

Pull out Strength Evaluation of Steel Bars Bonded-in to 45° in Round Timbers of *Corymbia citriodora* Treated with CCA

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Abstract With the possibility of developing simple connections, of easy execution, strong and durable, the bonded-in steel bars with structural resins have started being applied to different situations, such as shear connectors in mixed wood-concrete structures. These connectors, when steel bars are inclined in relation to the grain, may work under axial forces transmitting more stiffness and strength to the connection. In this research, the pull out strength of bonded-in steel bars was evaluated, bent 45° in relation to wood grain, using epoxy resin Sikadur-32 Fluid. In random sample of round pieces of *Eucalyptus citriodora* (*Corymbia citriodora*), CCA treated, with six replications in each observation, and considering the variability of the parameters: natural wood mechanical properties; apparent density; bar diameters; adherence surface and the moisture content. Steel bars used were highly resistant ones (CA-50), with threaded surface solicited by axial force, under monotonic loadings, with two consecutive load cycles. From the analysis of variance (ANOVA), the increase in the moisture content promoted reductions in the values of the compressive strength. The estimate of the pullout strength by the multivariable regression model, the moisture content was considered not significant, increases in the area of anchoring strengths implied significant increases in anchorage strength values, and the interaction between the factors (anchoring area and moisture content) promoted reductions in the anchor strength values of the steel bars.

Keywords Glued steel bars, Round timber, Anchorage strength, Shear connections, Epoxy resin

1. Introduction

The wood is a material of natural and renewable source, and has good relation between strength and density [1-8]. The natural round wood is an excellent solution because it does not require wood processing [8-14], commonly used in structural projects, such as bridges, in which concrete can also be used in conjunction with wood [15], consisting of steel bars and resins as the joining elements between wood and concrete materials.

The use of steel bars bonded to timber structures began with the need to fix screws in certain positions, subject to axial, lateral actions or combinations of both. Such connections are recommended for their excellent performance, simplicity, economy and pleasing aesthetics. The use of bonded steel bars in holes with larger diameters

represents an innovative and improved method of connections, being an important aspect of wood engineering techniques for connections using adhesives [16].

Steel bars anchoring with epoxy resins are economical and reliable, when well designed and executed. Although they have been used for over 20 years in some Scandinavian countries and Germany, performance requirements and design regulations differ among them [17].

The study of steel bars bonded as shear connectors in mixed structures of wood and concrete, until then, has been poorly developed. In Brazil, there are few published studies on mixed structures of wood and concrete, most of them using connectors such as nails, screws or bolts, perpendicular to the interface of the two materials. [18] notes the advantages of the "X" arrangement relative to the perpendicular position, in which connectors are stressed axially, presenting stiffness of two to ten times greater compared to the perpendicular connectors, depending on the diameter in question.

Glued bars are often used in Europe as connecting elements. This practice has been more directed to the

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insertion of steel bars bonded parallel to grain in top links, between structural pieces or columns fixation in concrete bases, being reported as connection systems of excellent behavior. In the bending elements, steel bars are glued with the greatest possible spacing from the center of gravity of the section, to maximize the bending capability. However, this positioning transfers force as a membrane connection, concentrating high stresses on small external sections of the piece of wood. In general, the cross section capacity is not fully utilized [19].

Variations in the position of bonded steel bars, initially surveyed by [19] apud [20] at the Tsniisk Institute in Moscow, showed excellent results. The glued steel bars inclined to grain in timber pieces are more efficient because: are able to transmit forces in their directions to the limit of the capacity of the steel; forward efforts to a larger region of wood pieces, allowing better stress distribution; are less vulnerable to cracking of wood in the bonding area; increase shear strength of wood; and presents excellent group behavior (all bars work simultaneously, allowing a high strength and stiffness bond).

[21] presented studies about connectors formed by steel bars bonded to the wood with epoxy and polyurethane resins, with slopes of 30; 45; 60; and 90° related to grain of Norway Spruce (*Picea abies*). They used high strength steel bars with threaded surface, required for tension and compression. They presented load diagrams versus displacements, evidencing the high stiffness, high strength and uniformity of behavior of these connections. They also presented a calculation model that allows evaluating the strength of a connection formed by several steel bars glued with different inclinations, from the knowledge of the anchoring strength of the individual bars.

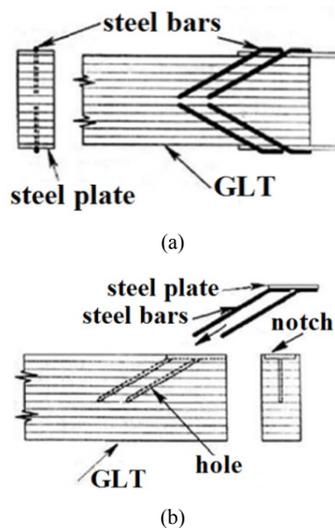


Figure 1. Connections with glued inclined bars - Russian connection (a). [20] proposition (b)

[22] presented partial results of a study of connectors with glued steel bars using epoxy adhesive, proposing a variation

in the positioning and the way to fix the steel plate that joins the outer ends of these bars. He suggests the connection, called "R", with parallel bars glued at 30° and pre-welded to the steel plate before being inserted into the holes with glue, according to Figure 1, differing from the Russian technique that suggests the welding of the steel plate after anchorage.

[22] repeated the design information for sizing the connections suggested by [21], presenting small changes, where the inlay strength was only considered in the calculation for the compressed bars. They also presented fire resistance test results with different protections.

[23] presented new test results on structural elements with connections made of bonded steel bars, comparing the experimental results with those predicted in the design suggested by [22]. It confirmed that it is an efficient and reliable ways of constructing timber structures with high magnitude stresses.

The dimensions of the steel bars, the bonding area of the steel bar with the wood, the wood specie, the moisture content of the wood and the orientation of the steel bars in relation to the wood are configured as variables that can affect in the values of the strength of the steel bar connections [24]. In this research, steel bars, bonded with epoxy resin, inclined at 45° in relation to grain studied, using round beams of *Eucalyptus citriodora* (*Corymbia citriodora*), in order to obtain "X" shear connectors type, as joint elements for mixed structures of wood and concrete. Considering that, in the elastic phase, the steel bars bonded present the same anchoring strengths when pulled or compressed, it is expected to reach a numerical model to obtain the mean strength of the "X" connections, based on the sum of the tangential strength components of the isolated bars.

2. Material and Methods

From a sample of *Corymbia citriodora* round wood beams, CCA treated, six air seasoned and six saturated pieces were obtained, with diameters about 20 cm. From each beam, a specimen was obtained with eight bonded steel bars, according to Figure 2. Air seasoned beams were numbered as: V9, V10, V11, V12, V13, V14; and saturated beams as: V1, V2, V3, V4, V5, V6.

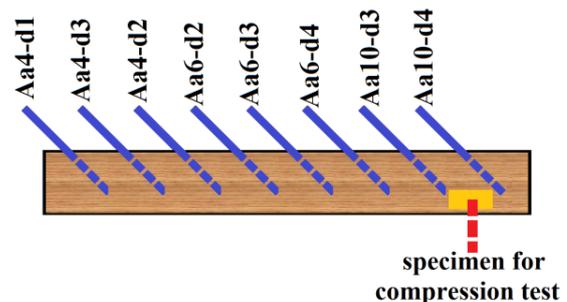


Figure 2. Specimen with glued steel bars at 45°, in CCA treated *Corymbia citriodora* beam

From each of the 12 beams used (V1-V5; V9-V14) a sample was extracted for the compression test parallel to the grain (f_{c0}) and also for the determination of the values of the wood density. The analysis of variance (ANOVA), at the 5% level of significance (α), was used to evaluate the influence of the moisture content (air seasoned woods [V9-V14] and saturated woods [V1-V5]) in the strength in parallel compression to the grain (f_{c0}).

In each specimen, steel bars were anchored with four diameters: 6.3; 8.0; 10.0; and 12.5 mm, with different lengths of anchors, forming three groups of anchorage areas: Aa4, Aa6, Aa10 (Table 1). Mean values of anchorage surfaces of the CA-50 steel bars, according to Equation 1, obtained by [25], were considered. From Equation 1, Aa is the mean of the anchorage surface per unit length of anchorage (cm^2/cm) and d is the nominal diameter of the steel bar (cm).

$$Aa = 0,365 \cdot d - 0,295 \quad (1)$$

Table 1. Experimental planning

| Beam | d (mm) | la (cm) | Aa (cm^2) | D (mm) | e (mm) |
|---------|--------|---------|----------------------|--------|--------|
| Aa4-d1 | 6.3 | 9.4 | 18.89 | 9.0 | 1.35 |
| Aa4-d2 | 8.0 | 7.1 | 18.82 | 10.5 | 1.25 |
| Aa4-d3 | 1.0 | 5.8 | 18.90 | 13.0 | 1.50 |
| Aa6-d2 | 8.0 | 10.9 | 28.89 | 10.5 | 1.25 |
| Aa6-d3 | 10.0 | 8.9 | 29.01 | 13.0 | 1.30 |
| Aa6-d4 | 12.5 | 6.7 | 29.01 | 16.0 | 1.75 |
| Aa10-d3 | 10.0 | 12.4 | 40.42 | 13.0 | 1.50 |
| Aa10-d4 | 12.5 | 9.4 | 40.70 | 16.0 | 1.75 |

d = nominal diameter of the steel bars; la = anchoring length; Aa = Anchorage area; D = hole diameter; e = thickness of glue line.

Figure 3 shows schematically the combinations of anchorage areas Aa4, Aa6 and Aa10, respectively, 18.9; 29.0; and 40.0 cm^2 , considering different diameters and lengths of anchors for dry and saturated pieces, with six replications.

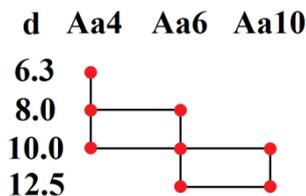


Figure 3. Combining variables in experiment planning

Considering the same anchorage areas, but with different diameters, one can observe the effect of the variation of the diameters in the means anchorage responses.

In all specimens, steel bars received surface cleaning treatment, applying a rotating steel brush on the end in contact with the resin, until the white color was reached. Then thinner (general purpose for cleaning) was applied as solvent to remove oily residues. CA-50 steel bars ($f_{y,k}=500$ MPa) were used axially in two load cycles with monotonic loads. The first cycle required up to 70% of the ultimate strength. The charge rate was 100 N/s. Figure 4 shows the anchorage tests of steel bars.

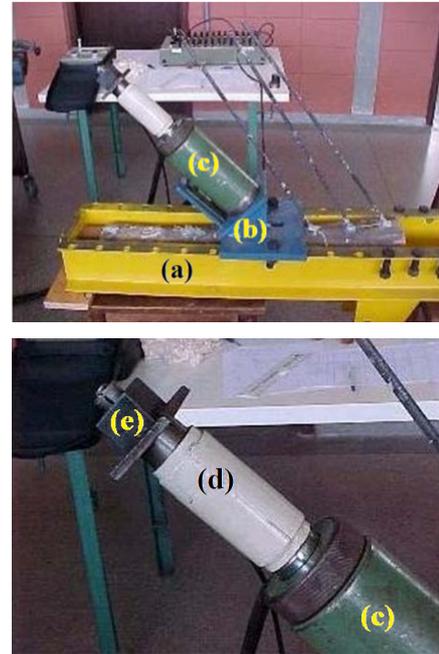


Figure 4. Anchorage tests of steel bars inclined 45° in round pieces of *Corymbia citriodora* reaction beam (a), support (b), hydraulic cylindrical (c), load cell (d), anchoring the outer end of the steel bar (e)

A regression model was used to investigate the influence of moisture content (U) and anchorage area (Aa) on anchor strength (RA) values. The regression model (Equation 1) was also evaluated by analysis of variance, evaluated at the 5% level of significance. The ANOVA of the regression models makes it possible to evaluate the influence of each factor and their interaction in the values of on anchor strength, and the coefficient of determination (R^2) measures the quality of the obtained model. By the formulation of the ANOVA hypotheses of the regression models, P-value (probability P) inferior to the level of significance implies that the coefficients of the model are significant, and not significant in the opposite situation (P-value < 0.05).

$$RA = a_0 + a_1 \cdot Aa + a_2 \cdot U + a_3 \cdot Aa \cdot U + \varepsilon \quad (2)$$

From Equation 1, α_i are the coefficients adjusted by the Least Squares Method and ε is the aleatory error. For validation of the ANOVA model, the normality, homogeneity and independence of the residues were investigated.

3. Results and Discussion

Table 2 shows the apparent density (ρ_{app}), the density at 12% moisture content (ρ_{12}) and the compressive strength values (f_{c0}) of the *Corymbia citriodora* wood for the two moisture content conditions (air seasoned and saturated woods).

The results of the ANOVA for the influence of the moisture content on the values of the strength compression (f_{c0}) are presented in Table 3, and the results of the validation tests are illustrated in Figure 5.

Table 2. Properties of the wood (beams)

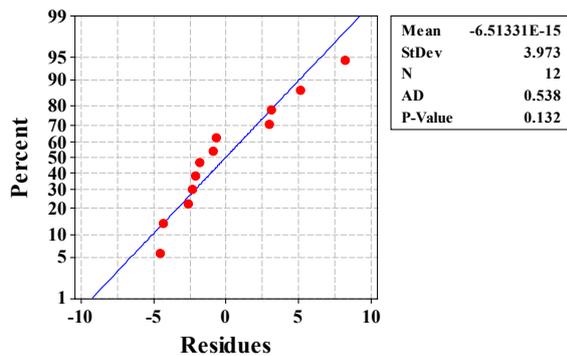
| Beams | ρ_{ap} (kg/m ³) | U (%) | f_{c0} (MPa) | ρ_{12} (kg/m ³) |
|-------|----------------------------------|-------|----------------|----------------------------------|
| V1 | 1100 | 30.0 | 52.91 | 1060 |
| V2 | 990 | 40.6 | 40.31 | 910 |
| V3 | 1060 | 27.9 | 47.63 | 1040 |
| V4 | 1030 | 40.2 | 42.34 | 1020 |
| V5 | 940 | 28.1 | 42.84 | 1020 |
| V6 | 960 | 28.9 | 42.06 | 940 |
| V9 | 1040 | 14.7 | 68.42 | 1030 |
| V10 | 1040 | 14.1 | 69.82 | 1020 |
| V11 | 1060 | 14.2 | 69.61 | 1050 |
| V12 | 1090 | 14.1 | 73.62 | 1070 |
| V13 | 1040 | 14.7 | 65.93 | 1030 |
| V14 | 1060 | 14.9 | 75.62 | 1040 |

- ρ_{ap} = apparent densities in each moisture content, U = moisture content, f_{c0} = strength in compression parallel to the grain, ρ_{12} = apparent densities in 12% moisture content.

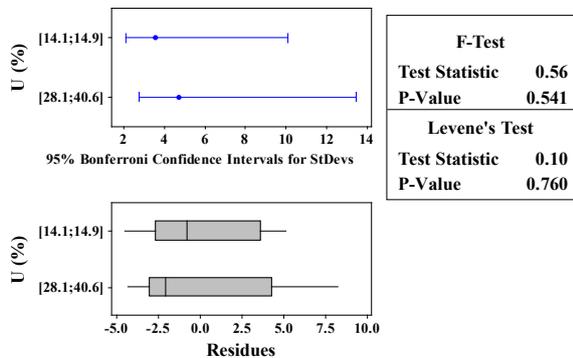
Table 3. Results of ANOVA - influence of moisture content on f_{c0} values

| Source | DF | SS | MS | F | P |
|--------|----|--------|--------|--------|-------|
| U (%) | 1 | 2000.3 | 2000.3 | 115.18 | 0.000 |
| Error | 10 | 173.7 | 17.4 | | |
| Total | 11 | 2173.9 | | | |

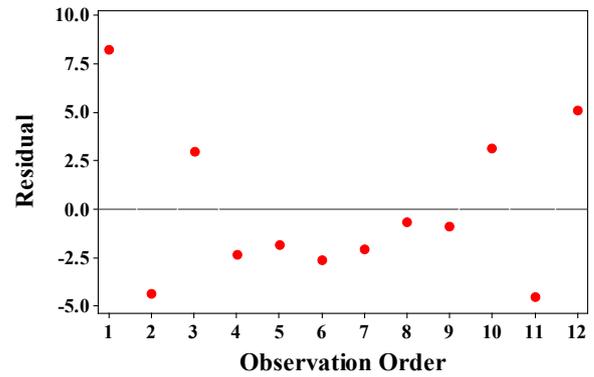
- DF = degrees of freedom, SS = sum of squares, MS = mean of squares, F = F statistic, P = P statistic.



(a)



(b)



(c)

Figure 5. Results of ANOVA validation test - normality (a), homogeneity (b) and independence of residues (c)

The results of Figure 5 validate the ANOVA results. From Table 3 it can be seen that the moisture content was considered significant in the values of the f_{c0} values (P-value<0.05). The reduction in moisture content promoted a 57% increase in the value of f_{c0} , as shown in Figure 6.

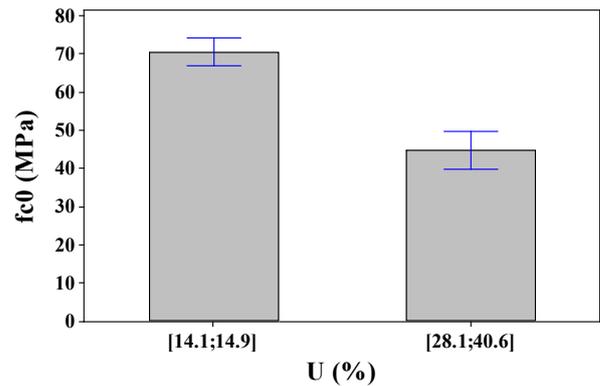


Figure 6. Mean values of confidence intervals (95%) of the f_{c0} values for the evaluated moisture content ranges

Ruptures of anchorages occurred, initially, by loss of chemical adhesion and later by loss of mechanical adhesion. In no case did fragments of wood be removed. In some anchoring trials with 6.3 mm diameter bars and 9.7 cm anchoring length, in seasoned air dried wood, steel bars ruptured prior to breakage of the anchors. Epoxy resin showed a glassy texture, after hardening, and good adhesion in the wood in the two moisture content levels: air dried and saturated. Figure 7 shows the rupture forms in steel and wood, regardless diameters and lengths of anchors used.

Table 4 present the anchor strength responses obtained in specimens tests, obtained according to the procedures of Brazilian standard [26].

Table 4. Results of anchorage strength (45°)

| CP | RA (kN) | Aa (cm ²) | U (%) | CP | RA (kN) | Aa (cm ²) | U (%) |
|------------|---------|-----------------------|-------|-------------|---------|-----------------------|-------|
| V1-Aa4-d1 | 20.42 | 19.69 | 25.0 | V5-Aa6-d3 | 31.37 | 32.60 | 30.3 |
| V2-Aa4-d1 | 18.43 | 19.49 | 33.0 | V6-Aa6-d3 | 35.36 | 33.25 | 31.9 |
| V3-Aa4-d1 | 22.91 | 19.49 | 27.9 | V9-Aa6-d3 | 42.08 | 31.30 | 14.7 |
| V4-Aa4-d1 | 19.42 | 20.50 | 32.0 | V10-Aa6-d3 | 42.83 | 30.97 | 14.1 |
| V5-Aa4-d1 | 19.17 | 19.08 | 30.3 | V11-Aa6-d3 | 43.33 | 34.56 | 14.2 |
| V6-Aa4-d1 | 19.92 | 20.91 | 31.9 | V12-Aa6-d3 | 44.07 | 31.30 | 12.7 |
| V10-Aa4-d1 | 23.90 | 20.10 | 14.1 | V13-Aa6-d3 | 43.33 | 31.30 | 15.7 |
| V1-Aa4-d2 | 18.43 | 21.20 | 25.0 | V14-Aa6-d3 | 43.82 | 31.30 | 12.0 |
| V2-Aa4-d2 | 15.44 | 18.55 | 33.0 | V1-Aa6-d4 | 29.38 | 31.18 | 25.0 |
| V3-Aa4-d2 | 19.92 | 20.41 | 27.9 | V2-Aa6-d4 | 26.39 | 31.18 | 33.0 |
| V4-Aa4-d2 | 19.92 | 22.00 | 32.0 | V3-Aa6-d4 | 32.62 | 31.18 | 27.9 |
| V5-Aa4-d2 | 17.93 | 18.82 | 30.3 | V4-Aa6-d4 | 26.89 | 33.77 | 32.0 |
| V6-Aa4-d2 | 17.43 | 20.14 | 31.9 | V5-Aa6-d4 | 36.11 | 32.04 | 30.3 |
| V9-Aa4-d2 | 24.40 | 19.88 | 14.7 | V6-Aa6-d4 | 30.88 | 32.91 | 31.9 |
| V10-Aa4-d2 | 25.90 | 19.35 | 14.1 | V9-Aa6-d4 | 41.83 | 31.61 | 14.7 |
| V11-Aa4-d2 | 28.88 | 19.35 | 14.2 | V10-Aa6-d4 | 42.83 | 31.18 | 14.1 |
| V12-Aa4-d2 | 24.40 | 19.35 | 12.7 | V11-Aa6-d4 | 45.82 | 30.31 | 14.2 |
| V13-Aa4-d2 | 23.90 | 20.14 | 15.7 | V12-Aa6-d4 | 37.60 | 32.04 | 12.7 |
| V14-Aa4-d2 | 25.90 | 20.14 | 12.0 | V13-Aa6-d4 | 37.85 | 31.18 | 15.7 |
| V1-Aa4-d3 | 20.17 | 20.54 | 25.0 | V14-Aa6-d4 | 40.34 | 31.61 | 12.0 |
| V2-Aa4-d3 | 17.93 | 20.54 | 33.0 | V1-Aa10-d3 | 40.84 | 41.08 | 25.0 |
| V4-Aa4-d3 | 19.92 | 19.89 | 32.0 | V2-Aa10-d3 | 41.33 | 41.40 | 33.0 |
| V5-Aa4-d3 | 19.92 | 20.86 | 30.3 | V3-Aa10-d3 | 38.84 | 41.73 | 27.9 |
| V6-Aa4-d3 | 20.42 | 20.86 | 31.9 | V4-Aa10-d3 | 41.83 | 40.42 | 32.0 |
| V9-Aa4-d3 | 27.89 | 21.84 | 14.7 | V5-Aa10-d3 | 40.84 | 42.05 | 30.3 |
| V10-Aa4-d3 | 30.63 | 20.86 | 14.1 | V6-Aa10-d3 | 39.84 | 39.77 | 31.9 |
| V11-Aa4-d3 | 30.88 | 20.21 | 25.0 | V9-Aa10-d3 | 48.31 | 40.75 | 14.7 |
| V12-Aa4-d3 | 28.88 | 21.19 | 33.0 | V10-Aa10-d3 | 48.80 | 41.08 | 14.1 |
| V13-Aa4-d3 | 28.39 | 21.84 | 27.9 | V11-Aa10-d3 | 45.32 | 41.08 | 14.2 |
| V14-Aa4-d3 | 28.88 | 20.54 | 32.0 | V12-Aa10-d3 | 47.81 | 41.08 | 12.7 |
| V1-Aa6-d2 | 25.15 | 28.62 | 30.3 | V13-Aa10-d3 | 50.80 | 41.08 | 15.7 |
| V2-Aa6-d2 | 26.39 | 29.42 | 31.9 | V14-Aa10-d3 | 51.79 | 43.68 | 12.0 |
| V3-Aa6-d2 | 28.39 | 28.89 | 14.7 | V1-Aa10-d4 | 46.81 | 48.06 | 25.0 |
| V4-Aa6-d2 | 25.40 | 29.95 | 14.2 | V2-Aa10-d4 | 44.32 | 46.33 | 33.0 |
| V5-Aa6-d2 | 29.38 | 30.21 | 12.7 | V3-Aa10-d4 | 48.31 | 49.80 | 27.9 |
| V6-Aa6-d2 | 26.39 | 29.95 | 15.7 | V4-Aa10-d4 | 42.33 | 49.80 | 32.0 |
| V9-Aa6-d2 | 33.86 | 29.95 | 12.0 | V5-Aa10-d4 | 44.82 | 46.76 | 30.3 |
| V11-Aa6-d2 | 36.35 | 30.74 | 25.0 | V6-Aa10-d4 | 42.83 | 46.30 | 31.9 |
| V12-Aa6-d2 | 32.87 | 29.68 | 33.0 | V9-Aa10-d4 | 56.77 | 48.06 | 14.7 |
| V13-Aa6-d2 | 32.37 | 29.15 | 27.9 | V10-Aa10-d4 | 52.29 | 49.36 | 14.1 |
| V14-Aa6-d2 | 36.85 | 30.21 | 32.0 | V11-Aa10-d4 | 58.76 | 48.06 | 14.2 |
| V1-Aa6-d3 | 34.86 | 30.32 | 25.0 | V12-Aa10-d4 | 61.75 | 47.63 | 12.7 |
| V2-Aa6-d3 | 29.88 | 31.30 | 33.0 | V13-Aa10-d4 | 52.29 | 47.63 | 15.7 |
| V3-Aa6-d3 | 38.65 | 31.62 | 27.9 | V14-Aa10-d4 | 62.75 | 50.23 | 12.0 |
| V4-Aa6-d3 | 32.37 | 31.30 | 32.0 | | | | |

- CP = specimen identification, RA = anchorage strength (45°), Aa = anchorage area, U = moisture content of wood.

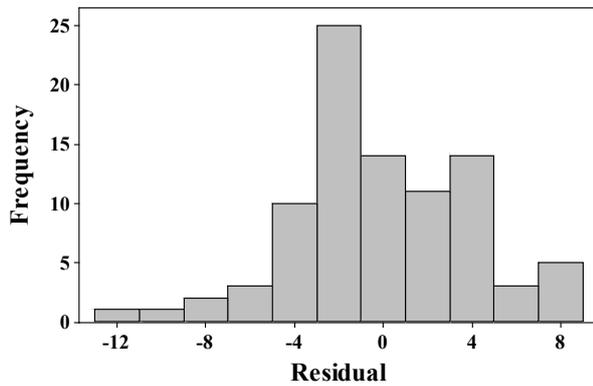


Figure 7. Shapes of rupture, regardless diameters and lengths of anchors

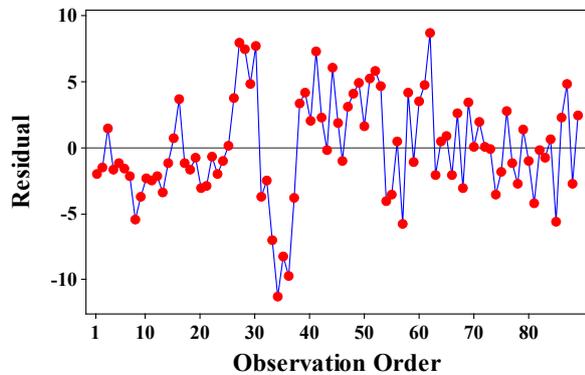
Table 5. ANOVA results of the regression model

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|-----------------------|----|---------|---------|---------|---------|-------|
| Regression | 3 | 10192.3 | 10192.3 | 3397.44 | 213.035 | 0.000 |
| Aa (cm ²) | 1 | 8982.0 | 1488.9 | 1488.90 | 93.361 | 0.000 |
| U (%) | 1 | 1124.4 | 1.0 | 1.04 | 0.065 | 0.799 |
| Aa·U | 1 | 85.9 | 85.9 | 85.86 | 5.384 | 0.023 |
| Error | 85 | 1355.6 | 1355.6 | 15.95 | | |
| Total | 88 | 11547.6 | | | | |

-DF = degrees of freedom, Adj SS = squared sums adjusted, Adj MS = adjusted squared mean, F = F statistic, P = P statistic.



(a)



(b)

Figure 8. Normality plot (a) and independence (b) of the ANOVA residuals of the regression model

The multilinear regression model and the respective coefficient of determination (R^2) for the estimation of the anchorage strength is expressed by Equation 2, Table 5 presents the ANOVA results of the regression model and Figure 8 illustrates the residue graphs for ANOVA validation.

$$RA = 4.75623 + 1.26515 \cdot Aa - 0.0448065 \cdot U - 0.0123721 \cdot Aa \cdot U \quad [R^2 = 88.26\%] \quad (3)$$

The graphs of Figure 8 validate the ANOVA model. From Table 5, the regression model was considered significant (P -value < 0.05), and the coefficient of determination obtained was equal to 88.26%, which reveals the good accuracy of the adjustment. The anchorage area and its interaction with the moisture content (Aa·U) were considered significant in the values of the anchoring strength, the same did not occur with the factor moisture content (P -value > 0.05). From the obtained model, increases in anchorage area values cause increases in the anchor strength, and the interaction between the two factors is responsible for the reduction in anchor strength values. Figure 9 shows the regression model obtained from Equation 2.

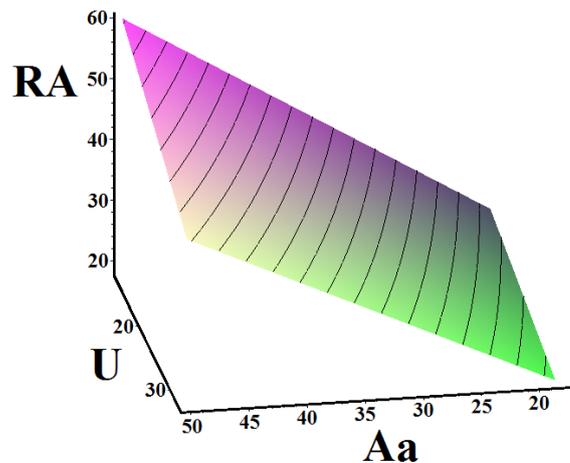


Figure 9. Graph of the adjusted multivariable regression model

4. Conclusions

The results obtained in this research make it possible to conclude that:

- the increase in moisture content significantly reduced the values of the compression strength (f_{c0});
- the anchorage did not show brittle rupture and the steel bars progressively lose the correspondent strength as the anchoring length decreases upon bar removal.
- the variation of the moisture content (U) was not significant in the estimation of the anchor strength values (RA);
- the anchorage area (Aa) was significant in estimating the anchor strength values of the steel bars. Increases in anchorage area values imply an increase in anchorage strength;
- the interaction between the anchorage area and the moisture content (Aa·U) was significant in the estimation of anchorage strength. Increase in the value of the interaction imply in the reduction of the anchoring strength.

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