BEHAVIOUR OF CONCRETE ELEMENTS STRENGTHENED WITH NEAR SURFACE MOUNTED CFRP STRIPS UNDER THERMAL CYCLES

Patrícia SILVA
PhD student, ISISE, University of Minho, Portugal
patricia.silva@civil.uminho.pt

Pedro FERNANDES
PhD student, ISISE, University of Minho, Portugal
pfernandes@civil.uminho.pt

José SENA-CRUZ
Associate Professor, ISISE, University of Minho, Portugal
jsena@civil.uminho.pt

Miguel AZENHA
Assistant Professor, ISISE, University of Minho, Portugal
miguel.azenha@civil.uminho.pt

Joaquim BARROS
Full Professor, ISISE, University of Minho, Portugal
barros@civil.uminho.pt

ABSTRACT: The present work intends to contribute for the knowledge on durability performance of the near-surface mounted (NSM) strengthening technique, which is an issue that still requires significant research effort. For that purpose, an experimental program was developed using cubic pullout and slab specimens strengthened with NSM carbon fiber reinforced polymer (CFRP) strips. These specimens were submitted to thermal cycles in order to study the effect of this environmental action on the effectiveness of the NSM technique. The thermal cycles were defined according to the EN 13687-3 standard. After being submitted to this action during up to eight months, the specimens were monotonically tested up to failure using four-point bending and pullout direct test configurations for slabs and cubic specimens, respectively. To compare the performance of these specimens with non-aging ones, control specimens were also tested. The obtained results indicate that the loading capacity of the slabs and damage mechanism were not affected by thermal cycles. Nevertheless, the bond strength increased with the number of thermal cycles. Therefore, these results suggest that the concrete elements strengthened with CFRP NSM technique are not susceptible to temperature in a range of -15°C to 60°C.

1. Introduction

During the last few years, the near-surface mounted (NSM) strengthening technique using fiber reinforced polymers (FRP) has been adopted to increase the load carrying capacity of reinforced concrete (RC) members. The existing research on the NSM technique mainly focuses on structural aspects (De Lorenzis and Teng, 2007). Nevertheless, some issues associated to the long-term behavior and durability still need to be clarified.

The temperature action is one of the main environmental degradation factors that can affect detrimentally the durability of RC structures. The available literature about the behavior of RC structures strengthened with NSM CFRP strips or rods submitted to temperature variation is scarce. Nonetheless, a few studies with high (>100°C) and low temperatures (~ -25°C) and freeze and thaw cycles (~ -25°C to 21°C) can be found in the literature. In terms of loading capacity and post-cracking stiffness, Burke *et al.* (2008) concluded that the strengthened slabs with CFRP strips according to the NSM technique were not affected after being submitted to constant low temperatures. The authors performed another experimental work with slabs under sustained service loads, being these slabs capable of withstanding over 40 min at

100°C and 30 min at 200°C, after which the failure mode occurred by debonding at the adhesive-concrete interface. The tests performed with epoxy resin specimens indicated significant losses in terms of resistance at elevated temperature, since the experimental tests occurred at temperatures exceeding considerably the glass transition temperature (T_g) of the used epoxy adhesives (Burke *et al*., 2013).

Palmieri *et al.* (2011) studied the bond behavior between NSM FRP strips and concrete at elevated temperatures (from 20ºC to 100ºC), through double shear tests. The results indicated that the T_g of epoxy adhesive had a significant influence on the bond strength and failure load of NSM-FRP system. For temperatures above of T_g the failure mode changed from the splitting of adhesive (at 50ºC) to the FRP pullout (at 100 ºC). In the study reported by Yu and Kodur (2014), concrete specimens were strengthened using NSM CFRP strips/rods and tested to evaluate bond strength in 20-400ºC temperature range. Firstly, specimens were heated to a target temperature, with a rate at 5-10ºC/min, and then the pullout tests were carried out. The authors concluded that the bond strength of the system at 200ºC decreased by ~80% when compared with that of control specimens tested at 20ºC.

This paper details an experimental program aiming to study the behavior of strengthened structures with NSM CFRP strips submitted to thermal cycles. Two different scales were used: the mesoscale by executing pullout specimens in order to evaluate the bond behavior and the full scale, in which slab specimens were used to assess the overall structural behavior.

2. Experimental program

Two strengthened slabs (SL) and eight direct pullout specimens (DPT) were submitted to thermal cycles in a climatic chamber (CC) during eight months. Moreover, twenty eight additional specimens were submitted to the same thermal conditions: four plain concrete specimens, twelve CFRP laminates and twelve epoxy specimens. The strengthening of the specimens occurred at about 86 days after concrete casting, and subsequently they were kept in laboratory environment (20°C ±5C) during five months until the beginning of the thermal cycles test. The thermal cycle was defined based on EN 13687-3:2002 standard, with a duration of twenty-four hours for cycle. As shown in Fig. 1, the applied temperatures ranged between -15°C and 60°C, with plateau that lasted for 12.5 and 10 hours for these two extreme temperature values. The temperature transition took 1.5 hours. Despite the target of 95% for the relative humidity (RH), there was a linear variation between 55% and 20% when the temperature was 60°C, and between 20% and 85% when the temperature was -15°C. This situation occurred due to the technical limitations of the CC. In this study was not intended to surpass the glass transition temperature (T_g) of epoxy adhesive (in between 55-60°C). At the end of 120 cycles (4 months), half of all specimens were removed from the CC and tested. Thereafter, the remaining specimens were kept during more 120 cycles (a total of 240 cycles). Reference specimens (R) (non-aging specimens) were kept in laboratory environment and also tested at the same time of the other specimens (SL, DPT, concrete, laminate and epoxy). Fig. 1 includes also results in terms of temperature into groove in epoxy adhesive. A slight delay can be found between the temperature in the interior of the CC and of the groove.

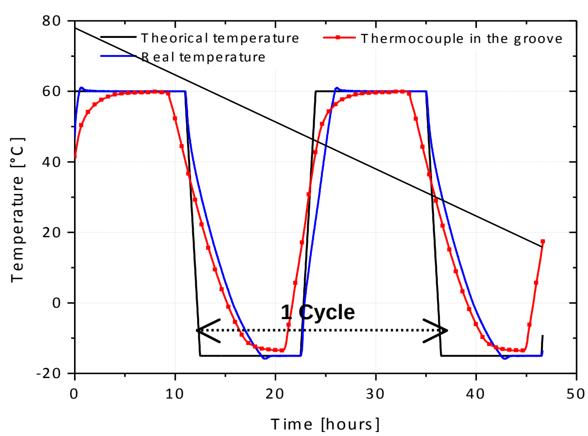

Fig. 1 – Measurements in terms of temperature: imposed, measured in the climatic chamber and in the groove.

2.1. Specimens and test configuration

Fig. 2 (a) and (b) show the geometry and test configuration of the direct pullout tests. The specimens' geometry consisted of concrete cubic blocks of 200 mm edge, into which a CFRP (10x1.4 mm^2) was embedded. The bond length started 100 mm far from the top of the block to prevent the premature splitting failure in the concrete ahead the loaded end. To guarantee negligible vertical displacement at the top of the concrete specimen during pullout test, a steel plate with 20 mm thickness was applied at the top of the concrete block. This plate was fixed to the base through four M10 steel threaded rods. A torque of 30 N×m was applied to fasten these rods, inducing an initial compression in concrete of about 2.0 MPa. The instrumentation of the specimens consisted of one displacement transducer (LVDT) and a load cell. The LVDT records the slip at the loaded end, s_l. The tests were controlled by another LVDT placed between the actuator and the grip, at rate of 2 µm/s. The applied force, F, was registered by a load cell placed between the grip and the actuator.

Fig. 2 (c) and (d) depict the geometry and test configuration/instrumentation of the slabs. The slabs are 2000 mm long, 300 mm wide and 80 mm thick. The longitudinal reinforcement is composed by 4Ø6, which corresponds to a longitudinal reinforcement ratio, ρ_l, equal to 0.47%. The flexural strengthening solution is composed by 3 NSM CFRP (10×1.4 mm^2) laminate strips, in correspondence to an equivalent longitudinal reinforcement ratio, $\rho_{s,eq}$, of 0.68%. In this experimental study, a four-point bending test configuration was adopted. The internal displacement transducer of the servo-control equipment is used to control the test at 20 µm/s. The instrumentation of the slab in the tests includes 5 LVDTs, a load cell and strain gauges (SG). Five SG were glued on the lateral surface of the intermediate CFRP to measure the strains at distinct sections. Two additional SG are also used to record the strains in the longitudinal reinforcement and concrete at the top fiber of the cross-section mid-span. Additionally, a K-type thermocouple was installed in the groove for temperature measurement. All the information related to the preparation of the strengthened specimens (SL and DPT) is available elsewhere (Sena-Cruz *et al.*, 2013). The strengthening was performed in the laboratory with a temperature of about 25ºC and 42% of RH.

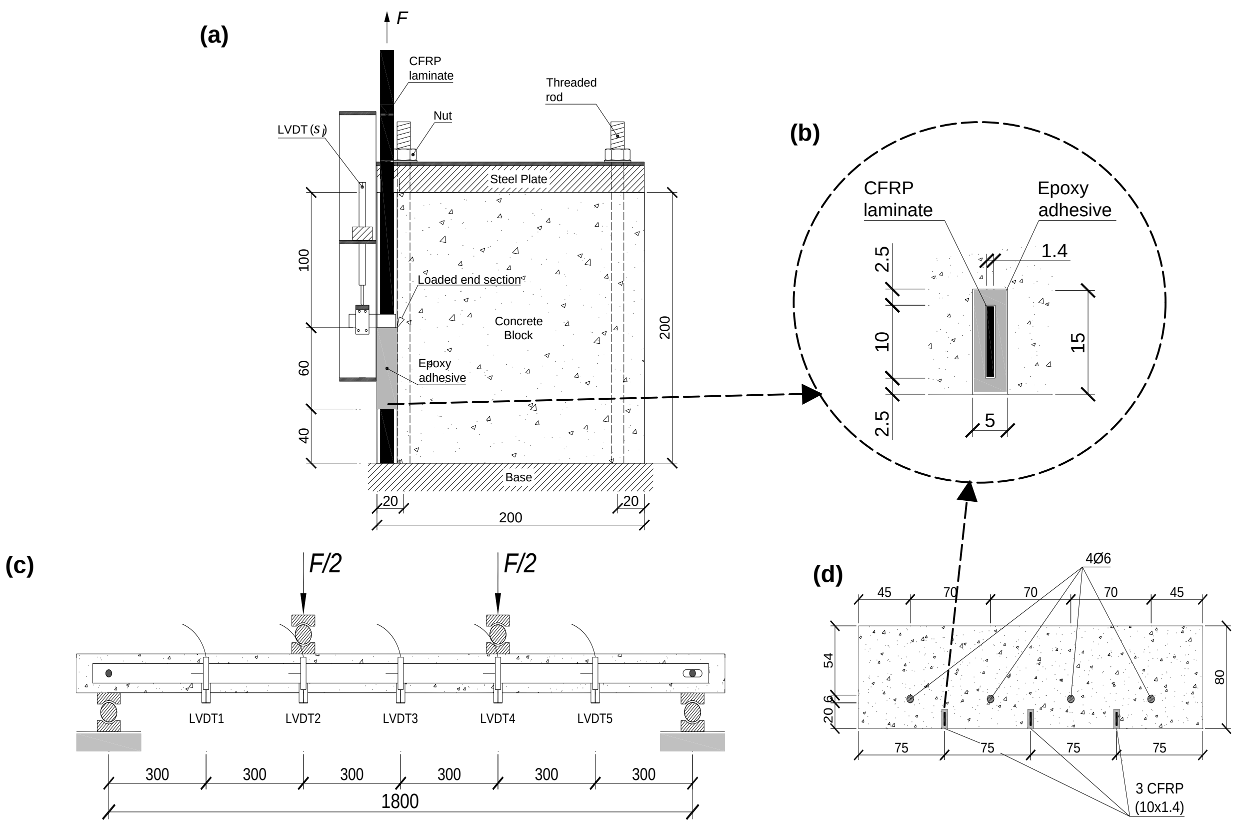

Fig. 2 – Tests configuration: (a) direct pullout specimen; (b) geometry details of the strengthening; (c) slab specimen; (d) slab cross-section (dimensions in mm).

2.2. Materials characterization

Table 1 includes the mechanical properties of the materials. The steel of the longitudinal reinforcement bars was characterized according to NP EN 10002-1:1990. The CFRP laminate strip and the epoxy adhesive used in the present experimental work was characterized according to ISO 527-5:1997 and ISO 527-2:1993, respectively. The obtained results are the average from the six tested specimens.

Table 1 – Mechanical properties of the materials – non-aging specimens (average values).

	Compressive strength [MPa]	**Modulus of elasticity** [GPa]	**Tensile strength** [MPa]
Concrete	52.3* (2.49%); 48.2** (3.19%)	-	-
Steel	-	212.2 (6.3%)	733.0 (1.0%)
CFRP	-	169.5*,** (2.5%)	2648.3*,** (1.8%)
Epoxy	-	7.21* (3.7%); n/a**	22.0* (4.5%); 20.7** (1.0%)

Notes: Control specimens tested at the same age of the aging specimens with 120* and 240** thermal cycles; values in parenthesis are the corresponding coefficients of variation (CoV).

3. Results and discussion

3.1. Concrete, laminate and epoxy

Fig. 3 (a) presents the strength variation observed in the materials (concrete, epoxy adhesive and laminate) in regard to reference specimens. The strength variation is defined as the ratio (TC – REF) / REF, with TC and REF corresponding to the strength of a generic material/series submitted to thermal cycles and the corresponding reference series at the same age, respectively. From these results it is clear that the aging action neither damaged the CFRP laminate nor the concrete. For the epoxy adhesive, the results show that the tensile strength increased of about 18% and 32% when the specimens were submitted to 120 and 240 thermal cycles, respectively. In the technical and safety data sheet of the product (epoxy) provided by the supplier, there is no information available about the curing and post-curing process. However, based on literature review about this topic it is possible to conclude that depending on the type of epoxy resins is common a post-curing phase that increase the final mechanical properties of the material (Moussa *et al.*, 2012). The post-curing process happens when the material is submitted to a temperature higher than of the first cure.

3.2. Pullout specimens

Fig. 3 (b) depicts the average pullout force *versus* loaded end slip (F_l-s_l) relationship of all the bond test series, whereas Table 2 includes the corresponding results. In this table, F_{fmax} is the maximum pullout force; s_{lmax} is the loaded end slip at F_{fmax}, $\tau_{max,av1}=F_{fmax}/(P_f\, L_b)$ is the average bond strength at the CFRP-epoxy interface, being P_f the perimeter of the CFRP cross-section and L_b is the bond length.

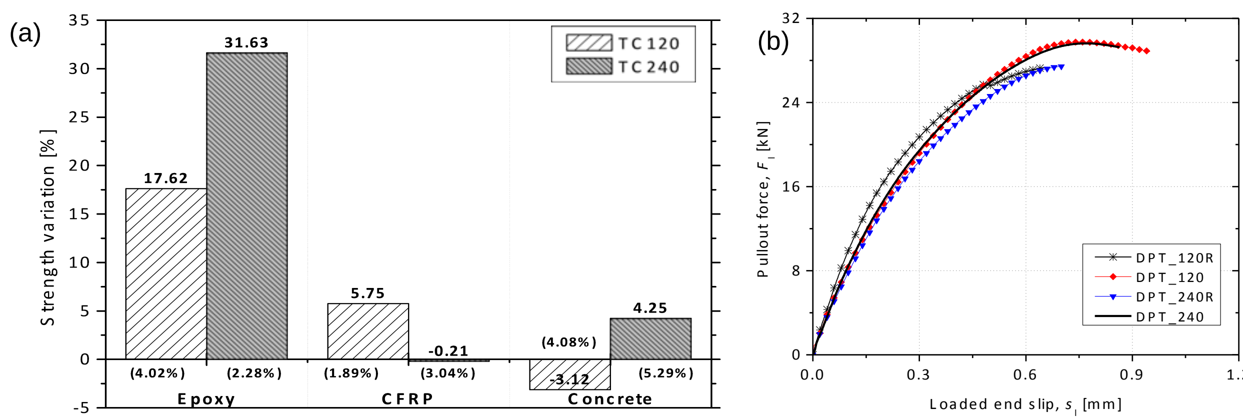

Fig. 3 – (a) Strength variation of the materials; (b) Pullout force *versus* loaded end slip.

The variation of maximum pullout force obtained from the experimental program is plotted in Fig. 4 (a). From these results it is clear that the thermal cycles improved the bond behavior, yielding to higher values of F_{fmax}, $\tau_{max,av1}$ and s_{lmax}, when compared with the reference specimens, although the high value of CoV obtained from loaded end slip of the reference specimens (DPT_120R). Two failure modes were observed in this experimental program (see Table 2): concrete splitting (C) and debonding at adhesive/laminate interface (D). Concrete splitting was characterized by a large area of detached concrete surrounding the bonded region. The occurred failure modes (mainly D) and the behavior observed for the epoxy under the thermal cycles (see section 3.1) justify the obtained bond performance.

Table 2 – Main results obtained in pullout tests (average values).

Series	F_{fmax} [kN]	s_{lmax} [mm]	$\tau_{max,av1}$ [MPa]	Failure mode
DPT_120R	28.02 (5.83%)	0.64 (24.59%)	20.28 (5.83%)	D(2)*; D+C(2)*
DPT_120	29.88 (1.57%)	0.75 (7.58%)	21.84 (1.57%)	D(2)*; D+C(2)*
DPT_240R	27.48 (3.45%)	0.70 (2.74%)	20.08 (3.45%)	D(3)*
DPT_240	29.75 (1.91%)	0.76 (7.27%)	21.75 (1.91%)	D(2)*; D+C(2)*

Note: the values in parentheses are the CoV; D - Debonding at adhesive/laminate interface; C - Concrete splitting; *the value between parenthesis is the number of specimens with this type of failure mode.

3.3. Slabs specimens

After being submitted to the thermal cycles during four and eight months, the slabs were tested monotonically up to the failure. Fig. 4(b) shows the obtained relationship between total load and mid-span deflection of the reference and aged slabs. When compared with the reference slabs, a negligible strength variation is observed (see Fig. 4(a)) for the aged specimens. This result was expected once mechanical properties of concrete and CFRP were not affected, whereas the ones of the epoxy adhesive were improved. Despite of the epoxy adhesive properties have improved, this benefit did not affect the structural member response, since the failure mode was controlled by the concrete properties.

Table 3 presents the values of the deflection and corresponding load at crack initiation, yielding and ultimate. Despite the load capacity of the slabs do not have been affected by thermal cycles, the CFRP strain of the SL_120 had a decrease of about 20% comparing to the reference slab (SL_120R). For the slab SL_240 it is not possible to define this value due to the malfunctioning of the SG. All the slabs failed by concrete crushing, except the SL_120R, which failed in shear. Once this failure mode was only verified in one slab, a plausible explanation could be related to a problem with vibration process during concreting. Moreover, it is worth remarking that the crack pattern observed in this slab revealed a higher concentration of cracks in the vicinity of the failure section, as opposed to the smeared crack nature over the mid-span observed in the remaining slabs.

(a)

(b)

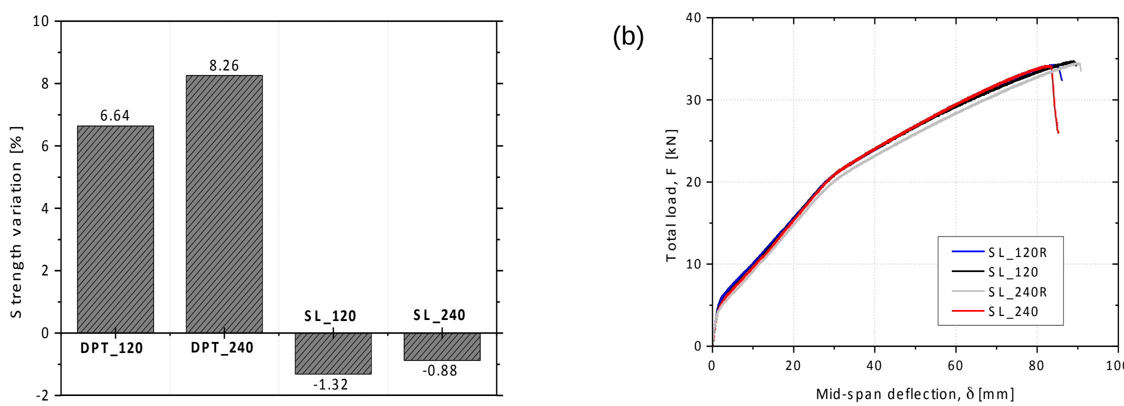

Fig. 4 – (a) Strength variation; (b) Total load *versus* mid-span deflection of all slabs.

Table 3 – Experimental results of the slabs monotonic tests.

Slab	δ_{cr} [mm]	F_{cr} [kN]	δ_y [mm]	F_y [kN]	δ_{max} [mm]	F_u [kN]	ε_f [‰]	**FM**[a]
SL_120R	1.75	4.95	29.67	20.76	89.64	34.75	14.18	SF[b]
SL_120	1.84	5.52	29.13	20.56	86.60	34.29	11.58	CC[c]
SL_240R	1.32	4.17	29.34	19.79	90.79	34.47	14.82	CC
SL_240	1.78	4.82	29.44	20.67	85.22	34.15	n.a.	CC

Notes: [a] FM – failure mode; [b] SF – shear failure; [c] CC – concrete crushing.

4. Conclusions

The present work summarizes a study on the effect of thermal cycles (in the range -15°C to 60°C) on concrete specimens strengthened with NSM-CFRP. The specimens were submitted to four and eight months of thermal cycles, and then they were tested up to the failure in order to evaluate the corresponding performance. The epoxy adhesive showed a higher strength with the application of the thermal cycles. Negligible variation was found for the other materials (concrete and CFRP). The results for the direct pullout tests showed a slight increase in terms of bond strength, but the failure mode was not influenced by the thermal cycles. The behavior of the slabs was not changed by this thermal action in terms of load carrying capacity.

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