Engenharia Agrícola

ISSN: 1809-4430 (on-line)

www.engenhariaagricola.org.br

Doi: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v40n2p232-237/2020

TECHNICAL PAPER

ESTIMATION OF WOOD TOUGHNESS IN BRAZILIAN TROPICAL TREE SPECIES

André L. Christoforo[1*], Diego H. de Almeida[2], Luciano D. Varanda[3], Tulio H. Panzera[4], Francisco A. R. Lahr[5]

[1*] Corresponding author. Universidade Federal de São Carlos (UFSCar)/ São Carlos - SP, Brasil.
E-mail: christoforoal@yahoo.com.br | ORCID: https://orcid.org/0000-0002-4066-080X

KEYWORDS

Apparent density, tropical wood species, modulus of elasticity, compression parallel to grain strength, toughness.

ABSTRACT

Wood has been used for several purposes such as in civil and rural construction. Knowing wood mechanical behavior under short-term loading is essential for safer structural designs. However, wood toughness is a mechanical property little investigated for this purpose. Thus, this study aimed to evaluate, using exponential and polynomial regression models (linear, quadratic, and cubic), the possibility of estimating toughness as a function of apparent density, compression parallel to grain strength, and modulus of rupture in static bending. Thirty-six Brazilian tropical wood species from south of Roraima, Mato Grosso do Sul, and north and northeast of Mato Grosso were tested. Our results showed the significance and representativeness of all investigated fits, among which a cubic polynomial function is the most indicated for wood toughness estimates.

INTRODUCTION

Wood has been widely used by man throughout history. It has been directly related to problem solving such as housing, crossing of natural and/or artificial barriers, production of multiple-purpose vehicles, storage and transport of agricultural goods, manufacturing of furniture, utensils and sporting artifacts, among others uses (Toong et al., 2014; Araújo et al., 2016; Cademartori et al., 2016; Calil Neto et al., 2017).

Knowledge of wood physical and mechanical properties allows its better use (Fiorelli & Dias, 2011; Carreira et al. 2012; Molina et al., 2012. Because of the difficulty of characterizing wood species, they are often used without basic understanding of their properties, what leads to material waste (Andrade Jr. et al., 2014; Chen & Guo, 2017).

Special attention has been paid to the performance of wood species used in impacting practices, mainly in applications such as the above mentioned, thus motivating research in the area. For instance, there are the studies of Beltrame et al. (2010), Beltrame et al. (2012), Stolf et al. (2014), and Stolf et al. (2015), which investigated the influence of factors such as wood moisture content and growth ring orientation on total absorbed energy or toughness (W), impact resistance, resilience coefficient, and dynamic dimension. However, these studies did not estimate toughness as a function of other properties of wood characterization (Almeida et al., 2014).

To increase knowledge about wood behavior under impact load, this study aimed to evaluate the possibility of predicting wood toughness as a function of apparent density (12% moisture) and also flexural and compressive strength parallel to grain using regression models.

MATERIAL AND METHODS

Apparent density (ρ), compression parallel to grain strength ($f_{c,0}$), modulus of rupture in static bending (f_m), and toughness (W) (using Charpy pendulum) were obtained according to the ABNT NBR 7190 (1997) standards.

Tests were carried out in the Laboratory of Wood and Timber Structures (LaMEM), São Carlos Engineering School/ University of São Paulo (EESC/USP). Twelve specimens were used for each Brazilian tropical wood species (Table 1) and each studied property.

---

[2] Fundação Universidade Federal de Rondônia (UNIR)/ Porto Velho - RO, Brasil.
[3] Instituto SENAI de Inovação Biomassa / Três Lagoas - MS, Brasil.
[4] Universidade Federal de São João del-Rei (UFSJ)/ São João del-Rei - MG, Brasil.
[5] Escola de Engenharia de São Carlos (EESC) da Universidade de São Paulo (USP)/ São Carlos - SP, Brasil.

Area Editor: Edilson Costa
Received in: 10-11-2017
Accepted in: 12-10-2019

TABLE 1. Brazilian tropical wood species and provenances.

Popular name	Scientific name	Region of provenance
Angelim Amoroso	*Vatairea fusca*	South of Roraima
Angelim Araroba	*Vataireopsis araroba*	South of Roraima
Angelim Ferro	*Hymenolobium sp*	South of Roraima
Angelim Pedra	*Hymenolobium petraeum*	South of Roraima
Angelim Pedra Verdadeiro	*Dinizia excelsa*	South of Roraima
Angico Preto	*Piptadenia macrocarpa*	South of Roraima
Branquilho	*Terminalia sp*	Mato Grosso do Sul
Cafearana	*Andira sp*	South of Roraima
Cambará Rosa	*Erisma sp*	North of Mato Grosso
Casca Grossa	*Ocotea odorifera*	South of Roraima
Castelo	*Gossypiospermum praecox*	Northeast of Mato Grosso
Catanudo	*Calophyllum sp*	Northeast of Mato Grosso
Cedro Amargo	*Cedrela odorata*	South of Roraima
Cedro Doce	*Cedrela sp*	South of Roraima
Cedrona	*Cedrelinga catenaeformis*	South of Roraima
Copaíba	*Copaifera sp*	South of Roraima
Cupiúba	*Goupia glabra*	South of Roraima
Cutiúba	*Qualea paraensis*	South of Roraima
Garapa	*Apuleia leiocarpa*	North of Mato Grosso
Guaiçara	*Luetzelbburgia sp*	North of Mato Grosso
Guarucaia	*Peltophorum vogelianum*	North of Mato Grosso
Ipê	*Tabebuia serratifolia*	South of Roraima
Itaúba	*Mezilaurus itauba*	North of Mato Grosso
Jatobá	*Hymenea sp*	South of Roraima
Louro Preto	*Ocotea sp*	South of Roraima
Maçaranduba	*Manilkara sp*	South of Roraima
Mandioqueira	*Qualea sp*	South of Roraima
Oitica Amarela	*Clarisia racemosa*	North of Mato Grosso
Oiuchu	*Rapanea sp*	Northeast of Mato Grosso
Paul-óleo	*Copaifera sp*	Northeast of Mato Grosso
Piolho	*Tapirira guianesis*	South of Pará
Quarubarana	*Erisma uncinatum*	South of Roraima
Rabo de Arraia	*Vochysia sp*	South of Roraima
Sucupira	*Diplotropis sp*	South of Roraima
Tatajuba	*Bagassa guianensis*	South of Roraima
Umirana	*Qualea retusa*	South of Roraima

The regression models for estimating wood toughness as a function of apparent density (ρ), compression parallel to grain strength ($f_{c,0}$), and modulus of rupture in static bending (f_m) were as follows: exponential, linear, polynomial, quadratic, and cubic. Fits were based on average values for each wood property.

Table 1 shows the 36 wood species used for estimation of toughness as a function of apparent density. Guaiçara and Tatajuba were not used in regressions involving compression parallel to grain strength. Angelim Pedra Verdadeiro, Guaiçara, and Piolho were not considered in regressions involving modulus of rupture in static bending due to high coefficients of variation (above 46%).

Model significance was assessed by analysis of variance (ANOVA) at 5% significance. Null hypothesis (H_0) was accepted when the model was not significant, while an alternative hypothesis (H_1) was accepted when the model was significant. Values of p below the level of significance implies rejecting H_0.

RESULTS AND DISCUSSION

Table 2 shows the averages of toughness, apparent density, compression parallel to grain strength, and modulus of rupture in static bending for all studied Brazilian tropical wood species. The CV_{min} and CV_{max} are minimum and maximum values of coefficient of variation per property, respectively. Figures 1, 2, and 3 show the regression models for wood toughness estimation as a function of apparent density (ρ), compression parallel to grain strength ($f_{c,0}$), and modulus of rupture in static bending (f_m), respectively.

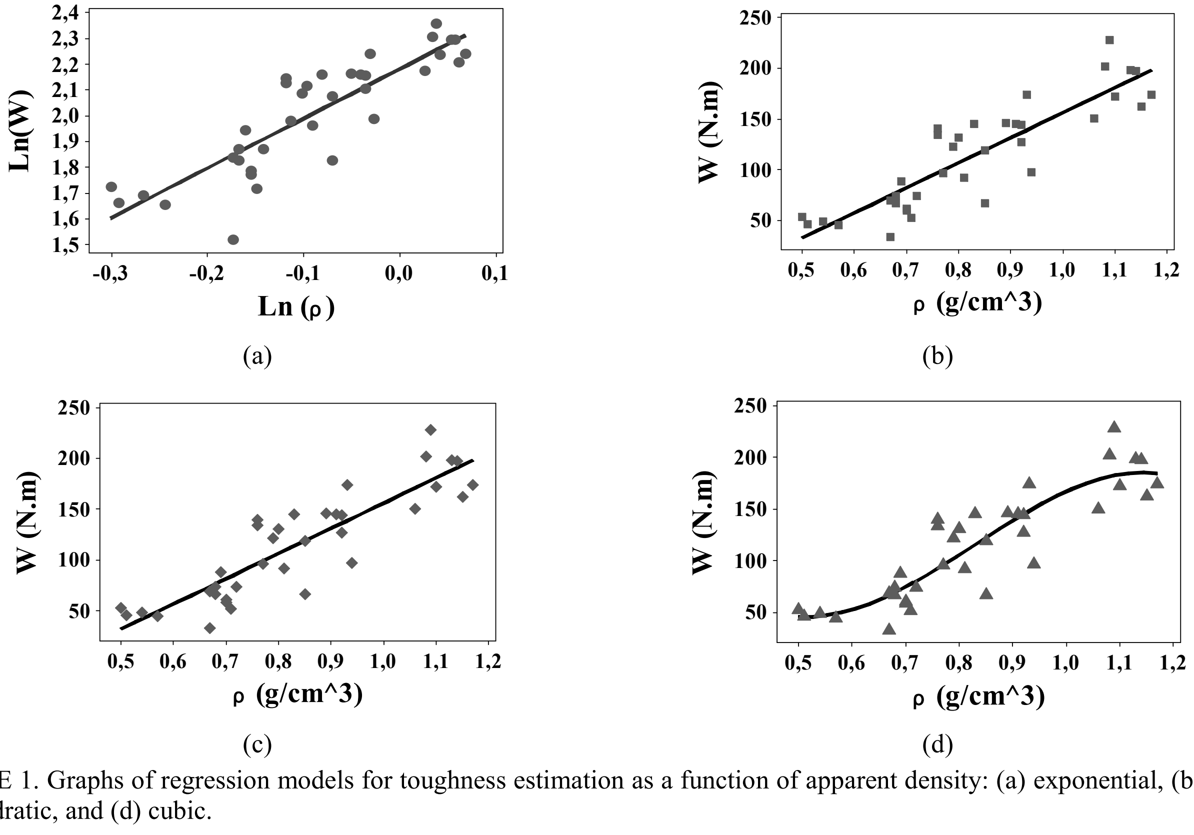
TABLE 2. Averages of wood properties for each Brazilian tropical species.

Wood Species	**W (N·m)**	**ρ (g/cm^3)**	**$f_{c,0}$ (10^5 N/m^2)**	**f_m (10^5 N/m^2)**
Angelim Amoroso	96	0.77	599	892
Angelim Araroba	69	0.67	508	754
Angelim Ferro	174	1.17	795	1320
Angelim Pedra	88	0.69	592	922
Angelim Pedra Verdadeiro	198	1.13	775	-
Angico Preto	146	0.89	725	1203
Branquilho	92	0.81	485	829
Cafearana	74	0.68	575	937
Cambará Rosa	33	0.67	345	632
Casca Grossa	122	0.79	585	1067
Castelo	140	0.76	548	1030
Catanudo	131	0.80	506	831
Cedro Amargo	46	0.51	391	669
Cedro Doce	53	0.50	315	566
Cedrona	45	0.57	413	605
Copaíba	59	0.70	502	799
Cupiúba	67	0.85	537	786
Cutiúba	162	1.15	790	1269
Garapa	144	0.92	734	1189
Guaiçara	228	1.09	-	-
Guarucaia	127	0.92	624	956
Ipê	150	1.06	762	1226
Itaúba	145	0.91	690	1166
Jatobá	202	1.08	935	1613
Louro Preto	67	0.68	569	927
Maçaranduba	197	1.14	829	1363
Mandioqueira	119	0.85	708	1131
Oitica Amarela	134	0.76	699	1075
Oiuchu	174	0.93	774	1225
Paul-óleo	61	0.70	524	800
Piolho	145	0.83	619	-
Quarubarana	49	0.54	378	674
Rabo de Arraia	74	0.72	575	793
Sucupira	172	1.10	937	1465
Tatajuba	97	0.94	-	1106
Umirana	52	0.71	533	656
CV_{min} (%)	12	4	9	7
CV_{max} (%)	28	17	21	23

Table 3 presents the regression models for estimation of toughness for a set of tropical wood species and the adjusted coefficient of determination (R²Adj.). A cubic regression model showed better determination coefficients (above 77.77%) to estimate toughness as a function of apparent density (ρ), compression parallel to grain strength (fc, 0), and modulus of rupture in static bending (fm). Toughness as a function of modulus of rupture in static bending had the highest R²Adj., above 85%.

TABLE 3. Regression models for wood toughness estimation.

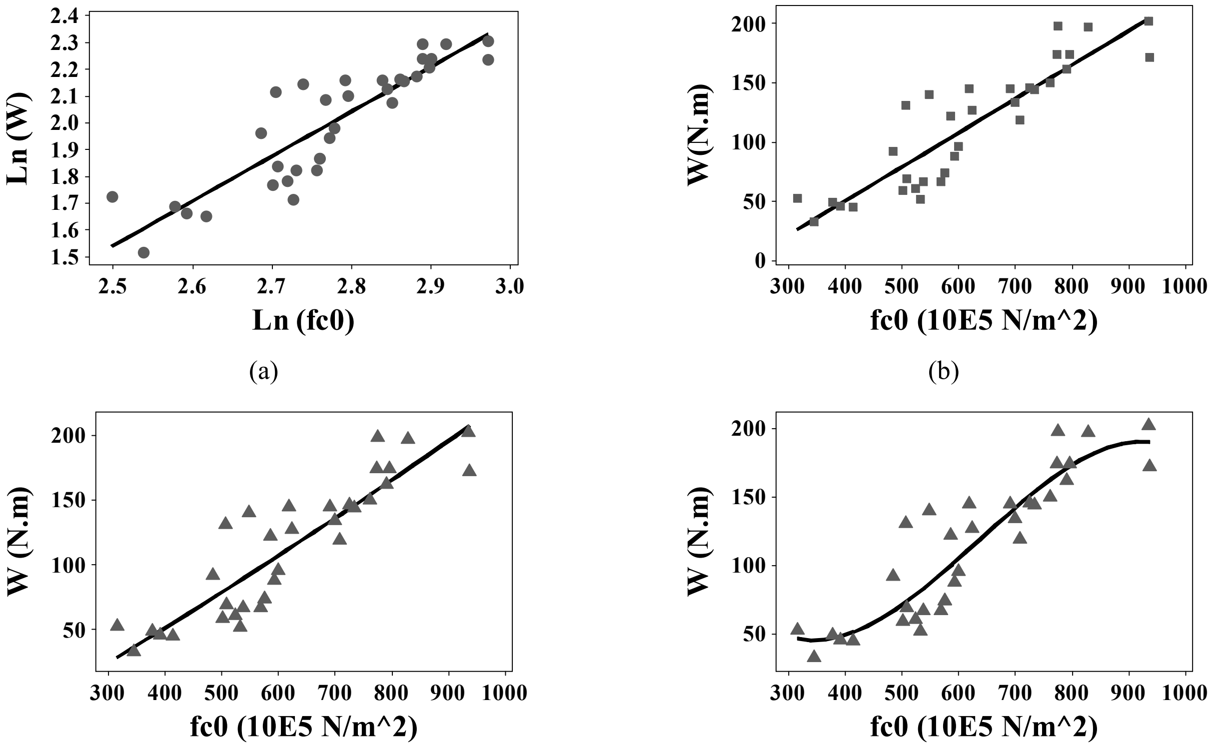
Regression Model	Equation	R^2Adj. (%)	F_{sig} (ANOVA)	P-value (ANOVA)
Toughness as a function of apparent density				
Exponential	$W = 152.06\cdot\rho^{1.93}$	74.70	104.54	0.000
Linear	$W = -91.23 + 247.3\cdot\rho$	77.20	119.64	0.000
Quadratic	$W = -90.62 + 245.8\cdot\rho + 0.9\cdot\rho^2$	76.50	58.06	0.000
Cubic	$W = 489.01 - 2018\cdot\rho + 2835\cdot\rho^2 -$ $-1139\cdot\rho^3$	77.77	41.62	0.000
Toughness as a function of compression parallel to grain strength				
Exponential	$W = 0.072\cdot f_{c,0}^{\;1.67}$	77.90	117.32	0.000
Linear	$W = -64.26 + 0.2870\cdot f_{c,0}$	79.91	125.52	0.000
Quadratic	$W = -51.58 + 0.2437\cdot f_{c,0} +$ $+0.000035\cdot f_{c,0}^{\;2}$	78.40	60.95	0.000
Cubic	$W = -258.5 - 1.413\cdot f_{c,0} +$ $+0.002818\cdot f_{c,0}^{\;2} - 0.000001\cdot f_{c,0}^{\;3}$	80.30	45.88	0.000
Toughness as a function of modulus of rupture in static bending				
Exponential	$W = 0.046\cdot f_m^{\;1.70}$	85.50	190.39	0.000
Linear	$W = -61.65 + 0.1723\cdot f_m$	86.80	212.93	0.000
Quadratic	$W = -81.84 + 0.2142\cdot f_m -$ $-0.000020\cdot f_m^{\;2}$	86.60	103.99	0.000
Cubic	$W = 93.9 - 0.3283\cdot f_m +$ $+0.000509\cdot f_m^{\;2} - 0.000007\cdot f_m^{\;3}$	86.80	70.94	0.000



(a) (b)

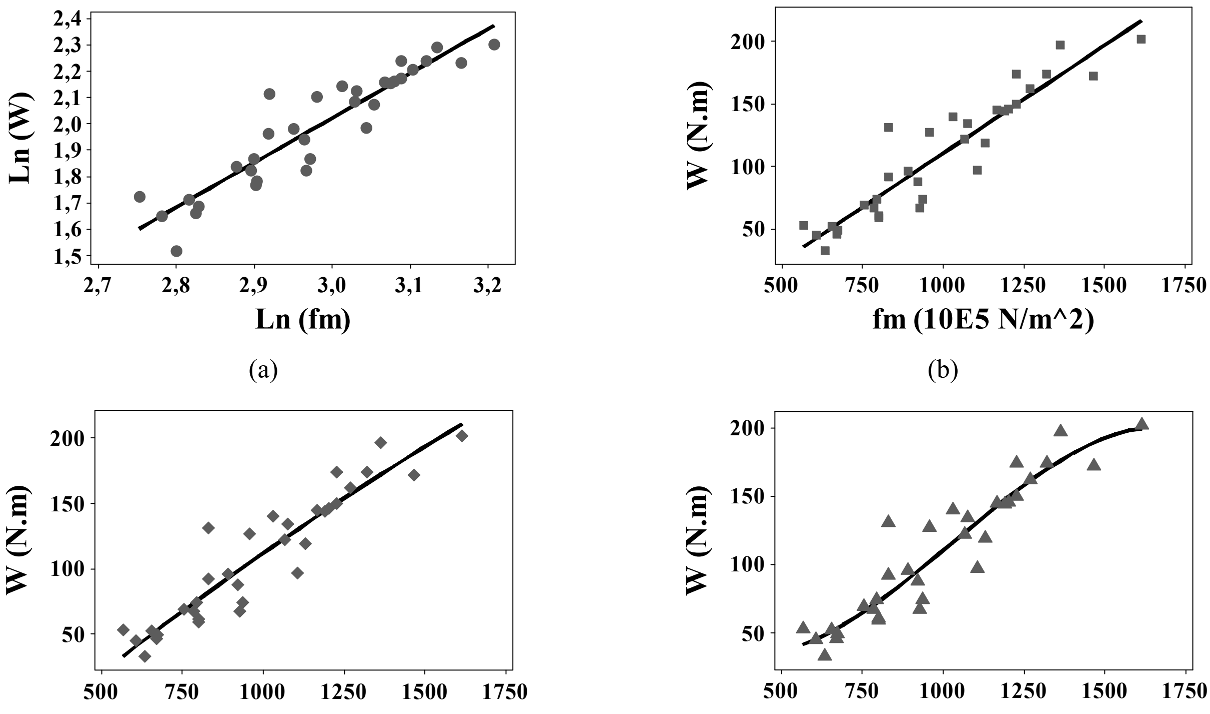
(c) (d)

FIGURE 1. Graphs of regression models for toughness estimation as a function of apparent density: (a) exponential, (b) linear, (c) quadratic, and (d) cubic.



(a) (b) (c) (d)

FIGURE 2. Graphs of regression models for toughness estimation as a function of compression parallel to grain strength: (a) exponential, (b) linear, (c) quadratic, and (d) cubic.



(a) (b) (c) (d)

FIGURE 3. Graphs of regression models for toughness estimation as a function of modulus of rupture in static bending: (a) exponential, (b) linear, (c) quadratic, and (d) cubic.

ANOVA p-values of regression models were lower than the 5% significance level, that is, all fits were significant.

The adjusted coefficients of determination (R^2Adj.) for all approaches were higher than 70%, i.e., all fits were significant (Montgomery, 2005). The highest p-values (ANOVA) derived from proxies using linear polynomials, followed by exponentials. Conversely, the highest R^2Adj. values, together with lower coefficients of variation (22% and 28%), derived from three-degree polynomials, showing a better toughness estimate by using cubic polynomial functions.

Almeida et al. (2014) used apparent density to estimate wood toughness of six wood species (Teca, Paricá, Pinus, Eucalipto, Jatobá and Angico) and obtained good regression models (R^2 > 70%). These authors concluded that toughness can be explained by wood apparent density, as shown in our findings.

Adamopoulos & Passialis (2010) carried out a linear regression model to estimate toughness as a function of modulus of elasticity of *Picea abies* L. Karsten at different fiber orientations (radial and tangential). They observed coefficients of regression ranging from 54.6% to 92.3%, showing a correlation between such properties.

CONCLUSIONS

From all of the foregoing we may conclude:

- Regression models for estimation of wood toughness showed to be significant in all cases, that is, wood toughness can be estimated as a function of apparent density, compression parallel to grain, and modulus of rupture in static bending, as all these properties had R^2Adj. above 70%;
- Regression model statistical results showed that a cubic polynomial model provided the best fit for the three investigated approaches; therefore, toughness can be estimated by apparent density, compression parallel to grain, or modulus of rupture in static bending. These results help estimate this property that is little explored in research on wood characterization but of great importance in structural projects, wherein woods are subjected to impacting actions.

ACKNOWLEDGEMENTS

The authors would like to thank the Brazilian Research Agency CNPq and the Wood and Woody Structures Laboratory (LaMEM – EESC/USP) for financial and technical support.

REFERENCES

ABNT - Associação Brasileira de Normas Técnicas. ABNT NBR 7190 (1997) Projeto de estruturas de madeira. ABNT.

Adamopoulos S, Passialis C (2010) Relationship of toughness and modulus of elasticity in static bending of small clear spruce wood specimens. European Journal of Wood and Wood Products 68(1):109-111.

Almeida DH, Scaliante RM, Christoforo AL, Varanda LD, Lahr FAR, Dias AA, Calil Jr C (2014) Tenacidade da madeira como função da densidade aparente. Revista Árvore 38(1):203-207.

Andrade Jr JR, Almeida DH, Almeida TH, Christoforo AL, Stamato GC, Lahr FAR (2014) Avaliação das estruturas de cobertura em madeira de um galpão de estoque de produtos químicos. Ambiente Construído 14(3):75-85.

Araújo VA, Cortez-Barbosa J, Gava M, Garcia JN, Souza AJD, Savi AF, Lahr FAR (2016) Classification of wooden housing building systems. BioResources 11(3):7889-7901.

Beltrame R, Gatto DA, Modes KS, Stangerlin DM, Trevisan R, Haselein CR (2010) Resistência ao impacto da madeira de Açoita-Cavalo em diferentes condições de umidade. Cerne 16(4):499-504.

Beltrame R, Mattos BD, Gatto DA, Lazarotto M, Haselein CR, Santini EJ (2012) Resistência ao impacto da madeira de nogueira-pecã em diferentes condições de umidade. Ciência Rural 42(9):1583-1587.

Cademartori PHG, Nisgoski S, Magalhães WLE, Muniz GIB (2016) Surface wettability of Brazilian tropical wood flooring treated with He plasma. Maderas. Ciencia y Tecnología 18(4):715-722.

Calil Neto C, Molina JC, Calil Jr C, Lahr FAR (2017) Modelagem numérica do comportamento de ligações com parafusos auto-atarraxantes em X em corpos de prova de MLC com madeiras do tipo Eucalipto urograndis. Revista Matéria 22(1):e11789.

Chen Y, Guo W (2017) Nondestructive evaluation and reliability analysis for determining the mechanical properties of old wood of ancient timber structure. BioResources 12(2):2310-2325.

Carreira MR, Segundinho PGA, Lahr FAR, Dias AA, Calil Jr C (2012) Bending stiffness evaluation of Teca and Guajará lumber through tests of transverse and longitudinal vibration. Acta Scientiarum. Technology 34(1):27-32.

Fiorelli J, Dias AA (2011) Glulam beams reinforced with FRP externally-bonded: theoretical and experimental evaluation. Materials and Structures 44(8):1431-1440.

Molina JC, Calil Jr C, Kimura EFA, Pinto EM, Regobello R (2012) Análise numérica do comportamento de elementos de madeira em situações de incêndio. Floresta e Ambiente 19(2):162-170.

Montgomery DC (2005) Design and analysis of experiments. John Wiley & Sons Inc., Arizona, 6th edition.

Stolf DO, Bertolini MS, Almeida DH, Silva DAL, Panzera TH, Christoforo AL, Lahr FAR (2015) Influence of growth ring orientation of some wood species to obtain toughness. Revista Escola de Minas 68(3):265-271.

Stolf DO, Bertolini MS, Ferro FS, Christoforo AL, Lahr FAR (2014) Influência do teor de umidade na propriedade de tenacidade de espécies florestais. Floresta e Ambiente 21(4):501-508.

Toong W, Ratnasingam J, Roslan MKM, Halis R (2014) The prediction of wood properties from anatomical characteristics: the case of common commercial Malaysian timbers. BioResources 9(3):5184-5197.