International Journal of Materials Engineering 2018, 8(4): 70-75
DOI: 10.5923/j.ijme.20180804.03

Pull Out Strength of Bonded-in Steel Rods Perpendicularly to the Grain in *Corymbia citriodora* and *Pinus oocarpa* Shiede Timber

Júlio C. Pigozzo[1], Felipe N. Arroyo[2], Diego H. Almeida[3], André L. Christoforo[3,*], Eduardo Chahud[4], Francisco A. R. Lahr[5]

[1]Department of Civil Engineering, Technology Center, State University of Maringá (UEM), Maringá, Brazil
[2]Faculdades Integradas de Cacoal (UNESC), Cacoal, Brazil
[3]Department of Civil Engineering (DECiv), Federal University of São Carlos (UFSCar), São Carlos, Brazil
[4]Department of Civil Engineering, Federal University of Minas Gerais (UFMG), Belo Horizonte, Brazil
[5]Department of Structural Engineering (SET), São Carlos Engineering School, São Paulo University (EESC/USP), São Carlos, Brazil

Abstract The study of pull out strength of glued in rods perpendicularly to the grain is presented. Three types of resin were used in order to evaluate their efficiency. Additionally, the effects of the variation of the moisture content and of the glue line thickness were considered. The beams were made of wood from *Corymbia citriodora*, ($\rho_{12\%}$ = 1000 kg/m^3) and *Pinus oocarpa* Shiede ($\rho_{12\%}$ = 550 kg/m^3). The wood specimens (four samples for each type of test) were seasoned to the expected moisture contents of 12, 15, 18 and 22%. The anchorage length of the glued in rods was 80 mm, the hole diameters were 7.5, 8.5, 9.5 and 10.5 mm and their respective glue line thickness, 0.6, 1.1, 1.6 and 2.1 mm. The deformed reinforcing bars used as rods, with the minimum yield strength of 500 MPa, had nominal diameter of 6.3 mm. The obtained results confirmed the assumption that type of resin, moisture content, glue line thickness are strength determining factors, while density is less than others. The results are presented in a comparative form. The failure modes are discussed and the need of a broad understanding of resin behavior on wood was emphasized.

Keywords Adhesives, Glued-in steel rods, Structural resin, Anchorage strength

1. Introduction

The use of glued steel bars on structural pieces of wood was initiated by making it clear the need to fix bolts that could receive axial, lateral or combined loads. Such a connection has received attention and recognition by: excellent performance when well designed and executed; aesthetic appearance; and low cost [1]. The bars used as connectors are preferably: threaded; galvanized and high strength; with deformed surfaces; and scored or threaded 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 [2].

The use of bonded steel bars is characterized by the sticking of bars into holes of larger diameters. It depicts an innovative and improved method of connections, being an important aspect for connections using adhesives. Its main advantages are: connections allow higher levels of effort transfers; top connections with glued bars can withstand large bending moments; the holes used in the connections do not weaken the structural members, as in the connections with bolts; possible errors in construction sites are avoided, such as improper drilling; makes it possible to join large pieces, having larger free spans; the structural members become more aesthetic, avoiding apparent connectors like toothed plates or screws and bolts; the connections are easily protected against fire; the connections are potentially cheaper, compared to the finger-joint system, as it does not require special machines for the execution; and the connections have less material and lower cost of production, compared to the bolted connections [3].

Bainbridge and Mettem [4] report that there are still no general technical standards governing the use of steel bars bonded to wood structures, although they have been used for more than twenty years. Performance requirements and project regulations differ between them. Due to the uncertainties in the behavior of these connectors and the lack of reliable calculation methods, they have not yet been

* Corresponding author:
alchristoforo@gmail.com (André L. Christoforo)
Published online at http://journal.sapub.org/ijme

introduced into the main part of the European Standard. It is currently listed in EUROCODE 5:1993 Part 1-1 [5] as recommendations for use in its annex.

Structural synthetic resins most commonly used in timber structures are: phenol resorcinol formaldehyde (PRF), polyurethanes (PUR) and epoxies (EP). Currently PRF does not require a hot cure and has fewer retractions and the EP is at a competitive cost. There were previously restrictions on the use of EP as a structural resin, suspected of having brittle ruptures with increasing temperature or against long loads. Currently, this adhesive is the most suitable for anchoring steel bars in structural timber, because they have better properties and fewer defects over time. A significant change appears when the EP is no longer considered as a set of resins with uniform behavior, but it is possible to compare different brands and manufacturers [3].

The variables that influence the anchorage strength of bonded-in steel bars are currently being studied by several researchers in Europe and New Zealand. The results, conclusions and suggestions presented are related to the characteristics of the adhesives used, however, few authors cite the commercial name and the manufacturer of these adhesives, impairing comparisons of results and, in many cases, preventing general conclusions.

About the influence of the mechanical properties of the wood on the anchorage strength. Riberholt [6] proposed an expression estimating average values of the anchorage strength, considering rupture model as the shear of the wood around the hole. This expression, adopted by EUROCODE 5:1993 Part 2 [5] and item A.2.2, considers the effect of wood density with a significant variable. On the other hand, Buchanan and Moss [8] and Bengtsson *et al.* [9] found no significant influence of wood density on the anchorage strength of bonded-in steel bars.

The aim of this work was to evaluate the behavior of two bi component epoxy resins and a bi component polyurethane resin, for the study of anchorage strength of steel bars bonded to beams of *Corymbia citriodora* and *Pinus oocarpa* Shiede in the direction perpendicular to the grain, without considering the natural variations of the mechanical properties. In addition to the anchorage strength, the objective is to know how some variables influence the anchorage strength, such as: wood density variations, comparing different species; variations of wood moisture at the time of bonding; and variations in the thickness of the glue line.

2. Material and Methods

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

Batchelar and Mcintosh [10], reviewing rupture models in experiments due to improper blends and/or incorrected epoxy adhesive applications *in situ*, concluded that the entire sizing operation should be done in a suitable environment with adequate quality control and specialized people.

Table 1. Resins employed in experiment

Commercial Name	Consistency	Type	Commercial Suppliers
Compound	Liquid	Epoxi	Otto Baungart S/A
Sikadur-32	Pasty	Epoxi	Sika S/A
Polyurethane	Liquid	Polyurethane	IQSC/USP

Specimens manufacture – Corymbia citriodora

In each beam, a resin was used and the mechanical properties of the wood were admitted constant along its length.

The studied beams of *Corymbia citriodora* ($\rho_{12\%}$ = 1000 kg/m^3) had dimensions of 5 x 20 x 300 cm with moisture content initially between 25 and 30% (Fig. 1). From each beam six specimens were obtained, with a length of 25 cm each. In order to obtain the expected humidity of 15, 18, 20, 24, 28 and 34%, the mass of water contained in each specimen was controlled, where some were immersed in water and others were air-conditioned in a kiln with forced ventilation and temperature control until they reach the desired weight. Then, the specimens were packed separately in transparent plastic bags, where they remained for a period of 40 days to homogenize the mass of water throughout its volume.

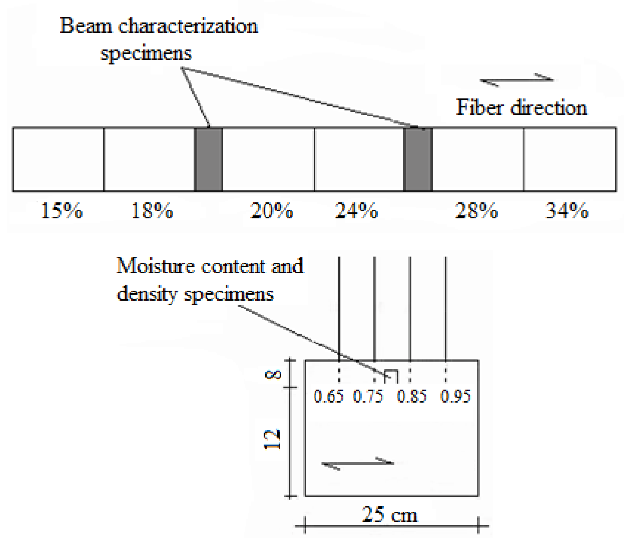

Figure 1. Specimens obtainment in each *Corymbia citriodora* beam, anchoring bars and diameters of holes for liquid resins

The experiment was designed so that there were two replications in each observation, considering the possibilities of excessive defects, as a result of forced drying. For the polyurethane resin, the low results and the two anchorage rupture behaviors presented initially suggested the possibility of errors in the preparation of the resin, leading to the repetition of the experiment. Therefore, the specimens were obtained in four beams and the results correspond to the average of four replications. For Compound resin, the specimens were obtained in two beams, and the results correspond to the average of two replications. For these resins, each specimen, according to Fig. 1, received four holes in the direction perpendicular to the grain, with depth of 8.0 cm and diameters of 6.5, 7.5, 8.5 and 9.5 mm.

For the Sikadur-32 resin, specimens were obtained in a single beam. The series of specimens corresponding to the second beam was neglected, due to excessive retraction defects due to drying. In these specimens, the diameters of the holes were 8.5, 9.5, 10.5 and 11.5 mm, considering the difficulty of injecting this resin into holes with smaller diameters. The thicknesses of the glue lines were, respectively, 0.58, 1.08, 1.58, 2.08, and 2.58 mm for the diameters used.

Specimens manufacture – Pinus oocarpa Shiede

In each beam, a resin was used and the mechanical properties of the wood were admitted constant along its length.

The beams of *Pinus oocarpa* Shiede ($\rho_{12\%}$ = 550 kg/m^3) were initially air dried, with moisture content between 11.5 and 12%. From each beam, with dimensions of 5 x 20 x 150 cm, four specimens with a length of 25 cm each were obtained, according to Fig. 2. In order to obtain the expected moisture, the mass of water contained in the specimens was checked were immersed in water until reaching the desired weights, corresponding to the expected moisture content of 12, 15, 18 and 22%. Then, the specimens were packed separately in transparent plastic bags, where they remained for a period of 30 days to homogenize the mass of water in its volume.

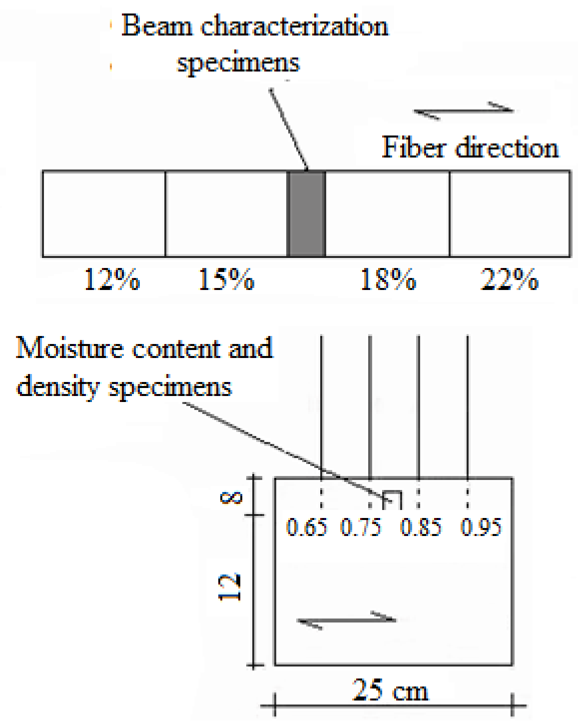

Figure 2. Specimens obtainment in each *Pinus oocarpa* Shiede beam, anchoring bars and diameters of holes for liquid resins

Each resin was studied in a single beam, considering the least possible loss of specimens with defects due to air conditioning. For the liquid resins (Polyurethane and Compound), each specimen received four holes in the direction perpendicular to the grain with depths of 8.0 cm and diameters of 6.5, 7.5, 8.5 and 9.5 mm.

For the Sikadur-32 resin, in each specimen the holes had depths of 8.0 cm and diameters of 8.5, 9.5, 10.5 and 11.5 mm, considering the difficulty of injecting this resin into holes with smaller diameters. The thicknesses of the glue lines were, respectively, 0.58, 1.08, 1.58, 2.08, and 2.58 mm for the diameters used.

Steel bars characterization

In all of the specimens, the steel bars received surface cleaning treatment by applying a rotating steel brush until it reached the white color at the end in contact with the resin. Subsequently, thinner (commonly used for cleaning) was applied as solvent to remove oil residues. CA-50 steel bars (fyd = 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. The adhesion surfaces of the steel bars were evaluated from the average size of the surface fillets, obtaining, on average, 2.03 cm^2 of surface area for each unit of bar length.

Statistical analysis

The results were submitted to statistical analysis to develop the most adequate statistical model, with the purpose of inferring average responses of anchorage strengths in the 90° direction from the experimental data for each resin. The statistical methods used were: multiple linear regression analysis, analysis of variance, residue analysis and normality test for residues.

3. Results and Discussion

Compound resin (liquid consistency) was partially absorbed or drained by small cracks in the wood, thus altering the anchorage length in the specimens. Even after the initial hardening, the specimens showed small variations in the anchorage areas, which became significant in the statistical model. For the purpose of comparing the results using the statistical models for this resin, the mean value of the anchorage area was 16.24 cm², which corresponds to an average anchorage length of 8.0 cm.

Statistical models present significant variables: moisture content of the wood at the time of bonding and the thickness of the glue line. Densities for each wood measured in the specimens showed small variations, not being significant in the studied models, considering that few beams were used for each resin and it was tried not to include the natural variability of the wood as variable in the experiment.

In some models for the epoxy resins, the residue analysis shows that the variable moisture content could be presented in quadratic form, but, due to the small number of observations, the linear model is also significant and valid for statistical models presented. Through the analysis of variance, it can be observed that all the models can be considered highly significant.

The studies of the residuals versus independent variables showed symmetry indicating zero mean and show that there is no correlation between the residues and the observed variables, indicated by the uniform dispersion of the points around zero.

Normal probability tests for residues indicate that the residues and hence the responses follow a normal distribution, so the tests used in each analysis are appropriate and possible to use.

Corymbia citriodora members

With the polyurethane resin of castor oil, for glue lines with thicknesses of 0.58, 1.08, and 1.58 mm and hole diameters: 7.5, 8.5, and 9.5 mm respectively, the anchorage rupture were characterized by shearing of the resin in the glue line. Presented average value to anchorage strength (RA) equal to 3.0 kN and did not depend on the variations of humidity or the thickness of the glue line. For the 0.08 mm glue line, corresponding to the 6.5 mm hole, the anchorage rupture also occurred with the resin shear, although another factor is influencing these results that clearly stood out in relation to the other glue line thicknesses (Fig 3.). Average anchorage strength equal to 10 kN was obtained for air dry wood, with small linear influence decreasing for increases in humidity.

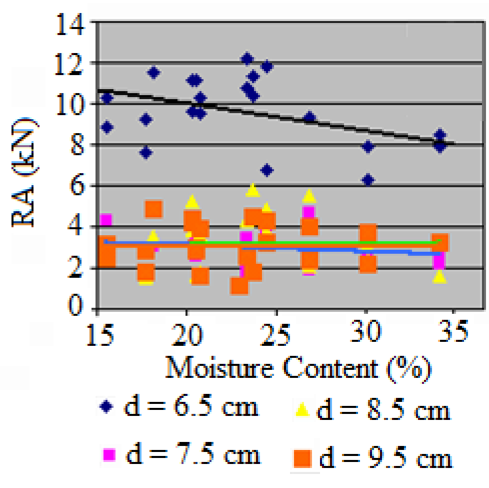

Figure 3. Anchorage strength and moisture content for polyurethane resin of castor bean oil – *Corymbia citriodora* member

Table 2. Anchorage strength and coefficient of determination (R^2) in 90° toward in the direction to *Corymbia citriodora*

Resin Type	Statistical Model	R^2(%)
Compound	RA = 23.23 + 5.050·e – 0.580·MC	81.70
Sikadur-32	RA = 18.70 + 3.560·e – 0.258·MC	72.80

Where: RA = anchorage strength (in kN); e = glue line (in mm); MC = moisture content (in %).

For the epoxy resins, the statistical models presented in Table 2 were obtained, with increasing linear variations for increases in the thickness of the glue line and decreasing linear variations for the increase of moisture content.

Fig. 4 presents the average values to anchorage strengths with glue lines thickness variations, for wood moisture content of 12 and 22% and anchorage strengths with wood moisture variations of 15 to 30%, for a glue line thickness equal to 1.58 mm.

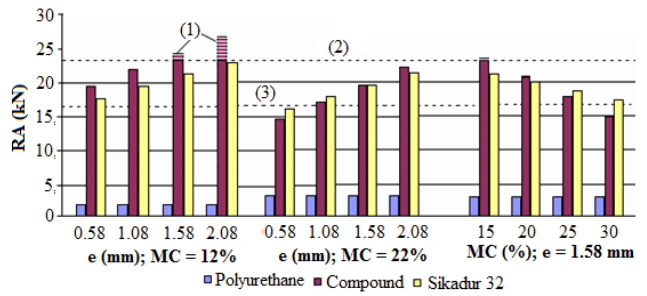

Figure 4. Comparative anchorage strength values for tree structural resins varying the glue line thickness and moisture content in *Corymbia citriodora:* (1) Theoretical values; (2) Bar rupture limit; (3) Bar yeld limit

Pinus oocarpa Shiede members

Anchorage strengths with the polyurethane resin in *Pinus oocarpa* Shiede specimens (Table 3), showed markedly greater values for the thickness of the glue line 0.08 mm, with tendencies to decrease rapidly as this variable grows, (Fig. 5). Regarding to moisture content, it presented a behavior similar to that observed in some analyzes, with the variable MC^2 behaving better in the statistical model than the variable MC. Considering the few observed results, the model presented in Table 3 was chosen for this resin.

Table 3. Anchorage strength and coefficient of determination (R^2) in direction to 90° at *Pinus oocarpa* Shiede

Resin Type	Statistical Model	R^2(%)
Polyurethane	RA = 12.60 – 0.0276·MC² - 1.65·*ln*(e)	97.80
Compound	RA = 28.64 – 1.04·MC + 3.62·e	92.00
Sikadur-32	RA = 27.10 – 0.559·MC + 1,23·e	79,70

Where: RA = anchorage strength (in kN); e = glue line (in mm); MC = moisture content (in %).

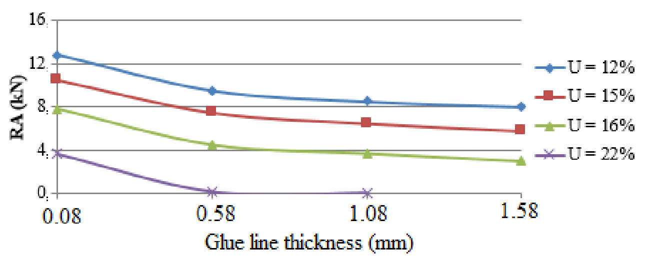

Figure 5. Anchorage strength in relation to glue line thickness for polyurethane resin of castor bean oil in various moisture content for hole diameter equal to 6.3 mm

For the epoxy resins, the statistical models are similar to those obtained with *Corymbia citriodora* wood, in which the anchorage strengths present increasing linear variations for increases in the thickness of the glue line and decreasing linear variations in the increase of moisture content presented in Table 3.

Fig. 6 presents the average values to anchorage strengths with glue line thickness variations, for wood moisture content of 12 and 22% and anchorage strengths with wood moisture variations of 12 and 22%, for a glue line thickness equal to 1.58 mm.

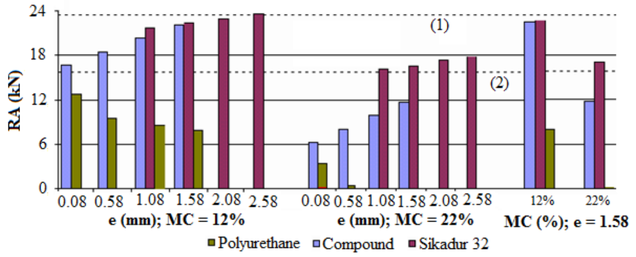

Figure 6. Comparative anchorage strength values for tree structural resins varying the glue line thickness and moisture content in *Pinus oocarpa* Shiede: (1) Theoretical values; (2) Bar yeld limit

Figure 7 shows, comparatively, the effect of the apparent density difference between *Corymbia citriodora* and *Pinus oocarpa* Shiede, also considering the effects of moisture content variation and epoxy resin type effects on anchorage strength, for glue line thickness equal to 1.58 mm.

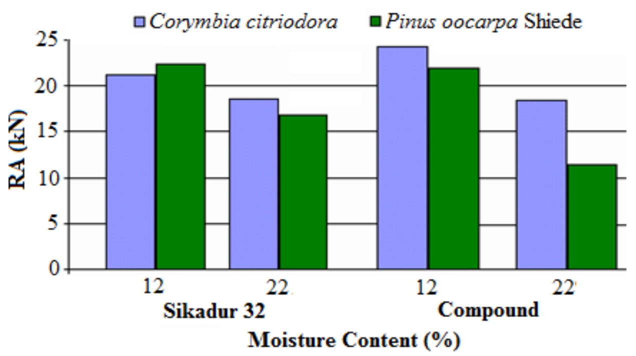

Figure 7. Comparative anchorage strength values for two epoxy resins in *Corymbia citriodora* and *Pinus oocarpa* Shiede

It is observed that the density variation among the wood species was not very significant. The results should be evaluated by considering the type of epoxy resin used and the differences in moisture.

For the dry-to-air woods, Sikadur-32 resin showed higher strength, about 5% in *Pinus oocarpa* Shiede compared to *Corymbia citriodora*. At 22% of moisture content, the anchorage strength in *Pinus oocarpa* Shiede was lower by 10%, compared to *Corymbia citriodora*. For Compound resin, the strength of anchorages in *Corymbia citriodora* were 11% higher, with moisture content of 12%, and 40% higher, with moisture content of 22%, compared to *Pinus oocarpa* Shiede.

4. Conclusions

The results of this study permit us to conclude:

- All anchorage rupture models to the polyurethane were instantaneous, characterizing brittle breaks with resin shear. Thickness of the glue line 0.08 mm stands out because it has higher anchorage strengths compared to other thicknesses. The polyurethane resin of castor oil studied is not suitable for the proposed purposes, considering that the reaction with the moisture contained in the wood incorporates CO_2 bubbles and, consequently, decreases its shear strength in the resin;
- Epoxy resins exhibited: glassy consistency after hardening and anchorage rupture occurs initially due to loss of adhesion on the steel surface and subsequent loss of mechanical adhesion, with the anchorage strength becoming progressively smaller as the bar is removed;
- Sikadur-32 resin presented better anchorage results at high moisture contents, although the resin was more difficult to use;
- The use of liquid epoxy resin requires replacement in the holes after initial hardening due to absorption or cracking in the wood;
- Variations of the anchorage strength with epoxy resins, relative to the independent variables, are as follows: linear negative variations with increasing moisture content and positive linear variations with increasing glue line thickness;
- The difference in apparent density between *Corymbia citriodora* and *Pinus oocarpa* Shiede did little to influence the anchorage strength;
- Behavior of all epoxy resins should be evaluated in different moisture content levels for each type of wood, considering the anchorage strength, the rupture model, the time available to use the mixture of the components and the difficulties of application of the product.

ACKNOWLEDGMENTS

For all the provided support, the authors thanks the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

REFERENCES

[1] Madsen, B. Timber connections with strength and reliability of steel. International Wood Conference, Toronto, Canada, p. 4-504, 4-511, 1996.

[2] Molina, J. C. Análise do comportamento dinâmico da ligação formada por barras de aço coladas para tabuleiros mistos de madeira e concreto para pontes. São Carlos, 2008. Tese (Doutorado em Engenharia de Estruturas) – Escola de Engenharia, Universidade de São Paulo, São Carlos, 2008.

[3] Aicher, S.; Gustafsson, P.; Wolf, M. Load displacement and bond strength of glued-in rods in timber influenced by adhesive, wood density, rod slenderness and diameter. 1st International RILEM Symposium on Timber Engineering,

Stockholm, Sweden, Sep. 13–14, p. 369–381, 1999.

[4] Bainbridge, R. J.; Mettem, C. J. Bonded in rods for timber structure: a versatile method for achieving structural connections. The Structural Engineering, v. 77, n. 15, p. 24-27, 1999.

[5] European Committee for Standartization. EUROCODE 5: Desing of timber structures, Part 1-1: General rules and rules for buildings, ENV 1995-1-1, European Committee for Standardization, Brussel, Belgium, Dec, p. 110, 1993.

[6] Riberholt, H. Glued bolts in glulam: proposal for CIB Code, Proc, Of the CIB – W18 Meeting, Timber Structure Meeting Twenty one, Parkville, Vancouver Island, Canada, p. 21-72, 1988.

[7] European Committee for Standardization. EUROCODE 5: Design of timber structures, Part 2, Bridges. UK, London, 45 p, 1993.

[8] Buchanan, A.; Moss, P. Design of epoxied steel rods in glulam timber. Pacific Timber Engineering Conference, Rotorua, New Zealand, March, p. 286–293, 1999.

[9] Bengtsson, C.; Kemmsies, M.; Johansson, C. J. Production control methods for glued-in rods for timber structures. 6th World Conference on Timber Structure, Vancouver, Canada, Jul 31-Aug 3, p. 7,4,1, 2000.

[10] Barchelar, M. L.; Mcintosh, K. A. Structural joint in glulam. 5th World Conference Timber Engineering, Montreux, Switzerland, v. 1, p. 289-296, 1998.