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Pull out Strength of Bonded-In Steel Bars Behavior in *Pinus oocarpa* Shiede Timber

Julio César Pigozzo[1], Felipe Nascimento Arroyo[2], André Luis Christoforo[3*], Diego Henrique de Almeida[4], Carlito Calil Junior[5] and Francisco Antonio Rocco Lahr[5]

[1]Department of Civil Engineering, State University of Maringá, Colombo Avenue, 5790, Maringá (PR), 87020-900, Brazil.
[2]Department of Civil Engineering, Integrated Faculty of Cacoal, Dos Esportes Street, 1038, Cacoal (RO), 76965-864, Brazil.
[3]Department of Civil Engineering, Federal University of São Carlos, Washington Luís Highway, SP-310, km-235, São Carlos (SP), 13565-905, Brazil.
[4]Department of Civil Engineering, Federal University of Rondônia, BR-364, km-9.5, Porto Velho (RO), 76801-059, Brazil.
[5]Department of Structures, University of São Paulo, Trabalhador São-Carlense Avenue, 400, São Carlos (SP), 13566-590, Brazil.

Authors' contributions

This work was carried out in collaboration between all authors. Authors JCP, CCJ and FARL designed the study, wrote the protocol and managed the analyses of the study. Author ALC wrote the protocol and statistical analysis. Authors DHA and FNA managed the analyses of the study, wrote the first draft of the manuscript and managed the literature searches. All authors read and approved the final manuscript.

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**Corresponding author: E-mail: christoforoal@yahoo.com.br;*

ABSTRACT

The study of pull out strength of bonded-in steel bars in *Pinus oocarpa* Shiede timbers ($\rho_{12\%}$ = 550 kg/m^3) is presented. The aim was to evaluate, with the design of experiment, statistical methods and experimental works, the moisture content and anchorage areas variations effects. In addition, three angles (0, 45 and 90º), between the rod and the direction of grain were considered and a polyurethane adhesive, based on castor oil, and three epoxy resins were used. The wood specimens were seasoned to the expected moisture contents of 12, 15, 18 and 22%. In each specimen, there were four holes with 9.0 mm diameter and 40, 60, 80 and 120 mm depths. The deformed steel bars with the minimum yield tensile strength of 500 MPa and nominal diameter of 6.3 mm were axially loaded with two load cycles. The results are presented in a comparative form after the statistical analysis. The rupture modes are discussed and the need for a broad understanding of resin behaviour is highlighted. Average anchorage strength presented positive linear relationships, with an increase of the anchorage area and negative linear relationships with increased moisture content for all the resins and directions between steel bar and wood grain studied.

Keywords: Adhesive; anchorage strength; bonded-in steel rods; timber structures.

1. INTRODUCTION

Bonded steel bars used in timber structural members started as an alternative to fastening bolts, which could receive axial, lateral or combined loads in some positions of the timber structures. This connection type has received attention and recognition for: delivering excellent performance when well designed and executed; by the aesthetic appearance; and low cost. Its main advantages are: bonded bar connections allow higher levels of strain transfer compared to conventional connections; they resist great bending moments; holes used do not weaken the structural parts, as with connections that use bolts; structural parts become more aesthetic, avoiding apparent connectors as plates or bolts; are easily protected against fire; are potentially cheaper than the finger-joint system, since they do not require special machines; presents less material; and lower cost of production, when compared to bolted connections [1,2].

Main uses for bonded steel bars are represented in Fig. 1: (a) top splicing; (b) structural part connections in foundation blocks; (c) prevention of rupture in areas of maximum bending of glued laminated beams; (d; e) transmission of forces within a structure or part thereof; (e) connecting elements on gantry nodes; (g) connecting elements of masonry, concrete or steel [3].

Bainbridge and Mettem [4] report that there are still no general technical regulations governing the use of bonded steel bars in timber structures, although they have been used for more than 20 years in some Scandinavian countries and in Germany. With this, performance requirements and project regulations differ between them. Due to the uncertainties in the behaviour of these connectors and the lack of reliable calculation methods, they have not yet been introduced into the main part of the European Standard Code. It is currently included in Eurocode 5:1993 Part 2 [5] as recommendations for use in its Annex.

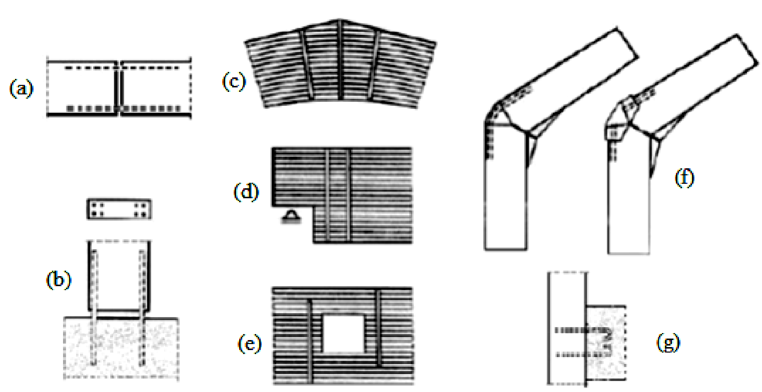

Fig. 1. Steel bars glued examples of application in timber structures [3]

The most commonly used structural resins in wood structures are classified into three groups: phenol-resorcinol formaldehyde (PRF), polyurethanes (PUR) and epoxies (EP), which have undergone continuous development and better properties and fewer defects over time. Many information and results obtained a few years ago do not apply to new existing resins [1]. Gardner [6] tested several adhesives in the development of reinforcement systems in glued laminated timber structures, present some resin properties, such as: PRF does not present good penetrability (filling capacity of failure), however, presents considerable retraction properties and requires hot cure; EP has high strength, good penetrability and no retraction, being relatively expensive. Currently, PRF does not require a hot cure and presents fewer retractions; EP, with many options, is at a competitive cost compared to other resins.

There were previously restrictions on the use of EP as a structural resin, with the suspicion of presenting brittle ruptures with temperature increase or against long loads. Currently, this adhesive is most suitable for anchoring steel bars in timber structural members. A significant change appears when the EP is no longer considered as a set of resins with uniform behaviours, denominated only as epoxy, but it is possible to compare different brands and manufacturers [6]. Buchanan and Deng [7] present results concluding significant differences between the three types of epoxies studied: Araldite 2005 presented the largest and West System the lowest results of anchorage strength (RA) of bonded steel bars, also presenting the distributions of shear stress along the anchoring length (Fig. 2).

Riberholt [8] proposed an expression estimating average values of the anchorage strength, considering the rupture model as the shear of the wood around the hole. This expression, adopted by Eurocode 5:1993, Part 2 [4], item A.2.2, considers the effect of wood density with a significant variable. On the other hand, Buchanan and Moss [9] and Bengtsson et al. [10] found no significant influence of wood density on the bond strength of bonded bars.

Steel bars used as connectors are preferably threaded, galvanized and high strength bars, bars with deformed, scored or threaded surfaces with high strength. Anchorage adhesion, initially, is the combination of chemical and mechanical adhesion. From a request level, the chemical adhesion breaks, remaining only mechanical adhesion. Buchanan and Deng [7] concluded that bars with deformed surfaces (surfaces with fillets) had lower anchoring strengths, resulting in more cracking ruptures than bars with threaded surfaces. The average anchorage strength of bars with deformed surfaces was 80% of the average of bars with threaded surfaces.

Specimens used for the analysis of bonded steel bars may be ordered on a single side or on two sides. Bengtsson et al. [10] analyzed two methods of control of the production of bars bonded to timber structures using Norway Spruce wood specie (*Picea abies*) specimens, concluding that the anchorage tests, requesting the double-sided specimen, produced strengths greater than the tests requesting the test specimens on one side (Fig. 3). Such an increase occurs due to the compressive stresses that arise perpendicular to the axis of the bars in the pull-out process. For EP and PUR, the differences were accentuated.

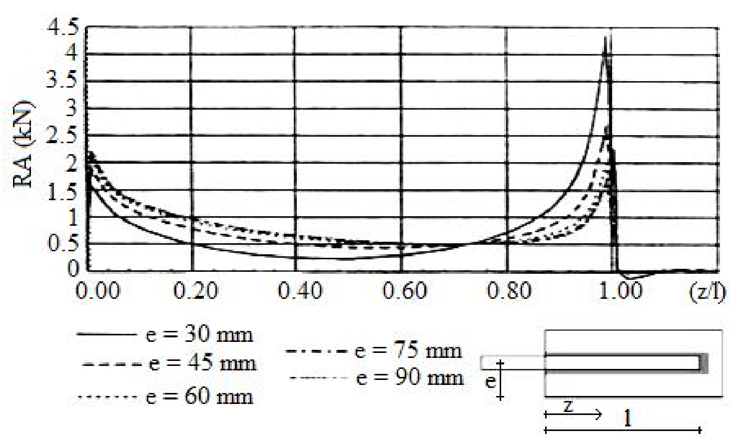

Fig. 2. Stress distribution along the anchored bar with epoxy resin [6]

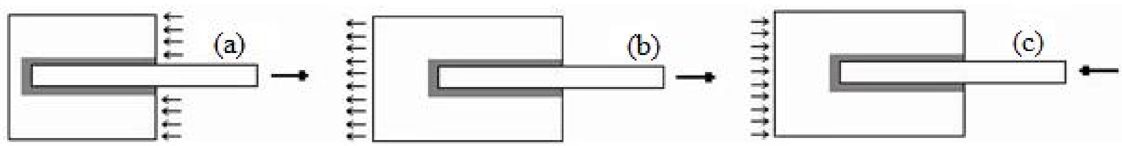

Fig. 3. Axial stresses in bonded bars type: (a) one-sided request; (b) and (c) two-sided requests [9]

Barchelar and McIntosh [11], reviewing connections breaking experiments due to inappropriate blends and/or misapplications of epoxy adhesives "*in loco*", concluded that the entire sizing operation should be done in the factory environment, with adequate quality control and by specialized people.

With all the knowledge already gathered about the anchoring of steel bars, we are still looking for: methods for characterization of resins and adhesion behavior in the various wood species and methods of testing for production control; the effects of fatigue, the behavior of anchorage with long loads and temperature variations are studied; the effects of distances between bars and between bars and ends of the wood; the effects of the main variables are studied: moisture of the hole surface at the time of bonding; changes in moisture after gluing; effects of variations in anchorage lengths; and variations in the diameter of the bars and thicknesses of glue lines. Of course, it is known that the best structural reliability is obtained by using a larger number of bars with smaller diameters, rather than a few bars with larger diameters [1].

The aim of this work was to evaluate the behaviour of three bi-component epoxy resins and a bi-component polyurethane resin used in the study of anchoring of steel bars in beams of *Pinus oocarpa* Shiede, without considering the natural variations of the mechanical properties of the wood. In addition to the anchorage strength, other objectives are also methods to inject these resins into holes of small diameters and varying depths of wood; know the time for application after mixing, considering that the viscosity increase is increasing in time; and develop procedures to avoid glue defects.

2. MATERIALS AND METHODS

Four beams of *Pinus oocarpa* Shiede ($\rho_{12\%}$ = 550 kg/m^3) [12,13] air-dried (around at 12% moisture content) of nominal dimensions 5 cm x 20 cm x 500 cm, twelve specimens were obtained from each beam (Fig. 4). The mass changes when immersed in water until reaching the desired weights, corresponding to the expected moisture of: 12, 15, 18 and 22%. Then, each specimen was in a waterproof packaging for 30 days to homogenize the moisture throughout its volume. The mechanical properties of the wood in each beam were assumed constant.

Table 1 shows the used structural resins, their consistencies and commercial suppliers. Polyurethane resin developed by the Institute of Chemistry of São Carlos, University of São Paulo (IQSC/USP), Brazil, was composed of prepolymer A249 and polyol 25015C, produced from castor oil.

In all of the specimens, the steel bars received surface cleaning treatment by applying a rotating steel brush until it reached the white colour at the end in contact with the resin. Subsequently, thinner (commonly used for cleaning) was applied as a solvent to remove oil residues. CA-50 steel bars (f_{yd} = 500 MPa) with a diameter of 6.3 mm, axially requested in two load cycles with monotonic loads, were used, the first cycle being with up to 70% of the ultimate strength [14].

Each test specimen received four holes with a diameter of 9.0 mm and depths of 4.0, 6.0, 8.0 and 12.0 cm (Fig. 5). In all holes, glue line thickness remained constant with 1.35 mm, considering the bar nominal diameter.

For the injection of the resins in the holes, a disposable applicator system was adopted that does not require cleaning. Portions of component A and B totalling the mass of 250 g were placed and held separately in a transparent and sturdy plastic bag. At the time of gluing, the components were manually mixed into the carton until homogenization. The injection was given through a tube adapted to the end of the package with the same outer diameter of the steel bar. When the resin is injected, with the outcrop at the outer end of the bore the volume required for anchoring is obtained. The injection is completed with an excess of 2 to 3% of resin, considering the total volume required.

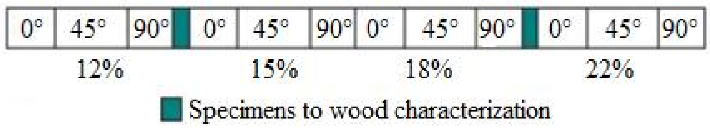

Fig. 4. Transversal section of calculation

Table 1. Resins employed in the experiment

Commercial name	Consistency	Type	Commercial suppliers
Vedacit	Liquid	Epoxy	Otto Baungart S/A
Sikadur32	Pasty	Epoxy	Sika S/A
Polyurethane	Liquid	Polyurethane	IQSC/USP
AR300	Liquid	Epoxy	Barracuda Tech & Prod.

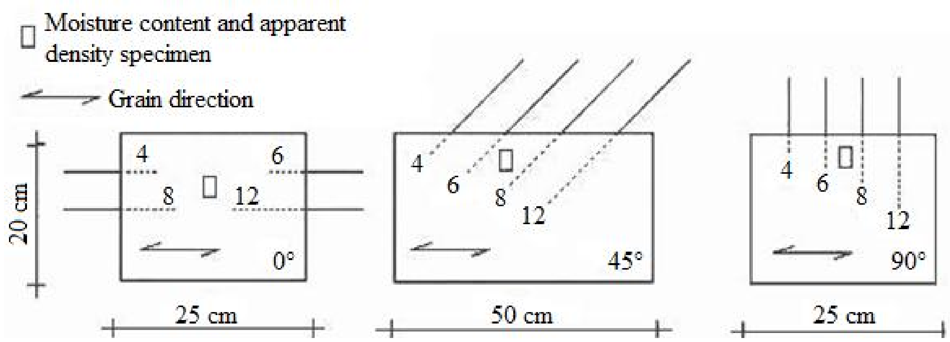

Fig. 5. Specimens and anchoring of steel bars in relation to the grain

Table 2. Anchorage lengths and surfaces

Anchorage length (Al) (cm)	4	6	8	12
Anchorage surface (Aa) (cm²)	8.12	12.18	16.24	24.36

To eliminate air bubbles during the introduction of the steel bar in the use of pasty resins such as Sikadur32, small rotational movements are applied, alternating sequentially from left to right until the excess resin comes out through the hole. In this way, it is confirmed that the resin always completely fills the voids in the hole. Steel bar adhesion surfaces were evaluated from the average dimensions of the surface fillets (Table 2).

Results were submitted to statistical analysis to develop the most adequate statistical model and to infer, on the experimental data, the mean anchoring response in the 0, 45 and 90º directions for each resin type.

Statistical methods used were: multiple linear regression analysis, analysis of variance, residue analysis and normality test for residues. All statistical analysis carried out in Minitab® version 14.

3. RESULTS AND DISCUSSION

Tables 3 to 6 shows anchorage strength (RA), anchorage surface (Aa), moisture content (MC) and apparent density (ρ) results for Vedacit, AR300, Sikadur32 and Polyurethane castor oil-based resin in three directions of bar in relation to the grain (0, 45 and 90º). The polyurethane resin was the first resin studied with anchors in the direction 90º in relation to the grain. Due to the low results obtained, the experiment was repeated to confirm the answers (Table 6). Thus, the corresponding statistical model presents mean responses with two replications (Table 7).

Table 3. Anchoring results for Vedacit resin

Direction 0º				Direction 45º				Direction 90º			
RA (kN)	Aa (cm²)	MC (%)	ρ (kg/m³)	RA (kN)	Aa (cm²)	MC (%)	ρ (kg/m³)	RA (kN)	Aa (cm²)	MC (%)	ρ (kg/m³)
5.80	7.51	12.10	503	7.32	4.47	12.90	470	10.60	7.92	12.80	503
10.30	12.18	12.10	503	7.72	5.08	12.90	470	15.60	12.38	12.80	503
10.80	12.18	11.50	503	16.43	10.15	12.90	470	19.70	16.24	12.80	500
18.00	22.74	11.50	503	18.92	14.82	12.90	470	9.30	8.12	15.30	500
6.30	6.90	19.50	575	9.96	7.11	14.80	470	16.60	12.38	15.30	500
11.60	16.24	19.50	575	16.43	11.77	14.80	470	17.80	15.43	15.30	575
8.50	12.18	15.10	500	22.66	15.63	14.80	470	7.80	8.12	17.00	503
18.40	22.94	15.10	500	7.32	4.47	12.90	470	10.60	7.92	12.80	575
5.30	7.51	15.90	510	8.47	5.89	14.20	480	12.40	11.57	17.00	575
13.40	16.44	15.90	510	12.95	9.14	14.20	480	16.50	16.24	17.00	575
9.50	11.77	18.70	460	22.91	16.65	14.20	480	21.40	23.14	17.00	520
13.70	22.33	18.70	460	6.97	6.29	16.30	495	8.00	8.93	18.30	520
5.30	7.31	19.80	470	11.95	10.76	16.30	495	12.50	12.79	18.30	520
12.20	15.83	19.80	470	19.92	17.05	16.30	495	17.10	17.26	18.30	520
8.00	11.57	19.60	505	8.47	5.89	14.20	480	21.70	22.53	18.30	520
15.85	22.53	19.60	505	-	-	-	-	-	-	-	-

Table 4. Anchoring results for AR300 resin

Direction 0º				Direction 45º				Direction 90º			
RA (kN)	Aa (cm²)	MC (%)	ρ (kg/m³)	RA (kN)	Aa (cm²)	MC (%)	ρ (kg/m³)	RA (kN)	Aa (cm²)	MC (%)	ρ (kg/m³)
9.65	8.12	12.10	520	8.47	7.92	12.90	460	11.50	8.12	11.20	520
18.25	17.05	12.10	520	12.95	10.96	12.90	460	16.30	12.18	11.20	520
12.30	11.98	12.10	505	20.91	18.47	12.90	460	22.60	16.24	11.20	520
21.30	23.14	12.10	505	7.22	7.51	16.00	475	12.20	8.73	16.00	485
4.25	6.09	16.70	450	10.46	10.76	16.00	475	15.10	12.59	16.00	485
10.30	12.18	16.70	450	21.41	17.66	16.00	475	18.00	16.24	16.00	485
12.20	16.65	16.70	450	9.21	7.31	14.80	485	23.40	23.14	16.00	485
21.30	23.14	16.70	450	13.94	9.74	14.80	485	8.70	9.34	18.50	500
5.70	7.31	18.50	465	18.92	16.65	14.80	485	12.50	12.38	18.50	500
11.90	17.66	18.50	465	10.70	7.71	12.00	445	15.00	16.44	18.50	500
11.30	11.77	18.50	550	14.19	10.56	12.00	445	19.40	23.14	18.50	500
20.00	22.33	18.50	550	20.92	17.46	12.00	445	8.40	9.14	20.60	450
6.65	8.32	21.50	480	-	-	-	-	11.50	12.18	20.60	450
10.20	16.85	21.50	480	-	-	-	-	14.90	16.44	20.60	450
10.60	12.38	21.50	455	-	-	-	-	19.10	23.14	20.60	450
17.00	19.29	21.50	455	-	-	-	-	8.70	9.34	18.50	500

Statistical models present significant variables: wood moisture content (MC) at the time of bonding and anchorage surface (Aa) (Table 7). Apparent densities measured in the specimens showed small variations and were not significant in the studied regression models, a condition already expected, since only one beam was used for each resin. It was sought not to include the natural variability of the wood as a variable in the experiment.

In some of the regression models, it was observed through the residue analysis that the variable MC would have better behaviour if it were presented in quadratic form (MC^2). However, due to the small number of observations, was opted for the linear regression model that was significant and valid for all statistical models presented. Through the analysis of variance, it can be observed that all the models can be considered highly significant.

Table 5. Anchoring results for Sikadur32 resin

Direction 0º				Direction 45º				Direction 90º			
RA (kN)	Aa (cm²)	MC (%)	ρ (kg/m³)	RA (kN)	Aa (cm²)	MC (%)	ρ (kg/m³)	RA (kN)	Aa (cm²)	MC (%)	ρ (kg/m³)
19.00	17.26	11.50	395	7.72	7.31	11.50	420	10.40	7.31	11.50	420
18.70	12.18	11.50	400	16.43	11.77	11.50	420	18.10	10.35	11.50	420
21.50	23.55	11.50	400	22.91	16.44	11.50	420	20.10	16.24	11.50	420
20.40	17.66	16.70	390	9.71	7.71	15.50	400	10.70	8.32	14.20	490
15.80	12.99	16.70	400	10.71	9.14	15.50	400	18.50	12.59	14.20	490
23.20	23.14	16.70	400	21.91	17.26	15.50	400	22.90	16.65	14.20	490
12.00	8.73	16.90	460	16.68	17.66	19.80	385	9.90	10.35	19.00	420
15.60	14.62	16.90	460	11.45	8.53	17.90	415	12.40	15.43	19.00	420
14.50	12.79	19.60	420	16.19	12.79	17.90	415	16.00	18.68	19.00	420
23.40	23.14	19.60	420	20.67	18.88	17.90	415	23.00	22.33	19.00	420
9.20	7.92	21.90	425	22.26	20.71	17.90	415	11.00	10.56	20.50	420
-	-	-	-	14.29	12.79	19.80	385	11.30	12.59	20.50	420
-	-	-	-	21.41	21.11	19.80	385	16.60	15.02	20.50	420
-	-	-	-	-	-	-	-	19.40	22.33	20.50	420

Table 6. Anchoring results for Polyurethane resin

Direction 0º				Direction 45º			
RA (kN)	Aa (cm²)	MC (%)	ρ (kg/m³)	RA (kN)	Aa (cm²)	MC (%)	ρ (kg/m³)
4.05	8.93	10.70	420	3.24	9.14	11.50	475
6.70	13.80	10.70	420	3.88	11.57	11.50	475
11.40	23.55	10.70	420	5.73	16.65	11.50	475
4.30	12.59	17.30	480	11.06	23.75	11.50	475
8.70	22.94	17.30	480	3.39	8.32	14.00	430
3.25	12.18	13.00	410	4.48	11.98	14.00	430
8.15	16.24	13.00	410	7.97	17.05	14.00	430
1.45	8.53	20.30	475	6.97	22.94	14.00	430
6.55	17.05	20.30	475	1.89	6.09	15.10	465
1.40	12.18	19.00	400	2.99	10.15	15.10	465
5.30	22.33	19.00	400	4.73	15.63	15.10	465
1.30	7.51	21.10	425	0.75	5.89	19.30	465
6.10	18.27	21.10	425	1.89	7.92	19.30	475
2.20	11.37	21.10	442	3.24	14.62	19.30	475
5.70	22.94	21.10	442	5.23	21.11	19.30	475
Direction 90º (Test 1)				Direction 90º (Test 2)			
RA (kN)	Aa (cm²)	MC (%)	ρ (kg/m³)	RA (kN)	Aa (cm²)	MC (%)	ρ (kg/m³)
4.60	9.14	12.20	430	1.40	13.40	19.40	430
5.30	13.80	12.20	430	4.50	17.05	19.40	430
8.40	16.85	12.20	430	8.40	22.94	19.40	430
11.20	22.33	12.20	430	1.80	8.53	17.30	430
4.55	8.93	13.60	425	4.60	13.60	17.30	430
7.00	13.20	13.60	425	6.90	17.05	17.30	430
11.00	17.26	13.60	425	8.40	22.74	17.30	430
0.80	9.14	18.00	425	0.60	8.53	21.10	430
1.40	12.99	18.00	425	0.90	12.59	21.10	460
4.10	17.46	18.00	425	2.20	16.85	21.10	460
9.00	22.94	18.00	425	4.90	23.14	21.10	460
3.00	9.34	16.00	425	1.60	9.34	20.00	460
5.80	13.40	16.00	425	4.00	14.41	20.00	453
6.65	17.05	16.00	425	3.50	17.05	20.00	453
11.10	22.33	16.00	425	6.60	23.55	20.00	453
0.40	8.93	19.40	430	1.40	13.40	19.40	430

Table 7. Regression models to estimate the anchorage strength and determination coefficient (R^2) for 0, 45 and 90° directions in relation to the wood grain

Resin	Direction	Regression Model	R^2 (%)
Polyurethane	0º	RA = 4.24 + 0.414·Aa – 0.322·MC	83.20
	45º	RA = 3.96 + 0.362·Aa – 0.291·MC	87.10
	90º	RA = 8.79 + 0.489·Aa – 0.653·MC	87.80
Vedacit	0º	RA = 3.73 + 0.703·Aa – 0.178·MC	94.60
	45º	RA = 13.2 + 1.310·Aa – 0.879·MC	96.20
	90º	RA = 12.3 + 0.972·Aa – 0.692·MC	97.90
AR300	0º	RA = 6.51 + 0.863·Aa – 0.376·MC	91.10
	45º	RA = 5.40 + 1.140·Aa – 0.346·MC	93.90
	90º	RA = 14.7 + 0.820·Aa – 0.676·MC	93.30
Sikadur32	0º	RA = 10.1 + 0.713·Aa – 0.232·MC	89.20
	45º	RA = 12.0 + 1.020·Aa – 0.589·MC	93.90
	90º	RA = 14.5 + 0.960·Aa – 0.738·MC	80.30

Where: RA = Anchorage strength (in kN); Aa = Anchorage surface (in cm²); MC = Moisture content (in %)

The residue studies *versus* significant independent variables showed: symmetry, indicating zero mean; and showing that there are no correlations between the residuals and these variables, which is observed by the uniform dispersion of the points around the zero and the good behaviour of these variables in the form that are presented in the model.

Average anchorage strength presented positive linear relationships, with an increase of the anchorage area and negative linear relationships with increased moisture content for all the resins and directions between bar and wood grain studied.

The normal probability tests for the residues indicate that the samples in each direction (0, 45 and 90º) present normal distributions, affirming the validity of the tests carried out.

Epoxy resins showed glassy consistency after hardening, and 90% of the anchorage ruptures occurred with losses of chemical adhesion and, later, losses of mechanical adhesion on the steel surface. Adhesion losses on the surfaces of the holes occurred with high humidity in only two observations. Another form of rupture, about 8%, showed mixed behaviour with partial loss of adhesion at the whole surface and partial on the steel surface. Shear rupture of the wood on the hole surfaces occurred in a high humidity observation. There were no shear ruptures of the resin.

There are significant differences between epoxy resins studied, depending on the wood moisture content conditions and the axial direction of the bars in relation to the wood grains. In the 0° direction, anchorage strength presented the lowest results and the lowest relative losses, comparing the adhesion in 12 or 22% moisture content. In the 45º direction, there was the highest average of anchorage strength and strength losses of 28%, for wood moisture content in 12 or 22%. In the 90º direction, the anchorage strength presented smaller variations for the epoxy resins, with absolute values of the same order of magnitude presented in the 45º direction, however, losses of approximately 35% of the anchorage strength to moisture content occurred in 12 or 22%.

4. CONCLUSIONS

Average anchorage strength presented positive linear relationships, with an increase of the anchorage area and negative linear relationships with increased moisture content for all the resins and directions between steel bar and wood grain studied.

Vedacit and AR300 liquid epoxy resins were readily applied, the time of application after mixing of A and B components was about thirty minutes. The use of liquid resins requires replacements after initial hardening, considering that these resins are absorbed or flow through internal timber cracks, decreasing the anchorage length.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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