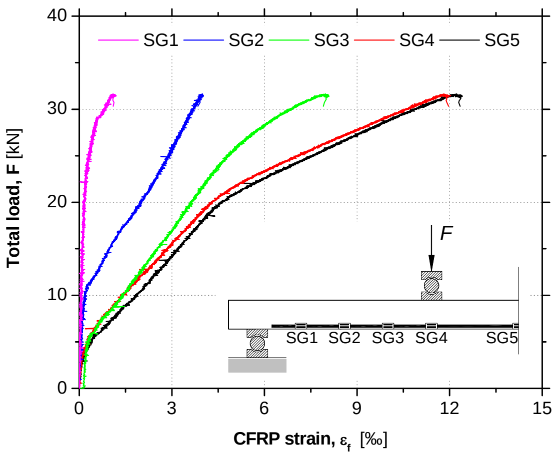
3.1 Monotonic tests

As previously referred, before starting the creep studies under distinct environmental conditions, monotonic tests were performed up to failure (see Table 1). Figure 2(a) shows the relationship between total load and midspan deflection, whereas Figure 2(b) illustrates the total load *versus* CFRP strain at different locations (STR slab). Table 2 presents the main results obtained for REF and STR slabs. In this table (δ_{cr}, F_{cr}), (δ_y, F_y) and (δ_{max}, F_{max}) are the midspan deflection and applied load for crack initiation, yield initiation of the longitudinal reinforcements and maximum load, respectively. This table also presents the ductility index (μ) reached in each test, defined as the δ_{max} / δ_y ratio, as well as the failure mode.

The results have shown the expected excellent performance of the NSM strengthening solution, when compared with unstrengthened slab. This performance is clear at different levels, mainly in terms of deflection and load carrying capacity at crack and yielding initiation, ultimate load, ductility and in terms of strain attained in the CFRP, at about 12‰.



(a)



(b)

Figure 2. (a) Relationship between total load and midspan deflection for REF and STR slabs: experimental and numerical results; (b) Total load *versus* CFRP strain at different locations (STR slab).

Table 2. Main results obtained in monotonic tests

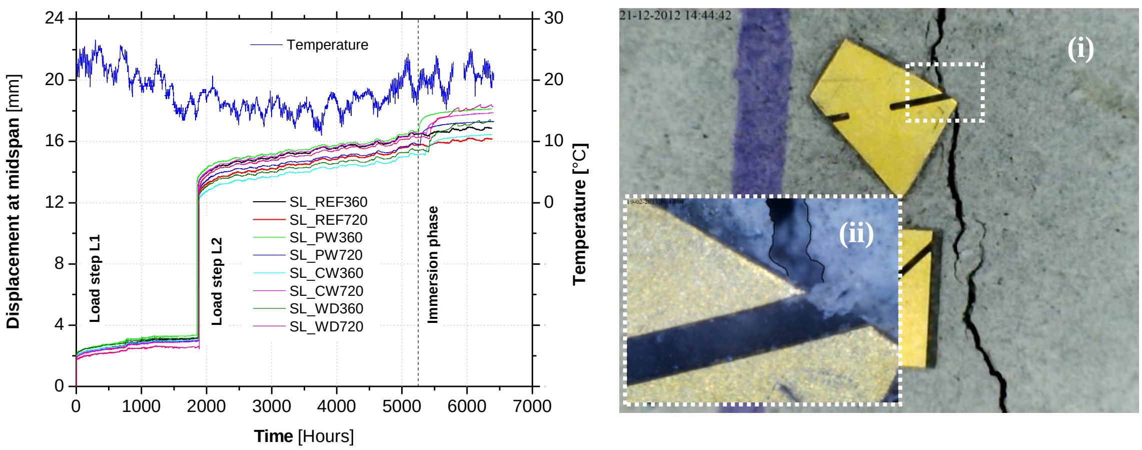
Slab	Crack initiation		Yielding		Ultimate		μ	Failure mode
	δ_{cr} [mm]	F_{cr} [kN]	δ_y [mm]	F_y [kN]	δ_{max} [mm]	F_{max} [kN]		
REF	1.03	2.57	25.11	11.42	52.80	12.03	2.10	CC
STR	1.47 (42.7%)	3.89 (51.4%)	32.92 (31.1%)	21.04 (84.2%)	86.30 (63.4%)	31.63 (162.9%)	2.62 (24.8%)	CC

Notes: the values between parentheses are the variation of the corresponding parameter when compared with the REF slab; CC – Concrete crushing.

3.2 *Creep tests*

The total creep load applied in each slab was 10 kN, which corresponds approximately to 1/3 of its corresponding ultimate load (see Figure 2(a)), as previously referred. For that purpose mixed concrete/steel profiles and rock blocks were used for applying this sustained load. The creep load was applied into two steps (L1 and L2). In the first load level (L1), at about 40% of the total creep load was applied, which caused an instantaneous deflection of about 2 mm for all the slabs (see Figure 3(a)). This deflection is in agreement with the results obtained in the monotonic test of slab STR (see Figure 2(a)). The differences between the deflections in the first step can be justified by the difference of the sustained loads used in each slab during step L1 (limited to 0.7 kN). At the second creep load step (L2), suitable adjustments were made in order to assure the same load level for all the slabs (10 kN per slab). Even so, a slight difference between the midspan deflections for the 8 slabs remained. After applying the creep load of step L2, the average deflection at midspan was about 13 mm, against the 11.5 mm obtained in the monotonic test of STR slab. The aging tests (see Table 1) started at about 5200 h after the beginning of the creep tests. During the immersion phase a non-negligible increment in terms of deflection was observed. This behavior may be explained by the thermal shock caused by the temperature of the water used, when compared with the temperature of the specimens.

Analyzing the evolution of midspan deflection for steps L1 and L2 due to creep phenomena, the deflection changed from 2.0 mm to 3.2 mm (a variation of about 60%) in 78 days (duration of step L1) and from 13.2 mm to 15.4 mm (a variation of about 17%) in 140 days (duration of step L2), respectively. After the immersion of the specimens, the behavior seems to be similar to the previous steps.



(a) (b)

Figure 3. (a) Evolution of the midspan deflection with the time for all the slabs to be submitted to accelerated aging actions; (b) Images taken with microscope: (i) 20 times amplification; (ii) 400 times amplification.

The cracks width of 4 slabs included in this ongoing project has been 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×. At the maximum magnification level, the field of measurement has about 1 mm by 0.75 mm, which means that each pixel corresponds to approximately 1.6 μm. To determine accurately the crack widths, the measurement procedure was based on the use of integrated circuits that were glued next to the cracks (as shown in Figure 3(b)): the thickness of the markers engraved in every utilized circuit was previously measured (approximately 180 μm), which enabled calibration during measurements for every captured image. The crack width measurements were first taken at several points of the cracks with 20× magnification (see Figure 3(b)) and afterwards confirmed through localized measurements at 400× magnification, as illustrated in Figure 3(b). The crack width measured ranges in between 0.18 mm and 0.22 mm. These values are in the range of acceptable values according to Eurocode 2 (2004). In fact the maximum admissible crack width of reinforced members is generally marked as 0.3 mm (for most environmental exposure conditions).

4 NUMERICAL MODELING

A cross-sectional fiber model was developed to support the analysis of current and further results. This own-made software named SECTION (Sena-Cruz 2013), assumes that a plane section remains plane after deformation and perfect bond exists between distinct materials. The concrete part of cross section is discretized with 4-noded quadrilateral elements allowing the analysis of sections of irregular shape and size. The material model apply to each quadrilateral element may vary from element to element thus allowing for the consideration of non-constant concrete properties in the cross section. A 2×2 Gauss-Legendre rule is adopted to evaluate the integrals related to each 4-noded finite element used in the discretization of the cross section. The contribution of the reinforcements is simulated with discrete elements. By imposing the axial force and varying the curvatures (in one or the two principal directions) it is possible to obtain the bending moment *versus* curvature relationships. Using the flexural stiffness derived from the bending moment *versus* curvature relationship, the force *versus* deflection relation of elements like beams or slabs failing in bending can be estimated. This computational tool is also included in SECTION software.

Numerical simulation of the REF and STR slabs was carried out with the SECTION software. For that purpose the model included in MC90 - Model Code 1990 (1993) to simulate the concrete under compression stress states was used. Linear elastic behavior was assumed for concrete under tension up to peak load. Then, the bi-linear tension *versus* crack opening model also included in MC90 (1993) was used to simulate tension softening phase of concrete. All the parameters required for both models (Young's modulus, tensile peak stress, fracture energy and crack band width) were estimated based on the evaluated compressive strength (see Section 2.1.1) and by using the expressions proposed by MC90. Bi-linear model was adopted for the simulation of the steel reinforcement with the mechanical properties included in Section 2.1.2. Lastly, a linear elastic behavior up to the peak was assumed for the CFRP laminate strips with the mechanical properties included in Section 2.1.3.

Figure 3(a) includes the results obtained numerically for the REF and STR. For the latter excellent agreement between numerical prediction and experimental results can be observed. For the case of the REF, the model slightly predicted higher values when compared with the experimental ones.

5 CONCLUSIONS

In order to assess to the behavior of slabs strengthened with NSM CFRP laminates strips submitted to creep tests under different environmental conditions an experimental program was launched. The present work presents the current results of these ongoing tests, which not include the effect of the different environmental conditions. Firstly, a reference slab (STR) monotonically tested up to the failure was used to define the creep load to be applied to the slabs under sustained load (creep). A creep load of 10 kN was adopted, which corresponds at about

33% of the load carrying capacity of the STR slab. After 265 days, the average creep deformation for all the 8 studied slabs was about 4.5 mm, which corresponds at to about 28% of the total deflection. Up to now, it is not possible to appraise the influence of the distinct environments on the global response of system. The crack widths are also monitored, being the current value at about 0.2 mm. A numerical sectional model was developed in ambit of the present R&D Project, being the obtained numerical simulations in agreement with the experimental results, especially for the STR slab.

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