Estimative of Wooden Toughness by the Apparent Density and Bending Strength

André Luis Christoforo^{1,*}, Sérgio Augusto Mello da Silva², Tulio Hallak Panzera³,
Francisco Antonio Rocco Lahr⁴

¹Department of Civil Engineering, Federal University of São Carlos, São Carlos - SP, 13565-905, Brazil

²Department of Civil Engineering, Paulista State University (UNESP), Ilha Solteira - SP, 15.385-000, Brazil

³Department of Mechanical Engineering, Federal University of São João del-Rei, São João del-Rei - MG, 36307-352, Brazil

⁴Department of Structural Engineering, University of São Paulo (EESC/USP), São Carlos - SP, 13565-905, Brazil

Abstract The wooden toughness is a mechanical property of interest in the project in the case of the design of structures and structural elements subjected to impact loads, however, not an integral part of the mechanical properties commonly investigated, such as the modulus of elasticity and strength modulus in tensile, in bending and others. In order to corroborate with the most knowledge about the toughness of wood, this study aimed to investigate the possibility of estimating the toughness by the apparent density and strength in bending, using linear, quadratic and cubic regression models. Were used 15 species of wood, equally distributed in the five strength classes defined by the Brazilian standard ABNT NBR 7190:1997, enabling greater coverage of the results to estimate the toughness of wood for various species. The results of the regression models showed to be representative all the functions evaluated, presenting the quadratic fits in function of the apparent density the best results.

Keywords Toughness, Wood, Regression models, Apparent density, Bending strength

1. Introduction

The stress caused by the impact loads acts only in a very short time interval, for example, a few microseconds [1]. A structural element of wood is considered tough one that supports large deformation under bending or twisting before fracture [2].

Usually has restricted the use of the toughness term to a particular mechanical property, to qualify the wood under the action of an impact load causing failure. A material that offers improved strength to failure than others will have a greater toughness value, according to Van Vlack [3]. For wood, shows high values of toughness in comparison with other materials. This makes it particularly useful for applications where the material is subjected to impact loads, according to Schneider et al. [4].

Toughness has been used to describe characteristics of the wood and its derivatives, being related to other properties such as shear strength and tensile strength in perpendicular to the grain. However, the toughness should not be considered separately to characterize a species, requiring the evaluation of the results of other tests [3].

In addition, changes in the values of toughness are good indicators of damage or abnormalities in structural lumber. The relationship between toughness and anatomical characteristics of the wood have been the subject of detailed examination, as records Van Vlack [3].

In general, the greater knowledge of the physical and mechanical properties of wood allows their best achievement [5-7]. Because of difficulties in performing tests for the characterization of the species, the wood is often used without the basic knowledge of their properties, thus leading to wastage of materials [8].

Special importance is on the study of wood in relation to its performance when applied to loads that cause impact [9], motivating the development of research on this topic.

Pazos et al. [10] investigated the toughness and impact strength of *Lysiloma bahamensis* wood, density 0.62 g/cm³, under dry air (12%), saturated. The values of toughness or work absorbed (W) obtained from saturated and dry woods were equal to 41.75J and 46.75J, respectively. Among others, the authors concluded that the saturated wood showed the highest toughness and impact strength.

Stangerlin et al. [11] conducting research on wood of *Eucalyptus dunnii* in order to investigate the effect of positioning the fiber (radial and tangential) for obtaining the toughness and impact strength. The authors concluded that the positioning in the radial direction provided higher values of impact strength and toughness when compared with the

* Corresponding author:

alchristoforo@yahoo.com.br (André Luis Christoforo)

Published online at <http://journal.sapub.org/ijme>

Copyright © 2014 Scientific & Academic Publishing. All Rights Reserved

specimens positioned in the tangential direction.

Stangerlin *et al.* [12] studied the impact strength of *Eucalyptus saligna* and *Eucalyptus botrioides* wood species, concluding, among other, not possible to estimate the toughness of the wood through the bulk density.

Beltrame *et al.* [13] evaluated, using the pendulum Charpy impact strength, coefficient of resilience and dynamic dimension wood-horse whips (*Luehea divaricata* Mart. Mart *et Zucc.*) Tested under equilibrium conditions at 12% moisture content (0.628g/cm^3) and saturated in water (1.076g/cm^3), using trees from two physiographic regions of the state of Rio Grande do Sul, were investigated also in this study the influence of the position (bone and shell) and direction (tangential and radial) of the specimen in the tests for obtaining those mechanical properties. The results showed that the wood-horse whips evaluated in saturated condition showed higher impact strength and toughness (37.03J), absorbing much of the applied load on it when compared to the strength and toughness at 12% of moisture content (28.87J), and with respect to the position and direction of the orientation of the specimens in obtaining the toughness, the results of statistical analysis showed equivalence, implying not significant effect of these two factors on the toughness of wood-horse whips.

Beltrame *et al.* [14] investigated the influence of moisture content (12% and saturated) and the impact strength of Walnut pecan (*Carya illinoensis*), from two physiographic regions of the state of Rio Grande do Sul (Brazil). Specimens were also prepared and tested for impact strength directions, radial and tangential positions and withdrawal, near the spinal cord and the next shell. As for the energy absorbed or toughness, saturated parts showed higher (7.774 kg m) compared the toughness of woods with 12% of moisture content (2.976 kg m), about 161% higher on average.

In order to generate subsidies to expand the knowledge about the behavior of wood when requested by impact loads, this study aimed to investigate, using polynomial regression models, the possibility of estimating the toughness as a function of density and bending strength, making use of fifteen species of wood chosen and equally distributed in five classes of strength (C-20, C-30 to C-60) presented by the Brazilian standard ABNT NBR 7190 [15].

2. Material and Methods

Table 1 shows the species of wood used in this research, being duly grouped in strength classes of Brazilian standard ABNT NBR 7190 [15].

The toughness tests (W) were performed according to the procedures and assumptions for the calculation of ASTM D5536-94 [16], using the Charpy pendulum, and the apparent density ($\rho_{12\%}$) and the bending strength (f_m) followed the recommendations of the Brazilian standard ABNT NBR 7190 [15]. We used 12 specimens per species of wood required for each type of test.

Table 1. Wood species investigated

Strength Classes	Vulgar Name	Scientific Name
C-20	Cedro Doce	<i>Cedrela sp</i>
	Cedrona	<i>Cedrelinga catenaeformis</i>
	Quarubarana	<i>Erisma uncinatum</i>
C-30	Canafistula	<i>Peltophorum dubium</i>
	Cedro Amargo	<i>Cedrela odorata</i>
	Cupiúba	<i>Goupia glabra</i>
C-40	Branquilha	<i>Terminalia sp</i>
	Cafearana	<i>Andira sp</i>
	Louro Preto	<i>Ocotea sp</i>
C-50	Castelo	<i>Gossypiospermum praecox</i>
	Angico Preto	<i>Piptadenia macrocarpa</i>
	Catanudo	<i>Calophyllum sp</i>
C-60	Garapa	<i>Apuleia leiocarpa</i>
	Champanhe	<i>Dipteryx odorata</i>
	Sucupira	<i>Diplotropis sp</i>

In order to relate the toughness with apparent density (W ; $\rho_{12\%}$) and toughness with strength in bending (W ; f_m), were tested polynomial regression models of linear, quadratic and cubic approximations. Therefore, the regression models evaluated through analysis of variance (ANOVA) were considered at a significance level of 5%, with the null hypothesis of no significance setting provided by the model ($\beta_i=0$) and the significance ($\beta_i\neq 0$) adjustment obtained as alternative hypothesis. P-value less than the level of significance set implies rejecting H_0 (Fdados > Fcrítico), accepting it otherwise.

3. Results

Table 2. Results of the properties from C-20 strength class

	Cedro Doce		
	$\rho_{12\%}$ (g/cm^3)	f_m (10^5 N/m^2)	W (J)
$\bar{X}$	0.50	567	51
C_v	12	19	23
$Min.$	0.38	470	32
$Máx.$	0.65	820	75
	Cedrona		
	$\rho_{12\%}$ (g/cm^3)	f_m (10^5 N/m^2)	W (J)
$\bar{X}$	0.57	572	46
C_v	7	15	17
$Min.$	0.50	410	34
$Máx.$	0.64	650	59
	Quarubarana		
	$\rho_{12\%}$ (g/cm^3)	f_m (10^5 N/m^2)	W (J)
$\bar{X}$	0.54	650	43
C_v	10	13	20
$Min.$	0.47	530	29
$Máx.$	0.67	790	56

Table 2 to 6 presents the results of physical and mechanical properties of wood evaluated, where $\bar{X}$ is the sample mean, C_v is the coefficient of variation and Min and Max the least and greatest values found.

Table 3. Results of the properties from C-30 strength class

Canafistula			
	$\rho_{12\%}$ (g/cm ³)	f_m (10 ⁵ N/m ²)	W (J)
$\bar{X}$	0.86	887	108
C_v	9	12	22
Min.	0.74	720	86
Máx.	0.95	1090	129
Cedro Amargo			
	$\rho_{12\%}$ (g/cm ³)	f_m (10 ⁵ N/m ²)	W (J)
$\bar{X}$	0.50	667	52.25
C_v	4	14	25
Min.	0.46	550	31
Máx.	0.53	870	73
Cupiúba			
	$\rho_{12\%}$ (g/cm ³)	f_m (10 ⁵ N/m ²)	W (J)
$\bar{X}$	0.85	900	75
C_v	4	16	17
Min.	0.77	710	57
Máx.	0.90	1140	96

Table 4. Results of the properties from C-40 strength class

Branquillo			
	$\rho_{12\%}$ (g/cm ³)	f_m (10 ⁵ N/m ²)	W (J)
$\bar{X}$	0.81	843	103
C_v	6	13	18
Min.	0.73	660	77
Máx.	0.89	1030	142
Cafearana			
	$\rho_{12\%}$ (g/cm ³)	f_m (10 ⁵ N/m ²)	W (J)
$\bar{X}$	0.67	910	86
C_v	8	19	18
Min.	0.61	720	65
Máx.	0.78	1270	119
Louro Preto			
	$\rho_{12\%}$ (g/cm ³)	f_m (10 ⁵ N/m ²)	W (J)
$\bar{X}$	0.68	1046	74
C_v	4	21	21
Min.	0.64	820	52
Máx.	0.74	1370	99

Table 5. Results of the properties from C-50 strength class

Castelo			
	$\rho_{12\%}$ (g/cm ³)	f_m (10 ⁵ N/m ²)	W (J)
$\bar{X}$	0.76	1030	144
C_v	9	6	19
Min.	0.60	892	115
Máx.	0.88	1119	199
Angico Preto			
	$\rho_{12\%}$ (g/cm ³)	f_m (10 ⁵ N/m ²)	W (J)
$\bar{X}$	0.89	1223	140
C_v	7	24	20
Min.	0.80	900	85
Máx.	1.03	1770	159
Catanudo			
	$\rho_{12\%}$ (g/cm ³)	f_m (10 ⁵ N/m ²)	W (J)
$\bar{X}$	0.80	885	126
C_v	5	12	19
Min.	0.74	690	83
Máx.	0.87	1040	165

Table 6. Results of the properties from C-60 strength class

Garapa			
	$\rho_{12\%}$ (g/cm ³)	f_m (10 ⁵ N/m ²)	W (J)
$\bar{X}$	0.92	1255	127
C_v	6	15	19
Min.	0.85	960	93
Máx.	1.03	1550	172
Champanhe			
	$\rho_{12\%}$ (g/cm ³)	f_m (10 ⁵ N/m ²)	W (J)
$\bar{X}$	1.09	1581	203
C_v	3	9	12
Min.	1.04	1320	167
Máx.	1.14	1820	243
Sucupira			
	$\rho_{12\%}$ (g/cm ³)	f_m (10 ⁵ N/m ²)	W (J)
$\bar{X}$	1.10	1465	168
C_v	6	15	14
Min.	0.99	930	136
Máx.	1.22	1660	214

Figures 1 and 2 illustrate the results of adjustments by the regression models for toughness as a function of density and bending strength, respectively.

Figure 1. Adjustments by polynomial regression models: (a) linear, (b) a quadratic and cubic (c) for toughness as a function of apparent density

Figure 2. Adjustments by polynomial regression models: (a) linear, (b) a quadratic and cubic (c) for toughness as a function of the strength in bending

Table 7. Adjustments obtained from regression models

$W \times \rho$		
Adjust	Equation	R ² (adj.)
1°	$W = -64,80 + 217,9 \cdot \rho_{12\%}$	63,30%
2°	$W = -5,76 + 57,91 \cdot \rho_{12\%} + 101,8 \cdot \rho_{12\%}^2$	67,80%
3°	$W = 70,90 - 255,8 \cdot \rho_{12\%} + 509,40 \cdot \rho_{12\%}^2 - 169,1 \cdot \rho_{12\%}^3$	67,60%
$W \times f_m$		
Adjust	Equação	R ² (adj.)
1°	$W = -11,04 + 0,1181 \cdot f_m$	58,50%
2°	$W = -39,08 + 0,1763 \cdot f_m - 0,000027 \cdot f_m^2$	58,70%
3°	$W = -68,80 + 0,2743 \cdot f_m - 0,000126 \cdot f_m^2 + 0,000003 \cdot f_m^3$	58,60%

Table 8. ANOVA results of the regression models for toughness as a function of apparent density

Linear Model					
Source	DF	SS	MS	F _{dados}	P-valor
Regression	1	318545	318545	369,37	0,000
Error	178	153507	862		
Total	179	472052			
Quadratic Model					
Source	DF	SS	MS	F _{dados}	P-valor
Regression	2	321565	160783	189,11	0,000
Error	177	150487	850		
Total	179	472052			
Cúbic Model					
Source	DF	SS	MS	F _{dados}	P-valor
Regression	3	321843	107281	125,70	0,000
Error	176	150209	853		
Total	179	472052			

Table 9. ANOVA results of the regression models for toughness as a function of bending strength

Linear Model					
Source	DF	SS	MS	F _{dados}	P-valor
Regression	1	277479	277479	253,84	0,000
Error	178	194573	1093		
Total	179	472052			
Quadratic Model					
Source	DF	SS	MS	F _{dados}	P-valor
Regression	2	279448	139724	128,40	0,000
Error	177	192602	1088		
Total	179	472052			
Cúbic Model					
Source	DF	SS	MS	F _{dados}	P-valor
Regression	3	279765	93255,1	85,36	0,000
Error	176	192287	1092,5		
Total	179	472052			

Table 7 shows the equations and the corresponding adjusted coefficient of determination (R² (adj.)), and Tables 8 and 9 the results of analysis of variance for toughness as a

function of apparent density and strength in bending, respectively; DF is the degrees of freedom, SS is the sum of squares and MS is the average of the square.

P-values obtained by ANOVA (Tables 8 and 9) are both higher than the level of significance set ($F_{\text{dados}} > F_{\text{critico}}$), all regression models should be accepted. Adjustments tested, the quadratic polynomial model proved to be the better for having the largest value of R² (adj.) for both adjustments (toughness as function of density and bending strength).

The R² (adj.) coefficients obtained by toughness as a function of apparent density was shown to be more accurate, indicating that the best estimate for the toughness of woods investigated.

4. Conclusions

The results of the regression models with the use of fifteen species of wood, conveniently chosen to cover the five classes of strength contemplated by the Brazilian standard ABNT NBR 7190:1997, indicate possible to estimate the toughness, revealing the quadratic polynomial model as function of the apparent density as the most suitable. Thus, the toughness of wood can be estimated with knowledge of the results of apparent density with the quadratic equation obtained by the least squares fit.

REFERENCES

- [1] Kollmann, F. F. P.; Cotê, W. A. Principles of wood science and technology: Solid wood. Springer, Verlag, 263p., 1968.
- [2] Askeland, D. R. The science and engineering of materials. 3ed., Bostons, PWS Publishing Company, 1994.
- [3] Van Vlack, L. H. Elements of materials science and engineering. 6ed., Addison, Wesley Publishing Company, 1989.
- [4] Schneider, M. H.; Phillips, J. G.; Brebner, K. I.; Tingley, D. A.

- Toughness of polymer impregnated sugar maple at two moisture contents. *Forest products Journal*, v. 39, n. 6, p. 11-14, 1989.
- [5] Fiorelli, J.; Dias, A. A. Glulam beams reinforced with FRP externally-bonded: theoretical and experimental evaluation. *Materials and Structures*, v. 44, p. 1431-1440, 2011.
- [6] Carreira, M. R.; Segundinho, P. G. A.; Rocco Lahr, F. A.; Dias, A. A.; Calil Jr., C. Bending stiffness evaluation of Teca and Guajará lumber through tests of transverse and longitudinal vibration. *Acta Scientiarum Technology (Impresso)*, v. 34, p. 27-32, 2012.
- [7] Christoforo, A. L.; Ribeiro Filho, S. L. M.; Panzera, T. H.; Rocco, F. A. L. Metodologia para o cálculo dos módulos de elasticidade longitudinal e transversal em vigas de madeira de dimensões estruturais. *Ciência Rural (UFMS. Impresso)*, v. 43, p. 610, 2013.
- [8] Stolf, D. O. Tenacidade da madeira. 2000, 1101 p. Dissertação (Mestrado em Interunidades em Ciência dos Materiais). Escola de Engenharia de São Carlos da Universidade de São Paulo. São Carlos - SP, 2000.
- [9] Souza, J. T.; Machado, W. G.; Beltrame, R.; Modes, K. S.; Vivian, M. A.; Haselein, C. R. Estudo do comportamento da flexão dinâmica em função da massa específica da madeira de *Araucaria angustifolia* (Bertol.) Kuntze. XVIII Congresso de Iniciação Científica (CIC), XI Encontro de Pós-Graduação (ENPOS) e a I Mostra Científica. Anais... CD ROM. Universidade Federal de Pelotas, Pelotas - RS, 5 p., 2009.
- [10] Pazos, G. B.; Morales, R. P. Z.; Candelaria, V. R. O. Correlación de los resultados de impacto o tenacidad de 16 maderas mexicanas utilizando dos métodos de prueba. *Revista Madera y Bosques*, v. 9, n. 1, p. 55-70, 2003.
- [11] Stangerlin, D. M.; Melo, R. R.; Domingues, J. M. X. Determinação da resistência ao impacto para as madeiras de *Eucalyptus dunnii*, *Corymbia citriodora* e *Pouteria pachycarpa*. In: XI Encontro Brasileiro em Madeira e Estruturas de Madeira. Londrina. Anais... CD ROM, Londrina, 2008.
- [12] Stangerlin, D. M.; Gatto, D. A.; Domingues, J. M. X.; Calegari, L.; Muller, M. T. Avaliação da resistência ao impacto para as madeiras de *Eucalyptus botrioides* e *Eucalyptus saligna*. In: X Congresso Florestal Estadual, Nova Prata, RS. Anais... CD ROM, 2008.
- [13] Beltrame, R.; Gatto, D. A.; Modes, K. S.; Stangerlin, D. M.; Trevisan, R.; Haselein, C. R. Resistência ao impacto da madeira de açoita-cavalo em diferentes condições de umidade. *Cerne (UFLA)*, v. 16, p. 499-504, 2010.
- [14] Beltrame, R.; Mattos, B. D.; Gatto, D. A.; Lazarotto, M.; Haselein, C. R.; Santini, E. J. Resistência ao impacto da madeira de nogueira-pecã em diferentes condições de umidade. *Ciência Rural*, v.42, n.9, 2012.
- [15] Associação Brasileira de Normas Técnicas ABNT NBR 7190. Projeto de estruturas de madeira. Rio de Janeiro, 1997.
- [16] American Society for Testing and Materials ASTM D5536-94. Standard methods of testing small clear specimens of timber. Philadelphia, 1995.