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Effect of Temperature on Bond Behavior of Externally-Bonded FRP Laminates with Mechanical End Anchorage

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ABSTRACT

The use of mechanical anchorage systems can delay or avoid premature failure of reinforced concrete (RC) structures with externally-bonded fiber-reinforced polymer (EB-FRP) laminates. This work reports the results of an experimental program aimed at studying the bond behavior of a metallic anchorage plate, typically used for pre-stressed EB-FRP systems. The overall experimental program comprised 17 concrete prisms with carbon fiber reinforced polymer (CFRP) laminates externally bonded to the concrete with mechanical anchorage at the end and where different levels of normal stress were applied. Direct shear tests were carried out using two configurations: (i) the steady-state tests, where the laminate was pulled out from the block with increasing force and constant temperature (20 ºC, 60 ºC and 80 ºC); (ii) and the transient tests, where the laminate was pulled out with constant force (0.36%, 0.45% and 0.54% of strain) and the temperature was gradually increased. Experimental results showed that the ultimate capacity of the mechanical anchorage can decrease by 44-59% depending on the temperature and level of normal stress.

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INTRODUCTION

Fiber reinforced polymers (FRP) have become a viable alternative to conventional materials like steel and concrete for the strengthening of existing structures. Generally used in the shape of laminates or sheets, carbon FRP (CFRP) have been used in several practical cases with increasing confidence due to its intrinsic properties (among the other FRP's, CFRP's present higher strength, stiffness and fatigue life, and are less susceptibility against aggressive environments and creep rupture) and the knowledge acquired over the last decades (ACI 440.2R-08 2008; CNR 2013; Pellegrino and Sena-Cruz 2016).

The externally bonded reinforcement (EBR) is the most common technique used to strengthen reinforced concrete (RC) structures and, typically, uses epoxy resin as a bonding agent. In most cases the stress transfer between the FRP and concrete is successfully achieved with epoxy resins. However, premature failure due to plate end debonding is several times observed. The reason is the development of high shear stresses and tensile stresses normal to the interface plane on the laminate ends (Ceroni and Pecce 2010; Kotynia et al. 2011; Sena-Cruz et al. 2015). One solution is the use of anchorage devices. These anchorage devices can be classified into (Kalfat and Smith 2013; Michels et al. 2013, 2016a): U-jacked anchors, mechanically fastened metallic anchors, FRP anchors and gradient anchorage. Among them, mechanically fastened (MF) metallic anchors have been demonstrated to be one of the most effective form of FRP anchorage device when applied to flexural strengthening (Kalfat and Smith 2013). In the present paper a mechanical anchorage system, which is a commercially available MF metallic anchor system (S&P 2010), was studied. With this mechanical anchorage, a controlled normal stress can be applied and, consequently, the maximum load supported by the anchorage increases because the normal stress enables additional friction in the cracked interface (Biscaia et al. 2015; Ceroni and Pecce 2010; Correia et al. 2015).

Typically, the capacity of the EBR system is limited by the effective bond length, l_e. However, when the EBR system is subjected to a normal stress its capacity is increased due to the development of additional frictional stresses. Consequently, the capacity of the EBR system is dependent on its length and on the level of normal stress (ACI 440.2R-08 2008; Biscaia et al. 2015; CNR 2013).

Over the last decades, several works were dedicated to the development and evaluation of anchorage systems, showing that end-anchorages enable a greater use of FRP tensile capacities (ACI 440.2R-08 2008; Aslam et al. 2015; Correia et al. 2015, 2017; Michels et al. 2016b; Pellegrino and Sena-Cruz 2016; Yang et al. 2009) and, in several cases, the full capacity of the FRP was attained (Aslam et al. 2015; Correia et al. 2015, 2017; Yang et al. 2009). The influence of the level of normal stress on a metallic anchorage was recently studied by Biscaia et al. (2016). In this research, double-lap shear tests were carried out on concrete specimens strengthened with GFRP plates subjected to several environmental conditions (reference, salt fog cycles, wet/dry cycles, and temperature cycles). Three levels of normal stress were considered (0 MPa, 0.5 MPa and 1.0 MPa) and, results showed that the increase in normal stresses enhanced the performance of the GFRP-to-concrete interface. Results have shown a 60% and 151% increase of the maximum supported load of the reference specimens with the normal stress of 0.5 MPa and 1.0 MPa, respectively, when compared to the reference specimens free of normal stress. In the remaining environments, the increase of the maximum load varied between 35% and 117% and between 144% and 181% for specimens with the normal stress of 0.5 MPa and 1.0 MPa. The normal stress imposed on the GFRP-to-concrete interface intended to simulate the effect produced by a mechanical anchorage system.

Another concern related to the EBR technique is the influence of moderate to high temperatures on the system. The stiffness and strength of a strengthening system can be severely deteriorated when the temperature reaches to the glass transition temperature, T_g, of the epoxy adhesive (60 ºC-120 ºC) (ACI 440.2R-08 2008; Firmo et al. 2012). Considering that these temperatures may be easily achieved in outdoor applications or in roof structures of several countries worldwide, the study of EBR systems behavior under the effect of high temperatures is of utmost importance.

A research work carried out by Firmo et al. (2015) has shown interesting results regarding the bond between concrete and CFRP strengthening system at elevated temperatures. Their experimental campaign included double-lap shear tests on concrete blocks with externally-bonded CFRP laminates (bonded with epoxy adhesive), conducted in steady-state and transient conditions. The steady-state tests were carried out with the temperature levels of 20 ºC, 55 ºC, 90 ºC and 120 ºC, and included specimens with and without a mechanical anchorage (MA) in the ends of the CFRP strip. Although no information about the normal stress at the mechanical anchorage was given, results showed that the use of the MA led to more uniform axial strain distribution and provided significantly higher bond strength (between 56% and 139%, depending on the temperature level). It is noteworthy to mention that at room temperature the specimens with the mechanical anchorage presented shear failure of the concrete block at the anchorage zone. From the tests carried out without the MA, Firmo et al. (2015) concluded that the effective bond length consistently increased with temperature and, simultaneously, the bond strength decreases (14%, 71% and 76% when compared with ambient temperature, for the temperatures of 55 ºC, 90 ºC and 120 ºC, respectively).

Krzywoń (2017) verified that a reinforced concrete structure externally-bonded with CFRP could reach 63.5 ºC (in the adhesive layer) during the summer months in the southern Poland. Their study included (experimental) four-point bending tests on six beams strengthened with CFRP according to the EBR technique, which were heated to the temperatures that varied between 51 ºC and 73 ºC. An unexpected and rapid failure (interface between adhesive and concrete) under a load much lower than the reference (room temperature) was observed for specimens tested at a temperature higher than 60 ºC.

Del Prete et al. (2015) studied the performance of RC bridge slabs, externally strengthened with FRP, at high temperature. The Italian and American code suggestions to determine the FRP debonding at room temperature were modified to take into account the effect of high temperature. It should be mentioned that, in order to define the reduction of the fracture energy at high temperatures, Del Prete et al. (2015) compiled seventy seven bond tests (single-lap shear tests and double-lap shear tests) performed on CFRP plates and sheets. The selected bond tests (Blontrock 2003; Cai ZH 2008; Klamer E 2009; Leone et al. 2009; ZS et al. 2004) followed a single-lap and double-lap shear test configurations, and included tests at room temperature and elevated temperature (50 ºC – 160 ºC). From all the above-mentioned bond tests, it was always observed a reduction on the bond strength for temperatures that surpassed the adhesive's T_g.

From the literature search carried out it was concluded that further research in the field of mechanical anchorage system of FRP materials is needed, especially under elevated temperatures. So, the present paper aims at investigating the bond behavior of a metallic anchorage plate, typically used for pre-stressed EB-FRP systems (Correia et al. 2015, 2017; S&P 2014a), under different thermal conditions. The laminate geometry, the normal stress provided by the torque level and the temperature are the main variables studied in an experimental campaign that included steady-state and transient direct shear tests.

EXPERIMENTAL INVESTIGATION

Experimental program, specimen geometry and preparation

The experimental program included seventeen large-scale shear tests (see Table 1). One CFRP laminate was externally bonded to each concrete prism (200×500×800 [mm]). The laminates had two different widths, w_f, (80 mm and 100 mm) and constant thickness of 1.2 mm. The CFRP laminates were mechanically anchored to the concrete surface through a hard-aluminum plate (12×200×270 [mm]) using six M16 8.8 bolts (see Fig. 1). The torque level, T_L, applied to each M16 bolt was controlled (100 N·m, 150 N·m and 200 N·m) to study the effect of normal stress on this mechanical anchorage, (σ_L), that varied from 7.7 MPa to 15.3 MPa. The level of normal stress was decided based on previous works carried out by the authors (Barris et al. 2018; Correia et al. 2015, 2017). Immediately after the anchorage plate, there is an unconfined bonded region of 250 mm, where the CFRP is bonded to the concrete surface using epoxy adhesive with a thickness of 1-2 mm. According to the CNR (CNR 2013), the unconfined bonded length (henceforth referred simply as "EBR region") surpassed the theoretical effective length, l_e, needed to achieve the maximum debonding load (equal to 200 mm according to (CNR 2013)). Consequently, with this specimen configuration it is possible to study the behavior of the EBR region, the mechanical anchorage and the transference of load from one region to the other.

The specimens were tested under the following two types of test configurations: (i) steady-state configuration, in which the temperature was kept constant at 20 ºC, 60 ºC and 80 ºC while the specimens were loaded up to failure; and (ii) transient configuration, in which the applied force was kept constant at 80 kN, 100 kN and 120 kN (0.36%, 0.45% and 0.53% of CFRP strain) while the specimens were heated up to failure. Each specimen was labeled with a generic denomination: L**X**_T**Y**_**Z**, where **X** is the laminate width in [mm] (80 or 100), **Y** is the torque level in [N·m] (100, 150 or 200), and **Z** is related to the type of test configuration (steady-state or transient test). In the case of steady-state tests carried out at 20 ºC, 60 ºC and 80 ºC the suffix **Z** is SS20, SS60 and SS80, respectively. In the case of transient test that failed with an applied constant load of 100 kN and 120 kN the suffix **Z** is CL100 and CL120, respectively. Table 1 shows the designation given to all direct shear test specimens performed in this study. In general, only one test specimen was considered for each combination of variables. However, as two of the transient tests were repeated, four specimens were labeled with an additional suffix (a or b). Due to the nature of the specimens, the test configuration (large scale), and the strict quality control in the preparation and execution of the experiments, a low variability between results of identical specimens was expected.

Fig. 2 shows all the procedures used in the preparation of the tested specimens. As can be seen, the preparation of the specimens was concluded after two main stages: (i) the preparation of the concrete prism and (ii) the strengthening procedure. The first stage was conducted approximately 28 days after casting. First, the surface of the concrete prisms was treated using the sandblasting technique. Six holes of 18 mm of diameter were drilled to accommodate the anchor bolts (see Fig. 2a) and then, the concrete surface and the holes were cleaned with pressurized air (see Fig. 2b). Finally, M16 metallic anchor bolts were fixed with a chemical bond agent (see Fig. 2c). In the second stage, the epoxy adhesive was prepared according to the requirements provided by the supplier (S&P 2010, 2013) and applied on the previously cleaned CFRP laminate strip (see Fig. 2d), on the concrete surface and on the surface of the metallic anchorage plate (see Fig. 2e). Then, the CFRP laminate was placed in its predefined location (see Fig. 2f) and the anchorage plate was installed on top of the laminate (see Fig. 2g). The M16 anchor bolts were torqued with the aid of a dynamometric key that ensured the target level of normal stress (see Fig. 2h). According to the adhesive's supplier (S&P 2013), the epoxy is fully cured after 3 days at 20 ºC. Specimens were kept in laboratory premises (average temperature of 20 ºC and 55% of relative humidity) for a period of 7 days before testing. It should be referred that during the preparation of the test specimens, a strict quality control was always followed to ensure homogeneity and reliability.

Test set-up and instrumentation

The bond behavior of the mechanical anchorage was assessed using two direct shear test configurations: (i) steady-state and (ii) transient. Each specimen was firstly placed onto the reaction floor against a 60 mm height metallic plate (a rough value for a hypothetical neutral axis depth for the case of a flexural member of 200 mm height). Then, the concrete prism was fixed against the reaction floor through a metallic beam (see Fig. 1). Once correctly placed and fixed, the CFRP laminate was connected to the hydraulic actuator by a metallic clamp specially designed for these tests (see Fig. 3b). As shown in Fig. 3a, these grips were 200 mm wide and 285 mm long, and were closed with six M20 bolts. In a previous experimental campaign (Barris et al. 2018), the same clamping system set was used and failure by CFRP rupture at its maximum tensile capacity was attained for the load close to 300 kN. Depending on the type of test, different procedures were adopted: (i) in the steady-state tests the laminate was pulled using a servo-controlled machine at a constant displacement rate of 0.30 mm/min until total debonding of the laminate's bonded length. Then the speed was increased up to 2 mm/min until the end of the test. The moment when the displacement rate was also changed is presented in Fig. 7 as a grey dot (with the label "A"). This figure clearly indicates that the change in the test velocity did not yield to critical changes on the load-slip relationships. During the steady-state tests the temperature was kept constant in the anchorage zone and EBR region. The temperature was achieved using an infra-red (IR) heating system, and the temperature levels were meant to keep the epoxy adhesive inside the mechanical anchorage (in-between the concrete and the

CFRP laminate) at a temperature lower than its T_g (20 ºC), near its T_g (60 ºC) and above its T_g (80 ºC). The IR heating system was developed by the authors of the present paper and is composed by four IR heaters of 1200 W, controlled by a thermostat. This system was designed by the author of the present work to reach the maximum temperature of 80 ºC in a relative short period of time (2 hours) and to produce an even distribution of temperature across the anchorage plate and on the EBR region. Fig. 4a shows the test set-up including the IR heating system. Fig. 4b and Fig. 4c presents the typical temperature evolution in the anchorage zone and in the EBR region. In the transient tests the IR heating system was used to gradually increase the temperature in the anchorage zone and EBR region. In a first stage of the transient tests, the temperature was kept constant at 30 ºC and the stress level on the laminate was increased up to a predefined load of 80 kN, 100 kN and 120 kN. Then the temperature raised up (average rate of about 0.4 ºC/min) until failure keeping the stress level constant. If the temperature in the mechanical anchorage reached 80 ºC and failure was not observed, the conditions of temperature (80 ºC) and load (80 kN, 100 kN and 120 kN) were kept for a period of one additional hour before ending the test (see Fig. 4c).

During the direct shear tests the instrumentation was composed of: 3 linear variable differential transformers (LVDT), to monitor the relative displacement between the CFRP laminate and the concrete surface (the slip); 5 strain gauges to record the strain evolution in the CFRP; 5 thermocouples with the aim of measuring the temperature; and, 1 load cell used to measure the applied load (P), with a maximum capacity of 300 kN and a linearity error of ±0.05%. Fig. 1b shows the position of each LVDT: one at the beginning of the EBR region (loaded-end, LVDT-1); a second placed before the mechanical anchorage plate (mid-end, LVDT-2); and the last one placed after the anchorage plate (free-end, LVDT-3). The LVDT-1 had a range of ±5.0 mm and a linearity error of ±0.24%, whereas the LVDT-2 and LVDT-3 had a range of

±2.5 mm and a linearity error of ±0.24%. Strain gauges (S1 to S5) were placed in the center of the EBR region, equally spaced by 62.5 mm (see Fig. 1a). The load cell was placed between the actuator and the metallic clamp. The thermocouples (type k) had a range from -50 ºC to 250 ºC and were placed at the center of the anchorage and at the EBR region, each location with several thermocouples. Results showed that the temperature variation between the thermocouples of the same region are negligible.

Materials

The behavior of the strengthening system and performance of the test specimens is related to the mechanical properties of the materials used. Concrete, CFRP laminate, and epoxy adhesive are the main materials used in the present experimental study. The ready-mixed concrete was produced with crushed granite (maximum aggregate size of 12.5 mm), Portland cement type CEM II/A-L 42.5R, and a water/cement ratio of 0.56. Two batches (B1 and B2) were used to cast the concrete prisms (see Table 1). Concrete characterization included evaluation of the modulus of elasticity and compressive strength through LNEC E397-1993:1993 (LNEC E397-1993:1993) and NP EN 12390-3:2011 (IPQ - Instituto Portugues da Qualidade; 2011) standards, respectively. For each concrete batch six cylindrical specimens (300 mm of height and 150 mm of diameter) were used. These tests were performed at approximately the same age of the direct shear tests. The results revealed an average compressive strength (f_c) of 33.4 MPa (CoV=4.33%) and 45.0 MPa (CoV=1.24%) for batches B1 and B2, respectively. The modulus of elasticity was also assessed for batch B1 (30.8 GPa, CoV=2.84%) and for batch B2 (32.8 GPa, CoV=0.72%). Although the concrete compressive strength was higher in batch B2 than in B1, the governing failure mode of all specimens was adhesive type at the interface concrete/adhesive. Thus, the difference in f_c presents marginal influence in the results of the present research.

The CFRP laminate strips used in the experimental work consisted of unidirectional carbon fibers (with a volume content fiber higher than 68%) held together by an epoxy vinyl ester resin matrix (S&P 2014b). The tensile properties of the CFRP laminate were assessed through the ISO 527-5:1997 (Iso-527-5 1997) recommendation. The CFRP laminate came from four different batches as described in Table 1. For each batch, six samples were used to assess the modulus of elasticity (E_f) and the tensile strength (f_{fu}), with the results presented in Table 1. An average E_f of 172.6 GPa and 178 GPa was obtained for the laminates with the width of 80 mm and 100 mm, respectively. The maximum tensile strength varied between 2428.0 MPa and 2895.2 MPa.

A two-component epoxy adhesive produced by the same supplier as for the CFRP laminate, was used to bond the CFRP laminate to the concrete substrate. According to its technical datasheet (S&P 2013), after the curing time of 3 days at the temperature of 20 ºC, the epoxy adhesive has a compressive strength higher than 70 MPa, a tensile modulus of elasticity higher than 7.1 GPa and shear strength higher than 26 MPa. Based on an assessment of its mechanical properties previously made in another experimental program (Silva et al. 2016), a modulus of elasticity of 7.2 GPa (CoV=3.7%) and a tensile strength of 22.0 MPa (CoV=4.5%) were obtained, after a curing time of one year at 22 ºC and 55% of relative humidity. In the same study a Dynamic Mechanical Analysis (DMA) was carried out to assess the glass transition temperature (T_g) of the adhesive. Based on the onset of the glass transition of the storage modulus, a value of 47.2 ºC was obtained after a curing time of 250 days. The adhesive's T_g was also measured with the curing time of 7 days and 480 days (with similar curing conditions) and a low variability between results (1.2%) was observed.

RESULTS AND DISCUSSION

Table 2 summarizes the results obtained in each test and the following discussion is divided into two sections: one for to the steady-state test results, and the other for the transient test results. In both sections an analysis on the overall behavior, debonding process and failure modes is carried out.

Steady-state tests

Load-slip behavior

Typical load-slip response at the loaded-end, the mid-end and free-end are illustrated in Fig. 5a for the specimens tested at room temperature (20 ºC) and in Fig. 5b for the specimens tested at elevated temperatures (60 ºC or 80 ºC). At room temperature, the test starts with an almost linear branch at the loaded-end. At the mid-end and at the free-end the registered slips are negligible and, consequently, the applied load is supported exclusively by the bonded length outside the mechanical anchorage. Then the debonding of the EBR region starts to occur and, during this phase the load remains almost constant whilst the slip increases considerably due to the elastic energy accumulated in the bonded length and due to the deformation of the new portion of CFRP strip that slips. The end of the debonding process in the EBR region is reached when the LVDT-2 starts to register displacements in the mid-end. After this stage, as the load increases so does the relative displacement at the loaded-end and the mid-end sections, until rupture of the CFRP is attained. In this last stage (after debonding), a fairly linear load-slip response is registered in all cases. Failure was obtained when the CFRP laminate reached its maximum tensile capacity. The LVDT-3, placed at the free-end, generally does not register any movement during the test. From these results it was clear that the mechanical anchorage used in this experimental program provides adequate normal stress of the CFRP laminate to the concrete substrate regardless of the applied torque level.

When the test temperature was 60 ºC or 80 ºC, the load-slip behavior significantly changed. In the early stages of the test, as the applied load increased, also did the slip registered with the LVDT-1. However, the relative displacement in the mid-end does not remain null. While the debonding process of the EBR region is in course, the LVDT-2 shows a small but consistent displacement increase with the load. These results demonstrate that in the early stages of the test the anchorage zone supports part of the load (see Fig. 5b). As the load increases and the debonding process evolves, the fraction of load supported at the EBR region decreases. Further details of the debonding process are given in the following section. From this stage onwards, the slip increases in both locations (loaded-end and mid-end). Then, the maximum force is reached and displacements in the free-end are also observed, marking the anchorage failure (slippage). Then, the displacements at the three locations (loaded-end, mid-end and free-end) increase while the load decreases. However, the load does not decrease to zero, but stabilizes at a load level that represents a residual bond stress. This last behavior was also observed in other works, e.g. Biscaia (2015).

Debonding process

Like the load-slip behavior, the debonding process of the EBR region in specimens tested at room temperature was different from those tested at elevated temperatures. Fig. 6 shows the strain evolution in the EBR region of specimens with the laminate of 100 mm and torque of 100 N·m, tested at different temperatures. The debonding load, P_{deb}, and temperature in the EBR region during the debonding process, T_{deb}, are presented in Table 2. During the first stages of loading at room temperature (20 ºC), the strain has a peak value at the loaded-end (location x=0 mm, see Fig. 6a) and null values near the anchorage plate (location x=250 mm, see Fig. 6a). As the test continues, more bonded area of EBR region is needed to support the additional loads and a change can be observed in the strain profile. When the length of the EBR region needed to support the load equals the effective bond length, l_e, the maximum debonding load is reached. According to the CNR (2013) the l_e of the tested specimens is around 200 mm. However, in the current test, the load does not remain constant until failure because the mechanical anchorage holds the CFRP extremity and avoids premature failure. At room temperature, the debonding load was set when the LVDT-2 starts to register movement. At this exact time, the strain near the anchorage plate increases significantly as does the slip at the mid-end (see Fig. 6a and Fig. 5a). Immediately after this point, the strain and slip continue to increase but at a lower rate and the CFRP laminate is completely detached from the concrete surface in the EBR region.

The debonding process observed in the specimens tested at elevated temperatures was different since its early stages. Results show an almost linear strain evolution (see Fig. 6c and see Fig. 6d), with a peak strain value on the loaded-end (location x=0 mm) and a gradual decrease towards the anchorage plate (location x=250 mm). All strain gauges show a continuous increase in strain since the test onset and, during the debonding process, the shape of the strain profile remains almost unaffected. Also, the LVDT-2 starts to register relative displacement since the initial stages of the test. Contrary to tests carried out at room temperature, where the complete debonding of the EBR region was observed with the swift and simultaneous increase of values at the LVDT-2 and at the strain gauge near the anchorage plate, in tests carried out at elevated temperatures, the strain gauge near the anchorage plate and the LVDT-2 started to register movement before the CFRP laminate was completely detached. As can be seen in Table 2, for the case of the tests at elevated temperatures the temperature in the EBR region during the debonding process, T_{deb}, surpassed the epoxy's T_g. The transition from a solid to a rubber-like state is a continuous process over a temperature range of 10-20 ºC and, during the steady-state tests, the epoxy adhesive at the EBR region either was at the beginning (T_{deb}≈51.1 ºC for

L80_T150_SS60, L100_T100_SS60 and L100_T150_SS60) or at the end (T_{deb}≈66.9 ºC for L80_T150_S80, L100_T100_SS80, L100_T150_SS80 and L100_T200_SS60) of this range. The reduction in the adhesive stiffness might be responsible for smoothing the shear stresses distribution at the interface CFRP/concrete and for the early strain and displacements increase near the mid-end. For that reason, it was impossible to clearly identify the debonding load. However, due to the elastic energy accumulated in the EBR region, there is a stage in the load-slip curves where a plateau can be observed at the mid-end (see Fig. 5b). This stage, shows the load for which the complete debonding of the EBR region occurs. At this point, the load supported by the EBR region does not represent the totality of the applied force because, as referred before, the anchorage is also responsible for supporting a fraction of the load since the early stages of the test. Tests carried out with the highest temperatures showed less strain variation from the loaded-end (x=0 mm, see Fig. 6d) to the mid-end (x=250 mm, see Fig. 6d).

According to the CNR (2013), the expected debonding load for specimens with the laminate of 80 mm and 100 mm is equal to 42.5 kN and 53.0 kN, respectively. The experimental results from tests carried out at room temperature are in accordance with the expected values (average P_{deb} of 42.9 kN and 49.1 kN for specimens with the laminate of 80 mm and 100 mm). As could be seen, the temperature changed the debonding process and the CNR (2013) formulation does not consider the effect of high temperatures on the debonding process. In all tests, the debonding of the EBR region occur due to failure in the concrete-epoxy interface. However, in the tests carried out at elevated temperature, remains of epoxy adhesive stayed adhered to the concrete surface. This observation points to the fact that, at elevated temperatures, the failure of the EBR region was, in part, cohesive in the adhesive (see Fig. 8c).

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Failure Modes

Two failure modes were observed: (i) CFRP rupture at its maximum tensile capacity and (ii) anchorage slippage. The CFRP rupture was observed in all specimens tested at room temperature, except for specimen L80_T150_SS20, where its maximum capacity was not attained because the clamping system failed to hold the pulled end of the CFRP. At room temperature, the mechanical anchorage system provided adequate normal stress of the CFRP laminate to the concrete substrate and enabled the full use of the reinforcement material. Anchorage slippage was the failure mode observed in all tests carried out at elevated temperature. Results show (see Table 2) that failure is highly influenced by the test temperature and by the normal stress level. In comparison to specimens tested at room temperature, the average reduction in the ultimate load, P_u, for specimens tested at 60 ºC and 80 ºC equals to 43.9% and 58.5%, respectively. Also, the ultimate slip registered at the mid-end, $s_{u,2}$, was higher in specimens tested at 60 ºC (1.3±0.2 mm) than in specimens tested at 80 ºC (0.9±0.2 mm). Fig. 7 shows the load-slip behavior of specimens with the normal stress level, σ_L, of 7.7 MPa (Fig. 7b, w_f =100 and T_L =100 N·m), 11.5 MPa (Fig. 7c, w_f =100 and T_L =150 N·m), and 14.4 MPa (Fig. 7a, w_f =80 and T_L =150 N·m). As can be seen, the load-slip behavior of each test is dependent on the test temperature (by comparing series 20 ºC, 60 ºC and 80 ºC) and level of normal stress (by comparing series L100_T100, σ_L=7.7 MPa, and L100_T150, σ_L=11.5 MPa), and follows the same stages that were described previously. Contrarily to CFRP rupture, the failure by anchorage slippage did not result in a swift decrease of load down to zero, but to a softened reduction of the supported load down to a residual value of 65.5-70.8% of its maximum capacity. The bond stress responsible for the residual supported load is a consequence of the normal stress applied on the anchorage zone (Biscaia et al. 2015). As expected, there is a relation between the residual capacity of the anchorage and the applied level of normal stress: the residual load, P_{res}, corresponds to a level of CFRP stress of 745.8 MPa, 875.0 MPa, 903.1 MPa and 981 MPa in specimens with the level of normal stress, σ_L, of 7.7 MPa, 11.5 MPa, 14.4 MPa and 15.3 MPa, respectively (only one specimen, L100_T200_SS60, was tested with the σ_L of 15.3 MPa; whereas, for the other cases, two specimens tested at different temperatures were considered). The level of normal stress also influenced the value of P_u and ε_u. In fact, results show that the load and CFRP strain at failure were higher in specimens with the greatest level of normal stress (see Table 2). Despite the positive influence of the level of normal stress, the temperature was the major influential factor in all ultimate parameters. As can be seen in Table 2, the reduction in the ultimate parameters P_u and ε_u, is close to 44% when the counterparts tested at 60 ºC are compared with the ones tested at 20 ºC; and is around 25% when specimens tested at 80 ºC are compared with the ones tested at 60 ºC.

Transient tests

Temperature-slip behavior

In the transient tests, six specimens were loaded up to a fraction of the CFRP strength (0.36%, 0.45% and 0.53% of CFRP strain) at room temperature and then heated up until 80 ºC. For each load level (80 kN, 100 kN and 120 kN) the maximum temperature supported was registered. The ultimate temperature (T_u) registered in the anchorage is presented in Table 2 and the slip evolution in the loaded-end and mid-end with the temperature is shown in Fig. 9 for specimens tested at a constant load of 100 kN and 120 kN. Fig. 9 also shows the instant when the temperature started to increase (t_i), the time when failure was observed (t_u), the time when the predefined maximum temperature was reached ($t_{80ºC}$) and the duration until failure was observed ($\Delta t_{80ºC}$). During the test of specimen L100_T150_CL120b the heating was stopped when temperature reached 60 ºC ($t_{60ºC}$) for a period of one hour ($\Delta t_{60ºC}$). This stage is presented in Fig. 9b.

It should be pointed out that specimens L100_T100_CL100, L100_T150_CL100a and L100_T150_CL100b, were previously tested under a transient configuration with a load of 80 kN and a subsequent with a load of 100 kN. These three specimens endured the initial tests (temperature variation from 30 ºC to 80 ºC and the subsequent steady-state of 80 ºC over one hour) without showing any traces of damage. At the end of the initial test, the strain registered at the EBR region and the relative displacement between the CFRP and the concrete surface (LVDT-1, LVDT-2 and LVDT-3) resumed their initial values. The tests in specimens L100_T100_CL100 and L100_T150_CL100a were repeated once again after 24 hours and the same result was observed. These three specimens were then tested with the final load of 100 kN and the behavior is presented in Fig. 9a.

The first stage of the transient test was the application of the predefined load (80kN, 100 kN, or 120 kN). The relative displacement at the loaded-end and mid-end when the predefined load was achieved are in agreement with the values obtained in the steady-state tests. As expected, higher loads levels matched with higher slip values at the loaded-end (1.0 mm, 1.6 mm and 2.0 mm for load of 80 kN, 100 kN and 120 kN, respectively) and mid-end (0.2 mm, 0.3 mm and 0.4 mm for load of 80 kN, 100 kN and 120 kN, respectively). Then, the second stage of the test started (at time t_i, see Fig. 9), and the IR system heated up the specimens up to 80 ºC. Most of the specimens failed during this stage (at time t_u, see Fig. 9) and the maximum temperature supported (T_u) was achieved, which was lower than the maximum predefined temperature. Specimen L100_T150_CL100a did not fail during this heating up phase. The following test step was to keep the temperature (80 ºC) and applied load (100 kN) constant for one hour and, within this period of time, failure of L100_T150_CL100a was observed. Also, in specimen

L100_T150_CL120b, the heating was paused at the temperature of 60 ºC (at time $t_{60ºC}$, see Fig. 9b) and, for a period, $\Delta t_{60ºC}$, of 63 min, the load and temperature conditions were kept constant. Specimens L100_T150_CL120b kept the same values of relative displacement in all three locations and no signs of failure were noticed. The test was resumed, with the intend of reaching 80 ºC, and failure was observed shortly afterwards.

Debonding process

The debonding process of the EBR region was also analyzed during the transient tests. In the first stage of the test, the load was increased up to the predefined values using the same procedure used in the steady-state tests: the laminate was pulled at a constant rate of 0.30 mm/min until the total debonding of the EBR region; then the speed was increased up to 2 mm/min until the predefined load was achieved. During this stage, all specimens were kept at a constant temperature of 30 ºC. Table 2 shows the debonding load, P_{deb}, and the temperature in the EBR region T_{deb}. The typical strain evolution in the EBR region of specimens tested using the transient configuration can be observed in Fig. 6b. An average debonding load of 61.8 kN (CoV=8.68%) was observed in specimens tested using the transient test configuration. The small coefficient of variation confirms the low result dispersion that is expected in these large-scale shear tests.

Few differences were observed between the debonding process at 20 ºC and 30 ºC. At both temperatures levels, the strain profile started with a peak strain value at the loaded-end (location x=0 mm, see Fig. 6b) and a null strain at the mid-end (location x=250 mm, see Fig. 6b). As the load increased, the strain profile changed, enabling higher strain values in middle of the EBR region. Eventually, the maximum capacity was achieved and, with the complete debonding of the laminate, not only the strain in the mid-end started to increase but also did the relative displacement registered by the LVDT-2. In general, at the same load levels, similar strain levels were observed for both temperatures. However, the debonding load, P_{deb}, for specimens tested at 30 ºC was around 61.8 kN. This value corresponds to a relative increase of 26%, when compared with the specimens tested at room temperature, and can be justified by the post-curing of the epoxy adhesive (Silva et al. 2016).

Failure Modes

All specimens tested under the transient configuration exhibited the same failure mode than those tested under the steady-state configuration at elevated temperatures, which was laminate slippage from the anchorage (see Fig. 8b and c).

As referred before, no signs of failure were noticeable when the transient tests were carried out with the lowest pull-out load of 80 kN. However, for the case of the load level of 100 kN, failure was observed when the temperature at the anchorage was of 67.7 ºC (L100_T100_CL100) and 80 ºC (L100_T150_CL100a and L100_CL150_T100b), depending on the torque level. For the later load level (100 kN), the level of normal stress induced by the level of torque proved to be a major factor in the anchorage capacity: the specimen with the lowest torque level failed when the temperature reached 67.7 ºC (above the adhesive T_g), whereas the specimens L100_T150_CL100a and L100_T150_CL100b reached the predefined maximum test temperature (80 ºC, well above the adhesive T_g). The L100_T150_CL100a specimen not only supported the highest predefined temperature but also endured almost one hour at those conditions before slippage failure. As can be seen in Fig. 9a, specimen L100_T150_CL100a showed a displacement increase in both locations after reaching the maximum predefined temperature ($t_{80ºC}$=137 min). However, the registered slip, which was almost negligible in the first 30 minutes, gradually increased up to 1 mm in all LVDT's just before failure was observed (t_u=193 min). The L100_T150_CL100b is a specimen with the same properties of the specimen

L100_T150_CL100a and, for that reason, was able to reach the predefined maximum temperature.

The remaining three specimens, tested with the highest load level (120 kN), failed shortly after the temperature in the anchorage surpassed the adhesive's T_g: the specimen L100_T100_CL120 failed at 63.4 ºC, the specimen L100_T150_CL120a failed at 64.2 ºC and the specimen L100_T150_CL120b failed at 71.2 ºC. These results show that there was a small increase of anchorage resistance with the level of normal stress. However, for this load level (120 kN), the level of normal stress has a considerable lower influence in the anchorage resistance when compared with the specimens with the load level of 100 kN. Results show that the increase in the level of normal stress, from 7.7 MPa to 11.5 MPa corresponded to an increase on the ultimate temperature, T_u, of 18.2% and 6.8% in tests carried out with the loads of 100 kN and 120 kN, respectively.

In short, the transient tests results showed the three possible scenarios when the applied load is the studied variable: (i) the first scenario is characterized by the low load level (80 kN) and the anchorage capacity of enduring the high temperatures without failure; (ii) the second scenario corresponds to a load level (100 kN) where failure is observed but it is highly influenced by other factors like the level of normal stress ; and (iii) the third and last scenario is related to the highest load level (120 kN), for which failure is attained shortly after the specimens temperature surpasses the adhesive's T_g, regardless of the level of normal stress. It should be highlighted that the transient tests were replicated (e.g. L100_T150_CL100a and L100_T150_CL100b) and the same outcome was observed. The repeatability of the obtained results is a consequence of (i) the strict and high-quality control kept during the preparation and execution of the experimental campaign, and (ii) the nature of specimens and test configuration (large scale tests).

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CONCLUSIONS

This paper presents the results of an experimental program aiming at studying the effectiveness of a mechanical anchorage of EBR CFRP system to concrete structures. For this purpose, 17 prismatic concrete blocks externally bonded with CFRP laminates were tested using two test configurations: the steady-state and the transient. From the experimental results, the following conclusions can be drawn:

1. In this experimental program, the mechanical anchorage provides adequate normal stress of the CFRP laminate to the concrete substrate at room temperature. The anchorage enabled the use of the CFRP laminate maximum capacity regardless the level of normal stress;
2. Distinct failure modes were obtained during the steady-state tests: (i) FRP rupture was observed for specimens tested at room temperature, whereas (ii) anchorage slippage was observed in all specimens tested at elevated temperatures. In all transient tests, the failure mode observed was anchorage slippage;
3. In the steady-state tests, a 43.9% and 58.5% reduction of the ultimate load was observed in the specimens tested at 60 ºC and 80 ºC, respectively, compared to the ones tested at room temperature;
4. At room temperature, the debonding load increased with the laminate width and it was obtained a good correlation between the experimental values and the prediction from the literature. When the temperature in the EBR region was 30 ºC (initial stage of transient tests), a relative increase in the debonding load of 23.4% was observed. Results also show that a fraction of the pull-out load was supported by the mechanical anchorage since the early stages of the debonding process for the specimens tested at 60 ºC and 80 ºC.

5. In the transient tests, three different outcomes were observed: (i) the low load level of 80 kN (0.36% of CFRP strain) was not enough to result in failure for the defined temperature variation; (ii) the medium load level of 100 kN (0.45% of CFRP strain) resulted in failure, but the level of normal stress worked as a relevant factor in the anchorage capacity; and (iii) the high load level of 120 kN (0.54% of CFRP strain) lead to the anchorage failure shortly after the temperature surpassing the adhesive's T_g;
6. The torque level was the tool used to control the level of normal stress of the anchorage and, based on the results from both test configurations it is a relevant factor to increase the anchorage capacity.
7. During the experimental campaign, the transient tests were replicated (e.g., L100_T150_CL100a and L100_T150_CL100b) and a similar outcome was observed. The repeatability was as expected, considering the nature of specimens, the test configuration (large scale) and the quality control. However, more research is needed to confirm these results and further understand the debonding and failure mechanisms of the mechanical anchorage.
8. Based on the results obtained it is important that further research be aimed at evaluating the influence of different levels of temperature, different levels of torque, and long-term exposure to different environmental conditions (e.g. moisture/water immersion; wet-dry cycles; freeze-thaw cycles; salt fog cycles; temperature cycles). However, the process used in this work is promising for the establishment of standardized procedures for the assessment of mechanical anchorage systems.

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List of Tables:

Table 1. Experimental Program

Specimen	w_f (mm)	T_L (N·m)	T (ºC)	σ_L (MPa)	E_f (GPa)	f_{fu} (MPa)	C.B.
L80_T100_SS20	80[i]	100	20	9.6	171 (0.3%)	2428 (4.6%)	B1
L80_T150_SS20	80[i]	150	20	14.4	171 (0.3%)	2428 (4.6%)	B1
L80_T150_SS60	80[ii]	150	60	14.4	175 (1.1%)	2868 (1.6%)	B2
L80_T150_SS80	80[ii]	150	80	14.4	175 (1.1%)	2868 (1.6%)	B2
L100_T100_SS20	100[iii]	100	20	7.7	169 (1.4%)	2480 (4.0%)	B1
L100_T100_SS60	100[iv]	100	60	7.7	187 (0.9%)	2895 (0.2%)	B2
L100_T100_SS80	100[iv]	100	80	7.7	187 (0.9%)	2895 (0.2%)	B2
L100_T150_SS20	100[iii]	150	20	11.5	169 (1.4%)	2480 (4.0%)	B1
L100_T150_SS60	100[iv]	150	60	11.5	187 (0.9%)	2895 (0.2%)	B2
L100_T150_SS80	100[iv]	150	80	11.5	187 (0.9%)	2895 (0.2%)	B2
L100_T200_SS60	100[iii]	200	60	15.3	169 (1.4%)	2480 (4.0%)	B1
L100_T100_CL100	100[iv]	100	--	7.7	187 (0.9%)	2895 (0.2%)	B2
L100_T100_CL120	100[iv]	100	--	7.7	187 (0.9%)	2895 (0.2%)	B2
L100_T150_CL100a	100[iv]	150	--	11.5	187 (0.9%)	2895 (0.2%)	B2
L100_T150_CL100b	100[iv]	150	--	11.5	187 (0.9%)	2895 (0.2%)	B2
L100_T150_CL120a	100[iv]	150	--	11.5	187 (0.9%)	2895 (0.2%)	B2
L100_T150_CL120b	100[iv]	150	--	11.5	187 (0.9%)	2895 (0.2%)	B2

Notes: The laminate of 80 mm belongs to two different batches, batch [i] and batch [ii]; the laminate of 100 mm belongs to two different batches, batch [iii] and batch [iv]; the values between parentheses are the corresponding coefficients of variation (CoV).

$\boldsymbol{w_f}$ – CFRP laminate width; $\boldsymbol{T_L}$ – Torque level; $\boldsymbol{T}$ – Test temperature; $\boldsymbol{\sigma_L}$ – level of normal stress;

$\boldsymbol{E_f}$ – CFRP modulus of elasticity; $\boldsymbol{f_{fu}}$ – CFRP tensile strength; **C.B.** – Concrete batch.

658 **Table 2.** Main Results

Specimen	T_{deb} (ºC)	P_{deb} (kN)	T_u (ºC)	P_u (kN)	ε_u (10^{-3})	$s_{u,1}$ (mm)	$s_{u,2}$ (mm)	P_{res} (kN)	F.M.
L80_T100_SS20	20.0(1)	43	20.0(1)	259	15.1	5.4	2.1	0	FRP rupture
L80_T150_SS20	20.0(1)	43	20.0(1)	171(2)	9.7(2)	2.3(2)	0.8(2)	0	-(2)
L80_T150_SS60	49.3	--	60.8	133	7.8	2.9	1.4	87	Slippage
L80_T150_SS80	69.0	--	80.5	123	7.2	2.5	1.0	86	Slippage
L100_T100_SS20	20.0(1)	56	20.0(1)	294	15.1	5.0	1.6	0	FRP rupture
L100_T100_SS60	50.2	--	60.5	157	7.6	3.5	1.3	103	Slippage
L100_T100_SS80	66.8	--	80.3	105	4.9	2.1	0.7	76	Slippage
L100_T150_SS20	20.0(1)	43	20.0(1)	298(3,4)	15.3(3,4)	4.2(3,5)	1.2 (3,5)	0	FRP rupture
L100_T150_SS60	53.8	--	60.5	189	9.1	3.4	1.2	125	Slippage
L100_T150_SS80	64.5	--	80.4	123	5.9	2.3	1.0	85	Slippage
L100_T200_SS60	67.3	--	60.3	167	8.3	3.3	1.5	118	Slippage
L100_T100_ CL100	30.0	68	67.7	120	-	-	-	-	Slippage
L100_T100_ CL120	28.0	55	63.4	120	-	-	-	-	Slippage
L100_T150_ CL100a	29.5	60	80.0	100	-	-	-	-	Slippage
L100_T150_ CL100b	30.0	58	80.0	100	-	-	-	-	Slippage
L100_T150_ CL120a	29.7	60	64.2	120	-	-	-	-	Slippage
L100_T150_ CL120b	29.4	70	71.2	120	-	-	-	-	Slippage

Note: (1) Estimated temperature based on the room temperature; (2) Premature failure from the clamping system; (3) The ultimate load, strain and relative displacement weren’t registered due to a technical problem; (4) This value corresponds to the theoretical expected result; (5) This value corresponds to the last registered value, at a load of 252 kN.

T_{deb} – Temperature in the bonded length during the debonding process; P_{deb} – Debonding load; T_u – Temperature in the anchorage region at failure; P_u – Load at failure; ε_u – CFRP strain at failure; $s_{u,1}$ – Slip at failure registered at the loaded-end; $s_{u,2}$ – Slip at failure registered at the mid-end; P_{res} – Residual load; **F.M.** – Failure Mode.

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