EXPERIMENTAL INVESTIGATION OF RC SLABS STRENGTHENED WITH NSM CFRP SYSTEM SUBJECTED TO ELEVATED TEMPERATURES UP TO 80 °C

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ABSTRACT

The application of carbon fibre-reinforced polymers (CFRP) according to the near-surface mounted (NSM) technique has proved to be one of the most effective systems to strengthen existing reinforced concrete (RC) members in flexure. In spite of that, there are many open issues that deserve investigation such as the effects of exposure to elevated temperatures on the flexural behaviour of RC slabs strengthened with NSM-CFRP systems. The present work aims to experimentally evaluate the mechanical performance of RC slabs strengthened with NSM-CFRP systems under elevated temperatures by using steady-state and transient heating situations combined with applied loads. The temperatures studied were: 20, 40, 50, 70 and 80 °C for the steady-state tests, and 20 and 80 °C for the case of transient tests. Deflections, strains, temperatures and loads were registered in all phases of the tests, in order to thoroughly analyse the response of the system in terms of the load-deflection curves, evolution of the strains of concrete, CFRP and bond stresses between epoxy adhesive and CFRP. The experimental results have shown that the RC slabs strengthened with NSM CFRP systems presented a slight decrease in the ultimate strength and a change on failure mode at the temperature of 80 °C only.

KEYWORDS

Concrete, NSM CFRP, RC slab, strengthening, elevated temperatures.

INTRODUCTION

In the last few decades, the application of near-surface mounted (NSM) technique by using carbon fibre reinforced polymers (CFRP) has been increasingly used in the strengthening of reinforced concrete (RC) structures. One of the key aspects in the structural strengthening performance of a system is its response to the environmental conditions. In the case of structures strengthened with epoxy adhesives, the environmental temperature plays an important role, limiting the application rang of such adhesives due to the glass transition temperature (T_g). The T_g indicates the transition of an epoxy from solid to a viscous state taking place over a certain temperature range (of about 10-20 °C) (Silva *et al.*, 2016; Michels *et al.*, 2015). Since the bridges can easily reach high temperatures (close to 80 °C) due to sealing layer and asphalt application for example (Silveira, 1996), the performance of structures strengthened with FRP materials bonded with epoxy adhesives should be evaluated.

Several authors have been studying the behaviour of NSM technique under elevated temperatures, such as the work developed by Burke *et al.* (2013). The beams, strengthened with NSM CFRP systems, were initially loaded up to sustained load (40% of CFRP ultimate tensile strain) at ambient temperature and then heated up to 100 °C and 200 °C, concluding the strengthening system was capable of withstanding over 40 and 30 minutes at 100 °C and 200 °C, respectively. The failure mode observed was debonding at the epoxy adhesive-concrete interface whilst the beams tested at ambient temperature failed by splitting bond of the NSM CFRP system in the concrete adjacent to the epoxy-concrete interface. Apparently, NSM CFRP strengthening systems at the conditions previously specified, are able to maintain their structural capacity for short term periods of exposure to temperatures higher than the T_g of the epoxy adhesives used (T_g=69 °C).

Firmo *et al.* (2014a) performed an experimental program comprising double-lap shear tests with CFRP strips installed according to the NSM technique for temperatures in interface varying between 20 °C and 150 °C. The T_g of the epoxy adhesive used was about 55 °C. In the experimental procedure adopted, the specimens were firstly heated up to a predefined temperature (20, 40, 55, 90, 120, and 150 °C), and then loaded up to failure. From the bond-slip curves obtained, a reduction on the stiffness and maximum bond strength of about 16% at 55 °C was observed. Also, when compared with the control specimen (at 20 °C), a significant bond strength loss was achieved for the test with temperatures much higher than the T_g of the epoxy adhesive, (84%, 40% and 33%, respectively, at 55, 90, and 120 °C) (Firmo *et al.*, 2014a; Firmo *et al.*, 2014b).

The present study aims to evaluate the behaviour of the RC slabs strengthened with NSM CFRP system when submitted to elevated temperatures in order to better understand the behaviour of the reinforced system during the glass transition process of the epoxy adhesive. An experimental program was developed including a total of 9 slabs, in which two different types of tests were performed: (i) steady-state tests, and (ii) transient tests. In the steady-state tests, the slabs were heated up to a predefined temperature, and then they were monotonically tested up to failure. In the case of the transient tests, firstly the slabs were preloaded up to 2/3 of ultimate load, and then submitted to an increase of temperature. When the slabs reached the target temperature, the slabs were unloaded and then, monotonically tested up to the failure. The temperatures tested were above and below the T_g of the epoxy adhesive used the present study.

EXPERIMENTAL PROGRAM

Protocols adopted for the tests at elevated temperatures

The experimental program is divided in two main groups: (i) the steady state tests (SS) and, (ii) the transient tests (TR). In the first group six slabs (SL) strengthened by the NSM CFRP technique were tested at different target temperatures, namely, 20, 40, 50, 70 and 80 °C. In the second group, one slab was tested at the target temperature 20 °C and the other two at target temperatures of 80 °C. As shown in Figure 1, in the steady state tests, the slabs were firstly heated up to the target temperature without any load application, and then, after reaching this pre-set temperature, they were monotonically tested up to failure. In the case of the transient tests, the two slabs were initially submitted to a constant load of 2/3 of ultimate load (applied in a quasi-static manner) and, then, keeping the load constant, they were submitted to an increasing the temperature up to the predefined value (see Figure 1). One of the slabs was exposed to the temperature at about 80 °C over a period that last 4h, another one a period of 12h, approximately. After this phase the slabs were unloaded and subsequently loaded until failure. Moreover, one control specimen (reference slab) was monotonically tested up to the failure under at temperature of 20 °C.

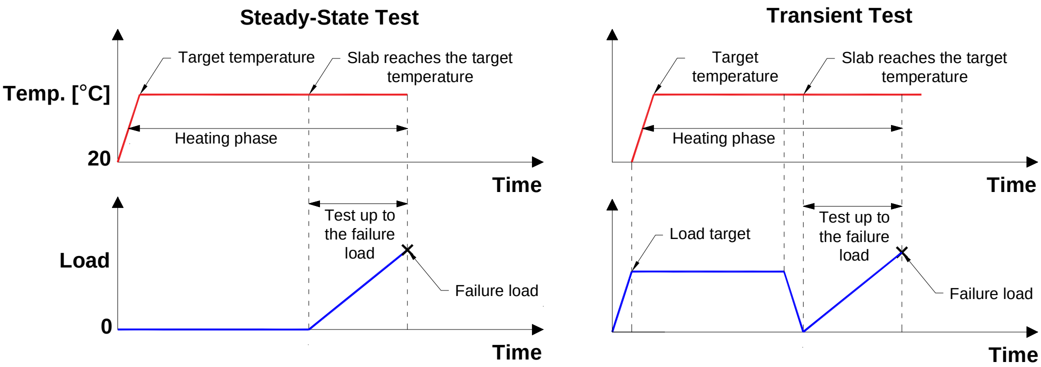
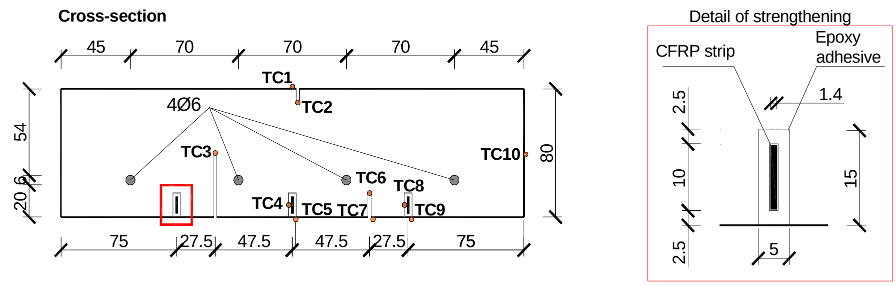


Figure 1 Protocol of the test steady-state and transient tests

Specimen's geometry and test set up

The tested slabs used in the present program are 2000 mm long, 300 mm wide and 80 mm thick. Figure 2a depicts the geometry of the cross-section, including the longitudinal reinforcement (4 bars of 6 mm of diameter - 4∅6), corresponding to a longitudinal reinforcement ratio of 0.47%. The slabs were strengthened with three CFRP laminate strips, which corresponds an equivalent longitudinal reinforcement ratio of 0.68%. Figure 2b details the geometry of the groove and corresponding reinforcement.



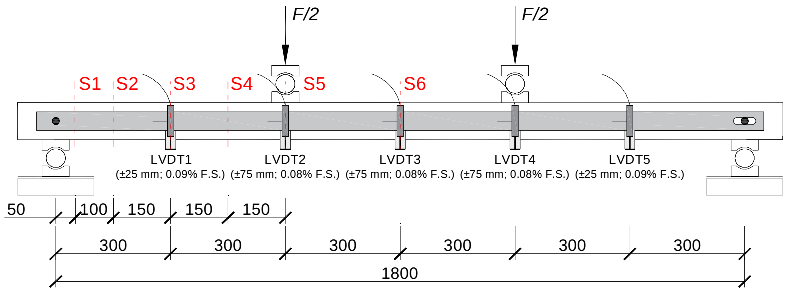
(a) (b)

Figure 2 Slab's geometry: (a) cross-section (b) details of the strengthening. [Note: all units are in millimetres]

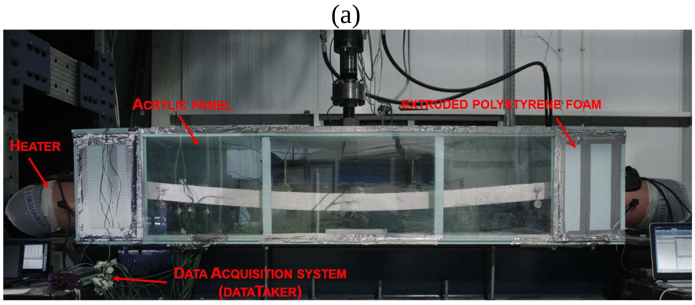
A four-point bending test configuration was used, with 600 mm of shear spans. The deflections were measured through 5 LVDTs (see Figure 3a). A total of 7 strain gauges (TML BFLA-5-3-3L) were used to measure the strains developed on the CFRP laminates and steel bars, 5 strain gauges in sections S2, S3, S4, S5 and S6 (see Figure 3a) and 2 placed in S6, respectively. One strain gauge (TML PFL-30-11-3L) was used to measure the strain at the top layer of concrete at mid-span section. Finally, the applied load (*F*) was registered by a load cell placed between the grip and the actuator, with a static load carrying capacity of 200 kN (linearity error < ±0.05% F.S.).

The monotonic tests up to failure were performed by displacement control of 0.02 mm/s. For the case of the TR tests, the load of 2/3 of slab's ultimate capacity carrying capacity, was applied under force control with a speed of 14 N/s. The unloading phase of unloaded at a velocity of 0.1 mm/s.

Figure 3b shows the general view of the prefabricated chamber and heating system where the SS and TR tests were performed, under controlled environmental temperature. The chamber was developed with extruded polystyrene foam and it was prepared to work up to 100 °C. Two industrial hot-air blowers heated the environment inside the chamber, controlled by an Arduino UNO (Arduino) using an MAX31855 thermocouple amplifier ADC, with cold-junction compensation. Also, a total of 25 thermocouples type-K were installed in order to register the temperature inside the chamber and, at different points of interest inside the slab, as shown in Figure 2a. Some holes were made to place thermocouples in the centre of the slab and at the depth of the strengthening (see Figure 2a). The number of thermocouples positioned in the mid-span cross-section were replicated in another cross-section at about 5 cm from the support and before the extremity of CFRP laminate strip (S1 in Figure 3a). Note the heating velocity of the materials, mainly concrete, was only dependent by the heating power of 6 kW of the hot-air blowers and by the target temperature fixed in the thermostat.



(a)



(b)

Figure 3 Test configuration: (a) test set up to the failure (b) overview of the chamber.

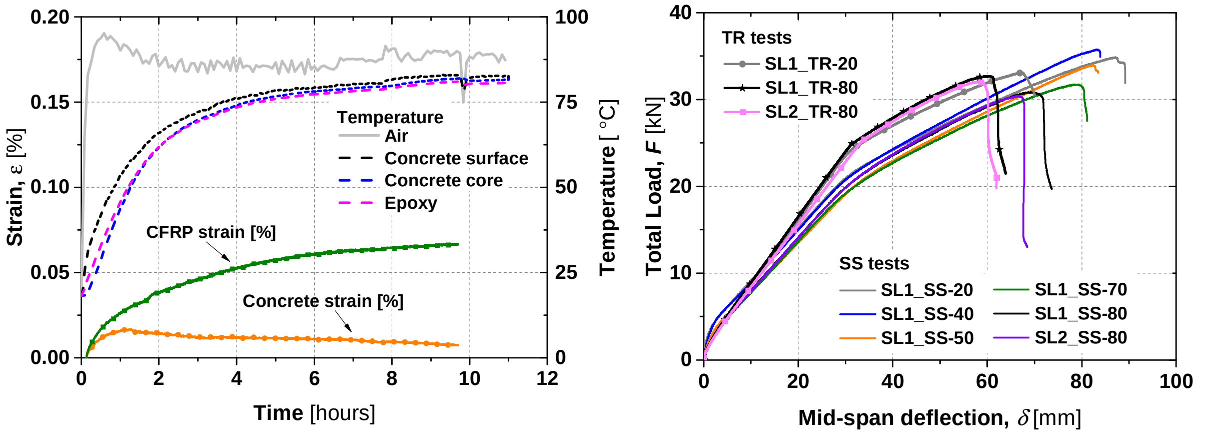
Material Characterization

The tested specimens had approximately 3 years of age and the compressive strength of cylinders (150 mm × 300 mm) was assessed by means of compression tests, following NP EN 12390-3:2011. The Young's modulus was determined according to LNEC E397-1993:1993. The average concrete compressive strength was 51.9 MPa (CoV=3.9%) and Young's modulus was 28.8 GPa (CoV=1.5%). The tensile properties of the CFRP laminate strips were assessed according to ISO 527-5:1997, presenting a tensile strength of 2648.3 MPa (CoV=1.8%) and a Young's modulus of 169.5 GPa (CoV=2.5%). The uniaxial tensile properties of hardened epoxy adhesive were evaluated according to ISO 527-2:1993, and the following average values were obtained: 22 MPa (CoV=4.5%) for tensile strength, 7.2 GPa (CoV=3.7%) for Young's modulus and 0.36% (CoV=15.2%) for the strain at the peak stress. The glass transition temperature (T_g) of the epoxy adhesive used is 55 °C (Silva *et al.*, 2016). The steel longitudinal reinforcement was evaluated according to NP EN 10002-1:1990, and the obtained average values of E-modulus, 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%).

RESULTS AND DISCUSSION

Steady-state tests

Figure 4a illustrates the evolution of the air temperature inside the chamber and the average temperature measured at top of slab (concrete surface) – TC1, in the epoxy (inside of groove) – TC4/TC8 – and in the concrete core – TC3 – for the slab SL2_SS_80 (see also Figure 2a). The average temperature was calculated considering the temperature measured by two thermocouples positioned at the two different cross-sections. Although the temperature target was distinct for each experimental test, all slabs tested presented similar temperature development: in which the temperature evolution in first phase was linear during approximately one hour, attaining of about 60% the target temperature. Regarding to the CFRP and concrete strain measured during the heating phase in the slab SL1_SS_80, Figure 4a shows the strain evolution caused by the effect of temperature increase in the slab: (i) in the first 2 hours, up to of about 60 °C of temperature, both strains at the CFRP and concrete increase to the expansion of the slab; (ii) then, the CFRP strain continues to increase and the concrete strain starts to decrease. This behavior it may be explained by the fact of during this phase the slab is submitted to the self-weight in addition to the steel devices used for the application of the load which causes deflection and the balance between the loss of stiffness of the epoxy and the axial stiffness of the concrete and CFRP reinforcement. However, this statement requires scientific support based on further works to be developed, mainly numerical modeling.



(a) (b)

Figure 4 (a) Time *versus* strain and temperature of slab SL2_SS-80; (b) total load *versus* mid-span deflection.

Figure 4b plots all the load-deflection curves (F-δ) obtained in the monotonic tests up to the failure (see also Figure 1). Table 2 includes the values of notable points of total load-deflection curves, such as: midspan deflection and applied load for crack initiation (δ_{cr}, F_{cr}), yield initiation of the longitudinal reinforcements (δ_y, F_y), maximum load (δ_{max}, F_p), and CFRP and concrete ultimate strains (ε_{CFRP} and ε_{conc}). The values of F_{cr}, F_y and F_p, and the variation of slabs submitted to the temperature and the reference one (SL1_SS-20) are also represented in Figure 5b. The slab SL1_SS_40 presented the highest ultimate carrying capacity, even comparing with the reference slab (SL1_SS_20). The third branch of the F-δ curve of this slab had a higher slope than the remaining slabs. Although, the air temperature has been constant during the heating phase and in the monotonic test up to the failure, the better performance of slab SL1_SS_40 may be related with a post-curing phase occurred during heating phase since the epoxy adhesive had been submitted to a temperature higher than the ones during the first its cure (Moussa *et al.*, 2012). The post-curing can increase the mechanical properties of the material due to an increase in chain branching and molecular strength. Additionally, the adhesion mechanisms between concrete and the epoxy as well as the epoxy and the CFRP may be also improved. Also, slab SL1_SS_50 was found to have a higher stiffness of the third branch, even though the ultimate capacity has been lower than the reference slab. In this case the slab was submitted to temperatures close to this trigger point (T_g) justifying this weaker behavior. The slabs submitted to a temperature of 70 °C or higher, presented a stiffness reduction in the first and third branches when comparing with the remaining ones. This behavior is related to the temperature effect on the epoxy adhesive since the temperatures studied in the present work marginally affect the response of concrete itself (Neville, 1995; Anderberg e Thelandersson, 1976). Moreover, the ultimate load started to be affected comparing to the reference one. The decrease was approximately 9.0%, 11.5% and 12.8% for slab SL1_SS_70, SL1_SS_80 and SL2_SS_80, respectively.

Regarding to the strains, the slabs SL1_SS_20 and SL1_SS_50 attained the maximum concrete strains of about 0.4%, while the maximum CFRP strains were registered in slabs SL1_SS_20 and SL1_SS_40 (at about 1.4%). The slabs tested between 20 °C and 70 °C failed by concrete crushing, while the slabs tested at 80 °C failed by cohesive failure at the epoxy. Consequently, the maximum CFRP strain of the slabs submitted at 80 °C presented a considerable decrease value (of about 25%).

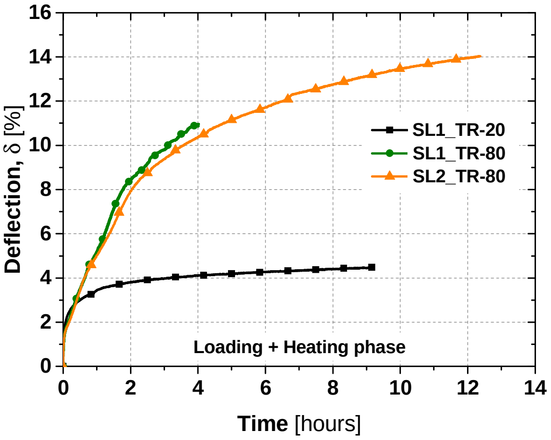
Transient tests

Figure 5a plots the evolution of deformations for the predefined temperatures. The deformation of the reference slab (SL1_TR_20) was at about 4.3 mm after 9 hours, while for the case of slabs SL1_TR_80 and SL2_TR_80 the deflection reached 11 mm and 14 mm after 4 and 12.5 hours, respectively. The high deformation in the slabs submitted to the 80 °C can be related with the simultaneous effects of creep of concrete and the decrease of the stiffness of epoxy adhesive. It is difficult to quantify the contribution of each effect individually since the creep deformation is greatly influenced by the temperature and the stiffness of the epoxy decrease significantly with the increase of temperature (Silva *et al.*, 2016). According to literature, the creep in the concrete at mean temperature of 40 °C is 25% higher than that at 20 °C (1992-1-1, 2004).

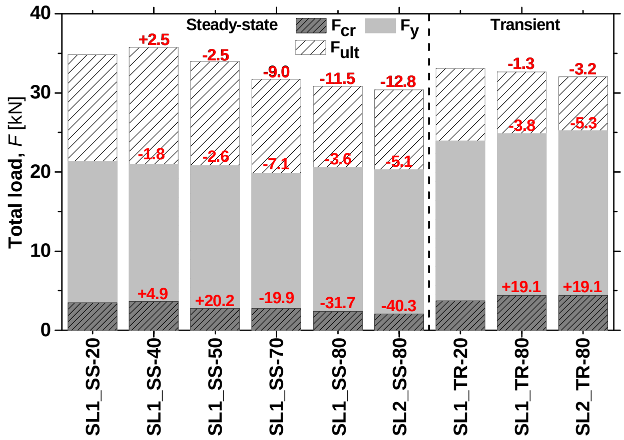
Table 1 Main results obtained in experimental tests

Slab ID	δ_{cr} [mm]	F_{cr} [kN]	δ_y [mm]	F_y [kN]	δ_{max} [mm]	F_{max} [kN]	ε_{CFRP} [%]	ε_{conc} [%]
SL1_SS-20	1.35	3.47	30.99	21.36	89.21	34.85	14.29	3.97
SL1_SS-40	1.67	3.64	30.47	20.97	83.92	35.74	13.71	3.27
SL1_SS-50	1.60	2.77	33.80	20.81	83.49	33.97	13.11	4.05
SL1_SS-70	2.08	2.78	31.61	19.84	81.16	31.73	12.11	3.69
SL1_SS-80	1.85	2.37	31.61	20.59	73.63	30.84	11.32(b)	2.97
SL2_SS-80	1.52	2.07	30.88	20.28	67.89	30.40	10.11(b)	2.99
SL1_TR-20	1.52(a)	3.72(a)	30.65(c)	23.93(c)	70.04	33.11	13.98(b)	4.12
SL1_TR-80	1.47(a)	4.43(a)	31.22(c)	24.84(c)	63.88	32.67	12.34	2.64
SL2_TR-80	1.62(a)	4.43(a)	33.47(c)	25.21(c)	61.97	32.03	12.71	2.36

Notes: (a) values reached at the pre-loading phase; (b) strains measured at point-load section; (c) yielding of the reinforcement after the submitted a sustained loading.



(a)



(b)

Figure 5 Experimental tests (a) loading and heating phase of TR tests; (b) variation of the notable points.

Thereafter, the slabs were unloaded before being submitted to the monotonic tests up to the failure. Figure 4b depicts the total load – mid-span deflection curves in which, as expected, a linear response up to the deformation reached in the heating phase was observed. Table 2 includes the values of notable points of these curves. The stiffness in the first linear branch of the slabs tested at higher temperatures was not affected when compared with the reference slab. The behavior in the branch after the yielding of the longitudinal reinforcements was also similar between the slabs submitted at the same conditions, but marginally stiffer than the reference one (SL1_TR_20). Regarding to the ultimate load, the slabs SL1_TR_80 and SL2_TR_80 only present a decrease of -1.3% and -3.2% when compared with the reference (SL1_TR_20). The slight difference between the ultimate load of the slabs SL1_TR_80 and SL2_TR_80 can be related with the period of time that slabs were submitted to the load conditions, that was of 4 and 12 hours, respectively. Regarding to the strains, the maximum CFRP strain attained by the slab SL1_TR_20 was 1.4% and the concrete one was at about 0.4% and, therefore, the failure mode occurred by concrete crushing. Since the remaining two slabs (SL1_TR_80 and SL2_TR_80) failed by cohesive failure at the epoxy, the CFRP strain only reached about 1.27% and 1.23% in the slab SL1_TR_80 and SL2_TR_80, respectively, approximately 12% less than the reference.

Figure 5b presents the evolution of cracking, yielding and ultimate load of all slabs tested. As can be observed, the slabs submitted at 80 °C under steady-state tests presented a higher decreased of ultimate load than the slabs submitted to the same temperature in the transient tests. Regarding to the yielding load, the TR tests presented higher values due to the cracking caused in the loading and heating phase. Moreover, the behavior of the slabs of TR tests presented a higher stiffness up to the yielding load than the remaining slabs, as can be seen in Figure 4b. In these tests, after the yielding of reinforcement, the laminate does not reach strains as high as the remaining slabs, perhaps associated to the residual deflection after the unloading and the damaged caused by the period of time that slabs were submitted to the loading and heating.

CONCLUSIONS

The main goal of the present work was to study the behaviour of reinforced concrete slabs strengthened with CFRP laminate according NSM technique when subjected to the elevated temperatures. For this purpose, two different types of experimental tests were performed, namely: (i) steady-state (SS) tests, and (ii) transient (TR) tests. In the case of SS tests, the slab submitted to 40 °C presented the highest ultimate load comparing with the reference slab tested at 20 °C, that could be related with a post-curing occurred in the epoxy adhesive. The ultimate load of slabs submitted to 80 °C were the most affected by the temperature, and when compared with the reference one, a decrease of approximately 12% was observed. Regarding to the TR tests, the slabs submitted at high temperatures suffer 3 times more deformation than slab tested at 20 °C during the heating phase, that may be related with the decrease of the stiffness of epoxy and the increase of creep effect of concrete at higher temperatures. However, in the monotonic test up to the failure a maximum decrease of about 3% was observed in comparison to the reference. In both types of tests, the slabs submitted at 80 °C of temperature failed by cohesive failure at the epoxy, while in remaining slabs the failure mode was concrete crushing. From the test results, it can be seen that the elevated temperatures up to 80 °C only have marginal effect of the the behaviour of RC slabs strengthened with NSM CFRP systems. However, further works (e.g. numerical modelling of the tests carried out) are necessary for a better and more in-depth understanding of the test results.

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REFERENCES

1992-1-1, C. E. (2004). "European Standard Eurocode 2: Design of concrete structures - Part 1-1: general rules and rules for buildings."

Anderberg, Y. and Thelandersson, S. (1976). "Stress and deformation characteristics of concrete at high temperatures. 2. Experimental investigation and material behaviour model." *Bulletin of Division of Structural Mechanics and Concrete Construction, Bulletin 54*.

Arduino "https://www.arduino.cc/en/Main/ArduinoBoardUno."

Burke, P. J., Bisby, L. A. and Green, M. F. (2013). "Effects of elevated temperature on near surface mounted and externally bonded FRP strengthening systems for concrete." *Cement and Concrete Composites,* 35**,** 190-199.

Firmo, J., Correia, J., Pitta, D., Tiago, C. and Arruda, M. (2014a). "Bond Behavior between Near-Surface-Mounted CFRP Strips and Concrete at High Temperatures." *Journal of Composites for Construction***,** 04014071.

Firmo, J. P., Pitta, D., Correia, J. R., Arruda, M. R. T. and Tiago, C. (2014b). "Experimental and numerical study on the bond behavior of CFRP-concrete interfaces at elevated temperature." *In:* 7th International Conference on FRP Composites in Civil Engineering (CICE2014).

Michels, J., Widmann, R., Czaderski, C., Allahvirdizadeh, R. and Motavalli, M. (2015). "Glass transition evaluation of commercially available epoxy resins used for civil engineering applications." *Composites Part B: Engineering,* 77**,** 484-493.

Moussa, O., Vassilopoulos, A. P., de Castro, J. and Keller, T. (2012). "Time–temperature dependence of thermomechanical recovery of cold-curing structural adhesives." *International Journal of Adhesion and Adhesives,* 35**,** 94-101.

Neville, A. M. (1995). *Properties of concrete*.

Silva, P., Fernandes, P., Sena-Cruz, J., Xavier, J., Castro, F., Soares, D. and Carneiro, V. (2016). "Effects of different environmental conditions on the mechanical characteristics of a structural epoxy." *Composites Part B: Engineering,* 88**,** 55-63.

Silveira, A. (1996). "The influence of thermal actions in the behavior of reinforced concrete bridges." (in Portuguese). PhD Thesis. LNEC, Lisboa.