Influence of temperature on the adhesion of fibre reinforced polymers to timber surface

Influência da temperatura na aderência à madeira de polímeros reforçados com fibras

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Abstract

Carbon and glass fibre reinforced polymer composites are being increasingly used in timber structures, where they can be exposed to harsh temperature conditions. In order to be properly used, information is needed on their adhesion to the substrate. The objective of this research is to evaluate the influence of temperatures between 20 and 80 °C on the adhesion of these reinforcements to the wood. The shear test of adhesive line and pull-off test of the reinforcement from wood surface were carried out using specimens made of Pinus spp. The results demonstrated that temperature causes the nonlinear reduction of the reinforcement adhesion. The specimens exposed to a temperature of 80 °C presented residual bond strength means of 34% and 20% of the mean strength at room temperature for CFRP and for GFRP, respectively. Caution in using the applied resins is required due to the presented behaviour even in the service temperature range specified by the manufacturers.

Keywords: Bonding. Polymeric adhesives. Temperature. Timber. Structural reinforcement.

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Resumo

Os reforços de compósitos poliméricos com fibras de carbono (CFRP) e de vidro (GFRP) têm sido largamente usados em estruturas de madeira, onde eles podem estar expostos a condições adversas de temperatura. Para serem usados adequadamente, são necessárias informações sobre a sua adesão ao substrato. O objetivo desta pesquisa é avaliar a influência de temperaturas entre 20 e 80 ºC na adesão à madeira destes reforços. Testes de cisalhamento na linha de cola e de pull-off do reforço foram realizados em corpos de prova de madeira de Pinus spp. Os resultados mostraram que o aumento da temperatura provoca a redução não linear da adesão dos reforços. As resistências residuais médias de colagem dos corpos de prova reforçados, expostos à temperatura de 80 ºC, foram iguais a 34% e 20 % dos valores médios obtidos à temperatura ambiente, para reforços com fibras de carbono (CFRP) e com fibras de vidro (GFRP), respectivamente. É recomendada cautela no uso das resinas testadas, mesmo para a faixa de temperatura de serviço especificada pelos fabricantes, devido ao comportamento observado.

***Palavras-chave**: Adesão. Adesivos poliméricos. Temperatura. Madeira. Reforço estrutural.*

Introduction

Changes in timber structures over their useful life span are normal, in order to adapt to the new building functions and for the replacement of constructive elements due to deterioration by the weathering action (CRUZ, 2001). The rehabilitation or strengthening of structures aims to adapt the existing structure to a new condition, in which minimum security requirements are ensured. Among the techniques currently available (FRANKE; FRANKE; HARTE, 2015), the application of fibre reinforced polymers (FRP) has proved suitable not only for strengthening of contemporary structures but also for the rehabilitation of historical structures (NEGRÃO; BALSEIRO; FARIA, 2011; SCHOBER *et al.*, 2015). This strengthening system, offers advantages such as speed of execution, low self-weight and discreet surface finishing with minimal esthetical interference in some cases.

FRP is a system composed by fibres, impregnated with polymeric matrix, which can be classified, according to the source, in natural and in synthetically made fibres. As example on the FRP building application, sisal can be mentioned as a natural fibre (CARVALHO, 2005) and glass (GFRP), carbon (CFRP), aramid and basalt (THÓRHALLSSON; SNAEBJÖRNSSON, 2017) as synthetic fibres. The fibres can be found in the form of strips and sheets. Strips are unidirectional fibres in an epoxy matrix, while sheets are made of unidirectional or bidirectional fibres, which can be either pre-impregnated or *in situ* impregnated with resin. They are highly conformable to the surface onto which they are bonded (BAKIS *et al.*, 2002). The mechanical behaviour of the fibres can be predominantly influenced by the temperature (WANG; WONG; KODUR, 2003; CAO; WANG; WU, 2011) and by the loading rate (MAHIEUX; REIFSNIDER, 2002; ELANCHEZHIAN; RAMNATH; HEMALATHA, 2014). The commonly used polymeric matrices in a fibre-reinforced composite are epoxy, polyester and acrylate blends (VINSON; SIERAKOWSKI, 1993; KODUR; HARMATHY, 2016). Typically, the matrix has a lower density, stiffness and strength than the fibres (VINSON; SIERAKOWSKI, 1993). The response characteristics for polymeric matrix materials are usually viscoeslastic or viscoplastic and, therefore, they are affected by age, temperature and moisture content (VINSON; SIERAKOWSKI, 1993; GIBSON; ASHBY, 1997; KODUR; HARMATHY, 2016).

Reinforcements with epoxy and FRP, with glass, carbon and basalt fibres, in their different forms, have been applied with the aim of increasing performance and improving the strength and stiffness of structural elements (FIORELLI; DIAS, 2003; BALSEIRO, 2007; NEUBAUEROVÁ, 2012; ROSA; ESCAMILLA; GARCÍA, 2013; BERTOLINI *et al.*, 2014; IANASI, 2015). According to Balseiro (2007), the timber reinforcement with glued fibre laminates has, as the most common failure mode, the delamination, either in the bond line or in the adjacent area. Therefore, research was developed aimed at evaluating the adhesion of the interface reinforcement-wood by shear tests and pull-off of the interface (BALSEIRO, 2007; BARBOSA, 2008; CUSTÓDIO *et al.*, 2009; SERRA, 2010; JUVANDES; BARBOSA, 2012; RUBINI; MORAES, 2012). The shear tests were performed with different bonding lengths, subjected to adverse environmental conditions, such as different wood moisture content and temperature. At temperatures close to the environment, this research has shown that: the average shear strength at the reinforcement-wood interface decreases with increasing bonding length (BALSEIRO, 2007; BARBOSA, 2008; SERRA, 2010; JUVANDES; BARBOSA, 2012); tests in specimens bonded with high moisture content have resulted in very low or zero shear strength values and in failures due to warping and delamination after drying (BALSEIRO, 2007).

In tropical and in some temperate regions, environmental temperatures can easily reach values higher than 30 °C and high relative air humidity, affecting the structural performance of reinforcements in wooden structures. Several authors have developed research on this topic (CUSTÓDIO; BROUGHTON; CRUZ, 2009; CUSTÓDIO *et al.*, 2009; VALLUZZI *et al.*, 2013, 2016). At high and adverse temperatures, the results were not conclusive on the influence of bonding length on the shear strength (SERRA, 2010). However, for a bonding length of 3 cm, Rubini and Moraes (2012) showed that the average shear strength decreases, in a non-linear way, with the increase in temperature. The pull-off tests showed that the mean tensile strength of the CFRP reinforcements is less than the mean strength directly on the wood surface (JUVANDES; BARBOSA, 2012), but nothing was found on the influence of temperature on these mechanical properties, requiring further research.

This research aims to experimentally evaluate the effect of temperatures between 20 and 80 °C in the reinforcement adhesion to the wood substrate of *Pinus spp*. by shear strength tests in specimens reinforced with carbon fibre fabrics and pull-off

tests in glass fibre reinforced specimens, in order to measure the adequacy of surface preparation before applying a repair or an overlay material.

Materials and methods

Materials and methods used to carry out shear and pull-off tests, preparation of the specimens, the standards followed, the required equipment for full implementation of the experimental study and the methodology for calculating the strength and the reducing strength factor are presented below.

Materials

Mechanical tests were carried out using specimens made of timber *Pinus spp.*, with average mass density of 554 kg/m³ and moisture content of 12.0%, for shear tests, and 13.9%, for pull-off, at room temperature. The timber comes from planted forests in the state of Santa Catarina, Brazil.

Carbon and unidirectional glass fibre fabrics were used. Epoxy-based resins were used as adhesive for attaching the fibres to the wood. For the carbon fibre reinforcement, an epoxy resin, named here as A, was used. This consisted of two components: the base and hardener, which were mixed at a ratio of 3:1, as specified by the manufacturer (MC-BAUCHEMIE, 2016). For fixing the glass fibre, the two-component epoxy resin (named here as B) was applied. The resin and hardener were mixed in a ratio of 7:3, as specified by the manufacturer

(ANCHORTEC, 2017). Mechanical and dimensional properties of the carbon fibre and the resins are shown in Table 1.

Samples and specimens

The specimens were obtained from visually graded timber, according to the Brazilian standard NBR 7190 (ABNT, 1997), annex G. They were free of defects and were taken from regions far from the piece ends, at least five times the smallest cross-section dimension of the considered timber, but never with less than 30 cm. The timber used for the manufacture of the specimens had dimensions of 2.50 m in length and cross section of 10.0 cm × 5.0 cm, approximately.

Shear test

The timber sample used in the shear test by tension loading was classified into 2 groups with statistically homogeneous mass densities (MONTGOMERY; 2003; MONTGOMERY; RUNGER, 2003), in order to reduce or eliminate the variability transmitted from nuisance factors (MONTGOMERY, 2003). They were named according to the bonding length of the reinforcement. A total of 80 specimens were tested, 40 for each group, 10 for each temperature level (Table 2). Four test sets were carried out, one for each temperature level: 20, 40, 60 and 80 °C, covering the temperature ranges that could naturally occur in a tropical country.

Table 1 – **Mechanical and dimensional properties of the fibres and adhesives**

Components	Thickness (mm)	Mass density (kg/m³)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Specified temperature range	Elongation at rupture (%)
Carbon fibre fabric	0.13	1760	4,300	238.0	-	1.8
Fibreglass fabric	0.27	2550	85	72.4	Until 800 °C	4.8
Adhesive A	-	1120	14	3.0	Between 8 and 40 °C	-
Adhesive B	-	1050	60	-	Between -35 and 80 °C under dry conditions. up to 40 °C under wet conditions	29.0

Source: Mc-Bauchemie (2016) and Anchortec (2017).

Table 2 – **Number of shear specimens for each temperature level**

Groups	Mass density (kg/m³)	Number of specimens for testing				Total
		20 °C	40 °C	60 °C	80 °C	
PRFC 4 cm	457 a 644	10	10	10	10	40
PRFC 5 cm	463 a 643	10	10	10	10	40
					Total	80

The specimen used in the determination of the shear strength of the reinforcement is shown in Figure 1. The specimen shape was determined from the results of Balseiro (2007), after preliminary studies, so that there was no failure by crushing in the fixing rod region and also no force eccentricity with relation to the reinforcement shear line. The bonding lengths are 4.00 cm and 5.00 cm CFRP. A spacing of 0.50 cm was left between the two segments of the specimen to avoid leverage between the parts, should any eccentricity in the resulting applied load occur.

Preparation of the specimens

The manufacture of the shear test specimens was performed in four steps, according to the supplier technical specifications (MC-BAUCHEMIE, 2016): scarifying the surface; applying the adhesive A on the rough surface; adhesive application on the carbon fibre, passing the roller and curing of the specimen (Figure 2). The bonding surfaces of the specimens receiving reinforcement were treated with chisel to increase its initial roughness (Figure 2a). Thus, grooves were made in different directions in relation to the wood fibres.

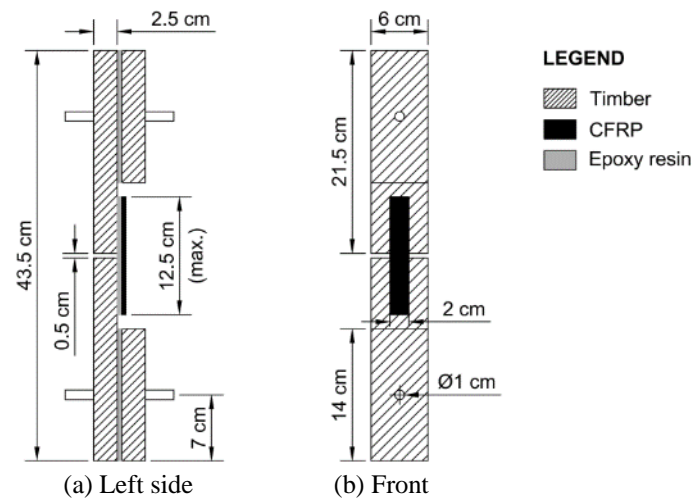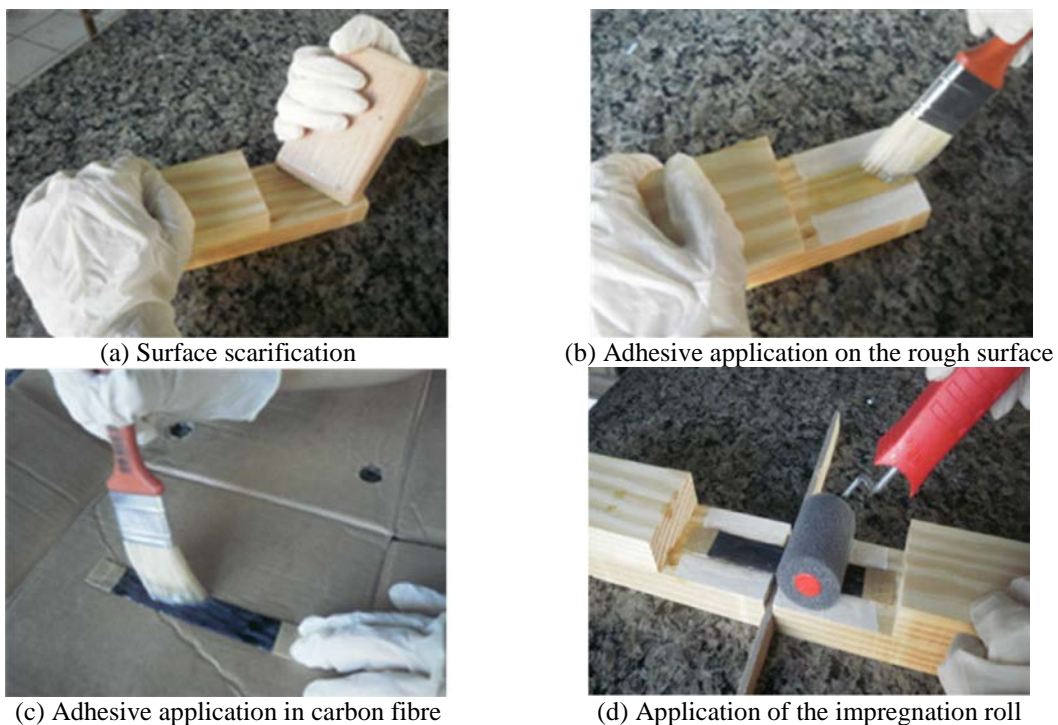Figure 1 - **Specimen with reinforcement**

(a) Left side (b) Front

Figure 2 - **Manufacturing process of the specimen**

(a) Surface scarification

(b) Adhesive application on the rough surface

(c) Adhesive application in carbon fibre

(d) Application of the impregnation roll

The adhesive was applied with a brush, always being careful not to let air bubbles and to obtain an approximately uniform thick layer (Figure 2b, 2c). Once applied to the carbon fibre, a roller was used to remove all possible air bubbles (Figure 2d). In order to ensure uniformity of the bond line, the technical staff who prepared the specimens was trained to perform this activity. A period of seven days was observed from the beginning of the gluing until the realization of the mechanical test, to complete the curing process.

Mechanical testing apparatus

The mechanical tests were performed in a thermal chamber coupled to a universal testing machine with a load cell of 50 kN, with an accuracy of 0.005 kN. The thermal chamber allowed the ambient air conditioning to reach the temperature levels of 20, 40, 60 and 80 °C, as specified in sequence.

Pull-off tests

Glass fibre pull-off of the timber was performed as specified by ASTM C 1583 (AMERICAN…, 2013), prescribing the pull-off through the bonding of a metal disc with a central hole, in which, by means of a screw, the pull-out force of the disc specimen is applied. In this research, the metal disc had a diameter of 50 mm and thickness of 10 mm, resulting in a contact surface of 1963.5 mm².

Tests were performed at three temperature levels: ambient (28 °C), 60 and 80 °C, covering the temperature range that could naturally occur in a tropical country. The ambient temperature was 28 °C, since the laboratory thermal chamber had no cooling facility.

For the pull-off tests, six specimens were prepared with dimensions of 30 cm × 10 cm × 5 cm (Figure 3). This geometric configuration was defined from preliminary studies, allowing four pull-off data on each specimen. In total, 24 data sets were obtained from 6 specimens, with 8 pull-out tests by temperature level (Table 3).

Manufacture of the specimens

The manufacture of the specimens for the pull-off test was performed in four steps by trained technical staff. According to ASTM C 1583 (AMERICAN…, 2013), the glass fibre fabric was cut into strips of dimensions 30 cm × 10 cm. In previous research, adhesion issues were verified caused by smooth surface or by chemical inactivation of wood surface by external or self-contamination (CUSTÓDIO *et al.*, 2009). Therefore, in order to increase the surface roughness, the timber was treated with sandpaper grain grit class 40 according to ANSI B74.12 (AMERICAN…, 2012) and cleaned with a cloth. For fibre fixing, an adhesive B layer was applied uniformly to the largest faces of the specimens (Figure 4a) and to the glass fibre reinforcement (Figure 4b). Subsequently, the fibre was pressed on the specimen (Figure 4c) and another adhesive layer was applied to ensure complete adhesion between the fibre and the timber (Figure 4d), according the manufacturing specifications (ANCHORTEC, 2017). The specimens were tested after an adhesive curing period of 7 days.

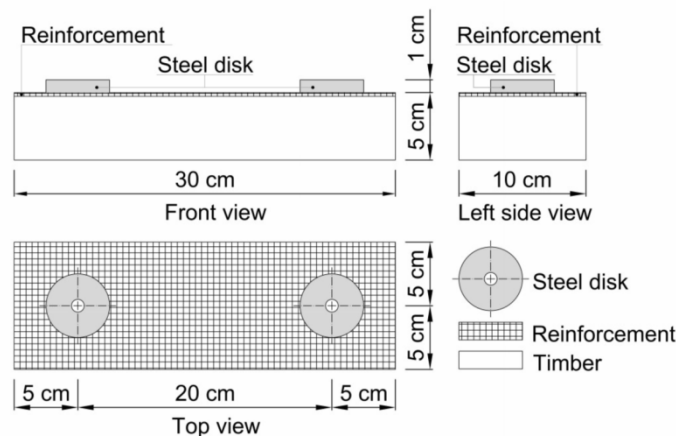Figure 3 – **Specimen dimensions and position of the pull-off tests**

Table 3 – **Number of pull-off tests for temperature levels**

Specimens	Number of pull-off			Total
	28 °C	60 °C	80 °C	
6	8	8	8	24

Figure 4 – Procedure for applying the glass fibre on timber surface: (a) first layer of epoxy resin on timber surface; (b) second resin layer on the glass fibre; (c) placement of fibreglass on the surface; e (d) third resin layer on the fibre already positioned
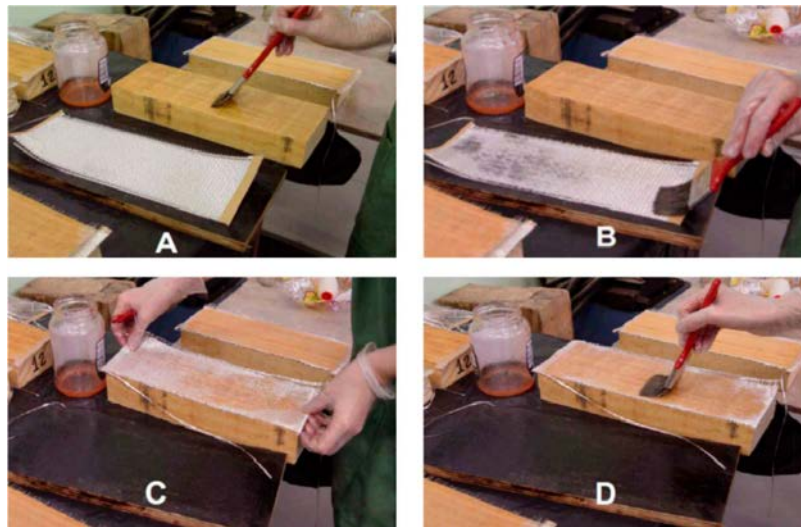
After the bonding of the fibres and the adhesive cure, the specimens were cut with a hole saw in order to delimit the pull-off area, as specified by ASTM C 1583 (AMERICAN…, 2013). The adhesive A, used for fixing the metal discs on the surface of the fibre reinforced specimens, was chosen after preliminary studies.

Pull-off procedures

The equipment used to perform the pull-off tests was a digital dynamometer, with an accuracy of 0.01 kN and a maximum capacity load of 20 kN. It had a memory device that records the maximum tensile strength during the test.

The test began with the application of an initial force of about 0.50 kN, measured on the dynamometer equipment. A tensile load was applied as the handle was rotated at a constant speed, until failure occurred. The failure load and mode were recorded and the nominal tensile stress at failure was calculated.

Heating of the specimens

The heating time of the specimens in the two tests was determined by preliminary studies, to ensure the desired adhesive temperature, according to Serra (2010). The shear specimens in tension loading were preheated for 120 min. After that, the specimens were transferred to the heated thermal chamber attached to the testing machine.

The pull-off specimens were heated for different periods of time: 120 min for the tests at 60 °C and 140 min for the tests at 80 °C. After heating, the dynamometer and the specimen were transferred to the thermal chamber heated at the test temperature and the tests were performed keeping open the chamber door.

Determination of wood moisture content

The determination of moisture content (MC) of shear test specimens was carried out using the specimens themselves. They were dried up in an electric oven. According to NBR 7190 (ASSOCIAÇÃO…, 1997), wood moisture content is calculated as the ratio of the mass of water and the dry mass of the wood, given by Equation 1:

$$MC(\%) = \frac{m_f - m_d}{m_d} \times 100 \qquad \text{Eq. 1}$$

In which:

m_f is the final mass of the specimen at the end of the shear test, in g; and

m_d is the dry mass of the specimen, in g.

The specimens were weighted at the end of the tests to determine the final mass (m_f). After that, they were dried up in an oven at a temperature of 103 ± 2 °C until a weight change between two consecutive measurements of less than or equal to 0.5% is detected. The last mass measurement was considered the dry mass (m_d).

In order to determine the moisture content of the pull-off test specimens, a hygrometer was used. The equipment had calibration for four wooden mass densities groups, accuracy of measurement of 0.1% and calibration for offsetting temperature from 0 to 80 °C.

Determination of shear strength

Shear strength at a temperature level θ ($f_{v,\theta}$) was determined by the ratio of the maximum tensile force acting on the specimen at a given temperature and the shear area, according to Equation 2.

$$f_{v,\theta} = \frac{Fv,max}{A_v} \qquad \text{Eq. 2}$$

In which:

Fv,max is the maximum force applied at the end of the specimen, in N, at a given temperature θ; and

A_v is the rupture projected area of the specimens, in mm², adapted from EN 14374 (EUROPEAN…, 2004).

The criterion to consider the shear tests as valid was that the rupture projected area should not exceed 20% of the contact area between the reinforcement and the specimen EN 14374 (EUROPEAN…, 2004). When the rupture occurs in the substrate, the failure surface can be bigger than the reinforcement shear area on the substrate or it is a curved surface. In these cases, the failure area was defined by the projection of the rupture surface on the adhesive shear plane.

Determination of the pull-off strength

The bond or tensile strength ($f_{po,\theta}$) value at temperature θ is defined by Equation 3.

$$f_{v,\theta} = \frac{Fv,max}{A_v} \qquad \text{Eq. 3}$$

In which:

$F_{po,max}$ is the maximum tension load registered by the dynamometer, in N, at a given temperature θ; and

A_{po} is the contact area between the test specimen and the metal disc, in mm².

The Standard ASTM C 1583 (AMERICAN…, 2013) gives as non-valid the tests in which the failure occurs at the bond line between the steel disc and the epoxy adhesive in the substrate. But, in this paper, this criterion was not considered. All results were included in the statistical analysis independently of the rupture type.

Determination of strength reduction factor

The reduction factor at a temperature level θ (k_θ) is calculated by Equation 4.

$$k_\theta = \frac{\overline{f_\theta}}{\overline{f_{amb}}} \qquad \text{Eq. 4}$$

Iin which:

$\overline{f_\theta}$ is the average strength in N/mm² at a given temperature θ; and

$\overline{f_{amb}}$ is the average strength in N/mm², at room temperature.

Statistical analysis

The statistical analysis was applied to assess the influence of the temperature on the shear and pull-off strength and the reinforcement lengths on the shear tests results. For the analysis of results, the existence of outlier values was initially verified (NATIONAL…, 2013). In shear strength results, two analyses were carried out separately: one to verify the influence of the temperature and other to verify the influence of the reinforcement lengths. The nonparametric Kruskal-Wallis test was applied at the 95.0% confidence level (MONTGOMERY, 2003; MONTGOMERY; RUNGER, 2003), since the assumption of independence, normality and homogeneity of data variance was not verified. More details about the statistical analysis can be found in Montgomery (2003) and Montgomery and Runger (2003).

Results and discussion

In this section, the results of the experimental investigation, moisture content, types of rupture, shear and pull-off strength in the reinforced elements are presented and discussed.

Wood moisture content

Moisture content of the specimens of shear and pull-off tests are presented in Figure 5. At room temperature, the average moisture content was 12.0% and 13.9%, for shear and pull-off tests, respectively. As expected, the reduction of moisture content with increasing temperature was observed. The bound water in the cell wall probably was not completely released due to the experimental heating process, since the highest temperature in the tests was 80 °C. According to Young and Clancy (2001), bound water evaporation begins at 100 °C.

Shear strength of the glued interface

The test results of carbon fibre timber specimens and adhesive A are presented in Figure 6 together with the average results obtained by Serra (2010) and by Rubini and Moraes (2012), both for *Pinus spp*. At room temperature, the average shear strength of the 4 cm reinforcement was 8.1 MPa, while for the 5 cm reinforcement was 5.7 MPa. The

average shear strength obtained for the 5 cm reinforcement was lower than the value of 6.7 MPa obtained by Serra (2010) for 5 cm length, at room temperature.

At 40 °C, the shear strength of 4 cm CFRP is higher than that at the room temperature. However, at 60 and 80 °C, the shear strength value is lower than that at room temperature. These results confirm the range of 8 to 40 °C for the temperature application, specified by the product data sheets (MC-BAUCHEMIE, 2016). It should be stressed that the number of the 4 cm reinforcement test repetitions was reduced, due to manufacture defects, from 10 to 8 and 10 to 6 at 40 and 60 °C, respectively.

Concerning the temperature, the non-parametric Kruskal-Wallis test (MONTGOMERY, 2003; MONTGOMERY; RUNGER, 2003) indicates that there is statistical difference between the shear strength at 20 and those at 80 °C, as presented by Table 4. This behaviour could be explained by the test temperature approaching that of adhesive glass transition (Tg) of 94.9 °C (Silva, M.M.V. Personal communication, September 3, 2016). The mechanical properties of the polymer matrix are highly temperature dependent: as temperature increases, the material behaviour changes from a hard glassy state to a soft rubbery state, according to Mahieux and Reisfsnider (2002).

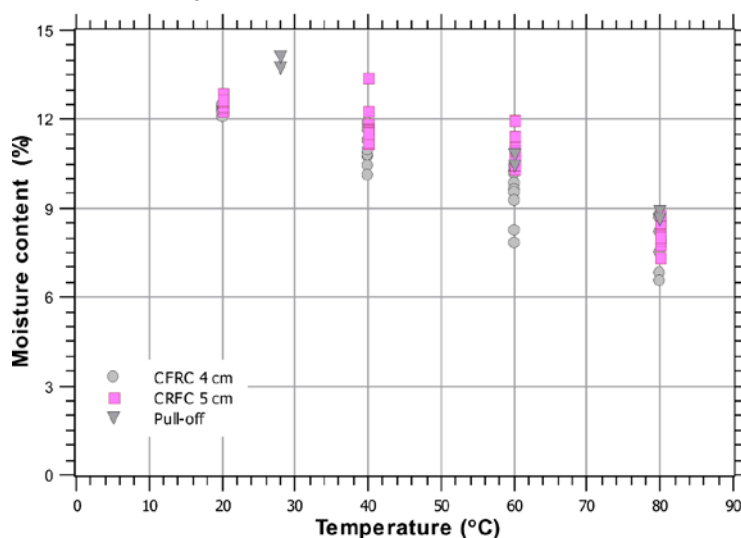Figure 5 – **Moisture content of the specimens**
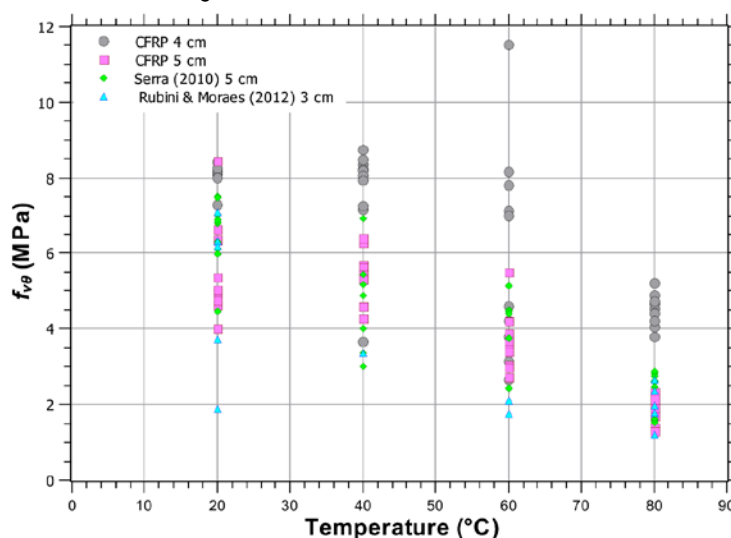

Figure 6 – **Shear reinforcement strength**

Table 4 – **Statistical analysis results of shear strength for each reinforcement length**

Reinforcement length (cm)	Temperature (°C)	$f_{v,\theta}$ (MPa)
4.0	20	8.1 (0.3) a
	40	8.1 (3.0) a
	60	7.6 (4.2) ab
	80	4.5 (0.4) b
5.0	20	5.7 (1,3) a
	40	5.1(1.1) ac
	60	3.3 (0.5) bc
	80	1.9 (0.4) b

Note: values between parenthesis corresponding to standard deviation; mean values in the same column followed by the same letter are not statistically different at 95.0% confidence level according to Kruskal-Wallis test (MONTGOMERY, 2003; MONTGOMERY; RUNGER, 2003).

Statistical analysis results of shear strength, for each temperature level, are presented in Table 5. For all temperature levels, the test shows statistical difference between the shear strength of the 4 and 5 cm reinforcement, corroborating the results obtained by Balseiro (2007), Barbosa (2008) and Juvandes and Barbosa (2012), at room temperature. Their results show that the shear strength decreases with increasing adhesion length. However, the results of Serra (2010), due to the reduced number of repetitions, were not conclusive on this topic. Future studies should be developed, in a unified experimental project, with a larger number of different bonding lengths in order to clarify the temperature influence.

Pull-off strength

Figure 7 illustrates the pull-off strength obtained in fibreglass timber specimens with adhesive B. The types of rupture of pull-off specimens are presented in Table 6. At room temperature, the failure occurred completely or partially in the substrate in 7 out of 8 tests. At 60 and 80 °C, all failures occurred at the epoxy interface between the glass fibre and the metal discs, where Adhesive A was applied. All results are included in the statistical analysis. The failure types suggest that bond line delamination between the disc and the glass fibre was due to the smooth surface of the metal.

The Standard NBR 7190 (ASSOCIAÇÃO…, 1997) criterion concerning moisture was applied and the pull-off strength of 2.4 MPa at room temperature was adjusted to 12% moisture content. At 60 °C, the pull-off strength was 1.6 MPa and 0.5 MPa at 80 °C. The room temperature results are similar to those found in the literature. Previous studies by Nardon (2010) found pull-off strength of *Picea spp.* specimens, with wood mass density of 405 kg/m^3 and 10% moisture content, as approximately 2.1 MPa at room temperature. Juvandes and Barbosa (2012) found the mean value of pull-off strength of *Picea abies* and carbon fibre specimens as 2.41 ± 0.65 MPa, at room temperature, with timber classified as Class C30 (EUROPEAN…, 2016), that is equivalent to the mean density of 460 kg/m^3.

For all temperature levels, the non-parametric Kruskal-Wallis test results show statistical differences between the pull-off strength at 28 °C and at the other temperatures, presented in Table 7.

Temperature strength reduction factor

Figure 8 illustrates the average reduction factors of shear and pull-off experimental strengths, with shear reinforcement lengths of 4 and 5 cm at room temperature, at 60 and at 80 °C. The shear strength reduction factor is in the range from 0.95 to 0.59, at 60 °C, and from 0.56 to 0.34, at 80 °C, while reduction factors of pull-off strength are 0.67 and 0.20, at 60 and 80 °C, respectively.

The temperature influence on the shear and pull-off strengths shows similarities at various temperature levels (Figure 8) except in CFRC 4 cm. In general, the mean strengths decrease as the temperature increases as a nonlinear function. This decrease is expected, mainly because of the epoxy resin thermal changes and the vicinity of matrix glass transition temperature (Tg) (MAHIEUX; REIFSNIDER, 2002). According to the manufacturers, the adhesives used in this work are recommended to be applied at temperatures below 40 °C, in case of carbon fibre applications, or below 80 °C for glass fibre reinforcement (Table 1). At 40 °C, the strength reduction factors were below 1.0, except in the CRFP reinforcement at bonding lengths of 4 cm (Figure 8), even though the temperature was within the temperature range specified by the manufacturers. This may affect the reinforcement safety. Caution in using such resins is required at high temperatures.

Table 5 – Statistical analysis results of shear strength for each temperature level

Temperature (°C)	Reinforcement length (cm)	$f_{v,\theta}$ (MPa)
20	4.0	8.1 (0.3) b
	5.0	5.7 (1,3) a
40	4.0	8.1 (4.2) b
	5.0	5.1 (1.1) a
60	4.0	7.6 (4.2) b
	5.0	3.3 (0.5) a
80	4.0	4.5 (0.4) b
	5.0	1.9 (0.4) a

Note: values between parenthesis corresponding to standard deviation; mean values in the same column followed by the same letter are not statistically different at 95.0% confidence level according to Kruskal-Wallis test (MONTGOMERY, 2003; MONTGOMERY; RUNGER, 2003).

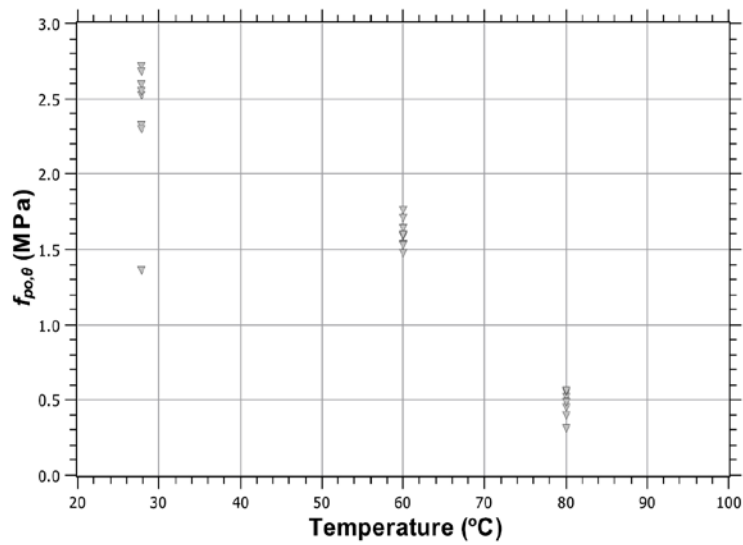Figure 7 – Pull-off strength of fibreglass reinforcement

Table 6 – Types of rupture in pull-off tests for each temperature level

Temperature	Type of rupture	Number of specimens
28 °C	100% of surface rupture in substrate	6
	70% of surface rupture in substrate and 30% in glue line between the substrate and the fibre	1
	100% of surface rupture in glue line between the disk and the fibreglass	1
60 °C	100% of surface rupture in glue line between the disk and the fibreglass	6
80 °C	100% of surface rupture in glue line between the disk and the fibreglass	6

Table 7 – Statistical analysis results of pull-off strength for temperature levels

Temperature (°C)	$f_{po,\theta}$ (MPa)
20	2.4 (0.4) a
60	1.6 (0.1) a
80	0.5 (0.1) b

Note: values between parenthesis corresponding to standard deviation; mean values in the same column followed by the same letter are not statistically different at 95.0% confidence level according to Kruskal-Wallis test (MONTGOMERY, 2003; MONTGOMERY; RUNGER, 2003).

Figure 8 – **Reduction factors of shear and pull-off strengths**
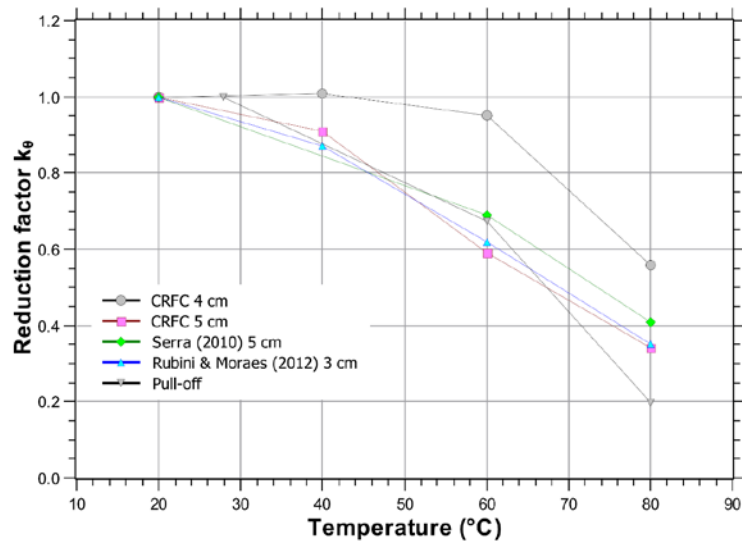
From the results in Tables 4 and 7, the adhesion strength reduction of the resin line at room temperature is recommended when the ambient temperature may reach 60 °C or higher. The recommended reduction factors, for these particular conditions, are 0.59 and 0.20 for predicted maximum temperature of 60 and 80 °C, respectively. The wood surface preparation is also suggested by scrapping off and cleaning, in order to improve mechanical engagement of the joint. A complementary evaluation for determining the roughness level for application of reinforcement on timber surface is suggested, in order to assess the influence of reinforcement lengths. Additional research is required on this topic.

Conclusions

In this research, the influence of temperature on the adhesion of polymer reinforcement to wooden substrate was evaluated by pull-off and shear by tension loading, in the range from 20 to 80 °C. The specimens were made with the wood species *Pinus spp*., with mass density of 554 kg/m^3 and moisture content of 12%, carbon and glass fibres and epoxy adhesives. The results obtained indicate that:

(a) there is statistical difference between the 4 and 5 cm reinforcement strengths; additional research is required for lengthier reinforcements;

(b) the epoxy adhesive strength is sensitive to temperature increase and presents nonlinear behaviour;

(c) the reinforcement adhesion decreases with the temperature increase and a strength reduction factor is recommended when the ambient temperature reaches 60 °C or higher, with values

of 0.59 and 0.20 for predicted maximum temperature of 60 and 80 °C, respectively; and

(d) caution in using the applied resins is required due to the reported behaviour, even in the service temperature range specified by the manufacturers.

The substrate roughness affects the reinforcement adherence, requiring an adequate preparation of the wood surface in order to improve the mechanical engagement of the joint. Additional research is required to assess its influence.

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