GFRP rebars for concrete structures. Effect of elevated temperatures on the bond behavior of GFRP bars to concrete

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Abstract:

The use of glass fibre-reinforced polymer materials (GFRP) in the civil engineering sector has gained increased importance due to the advantages they present over traditional materials (especially steel), namely the low weight, high tensile strength and increased durability. However, there are concerns about the behaviour of these materials when exposed to high temperatures or fire. In fact, the GFRP's mechanical properties are highly susceptible to elevated temperature, especially when the temperature approaches the glass transition temperature of the polymeric matrix (T_g).

In this dissertation an experimental study was developed about the bond behaviour of GFRP rebars to concrete at elevated temperatures. To this end, pull-out tests on GFRP rebars embedded in concrete cylinders were performed at the following temperatures: 20ºC, 60 ºC, 100 ºC, 120 ºC. 140 ºC, 220ºC and 300 ºC. Particular attention was given to the influence of the geometry of the embedment length (straight *vs.* bent at 90º) on the GFRP-concrete bond at elevated temperatures was also assessed. In a first stage of the test procedure, the specimens were heated up to the target temperature and then subjected to a tensile load on the rebars; the applied load and the slip of the rebars at both the loaded and free ends were monitored during the tests.

The results obtained confirmed the susceptibility of the GFRP-concrete bond to elevated temperatures – at 120 ºC the bond strength reduction was 58 % for the straight rebars and 73 % for the bent rebars. Regarding the influence of the geometry of the embedment length, with the bent rebars significantly higher bond strengths were obtained at all elevated temperatures.

Keywords: GFRP rebars; GFRP-concrete bond; pull-out tests; straight rebars; bent rebars at 90º; high temperatures.

1. Introduction

The use of steel reinforcement in concrete elements led to a major revolution in civil engineering constructions. In fact, since the beginning of the last century, reinforced concrete has become the main material in the construction of new buildings. However, there is a main issue concerning the use of steel and concrete structures – corrosion -, which, together with the need for growing speed of construction, led to the development of new materials that could be a non-corrodible alternative to steel.

Fibre Reinforced Polymers (FRP) gained a special role in the aeronautic and aerospace industries since the 1940's, resulting in the appearance of materials with high resistance, light weight and more resistant to corrosive environments [1].

The combination of several factors, such as durability in corrosive environments and the high tensile strength, make GFRP a very interesting material, with a resistance-to-weight ratio 10 to 15 times higher than that of steel [2].

Despite such potential of GFRP, namely as rebars for concrete (internal reinforcement), there are still great concerns about their behaviour at elevated temperature and when expose to fire. Besides the serious degradation of mechanical properties when temperature reaches the glass transition temperature (T_g) of the polymeric matrix, the bond of GFRP to concrete is also affected [3].

Katz *et al.* [4] performed several pull-out tests in steel and GFRP rebars with different superficial finishing. The T_g of the different GFRP rebars was determined and varied from 60 ºC to 124 ºC. The GFRP rebars were placed vertically in concrete cylinders with an embedment length of 5 diameters and heated up from room temperature (20ºC) up to 250-350 ºC. The temperature evolution was monitored using several thermocouples in the concrete-rebars' interface. The authors concluded that: (i) in all types of GFRP rebars, a reduction of the bond strength was registered, between 80 to 160 ºC; (ii) at 200 ºC the bond strength was reduced to 80% in the GFRP rebars, while in the steel rebars the reduction was only 38%; (iii) above 200 ºC, the bond strength did not suffer further reductions; (iv) above 400 ºC, the polymeric matrix started to decompose.

Katz and Berman [5], in other experimental tests, obtained results that allowed them to validate the previous study. The main conclusion concerned the bond strength of GFRP to concrete at high temperature; the authors highlighted that this relation depends mainly on the rebars' material, surface and geometry, setting: (i) the bond strength at room temperature; (ii) the T_g of the polymer at the surface of the rebar; (iii) the degree of crosslinking of the polymeric material; (iv) the residual bond strength (*i.e* at a certain temperature, the reduction of the bond strength is no longer relevant).

Bisby *et al.* [6] studied the bond between GFRP rebars and concrete at elevated temperatures, from 25 ºC and 150 ºC, through pull-out tests. In this study the authors used two different types of rebars: (i) a sand coated rebar with double helical fibre wrap (BPG); (ii) a sand coated rebar (PTG). The T_g of the rebars were 86 ºC and 84 ºC, respectively, obtained through DMA tests. The overall conclusion is that the bond strength of the rebars decreases with temperature, and for temperatures close to the T_g the reductions observed were roughly 60% for the BPG rebar and 80% for the PTG rebar. At 150 ºC the maximum bond strength was only 37% of the value registered at room temperature (BPG) and 18% for the PTG rebar.

Despite being the most important factor in the bond-strength of the GFRP rebars to concrete, there is very limited literature available about the influence of high temperature in this relation; as a consequence, some guidelines for the design of concrete structures with FRP reinforcement do not recommend the use of these composite materials if the structures are to exposed to elevated temperature or fire.

The main objective of this paper is to present an experimental investigation on the effects of high temperature in the bond strength behaviour of GFRP rebars to concrete. This study shows the result of pull-out tests performed in GFRP rebars with two different anchoring solutions: straight and bent. Both types of rebars were embedded in concrete cylinders and heated from room temperature up to 300 ºC. In each test, the following properties of the bond strength were evaluated: (i) bond resistance; (ii) stiffness; (iii) load-displacement response; (iv) bond-slip response; (v) failure modes.

2. Experimental programme

2.1. Test Programme

The experimental campaign comprised pull-out tests on two different GFRP rebars solutions, straight and bent, embedded in concrete cylinders that were heated from room temperature (20ºC) to 300 ºC (including the T_g of the materials – 104 ºC). For each temperature, a minimum of 3 tests were carried out. These tests allowed establishing the bond-slip curves for each temperature.

2.2. Materials

The GFRP rebars used in the experimental programme were supplied by Schöck (model ComBar, properties Table 1), with 12 mm of diameter and with a ribbed surface (Figure 1). Dynamic mechanical analyses (DMA) were performed following the ASTM E1640 recommendations, and allowed determining the T_g as 104 ºC based on the onset of the storage modulus curve.

Figure 1 – GFRP rebar used in the present experiment (dimensions in [mm])

Table 1 - Mechanical properties of the ϕ12 GFRP rebars used in the present campaign (data provided by *Schöck*)

Rebar	Tensile strength f_{fu} (MPa)		Elastic modulus (GPa)	T_g (ºC)
	Straight section	Bent section		
Ø 12	1000	700	55	120

The concrete used to produce the cylinders was a ready-mixed concrete supplied by *Unibetão*, class C25/30 with cement type CEM II/A-L 42.5R and limestone aggregates with maximum dimension of 22 mm. The concrete's tensile and compressive properties were determined at the age of 28 and 272 days (age of testing). To characterize the properties of the concrete at the age of 28 days, the specimens were cured in the laboratory facilities at room temperature and with a relative humidity of 100 %; the specimens with the age of 272 days, were maintained at the same conditions to the pull-out specimens (inside the laboratory – temperature and humidity not controlled). The compressive and splitting tensile strength tests were performed according to standard procedures ([6] and [7], respectively), providing the following values for the compressive and tensile strength at the age of testing: 29,6 MPa and 31,7 MPa, respectively.

2.3. Geometry of the specimens

The specimens for the pull-out tests included a single GFRP rebar embedded vertically along the central axis of the cylinder concrete cylinders (150 mm of height and 150 mm of diameter – for the straight rebars; 230 mm of height and 150 mm of diameter – for the bent rebars). The dimensions used were determined to prevent unwanted failure modes and to allow for an easy handling of the specimens taking into account the dimensions of the thermal chamber. According to the ASTM D7913 [9] and ACI 440.3R-12 [10] standards, the embedded length of the rebars was set at 5 times their diameter, and the unbonded length of the rebars was set by using a PVC tube. To prevent tensile failure at the grip of the universal testing machine, the loaded end of the rebars was protected by a stainless steel tube (22 mm of diameter and 0,7 mm thick) filled with epoxy adhesive.

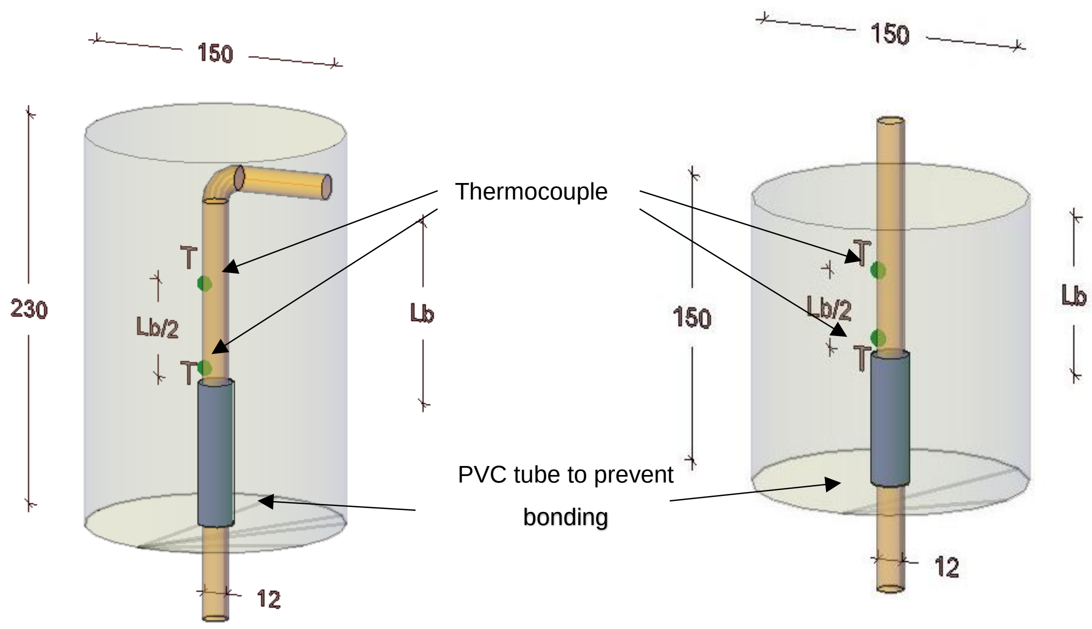

Figure 2 – Pull-out test specimens geometry and thermocouples placement: (left) bent rebars; (right) straight rebars), (dimensions in mm).

Some preliminary tests showed that splitting failure occurred in some cases; for this reason, to overcome this failure mode stainless steel brackets (28 mm of height, 1,5 mm of thickness, 10 mm of spacing) were used to confine the concrete, distributed along the cylinder and applied with a toque of 15 Nm.

2.4. Test setup and instrumentation

The test setup used in the pull-out tests is illustrated in Figure 3. To perform the experimental campaign, an *Instron* universal testing machine was used with a 250 kN capability (Figure 4). To heat the specimens, a *Tinius Olsen* thermal chamber was used, with dimensions of 605 x 250 x 250 mm and a maximum heating temperature of 300 ºC. To measure the temperature inside the specimens during the test, type K thermocouples with 0,25 mm diameter were used, positioned as illustrated in Figure 2, in the rebar-concrete interface; to measure the temperature inside the chamber, a third thermocouple was used.

To place the concrete specimens inside the thermal chamber, a special metal frame was built, composed of two metal plates and connected with steel rods, with dimensions of 200 x 200 x 16 mm.

The GFRP-concrete slip at the free end of the rebars (only in the straight rebars) and at their loaded end (in both types of rebars) was measured using a video extensometer, with the following components: (i) *Sony XCG-500E* video camera; (ii) tripod to install the video camera; (iii) computer with a *LabView* software; (iv) *HMB MX-1609* dataloggers.

To perform the slip reading between the GFRP rebars and the concrete, it was necessary to mark some stationary points in the metal frame and in the rebars.

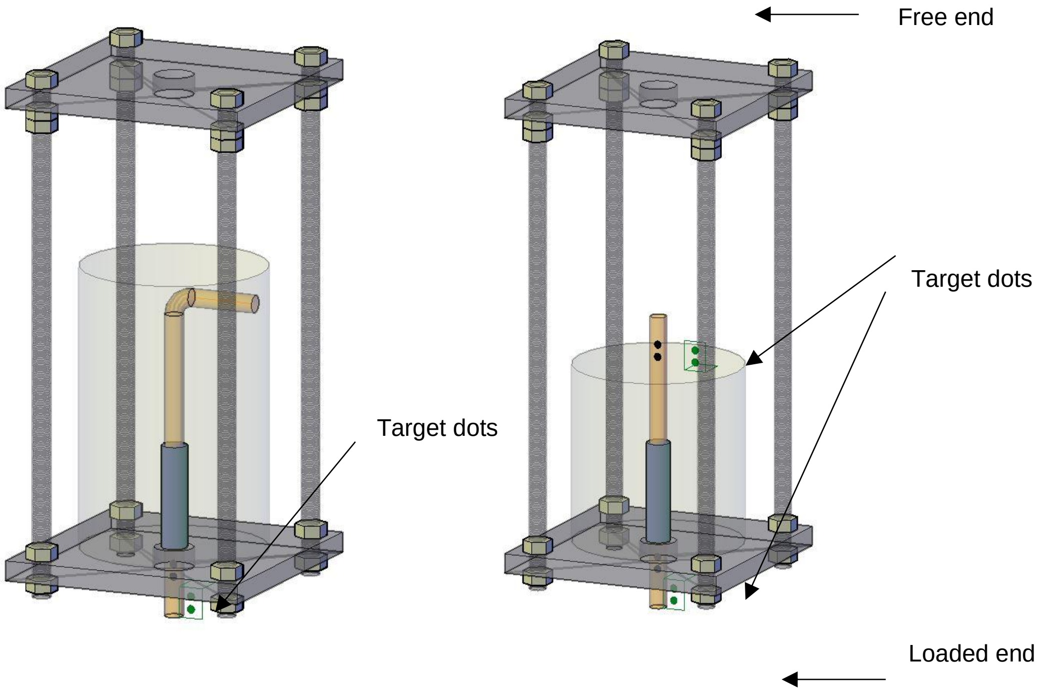

Figure 3 – Pull-out test setup used: (left) bent rebars; (right) straight rebars.

Figure 4 – Instron Universal testing machine (left); metal frame used in the pull-out tests (right).

2.5. Test Procedure

The experimental procedure consisted of two different stages. First, the specimens were heated to the target temperatures (measured at the GFRP-concrete interface), at an average heating rate of the air inside the thermal chamber of 8,4 ºC/min. The second stage of the test procedure consisted of loading the specimens under displacement control at a constant speed of 1 mm/min, while maintaining a constant temperature inside the thermal chamber and at the GFRP-concrete interface.

3. Experimental results and discussion

3.1. Load *vs.* displacement curves and load *vs.* slip curves

The representative load-displacement curves are illustrated in Figure 5. The displacement measurement corresponds to the cross-head displacement of the test machine, including the following components: (i) elongation of the rebar; (ii) GFRP-concrete interface slip, (iii) elongation of the metal parts of the test setup; and (iv) the (possible) slip of the rebars at grips of the universal machine. The behaviour of the curves obtained can be separated in two different stages: (i) an approximate linear behaviour until the maximum load is attained; (ii) after the maximum load value, a sudden drop occurred, followed by a progressive load reduction until the end of the test.

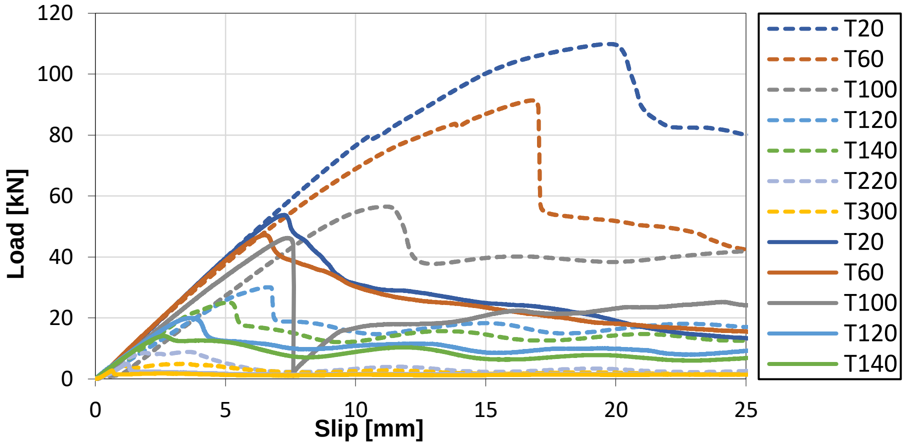

Figure 5 – Load-displacement average curves: (full line) straight rebars; (dashed line) bent rebars

The tests performed in the straight rebars at 100 ºC, showed a different behaviour in the load-displacement curve. At this temperature, the drop was more severe. The possible explanation of this phenomenon may be related to the fact that this temperature is close to the T_g of the material (104 ºC) and in some specimens concrete splitting failure occurred (although the specimens were confined with steel brackets).

Figure 6 and Figure 7 show the average bond stress *vs.* slip curves obtained for the straight and bent rebars, respectively. The average bond stress was calculated using the equation (equation 1), that assumes a uniform distribution of bond stress along the bond length.

$$\tau = \frac{F}{\pi \times D \times l} \quad (1)$$

Where, τ corresponds to the average bond stress, F is the applied load, l is the bond length and D the diameter of the rebar.

Overall, the behaviour of the average bond stress *vs.* slip curves is similar to that of the load-displacement curves, reflecting a linear behaviour in the first stage of the curves, until the maximum value is obtained and then a drop and a progressive reduction until the end of the test.

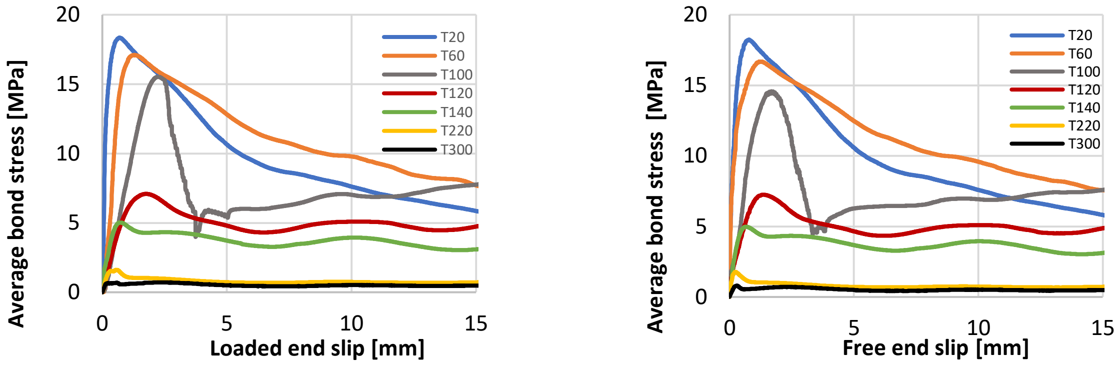

Figure 6 – Average bond stress *vs.* slip curves of the straight rebars: Loaded end slip(left); free end slip (right).

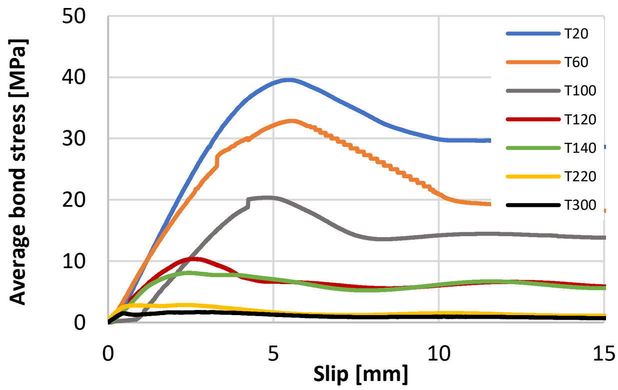

Figure 7 – Average bond stress vs. slip curves of the bent rebars.

Considering the pull-out tests performed to the straight rebars at 100 ºC, the curves obtained represented a different post-peak behaviour compared to the rest of the tests, where after the maximum value of the bond stress, a sudden load drop occurred – this phenomenon may be explained due to a different failure mode observed in these specimens, as detailed next.

As expected, the overall stiffness decreased with the temperature increase, except in some cases for which the stiffness showed a slight increase compared to lower temperatures. For instance, In the case of the straight rebars, at 140 and 220 ºC the stiffness was higher than at 120 ºC; in the bent rebars, at 140 and 220 ºC, the stiffness was higher than at 100 ºC. This may be explained by the radial expansion of the rebar – despite the thermal degradation of the mechanical properties at higher temperatures, the radial expansion (and the associated friction) might have been more relevant than the degradation observed in the material.

3.2. Failure modes

In both series of pull-out tests (straight and bent rebars) most of the failure modes consisted of pull-out of the GFRP rebar. In the straight rebars at 100 ºC the failure mode occurred by concrete splitting - in this case the confinement provided by the metal brackets was not enough to prevent this premature failure mode.

After all the tests, the specimens were saw cut in two parts, for a visual confirmation of the failure modes and to determine the extension of the damage underwent in the materials and in the GFRP-concrete interface. In both campaigns the damage of the rebars increased with temperature. Between 140 and 220 ºC the ribs were ripped off from the surface of the rebar, with some broken fibers were observed at the rebars' surface Figure 8. At 300 ºC the damages were more severe, with the ribs totally ripped off from the rebar's core, and with more broken fibers visible at the surface. Some residues of resin and fibers were also found at the concrete surface Figure 9.

For the pull-out tests with bent rebars at ambient temperature, tensile failure of the rebars were observed in two of the specimens, while for the remaining two specimen the detachment of the concrete above the bent portion of the rebar was observed. At elevated temperatures two failure modes were observed: i) the detachment of the concrete above the bent portion of the rebar and ii) pull-out of the rebars. For the higher testing temperatures, only the failure mode ii) was observed.

Figure 8 –(left) specimen tested at 140 ºC; (right) specimen tested at 220 ºC.

Figure 9 – Failure modes observed during the pull-out tests performed: (left) splitting failure in the straight rebars at 100 ºC; (right) bent rebar at room temperature.

3.3. Bond strength

Figure 11 presents the absolute values of the bond strength as a function of temperature for both types of rebars and Figure 10 presents the variation with temperature of the normalized maximum average bond stress and the storage modulus. It is possible to observe that the temperature is responsible for a decreasing of the bond strength, specially for temperatures higher than the T_g of the material.

At room temperature, the average bond strength of the bent rebars was almost the double of that of the straight rebars: 39,6 MPa *vs.* 18,6 MPa, respectively. At 100 ºC, in the straight rebars specimens, the bond strength reduction was 24 %, while in the bent rebars that reduction was 50 % (reduction compared to the respective bond strengths at ambient temperature). This difference may be related to the value of the bond strength at room temperature, for each campaign. The reference value to normalize the values at room temperature is bigger for the bent rebars, consequently the drop observed for both campaigns is different Also at this temperature: (i) in the straight rebar splitting failures were observed; while (ii) in the bent rebars failure occurred by pull-out of the rebars.

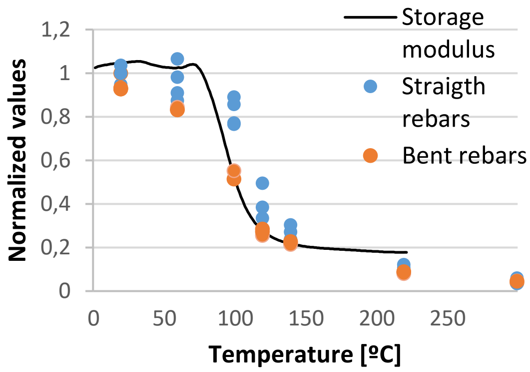

Figure 10 – Normalized values of the average bond strength and the storage modulus.

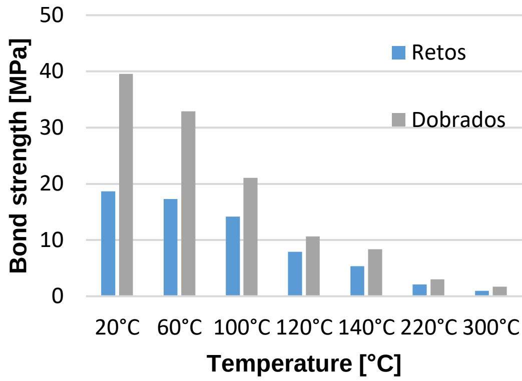

Figure 11 – Absolute values of the bond strength for both types of rebars.

3.4. Comparison with available literature

In the present experimental campaign, the obtained results were compared with the studies of McIntyre *et al.* [5], Katz *et al.* [4] and Rosa *et al.* [2]. Figure 12 shows the normalized values of the maximum bond strength obtained in those studies and the values obtained in the straight rebars tested herein. The following comments are prompted: (i) the first authors evaluated two different types of rebars, both with sand-coated surface; (ii) the rebars used by Katz *et al*. had four different types of surfaces (CB – ribbed; CPI - helical wrap; CPH helical wrap with a small sand layer; NG – helical wrap and sand-coated); (iii) Rosa *et al*. presented values related to straight sand-coated rebars. From the studies presented, it is possible to confirm the tendency of bond strength degradation with the increase of temperature. The bond strength for higher temperatures is lower, with some studies showing a residual bond strength of 10 to 20 % of their initial value, for temperatures above 150 ºC.

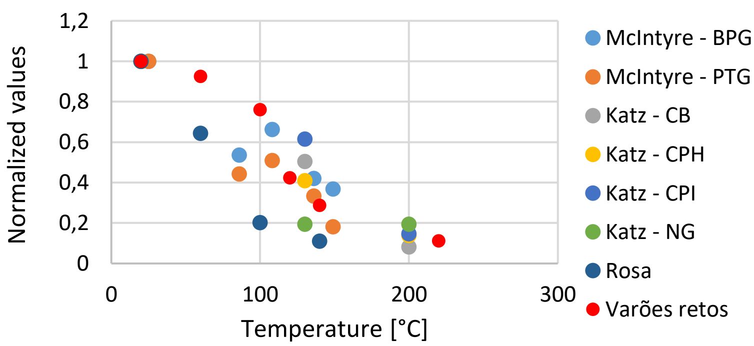

Figure 12 – Comparison with several experimental studies.

In addition, we can notice that there is a very significant scatter of the normalized values, comparing with the present campaign. This may be related with several factors, among them: (i) different types of rebars used; (ii) different methods used during the tests performed; (iii) different failure modes observed.

4. Conclusions

The results obtained in the present experimental campaign about the effect of elevated temperatures on the bond behaviour of GFRP bars to concrete allows drawing the following conclusions:

1. The temperature is a key factor in the degradation of the bond strength of GFRP rebars to concrete: for temperatures around the T_g of the GFRP (104 ºC), the bond strength of the straight rebars was 75 % to that of at room temperature, while for the bent rebars that value of only 55 %.
2. The visual observations of the specimens allowed confirm the damage underwent by the rebars and GFRP-concrete interface. For temperatures above 120 ºC the surface of the rebars was severely damage, with the ribs ripped off from the rebars core; Between 140 ºC and 220 ºC most of the rebar was severely damage, with fibers residues in the concrete. At 300 ºC the core of the GFRP rebar was damage with fibers exposed along the rebar
3. Comparing the two different solutions (bent rebars and straight rebars), it is possible to conclude that for the same conditions and temperatures, the bent rebar specimens provide higher values of bond strength at ambient temperature: at 20 ºC the bond strengths were 18,7 MPa for the straight rebars and 39,6 MPa for the bent rebars. In addition, the bent rebars also provided higher bond strength values at all elevated temperatures tested.

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