Behaviour of the adhesive bond between low-grade wood and GFRP reinforcements using epoxy resin

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Highlights

- The behaviour of the adhesive bond of low-grade wood (*Populus x euroamericana* I-214) reinforced with glass fibre reinforced polymer (GFRP) strips was tested.
- The tested epoxy adhesives exhibited good resistance to the different hydrothermal stresses imposed on the bonded joints.
- The test specimens exhibited different major failure modes between the dry-condition tests and the accelerated ageing tests.

Abstract

In this study, shear tests and pull-off tests were carried out to investigate the bond performance of glass fibre-reinforced polymer (GFRP) strips bonded to low-grade poplar wood (*Populus x euroamericana* I-214). Accordingly, 180 shear specimens and 72 pull-off specimens were produced using three different structural epoxy adhesives. These specimens were divided into two joint types (wood-wood and wood-GFRP configurations), which were tested under dry conditions and after exposure to hydrothermal cycles (i.e., accelerated ageing). The results showed that the epoxy adhesives exhibited good behaviour in the wood-GFRP samples exposed to different hydrothermal conditions. The samples exhibited shear strength values between 4.93 MPa to 8.49 MPa and pull-off strength values between 1.72 MPa to 2.69 MPa. Additionally, there were different main failure modes between the dry specimens and the aged specimens.

Keywords: Bonding; low-grade timber; Glass Fibre Reinforced Polymer (GFRP); epoxy adhesives; shear test; pull-off test.

1. Introduction

Fibre-reinforced polymer (FRP) materials are commonly used to retrofit existing timber structures [1], and several research studies have examined the use of different external [2][3][4] and internal [5][6] reinforcements. Nevertheless, the use of FRPs in the industrial production of new timber products is still underdeveloped [7]. The introduction of FRP reinforcements inside glulam beams improves their mechanical properties, increasing strength and flexural rigidity [8][9][10][11]. Currently, the timber industry has experienced a rapidly growing demand for structural timber, which has forced researchers to look for alternative wood species. Moreover, the timber industry has started to look for improved applications of low-grade species with the aim of adding value to the production chain.

The production of FRP-reinforced glulam would enable fast-growing, low-grade wood species to be used for structural applications [12][13][14]. Some extensively cultivated wood species, such as *Populus* spp., have been reinforced with FRPs and shown promising results [15]. These low-grade wood species are often inexpensive. Their fast growth and low price make these wood species economically viable commercial products, despite the increase in cost from the addition of FRP reinforcements. Of all types of FRP materials, glass fibre (E-glass) reinforced polymers (GFRP) have been shown to be the best choice because of their low cost and high mechanical properties [16].

In the present study, the bonding interface of a duo laminated beam of poplar wood reinforced with a GFRP sheet in the bond line [17] was analysed.

1.1. State of the art

The performance and efficiency of any FRP reinforced element is conditioned not only by the shape, ratio, and properties of the FRP but also by the connection (bond) between the components [18]. Adhesive bonds have been demonstrated to be the most efficient solution for FRP reinforcements, as these connections offer excellent stress transfer without stress concentration points [19]. However, wood and FRP reinforcements have different properties, such as strength, elastic modulus, surface properties, and environmental responses. In this context, it is crucial to find a suitable adhesive for each FRP type and surface material, in this case wood species [20] [21][22].

Generally, the strength of adhesive joints is limited by the strength of the wood itself, and wood failure is considered the optimal bonding response. Wood properties are usually related to wood density, and the strength of adhesive joints increases with increasing wood density [23]. In addition, the strength and durability of an adhesive connection is also conditioned by the influence of environmental changes on the wood. Wood is a hygroscopic material, for which the moisture content continuously changes searching for equilibrium with the surrounding temperature and relative humidity (RH), inducing variations in the physical and mechanical properties of the wood [25][26]. These dimensional variations are greater under rapid humidity changes and larger in the tangential direction than in the radial direction (on average, the changes in the tangential direction are twice as large as those in the radial direction) or grain direction; however, each wood species has different shrinkage and swelling coefficients, which usually increase with increasing wood density [27]. These dimensional variations induce an internal stress and strain that can decrease the strength of adhesive joints [28]. The behaviour of FRPs under the influence of environmental changes depends mainly on the type of polymer matrix. Several studies have investigated the durability of FRPs and have reported that under the most severe dynamic environmental conditions, the mechanical properties of FRPs are decreased but without any dimensional variations [29][30][31]. This loss of mechanical properties is especially significant under high temperatures [32]. Because environmental conditions affect the mechanical properties of wood and FRPs, it is important to analyse the stress and strain that these environmental changes promote inside the FRP-wood adhesive bond [33].

Of all structural adhesives used in timber, only a few types (such as epoxy, polyurethane, and phenol-resorcinol-formaldehyde adhesives) can be used to bond FRP materials, and several researchers have reported that epoxy (EPX) adhesives are the most suitable [34][35]. In addition, these adhesive types have been widely tested and used for the repair of timber structures, in some cases with FRP bars [36][37][38]. There is a large variety of different epoxy products, with different physical and mechanical properties for each application, material or surface bond. Moreover, epoxy adhesives have some advantages, such as not requiring high-pressure curing, achieving a good cure and bond in any type of environment, and enabling bond line thickness variations [39]. Different studies have reported that epoxy adhesives are rather sensitive to temperature changes, which decreases their mechanical properties at temperatures close to their glass transition temperature [40]. Over 50°C, epoxy adhesives reach their critical temperature [41][42]. Similarly, a study researched the influence of humidity on the mechanical properties of epoxy adhesives. The results concluded that epoxy adhesives were reliable for bonding FRPs under dry conditions, but after some humidity cycling tests, the bonded joints lost approximately 50% of the average dry strength [43]. However, another study tested the same specimens under similar conditions. They determined that there was a loss of strength under wet conditions, which was conditioned by the internal bond line strain resulting from the difference in swelling between wood and adhesive. However, after redrying, this strength was partially recovered [44]. Important research efforts have been made to compare and understand the mechanical behaviour of bonded joints with different adhesives, wood species, FRP types, and adhesive thicknesses under hygrothermal changes, in which several different test methods have been used [45][46][47][48].

1.2. Objectives

This study is part of a line of research whose general objective is to re-evaluate and determine new uses for fast-growing, low-cost wood species, such as poplar wood, from sustainable plantations. The specific objective of the present work is to evaluate the bonding behaviour between glass fibre reinforced polymer (GFRP) strips and low-grade poplar wood using different commercially available structural epoxy adhesives under different dry and wet conditions. For that purpose, the assessment of epoxy bond lines will be carried out by shear and pull-off tests.

2. Materials and methods

2.1. Wood species

In the present experimental programme, poplar wood from the *Populus x euroamericana* I-214 clone was used for all the test specimens. The complete batch of wood was provided by the same sawmill and was harvested from the same existing plantation in Berzosilla (Palencia, Spain). Through this approach, the variability in the wood resulting from different environmental conditions during growth was statistically reduced. The logs were transformed into timber planks with a length of 2500 mm and a nominal cross-section of 150 mm × 50 mm. A visual grading of the wood was performed, in accordance with EN 56544:2011 [49], to select only wood without visual defects. The timber planks were first dried under natural conditions at the sawmill until the moisture content was less than 18%. Upon delivery to the laboratory, the timber planks were maintained inside a climatic chamber under controlled hygrothermal conditions of 65±5% relative humidity and a temperature of 20±2°C for 2 months. After this period, a moisture content (MC) closer to 12% was reached in the wood, and an average wood density of 362.6 kg/m^3 (COV=9.01%) was recorded, which was measured in accordance with EN 13183:2002 [50].

The average values of the timber mechanical properties were obtained from a previous test campaign [51]. The wood characterization was conducted on 30 specimens with dimensions 140 mm × 40 mm × 2500 mm, which were tested in accordance with EN 408:2011 [52]. Under bending conditions, the mean modulus of elasticity (MOE) was 7835 MPa (COV=10.18%) and the mean modulus of rupture (MOR) was 36.02 MPa (COV=25.51%). Additionally, 15 solid wood control specimens were manufactured using the same geometry and dimensions specified in ISO 6238:2018 [54]. The mean shear strength of the wood, which was tested in accordance with ISO 6238:2018 [54], reached 8.63 MPa (COV=27.62%).

2.2. GFRP strips

Rigid glass fibre-reinforced composite strips of 1200 g/m^2 and a main thickness of 2,13 mm (COV 3,76%) were fabricated using high-pressure vacuum infusion techniques from unidirectional 'E-glass' fibres embedded in an isophthalic resin of unsaturated polyester. The E-glass material was selected because it is the least expensive fibre reinforcement in relation to its properties; in comparison, natural fibres, carbon fibres and aramid fibres have a worse cost-to-benefit ratio [16]. Despite the low cost of E-glass, its modulus of elasticity is significantly higher than that of poplar wood. Main physical properties of GFRP sheets used in test campaign are shown in Table 1

Table 1. Physical properties of the GFRP rigid sheets.

Grammage (g/m^2)	Thickness (mm)	Fibre percent volume (%)	Fibre Type	Mean fibre diameter (µm)	Adhesive Type	FRP density (kg/m^3)
1200	2.13 (3.76*)	29.23 (9.32*)	Unidirectional E-glass	19.90 (9.38*)	Resichim 317	1711.27 (9.15*)

**Coefficient of variation (COV) (%)*

In a previous test campaign [17], in accordance with ISO 527-5/B [53], 20 specimens of GFRP rigid sheets were tested under tension on an INSTRON MEN-102/100 machine equipped with a 1000 kN load cell and pneumatic clamps. These tests resulted in an average tensile strength of 455 MPa (COV=6.26%) and a modulus of elasticity of 21610 MPa (COV=4.43%).

2.3. Adhesives

In the present experimental work, three commercially available structural epoxy adhesives were used. Both Epoxy 1 and Epoxy 2 were supplied by Sika, and their product trade names are Sikadur 330 and Sikadur 30, respectively. They are well-known thixotropic epoxy adhesives that are used in civil engineering for the structural bonding of FRPs to different surfaces. Epoxy 3 was MapeWood Paste 140, which was supplied by Mapei. This thixotropic epoxy adhesive is currently used for the restoration of timber structural elements and is composed of two parts, a base resin (part A) and a curing agent (part B). All the adhesives were two-component thixotropic adhesives that were room-temperature cured and gap-filled and were specifically formulated to bond FRPs.

According to the data sheets provided by the manufacturers (Table 2), Epoxy 1, Epoxy 2 and Epoxy 3 had modulus of elasticity values of 3800 MPa, 2000 MPa and 4000 MPa and tensile strength values of 30 MPa, 31 MPa and 18 MPa, respectively.

Table 2. Physical and mechanical properties of the epoxy adhesives (manufacturer information).

	Epoxy 1	Epoxy 2	Epoxy 3
Mixing ratio comp. A: comp. B	4:1	3:1	2:1
Specific gravity of mix (g/cm^3)	1.30	1.65	1.5
Brookfield viscosity of mix (mPas)	5000	4000	490000
Shear strength (DIN 53483) (MPa)	-	19	10
Compressive strength (ASTM C579) (MPa)	-	80	45
Tensile strength (ISO 527) (MPa)	30	31	18
Compressive modulus of elasticity (ASTM C579) (MPa)	-	9600	3000

Tensile modulus of elasticity (ASTM C579) (MPa)	4500	11200	-
Bending modulus of elasticity (ISO 178) (MPa)	3800	2000	4000
Maximum layer thickness (mm)	1	3	5

2.4. Experimental programme

To analyse the bond performance of adhesive joints between GFRP reinforcements sheets and low-grade poplar wood, 180 shear specimens and 72 pull-off specimens were produced using 3 different epoxy adhesives (EPX1, EPX 2, and EPX3). These specimens were divided into two joint types (wood-wood joint, and GFRP-wood joint), and each joint type was tested under two different test conditions; under dry conditions and after exposure to accelerated ageing. This experimental programme is summarized in Fig. 1.

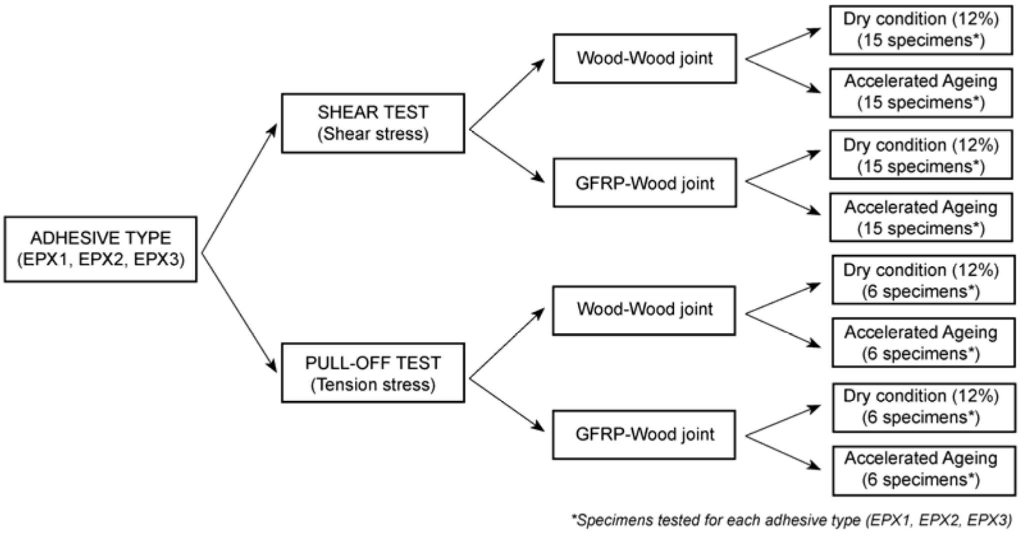
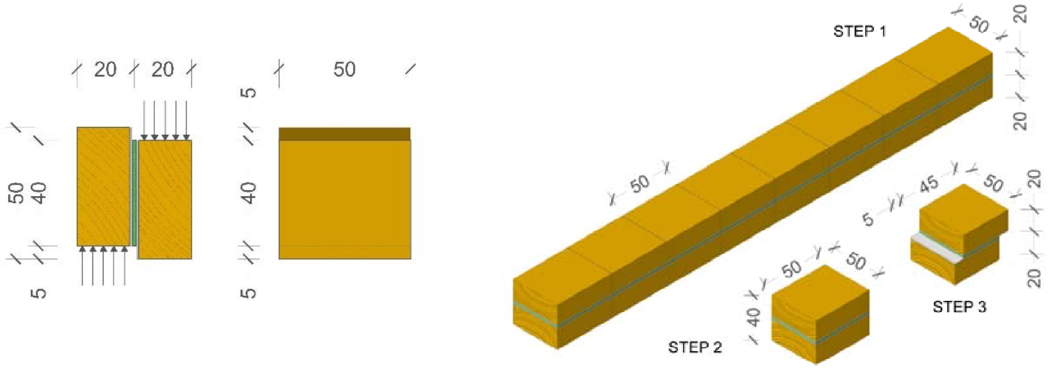


Fig. 1. Experimental programme planned to analyse bond behaviour.

2.5. Preparation of the shear test specimens

The preparation and testing of the shear specimens was performed in accordance with ISO 6238: 2018 [54]. For each adhesive type, 60 specimens were manufactured, 30 of which had GFRP strips inside the bond line. Overall, 180 shear specimens were tested. The typical shear test specimens and their standard dimensions are shown in Fig. 2.



a) Shear test specimen dimensions.

b) Manufactured shear test specimen (partial view).

Fig. 2. Shear test specimen configuration (dimensions in millimetres).

A visual grading of the wood boards was performed, and those with distorted grains or defects, such as knots, holes or cracks, were rejected. From all stocks, the best boards were sawn into 24 thin slats of clear wood with nominal dimensions of 50 mm × 20 mm × 1200 mm. Every surface of the slats was prepared using a knife plane at least 48 h before bonding.

All adhesive products and GFRP strips were stored in their original packing inside the climatic chamber at a constant temperature of 20±2°C and 65±5% relative humidity until use. The epoxy adhesives were mixed in accordance with the technical instructions. An electronic precision balance (KERN; model: EMB 500-1; error ±0.01 g) was used to weigh partial quantities of the epoxy parts—the base resin (part A) and the curing agent (part B)—at each use. The two epoxy parts were mixed together until the product was completely homogeneous using a low-speed electric drill. During the adhesion process, the resin temperature and the maximum working time of the mixture were precisely controlled. Using a spatula hand tool, a slim line of adhesive was brushed over the wood surface of both slats and, in the reinforced specimens, over both faces of the GFRP strip. Previously, the adhesion of the GFRP strips was improved by smooth surface abrasion and cleaning the surface with acetone (C_3H_6O) after working. Once the adhesive was extended, a homogeneous pressure of approximately 0.5 N/mm^2 was applied for a curing time of 48 h. The thickness of adhesive layer was lesser than 0,5mm for Epoxy 1 and Epoxy 3, and lesser than 1mm for Epoxy 2. Later, bonded wood slats were placed inside a climatic chamber under controlled hydrothermal conditions of 65±5% relative humidity and a temperature of 20±2°C for at least 15 days. The bonded wood slats were cut to obtain fifteen double-notched test specimens with nominal dimensions of 50 mm in length (with a notch of 5 mm on each loading face) × 50 mm in width × 40 mm in thickness (Fig. 2b). Before testing, every shear test specimen was numbered, and the corresponding shear area was measured with a digital calliper (error ±0.01 mm).

2.6. Shear strength experimental evaluation

To evaluate the ultimate shear strength, bond interface integrity, and wood failure type, an experimental campaign was planned in two parts: a dry shear strength test (at 12% MC) and a shear strength test after six hydrothermal cycles, which accelerated sample ageing. The experimental programme included the testing of 3 different epoxy adhesives with poplar wood (wood-wood specimens) and GFRP strips (GFRP-wood specimens). For each type of epoxy adhesive, 15 wood-wood specimens and 15 GFRP-wood specimens underwent dry shear strength tests, and 15 wood-wood specimens and 15 GFRP-wood specimens underwent shear strength tests after accelerated ageing. Hence, there were 180 samples in total.

The aged specimens were placed inside an ARALAB climatic chamber (model: Fitoclima 1000) with a temperature range of -45 to 180°C (±0.5°C) and a humidity range of 10 to 98% (±2%). The experimental setup is programmed with 2 environment cycles, which are used to compare the effect of a very humid climate and another very dry climate, following the approach used in an experimental work by other researchers [55]. The first environment was dry, in which the samples were exposed to a 5°C temperature and a 40% relative humidity (equivalent to 8% wood moisture content [56]) for 4 days. The second environment was humid, in which the samples were exposed to a 40°C temperature and a 90% relative humidity (equivalent to 18% wood moisture content [56]) for 3 days. This hydrothermal cycle was repeated 6 times over 45 days. Before the accelerated ageing, the specimens were placed under controlled conditions of 65±5% relative humidity and a temperature of 20±2°C for 7 days.

a) Shear test.

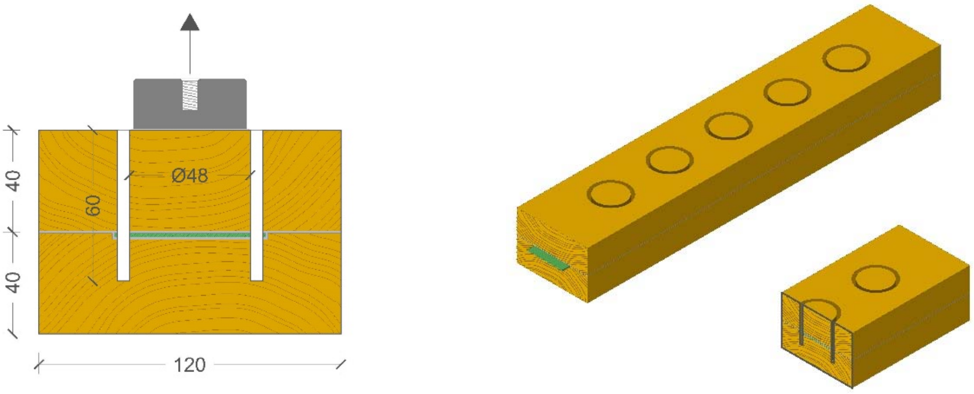
b) Pull-off test.

Fig. 3. Shear and pull-off test setups.

The shear test setup used in this study is shown in Fig. 3a. The test was carried out in accordance with ISO 6238:2018 [54] on a universal machine equipped with a 25 kN load cell. Local deformations were measured during the test using three 20-mm-long linear variable differential transformers (LVDTs) located on the top of the shearing tool. The tests were performed under a constant displacement rate of 0.01 mm/s, and the joint always failed within 60±20 s. Before testing, each specimen was carefully placed in its correct position and preloaded with 50 N. The shear strength of each specimen was determined by dividing the ultimate load by the contact area, which was measured on each specimen before testing.

2.7. Preparation of the pull-off test specimens

The preparation and testing of pull-off specimens were performed in accordance with EN-ISO 4624:2016 [57]. For each adhesive type, 12 specimens were manufactured, among which 6 specimens had a GFRP strip inside the bond line. In total, 36 pull-off specimens were tested. Typical pull-off test specimens and their standard dimensions are shown in Fig. 4.



a) Pull-off test specimen dimensions (in millimetres). b) Manufactured pull-off test specimen.

Fig. 4. Pull-off test specimen configuration.

The fabrication of the wood-wood and wood-GFRP-wood pull-off test specimens followed the same process as that used for the shear test specimens: 12 wood boards with nominal dimensions of 120 mm × 80 mm × 1200 mm were constructed. Once the adhesives were fully cured and before testing, a hole was drilled in the wood face over the bond line, cutting at least 10 mm more from that bond line. An electric drill equipped with a crown bit that was 55 mm in diameter (the free internal diameter was 48 mm after cutting) and 60 mm in length was used.

2.8. Pull-off strength experimental evaluation

To evaluate the ultimate pull-off strength, bond interface integrity, and wood failure type, experimental work was planned in two parts: a dry pull-off strength test (at 12% MC) and a pull-off strength test after six hydrothermal cycles of accelerated ageing (the same conditions as those used in the shear strength tests). The experimental programme included the testing of 3 different epoxy adhesives with poplar wood (wood-wood specimens) and GFRP strips (GFRP-wood specimens). For each epoxy adhesive type, 6 wood-wood specimens and 6 GFRP-wood specimens were tested under dry conditions, and 6 wood-wood specimens and 6 GFRP-wood specimens were tested after accelerated ageing. The hydrothermal cycles inside the climatic chamber had the same conditions as those used for the shear specimens. A total of 72 samples were tested.

The pull-off strength tests were carried out in accordance with ISO 4624:2016 [57] on a universal testing machine equipped with a 25 kN load cell. The connection between the specimen and the actuator was made by bonding a steel plate (the plate has a diameter of 40 mm and a thickness of 25mm,and it has a centred thread hole that is 8 mm in diameter) to the wood surface with the drilled hole. High-quality epoxy adhesive Sika Icosit K-101N was applied to bond the metal plates and wood for a minimum of 15 days before testing. Global deformations were measured during the test using a linear variable differential transformer (LVDT) that is 50 mm in length. Local deformations were measured using a ring with 3 LVDTs that are 20 mm in length, which is connected to the pull-off metal plate, as shown in Fig. 3b. The tests were performed under a constant displacement rate of -0.05 mm/s, and the test joint always failed within 90±20 s.

The pull-off strength of each specimen was determined by dividing the ultimate load by the contact area, which was measured on each specimen before testing.

3. Results and discussion

3.1. Failure modes

A detailed inspection of the failure modes obtained in both tests (shear and pull-off) was carried out, and their analysis was divided into four main types, represented by the letters A through D, as explained in Fig. 5:

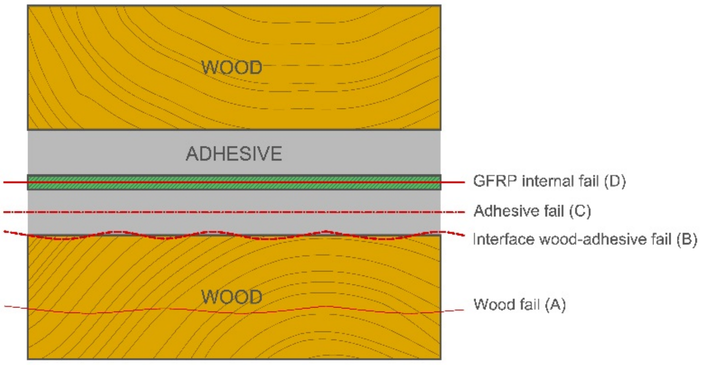


Fig. 5. Representation of the main failure mode types observed in the test specimens.

3.2. Statistical analysis

A previous statistical analysis of the results has been performed, due to the fact that the greater variability of wood as it is a natural, anisotropic and heterogeneous material. For statistical analysis, the normality of the data was checked for all populations using the Kolmogorov-Smirnov normality test with Lilliefors correction, the Shapiro-Wilk test and a Q-Q normal probability plot, and it was possible to assume normality in all cases. The homoscedasticity condition was also met, and both Barlett's and Levene's tests were analysed. Multiple comparison tests for the determination of homogeneous groups were performed using Tukey's HSD test. To detect differences in shear and pull-off strength between the tested adhesive groups, one-way ANOVA was performed for each case.

3.3. Shear behaviour

The shear strength results and the main failure modes of the three epoxy adhesives under both conditions (dry and after accelerated ageing) are shown in Table 3.

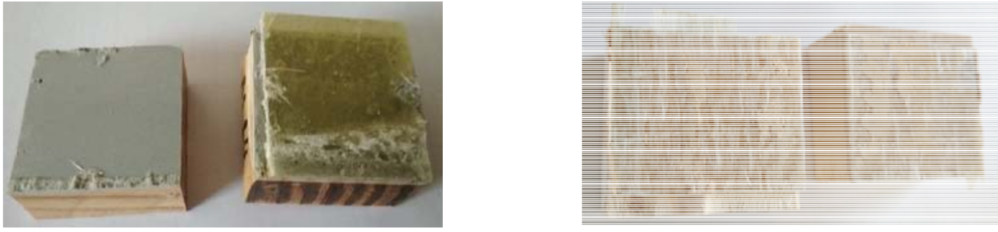
Table 3. Shear behaviour. Strength and percent material failure.

Bonded interface (condition)	Number of specimens	Mean Shear Strength (MPa)	Min. Shear Strength (MPa)	Max. Shear Strength (MPa)	Std. Dev. (MPa)	COV (%)	P value*	Material Failure** (%)	Main Failure mode
Epoxy 1 W-W (12%MC)	15	5.34	2.46	8.66	1.72	31.04	0.9691	93.3	A
Epoxy 1 W-W (hydrot. cycles)	15	6.74	4.20	9.50	1.62	23.29	0.9720	80.0	A
Epoxy 1 FRP-W (12%MC)	15	4.93	3.75	6.58	0.90	17.60	0.8010	46.7	B-C
Epoxy 1 FRP-W (hydrot. cycles)	15	5.58	3.60	8.78	1.53	26.57	0.8534	40.0	B
Epoxy 2 W-W (12%MC)	15	6.32	3.28	8.83	1.69	25.85	0.9855	93.3	A
Epoxy 2 W-W (hydrot. cycles)	15	6.63	3.88	8.13	1.33	20.28	0.9929	73.3	A
Epoxy 2 FRP-W (12%MC)	15	7.17	4.57	9.69	1.93	25.86	0.9440	73.3	D
Epoxy 2 FRP-W (hydrot. cycles)	15	6.80	4.81	8.96	1.40	19.93	0.7983	53.3	B
Epoxy 3 W-W (12%MC)	15	8.49	4.89	9.68	1.51	16.89	0.5554	93.3	A
Epoxy 3 W-W (hydrot. cycles)	15	7.52	2.69	10.05	2.32	29.81	0.7289	53.3	A
Epoxy 3 FRP-W (12%MC)	15	6.82	2.56	9.64	2.31	32.71	0.9571	93.3	A
Epoxy 3 FRP-W (hydrot. cycles)	15	5.96	2.09	9.31	2.22	36.01	0.9900	13.3	B-C

**Statistical analysis of data normality using Kolmogorov-Smirnov normality test. **Material failure is referred to a fail type (A) inside wood.*

Since wood was usually the weakest link of the connection, the failure mode obtained with different epoxy adhesives was mainly mode A, and the maximum shear strength was similar for both wood-wood and GFRP-wood specimens. However, the bonded interface with GFRPs was different with each epoxy adhesive. This different behaviour at the GFRP bonded interface was most notable for specimens exposed to accelerated ageing. Main shear specimens fail after testing is shown in Fig. 6. Furthermore, specimens without or with the GFRP showed a similar shear strength, but the prevalent failure mode changed location from wood fail to new failure modes.

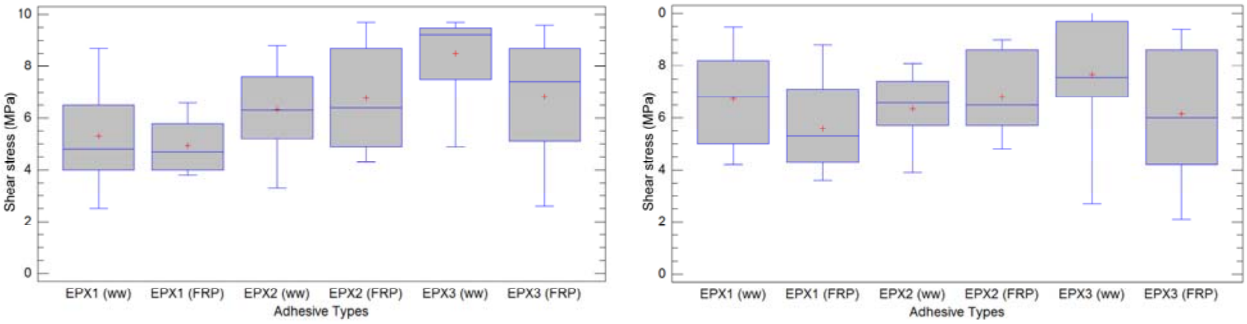
a) Shear specimen wood fail (type A)   b) Shear interface wood-adhesive fail (type B)



c) Shear specimen adhesive fail (type C)   d) Shear specimen GFRP internal fail (type D)

Fig. 6. Shear specimens type fail after testing.

As shown in Fig. 7, of the three epoxy adhesives tested, Epoxy 3 (wood-wood joint) achieved the highest shear strength under both test conditions (dry and after accelerated ageing). In contrast, Epoxy 1 (FRP-wood joint) achieved the lowest shear strength in both test conditions. However, the results also showed a general high dispersion in the shear strength values for all adhesives, and just Epoxy 1 (FRP-wood joint) in dry conditions and Epoxy 2 (wood-wood joint) in accelerated ageing achieved the lowest dispersion results. While, the Epoxy 3 samples showed a higher standard deviation than the other 2 adhesives tested.



a) Test under dry conditions   b) Test after accelerated ageing

Fig. 7. Box-plots of the shear strength test results for each adhesive type.

To estimate and compare the initial shear stiffness, in Fig. 8 it is shown bond-slip behaviour for each adhesive tested and for different condition tested. These graphics were calculated from zero to maximum load as a mean of all the slopes of each shear sample tested.

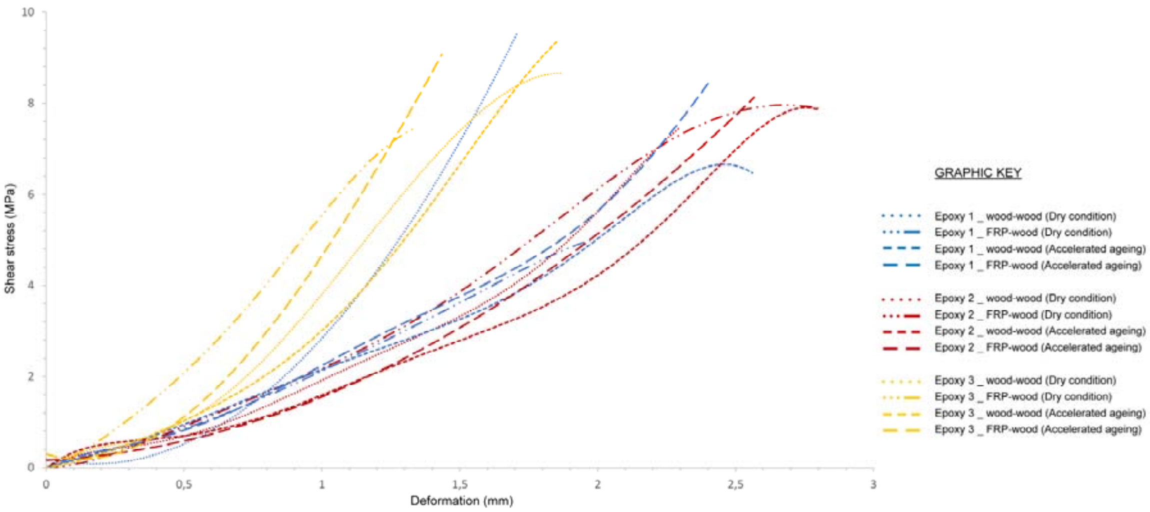


Fig. 8. Load-slip relationship of shear specimens under dry conditions and after accelerated ageing.

3.4. *Pull-off behaviour*

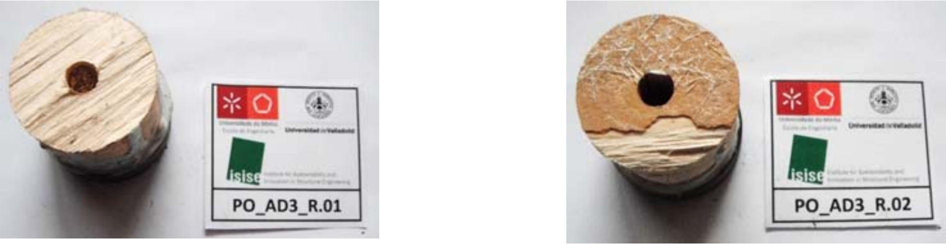
The strength results and main failure modes obtained in the pull-out tests of the three epoxy adhesives under both test conditions are shown in Table 4.

Table 4. Pull-off behaviour. Strength and percent material failure.

Bonded interface (condition)	Number of specimens	Mean Strength (MPa)	Min. Strength (MPa)	Max. Strength (MPa)	Std. Dev. (MPa)	COV (%)	P value*	Material Failure** (%)	Main Failure mode
Epoxy 1 W-W (12%MC)	6	2.66	1.51	3.61	0.70	23.93	0.9857	100	A
Epoxy 1 W-W (hydrot. cycles)	6	2.55	1.69	3.56	0.60	21.58	0.6487	16.7	B
Epoxy 1 FRP-W (12%MC)	6	1.83	1.26	2.72	0.49	24.61	0.7505	100	A
Epoxy 1 FRP-W (hydrot. cycles)	6	1.84	0.93	2.95	0.82	39.77	0.9049	66.7	B
Epoxy 2 W-W (12%MC)	6	2.69	2.05	3.12	0.39	13.40	0.9721	100	A
Epoxy 2 W-W (hydrot. cycles)	6	1.77	0.98	2.45	0.62	31.50	0.9184	83.3	A
Epoxy 2 FRP-W (12%MC)	6	2.64	1.76	3.37	0.66	22.72	0.9615	83.3	A-D
Epoxy 2 FRP-W (hydrot. cycles)	6	1.73	1.10	2.34	0.67	33.59	0.8471	66.7	D
Epoxy 3 W-W (12%MC)	6	2.71	1.05	3.53	0.85	28.74	0.9812	100	A
Epoxy 3 W-W (hydrot. cycles)	6	1.72	1.50	2.17	0.24	12.59	0.9131	83.3	A
Epoxy 3 FRP-W (12%MC)	6	2.28	1.61	2.85	0.51	20.22	0.9197	66.7	A-D
Epoxy 3 FRP-W (hydrot. cycles)	6	2.59	2.34	3.08	0.31	11.01	0.9217	50.0	B

**Statistical analysis of data normality using Kolmogorov-Smirnov normality test. **Material failure is referred to a fail type (A) inside wood.*

The results of the pull-off tests showed that the failure modes of the specimens, with different epoxy adhesives and under dry conditions, had a prevalence of mode A. However, under accelerated ageing conditions other modes were detected. The main failure modes were mode B, due to an interface wood-adhesive failure, and mode A, due to wood failure. And also a mode D, due to a breakage of the internal GFRP strips from perpendicular tension, was detected just in epoxy 2. The average strength value was akin under both conditions, dry conditions and accelerate ageing, just for epoxy 1, while for epoxy 2 and epoxy 3 are higher in dry condition than in accelerate ageing samples. However, for all epoxy adhesives tested, their strength values were available and similar to strength values reported in studies with other wood species but achieved under equal testing conditions [58]. Main pull-off specimens fail after testing is shown in Fig. 9.

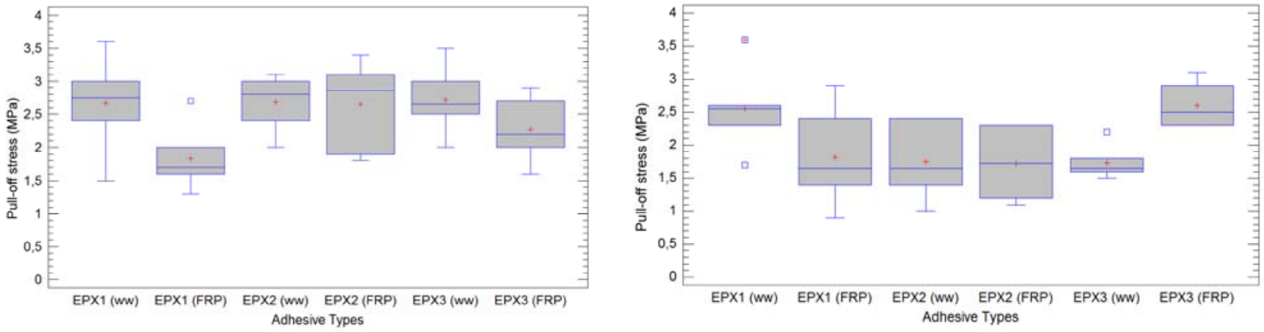


a) Pull-off specimen wood fail (type A) b) Pull-off interface wood-adhesive fail (type B)

c) Pull-off specimen adhesive fail (type C) d) Pull-off specimen GFRP internal fail (type D)

Fig. 9. Pull-off specimens type fail after testing.

As shown in Fig. 10, under dry condition the average strength values obtained for wood-wood specimens were analogous for all epoxy adhesives tested, while the behaviour of the GFRP-wood specimens achieved lower average strength values . After accelerate ageing specimens had lower failure strength; until epoxy 1 where strength of each sample (wood-wood on one hand, and FRP-wood on other hand) are similar , and FRP-wood specimens of epoxy 3 where accelerated ageing samples achieved a little higher mean strength values than dry condition samples.



a) Test under dry conditions b) Test after accelerated ageing

Fig. 10. Box-plots of the pull-off results for each adhesive type.

To estimate and compare the initial pull-off stiffness, in Fig. 11 it is shown bond-slip behaviour for each adhesive tested and for different condition tested. These graphics were calculated from zero to maximum load as a mean of all the slopes of each pull-off sample tested.

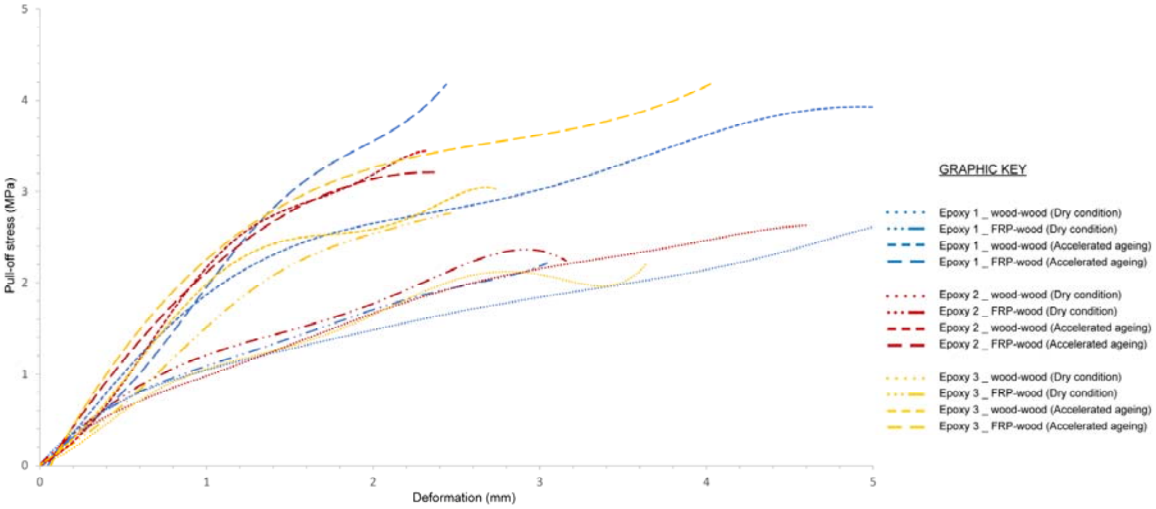


Fig. 11. Load-slip relationship of pull-off specimens under dry conditions and after accelerated ageing.

3.5. Effect of accelerated ageing

A statistical analysis between groups (dry conditions and accelerated ageing) was made to compare the influence and effect of accelerated ageing process over each adhesive and joint type. A comparative analysis of the shear strength of the three groups of adhesives showed that there were statistically significant differences in the shear strength in the dry shear test, both for the wood-wood joint (p value of 0.0002) and for the GFRP-wood joint (p value of 0.0045). No differences in shear strength between the adhesive types were detected in the shear test after accelerated ageing for the wood-wood joints (p value of 0.2126) or the GFRP-wood joints (p value of 0.1593). In addition, an analysis of the effect of the climatic chamber variables was also performed for each adhesive individually. Statistically significant differences in shear strength between dry and aged specimens were not shown for all adhesives (p value>0.05 for all adhesives). A comparative analysis of the pull-off strength of the three adhesive groups showed that there were only statistically significant differences in the pull-off strength for the wood-wood specimens under dry conditions (p value of 0.0250). There were no differences in the pull-off strength for the GFRP-wood joints (p value of 0.0813) under dry conditions. Under accelerated ageing conditions, no significant differences in pull-off strength were detected for the wood-wood joint (p value of 0.7815) or the GFRP-wood joint (p value of 0.0801). Individually, no statistically significant differences in the pull-off strength between dry and aged specimens were found for all adhesives (p value>0.05 for all adhesives).

Furthermore, in general, the average shear strength and average pull-off strength of the aged specimens were lower than those of the dry specimens, except for Epoxy 1. The strength variation is shown in Table 5.

Table 5. Strength variation between dry and aged test specimens.

Adhesive type	Shear strength variation (%)	Pull-off strength variation (%)

	W-W	FRP-W	W-W	FRP-W
Epoxy 1	26,22	13,18	-4,14	0,55
Epoxy 2	4,91	-5,16	-34,20	-34,47
Epoxy 3	-11,43	-12,61	-36,53	13,60

4. Conclusions

The test campaign carried out in this paper demonstrated that the epoxy adhesive under examination, which was used to bond low-grade wood species and an experimental rigid GFRP reinforcement, exhibited a good structural performance. Both specimen types (wood-wood joint and GFRP-wood joint) under both environmental conditions (12% MC and after six hydrothermal cycles) exhibited good mechanical properties in the shear and pull-off tests.

Based on the test results obtained, the following final conclusions can be drawn:

- All epoxy adhesives tested in this study provided sufficient strength between the selected wood and GFRP materials, even after hydrothermal cycles, in both shear and pull-off tests. Under dry conditions, the failure modes were produced mainly inside the wood, where the strength of the wood was the weakest link in the joint. After accelerated ageing, although the bond strength was like that of the dry test specimens, the failure modes were different: the main failure mode was at the wood-adhesive interface and—to a lesser extent—internal GFRP failures. This change in the main failure modes may indicate that the repeated and extreme cycles of humidity and temperature tested affected the behaviour of the adhesive-wood interface.
- The shear strength values of the wood-wood samples ranged from 5.34 MPa (EPX1) to 8.49 MPa (EPX3), and the strength variation ranged from 4.91% (EPX2) to 26.22% (EPX1) between dry and aged conditions. For GFRP-wood samples, very similar shear strength values were achieved: the values ranged from 4.93 MPa (EPX1) to 7.17 MPa (EPX3), and the strength variation ranged from 5.16% (EPX2) to 13.18% (EPX1) between dry and aged conditions. According to these results, the best general behaviour (balance between the different values achieved for joint types and test conditions) was achieved by Epoxy 2.
- The load-slip behaviour of shear specimens (Fig. 8) showed a higher stiffness in wood-wood joints than in FRP-wood joint. May be due to the FRP reinforcement sheet influence inside the joint. There wasn't stiffness different between dry or accelerated ageing joints.
- Lower strength values were obtained from the pull-off tests in comparison with shear results. The pull-off strength of the wood-wood samples ranged from 1.72 MPa (EPX3) to 2.69 MPa (EPX2) and the strength variation ranged from 4.14% (EPX1) to 36.53% (EPX3) between dry and aged conditions. The pull-off strength of the GFRP-wood samples ranged from 1.73 MPa (EPX2) to 2.59 MPa (EPX3), and the strength variation raged from 0.55% (EPX1) to 34.47% (EPX2) between dry and aged conditions. The best behaviour was reached by Epoxy 1.
- The load-slip behaviour of pull-off specimens (Fig. 11) showed a higher stiffness in wood-wood joints than in FRP-wood joint.
- The hydrothermal cycles used in this study produced stress on the GFRP-wood interface due to wood shrinkage and swelling, equivalent to service class 2 (see Eurocode 5). The high temperature in the test was kept below the glass transition temperature of the epoxy to avoid internal damage to the adhesive. Under both dry and aged conditions, the test results obtained suggest that all epoxy adhesives achieved a high-quality bond line.

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6. References

[1] S. Thelanderson, H.J. Larsen, Timber engineering, London, 2003.

[2] F.H. Theakston, A feasibility study for strengthening timber beams with fiberglass, Can. Agric. Eng. January (1965) 17–19.

[3] T.C. Triantafillou, N. Deskovic. Prestressed FRP sheets as external reinforcement of wood members. J. Struct. Eng. 118 (1992) 1270–1284. https://doi.org/10.1061/(ASCE)0733-9445(1992)118:5(1270)

[4] J. Fiorelli, A. Alves Dias, Glulam beams reinforced with FRP externally bonded: theoretical and experimental evaluation, Mater. Struct. 44 (2011) 1431–1440. https://doi.org/10.1617/s11527-011-9708-y

[5] A. Harte, P. Dietsch, (2015) Reinforcement of Timber Structures. A state-of-the-art report, ed. Shaker Verlag, Aachen, 2015.

[6] K.U. Schober, A.M. Harte, R. Kliger, R. Jockwer, Q. Xu, J.-F. Chen, FRP reinforcement of timber structures, Constr. Build. Mater. 97 (2015) 106–118. https://doi.org/10.1016/j.conbuildmat.2015.06.020

[7] Z.A. Martin, J.K. Stith, D.A. Tingley, Commercialization of FRP reinforced glulam beam technology. In: Proceedings of the 6th world conference on timber engineering, Whistler, 2000.

[8] A. Parvez, The reinforcement of timber for structural applications and repair. PhD thesis, dept Mech Eng University of Bath, 2004.

[9] R.C. Hernandez, R., Davalos, J.F. Sonti, S., Kim, Y., Moody, Strength and Stiffness of Reinforced Yellow-Poplar Glued-Laminated Beams, Madison, WI U.S. Dep. Agric. For. Serv. FPL–RP–554 (1997) 28.

[10] R. Kliger, M. Al-Emrani, M. Johansson, R. Crocetti, Strengthening glulam beams with steel or CFRP plates, in: S.T. Smith (Ed.), Asia-Pacific Conf. FRP Struct. (APFIS 2007), 2007.

[11] M. Fossetti, G. Minafo, M. Papia, Flexural behaviour of glulam timber beams reinforced with FRP cords, Constr. Build. Mater. 95 (2015) 54–64. https://doi.org/10.1016/j.conbuildmat.2015.07.116

[12] H.J. Dagher, T.E. Kimball, S.M. Shaler, B. Abdel-Magid, Effect of FRP Reinforcement on Low Grade Eastern Hemlock Glulams, in: Natl. Conf. Wood Transp. Struct., General Technical Report No. FPL-GTR-96, Madison, WI:USA, 1996: pp. 207–214.

[13] G.M. Raftery, A.M. Harte, Low-grade glued laminated timber reinforced with FRP plate, Compos. Part B. 42 (2011) 724–735. https://doi.org/10.1016/j.compositesb.2011.01.029

[14] G.M. Raftery, C. Whelan, Low-grade glued laminated timber beams reinforced using improved arrangements of bonded-in GFRP rods, Constr. Build. Mater. 52 (2014) 209–220. https://doi.org/10.1016/j.conbuildmat.2013.11.044

[15] J.M. Moulin, G. Pluvinage, P. Jodin, FGRG: Fibreglass reinforced glulam - A new composite, Wood Sci. Technol. 24 (1990) 289–294. https://doi.org/10.1007/BF01153561

[16] L.A. Basterra, L. Acuña, G. Casado, G. Lopez, A. Bueno, Strength testing of Poplar duo beams, Populus x euramericana (Dode) Guinier cv. I-214, with fibre reinforcement, Constr. Build. Mater. 36 (2012) 90–96. https://doi.org/10.1016/j.conbuildmat.2012.05.001

[17] L.A. Basterra, J.A. Balmori, L. Acuña, M. Casado, L. Morilla, Internal reinforcement of laminated duo beams of low-grade timber with GFRP sheets, Constr. Build. Mater. 154 (2017) 914-920. https://doi.org/10.1016/j.conbuildmat.2017.08.007

[18] C.E. Bakis, L.C. Bank, V.L. Brown, E. Cosenza, J.L. Davalos, J.J. Lesko, A. Machida, S.H. Rizkalla, T.C. Triantafillou, Fiber-Reinforced polymer composites for construction - State of the art review, J. Compos. Constr. 6:2(73) (2002) 73–87. https://doi.org/10.1061/(ASCE)1090-0268(2002)6:2(73)

[19] K.U. Schober, T. Tannert, Hybrid connections for timber structures, Eur.J.Wood Prod. 74 (2016) 369-377. https://doi.org/10.1007/s00107-016-1024-3

[20] J.S. Lyons, M. Ahmed, Factors affecting the bond between polymer composites and wood, J. Reinf. Plast. Compos., 24(4) (2005) 405–412. https://doi.org/10.1177/0731684405044898

[21] C. Bedon, C. Louter, Numerical investigation on structural glass beams with GFRP-embedded rods, including effects of pre-stress, Compos. Struct. 184(2018) 650-661. https://doi.org/10.1016/j.compstruct.2017.10.027

[22] A. Cecchi, S. Russo, F. Sciarretta, Preliminary investigation on FRP profiles for the structural retrofit of masonry structures, Key Eng. Mater. 747 (2017) 77-84. https://doi.org/10.4028/www.scientific.net/KEM.747.77

[23] Forest Products Laboratory, Wood handbook; Wood as an engineering material, General Technical Report FPL-GTR-190. Department of Agriculture, Forest Service, Forest Products Laboratory. Madison, WI: U.S., 2010.

[24] R. Widmann, R. Steiger, E. Gehri, Pull-out strength of axially loaded steel rods bonded in glulam perpendicular to the grain, Mater. Struct. 40 (2007) 827-838. https://doi.org/10.1617/s11527-006-9214-9

[25] C. Silva, J.M. Branco, A. Camões, P.B. Lourenço, Dimensional variation of three softwood due to hygroscopic behaviour, Constr. Build. Mater. 59 (2014) 25-31. https://doi.org/10.1016/j.conbuildmat.2014.02.037

[26] D.W.Green, D.E. Kretschmann, Moisture Content and the Properties of Clear Southern Pine, Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory, 1994.

[27] W. Simpson, A. TenWold, Physical properties and moisture relations, In: F. P. Laboratory, Wood handbook—Wood as an engineering material. Madison, WI (US): Department of Agriculture, Forest Service, Forest Products Laboratory, 1999.

[28] J. Jönsson, S. Thelandersson, The effect of moisture gradients on tensile strength perpendicular to grain in glulam, Holz als Roh-und Werkstoff, 61(5) (2003) 342-348. https://doi.org/10.1007/s00107-003-0405-6

[29] J.S. Earl, R.A. Shenoi. Hygrothermal ageing effects on FRP laminate and structural foam materials, Compos. Part A 35 (2004) pp. 1237-1247. https://doi.org/10.1016/j.compositesa.2004.04.007

[30] X. Jiang, H. Kolstein, F. Bijlaard, X. Qiang, Effects of hygrothermal aging on glass-fibre reinforced polymer laminates and adhesive of FRP composite bridge: Moisture diffusion characteristics, Compos. Part A 57 (2014) 49-58. https://doi.org/10.1016/j.compositesa.2013.11.002

[31] S.A. Grammatikos, M. Evernden, J. Mitchels, B. Zafari, J.T. Mottram, G.C. Papanicolaou, On the response to hygrothermal aging of pultruded FRPs used in the civil engineering sector. Mater. Des. , *96* (2016) 283-295. https://doi.org/10.1016/j.matdes.2016.02.026

[32] K. Liao, C.R. Schultheisz, D.L. Hunston, Effects of environmental aging on the properties of pultruded GFRP, Compos. Part B *30*(5) (1999) 485-493. https://doi.org/10.1016/S1359-8368(99)00013-X

[33] E. Barbero, J. Davalos, U. Munipalle, Bond strength of FRP-wood interface, J. Reinf. Plast. Compos. 13(9) (1994) 835-854. https://doi.org/10.1177/073168449401300905

[34] M. Kemmsies, Comparison of pull-out strengths of 12 adhesives for glued-in rods for timber structures. SP Swedish National Testing and Research Institute. Building Technology. SP Report 20, 1999.

[35] P.J. Gustafsson, E. Serrano, Glued-in rods for timber structures - development of a calculation model. Report TVSM-3056. Lund University, Division of Structural Mechanics, Lund, 2001.

[36] A.S. Wheeler, A.R. Hutchinson, Resin repairs to timber structures, Int. J. Adhes. Adhes., 18 (1998) 1-13. https://doi.org/10.1016/S0143-7496(97)00060-2

[37] G. Tlustochowicz, E. Serrano, R. Steiger, State-of-the-art review on timber connections with glued-in steel rods, Mat. Struct., 44(5) (2011) 997-1020. https://doi.org/10.1617/s11527-010-9682-9

[38] R. Steiger, E. Serrano, M. Stepinac, V. Rajcic, C. O'Neill, D. McPolin, R.Widmann, Strengthening of timber structures with glued-in rods, Constr. Build. Mater. 97 (2015) 90-105. https://doi.org/10.1016/j.conbuildmat.2015.03.097

[39] J. Custodio, J. Broughton, H. Cruz, A review of factors influencing the durability of structural bonded timber joints, Int. J. Adhes. Adhes., 29 (2009) 173-185. https://doi.org/10.1016/j.ijadhadh.2008.03.002

[40] H. Cruz, J. Custodio, Thermal performance of epoxy adhesives in timber structural repair, In 9th world conference on timber engineering, Portland, USA, 2006.

[41] V. Di Maria, L. D'Andria, G.Muciaccia, A.Ianakiev, Influence of elevated temperature on glued-in steel rods for timber elements, Constr. Build. Mater. 147 (2017) 457-465. https://doi.org/10.1016/j.conbuildmat.2017.04.038

[42] M.A. Lahouar, J.F. Caron, G. Foret, K. Benzarti, R. Mege, Temperature effect on the mechanical behaviour of glued-in rods intended for the connection of timber elements, Constr. Build. Mater. 186 (2018) 438-453. https://doi.org/10.1016/j.conbuildmat.2018.07.122.

[43] R.E. Rowlands, R.P. Van Deweghe, T.L. Laufenberg, G.P. Krueger, Fiber-reinforced wood composites. Wood fiber Sci., 18(1) (1986) 39-57.

[44] C.R. Frihart, Are epoxy-wood bonds durable enough? Wood adhesives, November 2-4, (2005) 241-246.

[45] K. Harvey, M.P. Ansell, Improved timber connections using bonded-in GFRP rods, In Proceedings of 6th WCTE world conference in timber engineering, Whistler, Canada, 2000

[46] G.M. Radftery, A.M. Harte, P.D. Rodd, Bonding of FRP materials to wood using thin epoxy glue lines, Int. J. Adhes. Adhes. ,29(5) (2009) 580-588. https://doi.org/10.1016/j.ijadhadh.2009.01.004

[47] J. Sena-Cruz, J. Branco, M Jorge, J.A.O. Barros, C. Silva, V.M.C.F. Cunha, Bond behaviour between glulam and GFRP's by pull-out tests, Compos. Part B, 43(3) (2012) 1045-1055. https://doi.org/10.1016/j.compositesb.2011.10.022

[48] G. Fava, V. Carvelli, C. Poggi, Pull-out strength of glued-in FRP plates bonded in glulam, Constr. Build. Mater. 43 (2013) 362-371. https://doi.org/10.1016/j.conbuildmat.2013.02.035

[49] EN 56544:2011 Visual grading for structural sawn timber. Coniferous timber.

[50] EN 13183:2002 Moisture content of a piece of sawn timber.

[51] M. Casado, L. Acuña, L.A. Basterra, G. Ramón, D. Vecilla, Grading of structural timber of Populus x euramericana clone I-214, Holzforschung, 66(5) (2012) 633-638. https://doi.org/10.1515/hf-2011-0153

[52] EN 408:2011 Timber structures - Structural timber and glued laminated timber. Determination of some physical and mechanical properties.

[53] ISO 527-5:2009 Plastics. Determination of tensile properties. Part 5: Test conditions for unidirectional fibre-reinforced plastic composites.

[54] ISO 6238:2018 Adhesives. Wood to wood adhesive bonds. Determination of shear strength by compressive loading.

[55] C. Silva, J. Branco, A. Ringhofer, P. Lourenço, G. Schickhofer. The influences of moisture content variation, number and width of gaps on the withdrawal resistance of self-tapping screws inserted in cross laminated timber, Constr. Build. Mater. 125 (2016) 1205–1215. https://doi.org/10.1016/j.conbuildmat.2016.09.008

[56] F. Kollmann. Tecnología de la madera y sus aplicaciones. Ministerio de Agricultura, IFIE, Madrid, 1959.

[57] ISO 4624:2016 Paints and varnishes. Pull-off test for adhesion.

[58] M.R. Valluzzi, E. Garbin, C. Modena, Flexural strengthening of timber beams by traditional and innovative techniques, J. Build. Appr., 3(2) (2007) 125-143. https://doi.org/10.1057/palgrave.jba.2950071