Study of Bond between Near Surface Mounted (NSM) CFRP strips and concrete at high temperature

Miguel Salgado de Oliveira Instituto Superior Técnico

Abstract: This paper presents an experimental study about the bond between near surface mounted (NSM) CFRP-strips and concrete at high temperatures. The experimental campaign consisted of two steps, in which an alternative adhesive to epoxy-adhesive was assessed and the bond CFRP-concrete behaviour at elevated temperature was analysed. First, the experiments comprised the evaluation of an alternative methacrylate-based adhesive through shear and tensile tests at elevated temperatures (until 120ºC). The results showed that in both tests the material properties present a reduction with increasing temperature. Comparing both adhesives, the methacrylate-based adhesive presented much lower properties at room temperature but presented better performance than the epoxy-adhesive at high temperatures. The bond behaviour tests consisted of static single-lap shear tests performed on concrete blocks ("U" shape) strengthened with CFRP-strips installed into slits made in concrete and bonded with both adhesives after being heated inside a thermal chamber (20ºC, 50ºC, 70ºC, 90ºC, 130ºC, 170ºC, 220ºC and 270ºC at the adhesive). From the obtained results the following conclusions were drawn: (i) the alternative adhesive did not provide a viable alternative, due to insufficient friction at the CFRP-adhesive interface; (ii) the bond properties of the epoxy-adhesive showed a decreasing tendency with the temperature increase; (iii) the use of strain gauges, although allowing to understand the evolution of deformations at the interface, caused a loss of bond; (iv) results obtained for the epoxy-adhesive agreed well with prior studies on CFRP-concrete bond; (v) relaxation models available in the literature were successful in predicting the bond strength reduction with temperature.

Keywords: Near surface mounted (NSM), Carbon fibre reinforced polymer (CFRP) strips, Bond, Epoxy adhesive, Alternative adhesive, High Temperature.

1. Introduction

Over the past years, the strengthening of RC beams with CFRP (carbon fibre reinforced polymer) composites has been a technique that has gained increasing interest due to the durability, high resistance and high elastic modulus of CFRP [1]. Nevertheless, the knowledge is still insufficient regarding the behaviour of these strengthening systems at elevated temperatures, and in this respect the adhesive has been identified as the main problem [2].

The strengthening of RC beams with CFRP composites can be done by two main techniques, EBR (externally bounded reinforcement) and NSM (near surface mounted). The first consists of bonding externally the CFRP strip or sheet to the RC structure, while in the second the bonding is done in small slits opened at the surface of the structure, improving the confinement of the laminate or rod. Prior studies [2] confirmed the superior bond performance of the NSM technique compared with EBR at both ambient and elevated temperatures.

To the present day, there are few studies concerning the bond at high temperatures, especially using the NSM technique with CFRP strips, the focus of the present study. Therefore, the literature review presented next describes the works on NSM systems at elevated temperature of Palmieri *et al.* [3], Yu and Kodur [4] and Firmo [5], concerning the use of an epoxy adhesive, and Al-Abdwais *et al.* [6], using an alternative adhesive.

Palmieri *et al.* [3] conducted double lap shear tests in which the specimens were first heated (between 20ºC and 100ºC) for 12 hours, using an epoxy adhesive (T_g of 65ºC) and strips or rods, and then loaded to failure. The authors observed that for temperatures below the T_g of the adhesive the bond strength increased (only observed in the rod specimens) and decreased for temperature above the T_g (41%-18% retention at the highest temperature) - this result was not expected.

Yu and Kodur [4] performed single lap shear tests on concrete specimens strengthened with CFRP strips and rods, using two epoxy adhesives with different T_g (82ºC and 120ºC, values from the producer). As expected, the results obtained showed a decreasing trend of bond strength with temperature; and the adhesive with the highest T_g provided the highest bond strength for all temperatures tested. On the other hand, for the CFRP strips the adhesive with higher T_g presented a higher performance reduction with temperature, when comparing with the pull-out force at room temperature.

More recently, Firmo [5] performed double lap shear tests on RC blocks using CFRP strips and two types of adhesives (epoxy and hybrid cement-epoxy adhesives) with NSM and EBR systems. For the NSM system, both adhesives had a consistent reduction of bond strength and maximum shear stress with temperature; in the hybrid adhesive this reduction started at lower temperatures. The effective bond length was not achieved at all temperatures in the hybrid adhesive and at high temperatures in the epoxy adhesive.

Up to now, only Al-Abdwais *et al*. [6] presented an experimental program comparing an alternative adhesive (cementitious-based adhesive) and a conventional epoxy adhesive at high temperatures using NSM system in which good results were reported. The methodology used consisted of two phases: firstly, single lap shear tests were conducted at room temperatures to determine the service loads at high temperature; next, single lap shear tests were carried out with predeterminate service loads and increasing temperature at a fix rate. The results showed that the alternative adhesive (for which rupture occurred between 235ºC and 255ºC) had 1.8 times better performance than the epoxy (presenting rupture at 140ºC).

Due to the insufficient knowledge in this area, this paper presents an experimental investigation about the influence of high temperatures (from 20ºC to 270ºC) in NSM systems using a conventional epoxy adhesive and an alternative methacrylate-based adhesive to bond CFRP strips to concrete.

2. EXPERIMENTAL INVESTIGATION

2.1 DESCRIPTION OF THE ADHESIVES

Prior to the bond tests, it was necessary to understand the properties of both adhesives. To that end DMA (dynamic mechanical analyses), tensile and shear tests at high temperatures were made.

The conventional adhesive used is a two-component epoxy adhesive with the commercial designation *S&P Resin 220*. The adhesive presents average values of tensile modulus and strength of 10 GPa and 14.2 MPa, respectively (according to ISO 527-2 [9]). From the DMA tests (dual cantilever setup, heating rate of 1 ºC/min), a glass transition temperature of 48 ºC was determined. Previously, Firmo [5] determined a decomposition temperature of the epoxy adhesive of 380 ºC (using TGA, thermogravimetric analysis, and DSC, differential scanning calorimetry).

The alternative adhesive used is a methacrylate-based adhesive with the commercial designation *HIT-HY200-A*. The DMA tests were not conclusive for this adhesive, nevertheless they showed a better retention of properties at elevated temperature compared to the epoxy adhesive, as illustrated in Figure 1. Based on the study of Roquette [10], for the same epoxy adhesive, and the results of tensile and shear tests, it was possible to determine that the methacrylate-based adhesive was considered as a potential alternative. In fact, despite its worse behaviour at room temperature, at elevated temperatures the methacrylate-based adhesive showed always a better performance than the epoxy adhesive (250% in tensile strength and 252% in shear

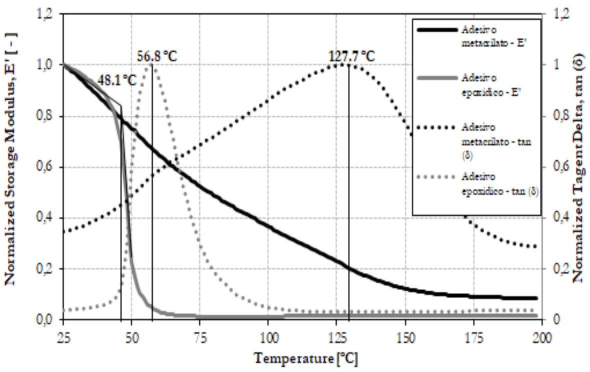

Figure 1 – DMA curves for epoxy and methacrylate-based adhesive.

strength of the epoxy adhesive results at 120 ºC).

2.2 Bond Tests

2.2.1 Experimental Program

The experimental program consisted of static single lap shear tests, at different temperatures. The tests had two phases; (i) heating the thermal chamber and the test specimens up to a predefined temperature without any load applied (this phase was not used at room temperature); (ii) applying a certain load at a fixed rate until rupture. The chosen temperatures were 20ºC, 50ºC, 70ºC, 90ºC, 130ºC, 170ºC, 220ºC and 270ºC, to capture the behaviour for temperatures, below, above and much higher than the adhesive's T_g.

For each temperature, 5 specimens were tested (from 20ºC to 170ºC), 3 without and 2 with strain gauges in the bonded length; at 220ºC and 270ºC, only 3 specimens were tested.

Due to the bonding problems encountered with the methacrylate-based adhesive (*ref.* 2.3), most of the bond tests were not executed for this adhesive; in fact, tests were only performed in a single specimen at 20ºC and 120ºC.

The nomenclature used in this paper was TxE_ext_z, for the epoxy adhesive, and TxM, for the methacrylate-based adhesive, where *x* represents the temperature, "ext" the use of strain gauges and *z* the specimen number.

2.2.2 Materials

These following materials were used in the bond tests: (i) concrete; (ii) CFRP strips; (iii) epoxy and methacrylate-based adhesives (*ref.* 2.1).

The concrete blocks used in this study were made of ready-mixed concrete, produced with limestone aggregates and Portland cement (CEM II/A-L 42,5R, according EN-197-1 [11]). The mechanical properties at the age of the tests were the following: (i) average compressive strength of 28.7 MPa; (ii) average splitting tensile strength of 1.73 MPa; (iii) elastic modulus of 27.2 GPa.

The CFRP strips used were commercially denominated as *S&P Laminates CFK 150/2000*, presenting a section of 10 mm x 1.4 mm [width x thickness]. The following average values of the tensile properties (according ISO 527-5 [12]) were obtained: (i) tensile strength of 2850 MPa; (ii) elastic modulus of 168 GPa; (iii) ultimate tensile strain of 16‰.

In a prior study, Firmo [5] obtained the values of the T_g (DMA, with a heating rate of 1ºC/min) and the T_d (DSC, differential scanning calorimetry, and TGA, thermogravimetric analysis, from room temperature to 800ºC at 10ºC/min rate) of the same CFRP strips, respectively 83ºC and 380ºC.

2.2.3 Specimen geometry and preparation

Figure 2 illustrates the dimensions and geometry of the test specimens. Due to condition of the setup and effects of eccentric loads, the “U” shaped was selected. The “U” shaped blocks had an exterior dimensions of 200 mm x 160 mm [width x height] and an interior dimensions of 50 mm x 95 mm [width x height], with four circular holes of 16 mm where were installed steel rods that connects to two steel plates (the upper one with a connection with the testing machine). The slits were made using a diamond saw with depth of 15 mm and thickness of 5 mm, according ACI 440.2R-08 [13]. The CFRP strips had a length of 700 mm with two steel plates at the end to prevent strip crush from the testing machine, according ISO 527-5 [12]. There were two types of specimens; (i) with one strain gauge outside the connection; (ii) with nine strain gauges, one outside the connection and eight inside the connection. According ACI 440.2R-08 [13] the recommended bonded length was 159 mm, although the bonded length used was 200 mm, for being expected superiors lengths at elevated temperatures.

The methodology used was; (i) slits execution with a diamond saw; (ii) cleaning dust particles form the slits and spacers placing; (iii) cleaning with acetone and bond strain gauges, when necessary, to CFRP strips; (iv) preparation and placing of the adhesive in the slit, positioning the strip at center and bottom of the slit and placing two thermocouples (at the adhesive surface and bottom); (v) adhesive curing at a controlled environment (20ºC and 56%RH); (vi) steels plates bond at the end of CFRP strip; (vii) target positioning and surface painting.

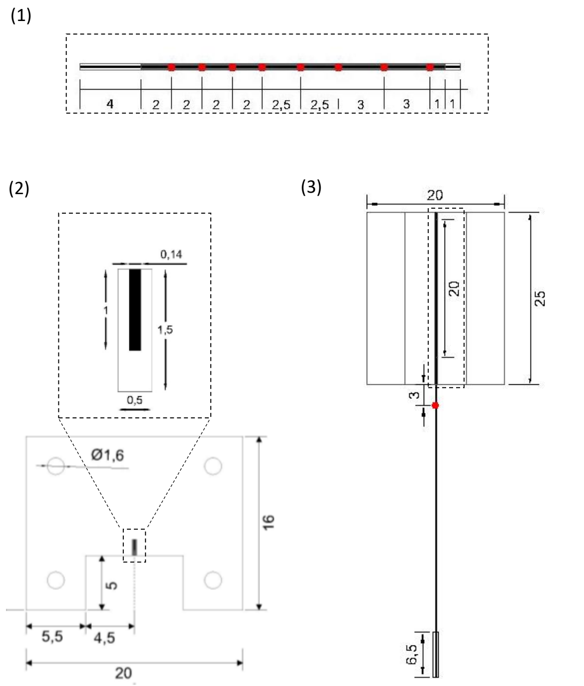

Figure 2 – Geometry of test specimens; (1) extensometers inside the bonded length, “ext” series; (2) section geometry; (3) schematic view of all series. Dimensions in cm.

2.2.4 Test setup, instrumentation and procedure

For the single lap shear tests, a universal testing machine with a capacity of 250 kN was used, including a steel fixture with rods and plates where the specimen was installed (Figure 3). At elevated temperature, a thermal chamber with the possibility to integrate the testing machine, with maximum capacity of 300ºC was used. The instrumentation used had the following objectives: (i) controlling the adhesive and thermal chamber temperature, through type k thermocouples; (ii) reading the load and cross-head displacement of the testing machine; (iii) reading the slip inside the bonded length, with targets at the end and beginning of the bonded length; (iv) measuring the deformations along the CFRP strip, with strain gauges installed along the bonded length.

The test procedure involved the following steps: (i) specimen positioning inside the thermal chamber and connection to the test machine; (ii) heating the thermal chamber to a predefined temperature, controlled by the thermocouple at the bottom of the specimen; (iii) closing the testing machine jaw at the bottom and starting of load transmission controlled by a displacement rate of 0.6 mm/min, until rupture.

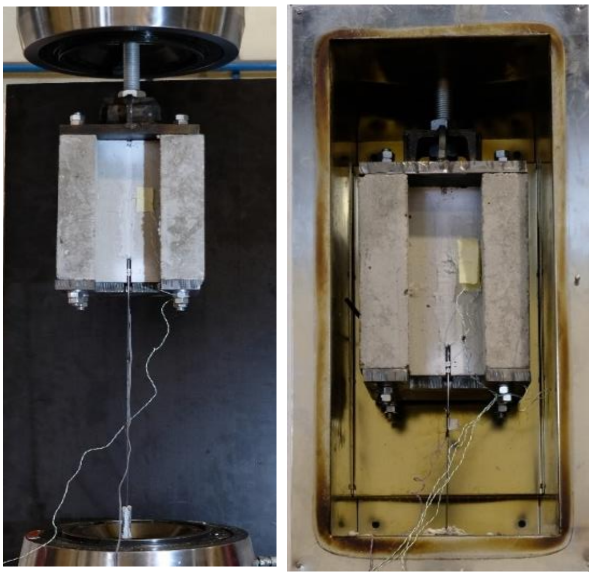

Figure 3 – Bond test setup for (1) room temperature and (2) elevated temperature.

3. Results and Discussion

3.1 Load *vs.* displacement curves

Figure 4 shows load *vs.* displacement curves of every specimen with epoxy adhesive and without strain gauges in the bonded length. In all curves it is possible to identify three different phases: (i) an almost linear branch up to a load close to the rupture load (20ºC and 50ºC) or peak load (remaining temperatures); (ii) a non-linear part until the peak load is attained; (iii) a steep load reduction after the peak load, with the load stabilizing in a non-null value. Temperature increase caused a degradation of strength and stiffness, due to the degradation underwent by the epoxy adhesive and the resin of the CFRP strip (associated with the transition glass process).

The methacrylate-based adhesive had been selected as a potential alternative to epoxy adhesive (*ref.* 2.1); however, the bond tests proved that the alternative adhesive could not mobilize enough friction from the CFRP strip. The results show that epoxy adhesive presented always better results than the alternative one at 20 ˚C and 120 ºC, as shown in Figure 5. For that reason, the following tests on methacrylate-based adhesive were abandoned.

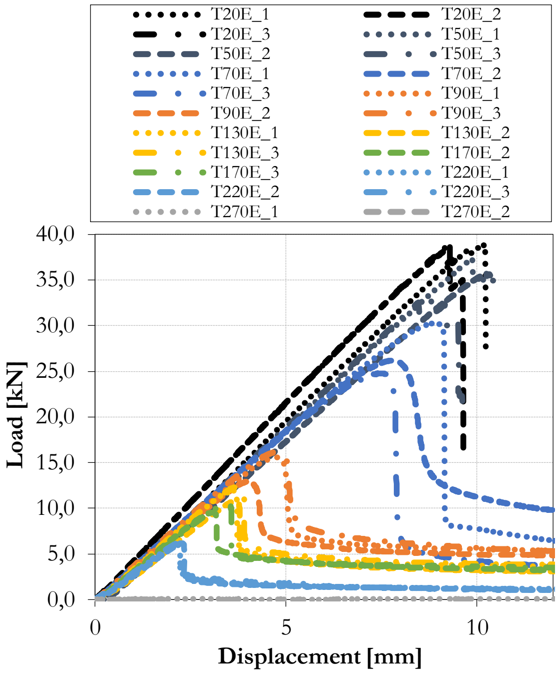

Figure 4 - Load vs. displacement curves of bond tests from all series without extensometers.

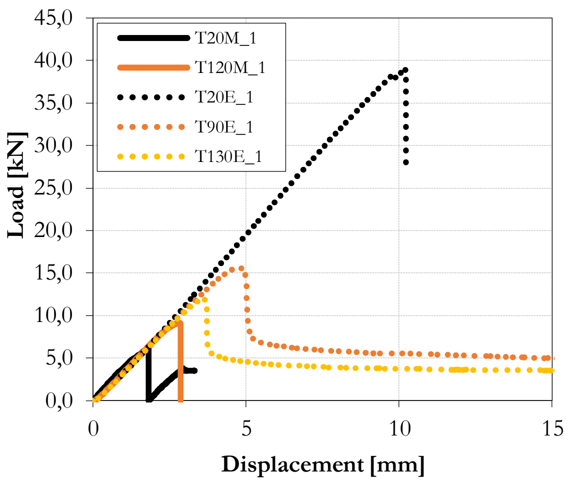

Figure 5 - Load vs. displacement curves of bond tests from methacrylate-based series and representative curves of 20 ºC, 90 ºC and 130 ºC, from epoxy series.

3.2 LOAD *VS.* SLIP CURVES

Figure 6 represents the load *vs.* slip curves at both free and loaded ends of every specimen with epoxy adhesive and without strain gauges in the bonded length (270ºC series are not represented as they presented a bond strength near zero). With temperature increase the free and loaded ends tend to reduce their peak slips gap; this behaviour is the result of the adhesive softening and loss of bond properties, due to the glass transition process. In both ends, there was strength and stiffness reduction with temperature rising. At room temperature and 50 ºC, the slip at free end is almost zero (lower than 0.1 mm), showing bond retention for the applied load and transmission of stresses (result in agreement with the fact that the joint was overdesigned according to ACI 440.2R-08 [13]). For the same temperatures the loaded end shows to phases; (i) a linear branch until two thirds of F_{max}; (ii) a non-linear transition phase until F_{max}. For temperatures higher than 50ºC, the results show the following pattern: (i) linearity loss on loaded and free ends; (ii) progressive reduction of peak load; (iii) in post-peak phase, stabilization at a residual load, significantly lower than the peak load. At elevated temperature, in opposition to room temperatures and 50 ºC, the slips increased for lower loads, as a result of bond degradation.

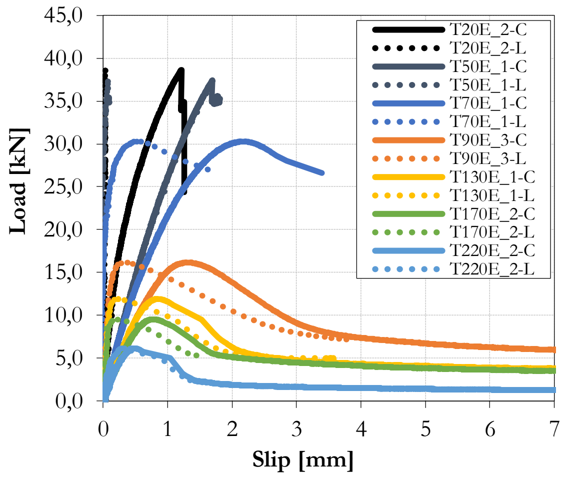

Figure 6 - Load vs. slip curves on free (L) and loaded (C) ends from representative specimens for each temperature.

3.3 STRAIN DISTRIBUTION

Figure 7 represents axial strain distributions along the bonded length in a representative specimen for each temperature (up until 170 ºC) and different fractions of rupture load, considering axial strains caused by the mechanical load (not accounting for axial strains caused from specimen heating). The axial strains were considered since the beginning of bonded length in the loaded end (x=0) to the end of the bonded length in the free end (x=200).

At room temperature, the distributions show a non-linear behavior, without any deformations near the free end (x=180 mm, position of the last extensometer) and maximum deformations near the loaded end (x=10 mm, position of the first extensometer). This result sustains that the bonded length used was the effective bonded length. On the other hand, increasing load leads to higher axial strains, especially on the loaded end, until 60%F_u, with stagnation after that fraction. For 50 ºC, the peaks become less visible near the loaded end and a more linear pattern along the bonded length, as a result of adhesive softening with temperature. For higher temperatures, a linear pattern is more visible and axial strains tend to decrease, caused by strength and stiffness loss of the adhesive and to some extent of the CFRP strip. It was also possible to conclude that the effective bond length increases with temperature; at 50 ºC, the bonded length slightly exceeds such effective bond length.

3.4 BOND *VS.* SLIP RELATIONS

The methodology used to calculate the shear stress and average slip at a pair of consecutive strain gauges, was the one put forward by Ferracutti *et al.* [14].

Figure 8 presents the shear stress vs. slip curves for all temperatures (up to 170 ºC, maximum temperature for which strain gauges were used). Each curve represents a pair of consecutive strain

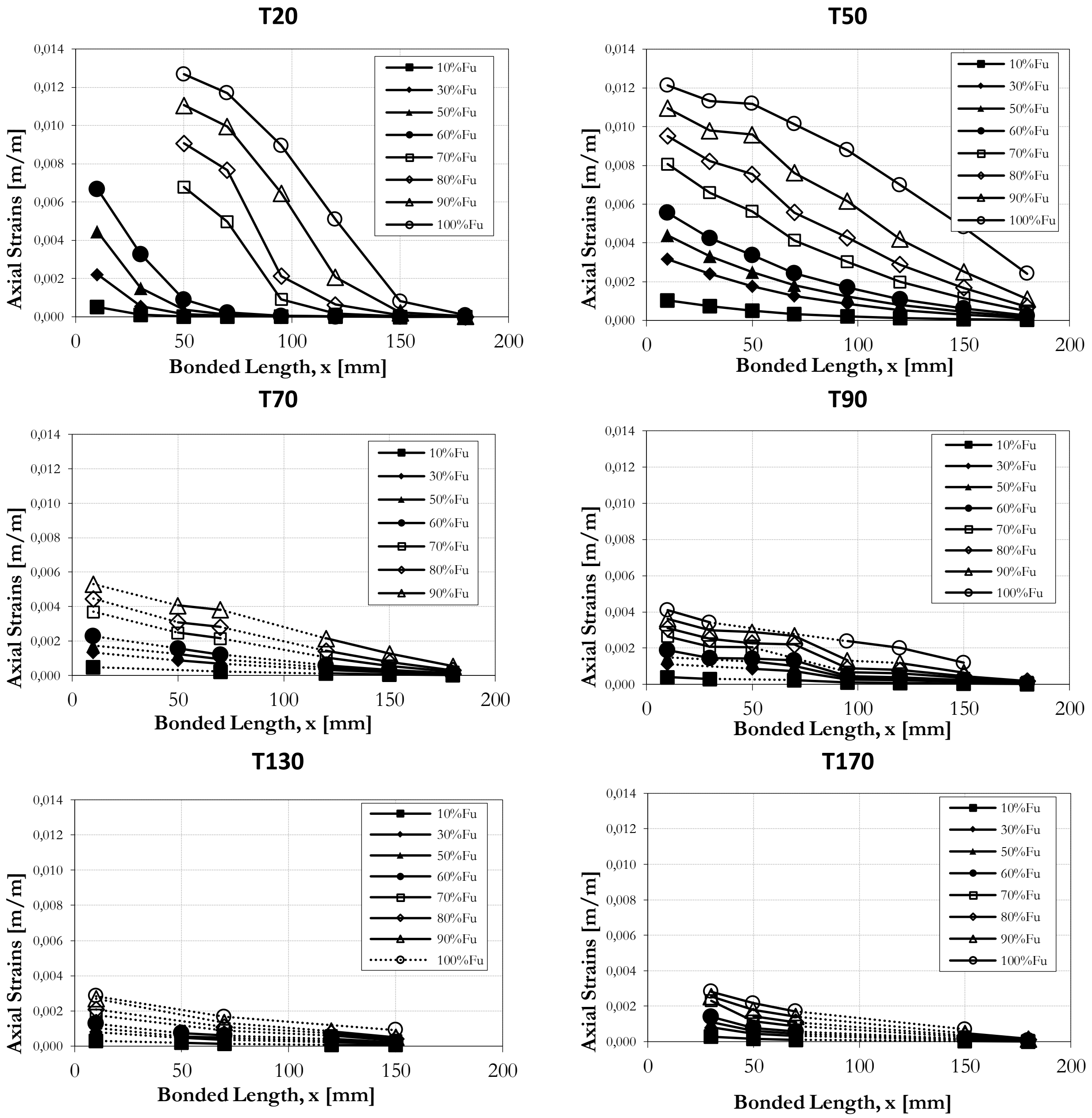

Figure 7 - Axial strain distributions along the bonded length (x) of representative specimens from epoxy adhesive series for varying percentages of failure load at 20ºC, 50ºC, 70ºC, 90ºC, 130ºC and 170ºC.

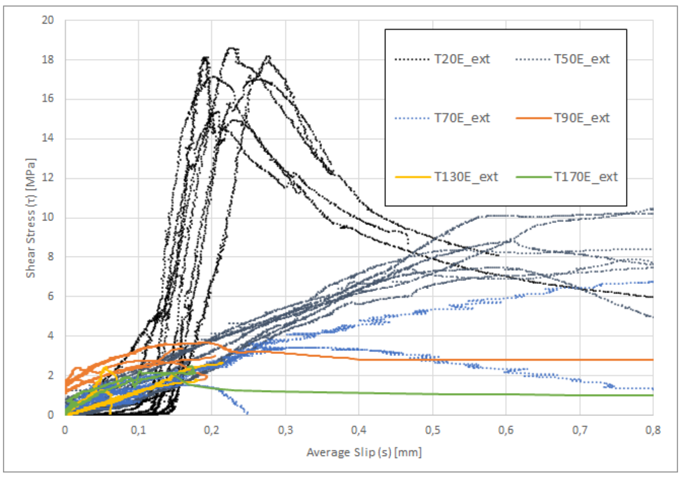

Figure 8 - Shear stress vs. slip curves for epoxy adhesive series for all temperatures tested.

gauges, in which valid readings were obtained. The results dispersion for a given temperature can be justified as follows: (i) nature and associated variability of the measurements; (ii) non-uniformity of adhesive thickness along the bonded length; (iii) possible existence of small voids within the adhesive. At room temperature an initial linear development was expected, which was not observed, as the curves exhibit an initial non-linear (toe) development and only become linear after a certain load. It was concluded that this phenomenon was caused by the specimen rotation at the beginning of the bond test. For a given temperature, well defined ascending and descending branches were observed, as reported in [5]. Temperature increase cause reduction of bond strength and stiffness. The highest reduction was observed at the transition to 50 ºC, temperature for which the biggest peak slip was measured. This is an indicator that the adhesive softened considerably, presenting the maximum distortion capacity (consistent with results of load *vs.* slip curves and with strain gauges along the bonded length).

3.5 Failure modes

Figure 9 shows the failure modes observed in this experimental campaign (epoxy series without strain gauges along the bonded length). At room temperature and 50 ºC, failure was caused by CFRP strip rupture. At 70 ºC, failure occurred at the adhesive-CFRP interface, with slip of CFRP strip and subsequent rupture in the adhesive-concrete interface (surface layer of concrete). This temperature marks a transition state in the adhesive behavior, retaining enough strength yet not enough to for not slipping. For the other temperatures, failure occurred in the adhesive-CFRP interface, with slip of the CFRP strip without any traces on the concrete surface. This type of rupture reflects the loss of bond properties due to the degradation of the adhesive.

Figure 9 - Failure modes from the epoxy adhesive series without strain gauges along the connection; (a) CFRP strip rupture; (b) rupture in the adhesive-CFRP interface, with slip of the CFRP strip and posterior rupture in the adhesive-concrete interface; (c) rupture in the adhesive-CFRP interface, with slip of the CFRP strip.

3.6 Bond strength

Figure 9 represents the evolution of bond strength with temperature for all tested series (including the methacrylate-based adhesive).

The epoxy adhesive shows non-linear reduction of bond strength with temperature (with and without strain gauges), attaining reductions higher than 50% at 90ºC, without strain gauges, and at 70 ºC, with strain gauges. The strain gauges used in the bonded length proved to have a deleterious effect in bond strength at elevated temperatures, showing relative differences of 31%, with exception of room temperature, for which no significant change was observed. The biggest

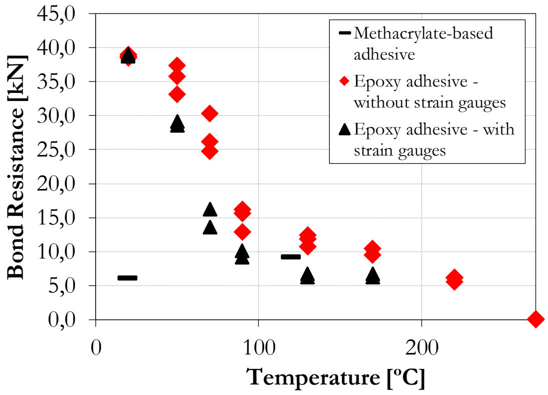

Figure 10 - Normalized bond strength with temperature evolution from all series tested.

reduction of strength occurred at different temperatures too (70 ºC and 50 ºC for without and with strain gauges respectively), allowing to conclude that strain gauges had a significant role in weakening the bond. Thus, series without strain gauges characterizes better the real behavior of strengthened structures: (i) initial loss until 50 ºC, 9% reduction; (ii) sudden reduction until 53% of the bond strength from 50 ºC to 90 ºC, caused by the evolution of the glass transition process; (iii) gradual loss of 38% from 90 ºC to 270 ºC, for which an almost zero bond resistance is observed (270 ºC mark the beginning of adhesive decomposition).

The methacrylate-based adhesive showed an unusual behavior by presenting a higher strength at elevated temperatures than at room temperature. This result is inconsistent with previous works, possibly resulting from the lack of bond characteristics at room temperature associated with accumulation of voids inside the adhesive. As referred previously (*ref.* 2.3.1), the methacrylate-based adhesive always presented worse results than the epoxy adhesive, not being an actual alternative to the conventional adhesives.

3.7 PRIOR INVESTIGATIONS AND PREDICTION MODELS

Figure 11 shows the comparison between previous investigations (Yu and Kodur [4], Palmieiri *et al.* [3] and Firmo [5]) and this experimental campaign. All these studies confirm the bond degradation with temperature increase (for CFRP strips and epoxy adhesives). This degradation starts early or later depending on the T_g of each adhesive; the single exception is the relatively high bond strength at higher temperatures reported by Yu and Kodur, which may be due to the type of adhesive used (T_g=120ºC) and the procedure adopted for temperature monitoring.

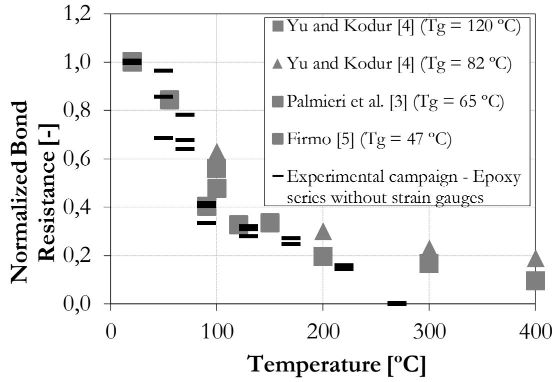

Figure 11 - Normalized bond strength with temperature evolution from epoxy series without strain gauges and prior investigations (Yu and Kodur [4]*, Palmieri et al.* [3] *and Firmo* [5]*).*

Figure 12 presents the curves corresponding to the prediction of bond strength as a function of temperature, obtained by fitting the experimental data of epoxy series (without strain gauges) to different models available in the literature. The corresponding expressions result from the investigations of Gibson *et al*. [15] (eq. 1), Mahieux *et al*. [16] (eq. 2) and Wang *et al*. [17] (eq. 3), where P_u and P_r are the property at room temperature and the residual property value after T_g, respectively, and the remaining parameters result from the fitting procedure.

$$P(T) = P_U - \frac{P_U - P_R}{2} \tanh\{k_m\,(T - T_{g,mech})\} \qquad (1)$$

$$P(T) = P_R - (P_U - P_R) \times exp[(T/T_0)^m] \qquad (2)$$

$$P(T) = P_U \times \left[A - \frac{(T - B)^n}{C}\right] \qquad (3)$$

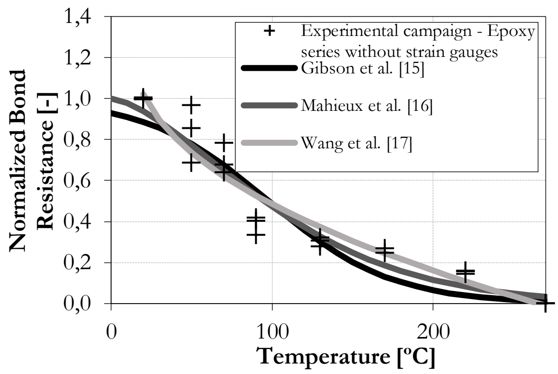

Figure 12 - Normalized bond strength with temperature evolution from epoxy series without extensometers and predition models (Gibson et al. [15]*, Mahieux et al.* [16] *and Wang et al.* [17]*).*

All the models tested presented a good adjustment to the test data (determination coefficient higher than 0.90), although the one with better adjustment was the model by Mahieux *et al*. [16].

4. CONCLUSIONS

The present paper presented the results of an experimental campaign about the influence of elevated temperatures on the CFRP-concrete bond, using NSM reinforcement system with a conventional epoxy and an alternative methacrylate adhesive. The following conclusions were drawn:

- The alternative adhesive used proved to be inefficient, as it could not mobilize enough friction between the CFRP strip surface and concrete; therefore, it provided much worse performance than the epoxy adhesive at room temperature and at elevated temperatures;
- Load *vs.* slip curves presented a degradation of strength and stiffness with temperature;
- Axial strains along the bonded length change with temperature increase, and the distribution changes from non-linear to linear, caused by the degradation (softening) of the adhesive layer;
- Even though the data obtained present some scatter, shear stress *vs.* slip curves allowed identifying a reduction trend of maximum shear stress and stiffness with increasing temperature;
- The effective bond length tends to increase with temperature, exceeding at some point (temperature) the design bonded length;
- The use of strain gauges in the bonded length proved to be detrimental for the bond behaviour, reducing the temperature that caused CFRP-adhesive rupture and decreasing the bond strength.
- The data obtained in the present study for the conventional epoxy adhesive are in agreement with the data from previous investigations, following the same decreasing trends with temperature;
- The prediction curves from different relaxation models were able to fit well the experimental data; nevertheless, in the future, different models should be developed to predict more accurately the different phases of the response observed in this study.

5. REFERENCES

[1] J. R. Correia, Fibre-Reinforced Polymer (FRP) Composites, in *Materials for Construction and Civil Engineering*, 2015, 501–556.

[2] J. P. Firmo, J. R. Correia, L. A. Bisby, Fire behaviour of FRP-strengthened reinforced concrete structural elements: A state-of-the-art review, *Composites Part B: Engineering*, vol. 80, 198–216, 2015.

[3] A. Palmieri, S. Matthys, L. Taerwe, Bond behavior of NSM FRP bars at elevated temperatures, *First Middle East Conference on Smart Monitoring Assessment and Rehabilitation of Civil Structures (SMAR 2011)*, 8 pages, 2011.

[4] B. Yu, V. K. R. Kodur, Effect of high temperature on bond strength of near-surface mounted FRP reinforcement, *Composite Structures*, vol. 110 (1), 88–97, 2014.

[5] J. P. Firmo, Fire behaviour of reinforced concrete structures strengthened with CFRP strips, Dissertação para obtenção do Grau de Doutor em Engenheiro Civil, Instituto Superior Técnico - Universidade de Lisboa, Lisboa, 2015.

[6] A. Al-Abdwais, R. Al-Mahaidi, A. Al-Tamimi, Performance of NSM CFRP strengthened concrete using modified cement-based adhesive at elevated temperature, *Construction and Building Materials*, vol. 132, 296–302, 2017.

[7] H. Lee, W. T. Jung, W. Chung, Bond behavior of near surface mounted CFRP rods under temperature cycling, *Engineering Structures*, vol. 137, 67–75, 2017.

[8] M. Emara, L. Torres, M. Baena, C. Barris, X. Cahís, Bond response of NSM CFRP strips in concrete under sustained loading and different temperature and humidity conditions, *Composite Structures*, vol. 192 (December 2017), 1–7, 2018.

[9] EN ISO 527-2, *Determination of tensile properties of plastics - Test conditions for moulding and estrusion plastics*, 1996.

[10] G. Roquette, Efeito da temperatura na eficácia de técnicas de reforço com laminados de fibras de carbono (CFRP), Dissertação para obtenção do grau de mestre em Engenharia Civil, Instituto Superior Técnico - Universidade de Lisboa, Lisboa, 2017.

[11] EN 197-1, *Cement. Part 1: Composition, specification and conformity for common cements, European Committee For Standarization (CEN)*, 200AD.

[12] ISO 527-5, *Plastics - Determination of tensile properties - Part 5: Test condicions for unidirectional fibre-reinforced plastic composites, International Organization for Standarization*, 2009.

[13] ACI, Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures., in *Report by ACI Committee 4402R-08*, 2008, 76.

[14] B. Ferracuti, M. Savoia, C. Mazzotti, Interface law for FRP-concrete delamination, *Composite Structures*, vol. 80 (4), 523–531, 2007.

[15] A. G. Gibson, Y.-S. Wu, J. T. Evans, A. P. Mouritz, Laminate Theory Analysis of Composites under Load in Fire, *Journal of Composite Materials*, vol. 40 (7), 639–658, 2006.

[16] C. A. Mahieux, K. L. Reifsnider, S. W. Case, Property modeling across transition temperatures in PMC 's : Part I - Tensile Properties, *Applied Composite Materials*, vol. 8, 217–234, 2001.

[17] K. Wang, B. Young, S. T. Smith, Mechanical properties of pultruded carbon fibre-reinforced polymer (CFRP) plates at elevated temperatures, *Engineering Structures*, vol. 33 (7), 2154–2161, 2011.