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TECHNICAL PAPER

ESTIMATION OF THE CHARACTERISTIC VALUE OF WOOD STRENGTH

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KEYWORDS

wood, compression, traction, shear, probability distribution, characteristic value.

ABSTRACT

For safety reasons, wood strength values, essential for structural dimensioning, are calculated based on the characteristic value, which corresponds to the 5% percentile of a given probability distribution model. For small samples, the Brazilian normative document ABNT NBR 7190 establishes an estimator of the characteristic wood strength, which can provide a significantly different result from the characteristic value coming from a suitable model of probability distribution. The main objective of this study was to evaluate the best probability distribution model (normal, lognormal, Weibull, and exponential) and the subsequent calculation of the characteristic value indicated by ABNT NBR 7190 (1997), allowing to evaluate its accuracy, being also investigated two relationships between characteristic values of the simplified characterization condition for woods of species already known. The best adhesion model was the normal model, which resulted in values statistically equivalent to the characteristic values according to ABNT NBR 7190 (1997). Among the evaluated relationships, the obtained results were significantly higher (up to 92%) when compared to those estimated by ABNT NBR 7190 (1997).

INTRODUCTION

Wood, a natural and renewable source material, has a good relationship between mechanical strength and density (Arruda et al., 2015; Baar et al., 2015; Cavalheiro et al., 2016), which makes it suitable for use in rural and civil constructions (Andrade Jr et al, 2014; Chen & Guo, 2017, Lahr et al., 2017).

Brazil presents an enormous potential for wood applications since the availability of species from the Amazon Forest is of the order of 11194, cataloged between 1707 and 2015 (Steege et al., 2016), which has motivated the development of new researches with the purpose of characterizing new species to substitute those commonly used in construction (Christoforo et al., 2017; Ferro et al., 2015, Freitas et al., 2016).

In Brazil, wooden structure projects are regulated by the Brazilian normative document ABNT NBR 7190 (1997) named Wooden Structure Project, and the structures must be dimensioned to move very little (geometrical linearity) and also to withstand satisfactorily and safely to the action of acting forces.

Due to the safety of the structure project, the strength values to the mechanical stresses of wood are obtained based on the characteristic value, which corresponds to the 5% percentile of the respective probability distribution.

According to the probabilistic method of ABNT NBR 7190 (1997), it is assumed normality in the distributions of strength values, and this hypothesis is based on the consideration of large samples (30 or more test specimens) together with a limit value of 18% of the coefficient of variation. Given the average strength value ($\overline{f}$) and its standard deviation (sd), the characteristic value (f_{wk}) of the property is determined using [eq. (1)].

$$f_{wk} = \overline{f} - 1.645 \cdot sd \quad (1)$$

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For a small number (n) of samples (n < 30), this normative document establishes the use of [eq. (2)] for estimating the characteristic strength value.

$$f_{wk} = \left(2 \cdot \frac{f_1 + f_2 + f_3 + ... + f_{(n/2)-1}}{(n/2)-1} - f_{n/2} \right) \cdot 1.10 \quad (2)$$

From [eq. (2)], n is the number of samples used in the mechanical tests and f_i consists of the strength values of the sample, and the results must be arranged in ascending order ($f_1 \leq f_2 \leq f_3 \ldots \leq f_n$), disregarding the highest strength value if the number of test specimens is odd and not assuming for f_{wk} a value lower than f_1 nor lower than 70% of the average strength value.

The adoption of [eq. (2)] to estimate the characteristic value can result in significantly different values (or not) from the characteristic value associated to a given probability density function, considering the diversity of probability density functions (Pinto et al., 2004), and once that of better adherence to the set of strength values is found, the characteristic value can be obtained with a greater reliability. If the characteristic value estimated by this equation is higher than that obtained by a given probability distribution model, this implies overestimating wood strength and underestimating it otherwise (unfavorable conditions to the project), which motivates the development of researches in this area.

It is not always possible to obtain all the physical and mechanical properties of wood to be used in a structure project because such variables are determined by means of tests involving equipment usually found in large technological and research centers (Icimoto et al., 2015).

In this sense, the Brazilian normative document ABNT NBR 7190 (1997) proposes a simplified wood characterization, in which characteristic strength values are estimated through relationships, as in eqs (3) and (4), which are based on results obtained from the compression test in the direction parallel to the fibers.

$$f_{c0,k} = 0.77 \cdot f_{t0,k} \quad (3)$$

$$f_{v0,k} = 0.12 \cdot f_{c0,k} \quad (4)$$

In addition, as considered in this normative document, researches have been developed with the purpose of proposing relationships among wood properties, such as the studies developed by Dias & Lahr (2004) and Almeida et al. (2016), in which the density was used as an estimator (via regression models) of physical and mechanical properties.

Considering the use of four probability distribution models (normal, lognormal, Weibull, and exponential) and five wood species, this study aimed to evaluate the best distribution models in obtaining the characteristic values of tensile ($f_{t0,k}$), compressive ($f_{c0,k}$), and shear ($f_{v0,k}$) strengths in the direction parallel to wood fibers, allowing verifying possible differences in characteristic values derived from the use of the expression adopted by the Brazilian normative document NBR 7190 (1997) (Equation 2). Besides the analysis of the characteristic value, the accuracy of eqs (3) and (4) proposed by this normative document was also evaluated.

MATERIAL AND METHODS

Strength properties (f_{t0}, f_{c0}, and f_{v0}) were obtained following the assumptions and the test and calculation methods of the normative document ABNT NBR 7190 (1997).

In order to obtain a greater comprehension of results, wood species were used (Table 1), being divided into strength classes of the hardwood group (ABNT NBR 7190, 1997) with a moisture content close to 12%, which consists of the equilibrium moisture content indicated by this normative document.

TABLE 1. Species of hardwood used.

Species		
Common name	**Abbreviation**	**Scientific name**
Cambará Rosa	CR	*Erisma uncinatum Warm, Vochysiaceae*
Cedro Amazonense	CA	*Cedrelinga catenaeformis*
Guarucaia	Ga	*Parapiptadenia rigida*
Cupiúba	Cup	*Goupia glabra Aubl., Goupiaceae*
Roxinho	Ro	*Peltogyne* spp.

The probability distributions considered in this research to determine the characteristic strength values consisted of normal, lognormal, Weibull, and exponential, whose probability density functions (f) on the random variable X are expressed in eqs (5), (6), (7), and (8), respectively.

$$f(x) = \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma^2}} \cdot e^{-\frac{1}{2} \cdot \left(\frac{x-\mu}{\sigma} \right)^2}, \quad x \in (-\infty, \infty) \quad (5)$$

$$f(x) = \begin{cases} \frac{1}{x \cdot \sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{1}{2} \cdot \frac{(\log(x)-\mu)^2}{\sigma^2}}, & \text{if } x>0 \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

$$f(x) = \begin{cases} \frac{\delta}{\alpha^\delta} \cdot x^{\delta-1} \cdot e^{-\left(\frac{x}{\alpha} \right)^\delta}, & x \geq 0 \\ 0, & \text{if } x<0 \end{cases} \quad (7)$$

$$f(x) = \begin{cases} \lambda \cdot e^{-\lambda \cdot x}, & \text{if } x \geq 0 \\ 0, & \text{if } x < 0 \end{cases} \quad (8)$$

In [eq. (5)], σ and μ consist of the standard deviation and the population mean, respectively. In [eq. (6)], σ is the standard deviation and μ is the population mean of the logarithm. In the Weibull probability density function (Equation 7), δ and α are the shape and scale parameters, respectively, and λ is the distribution rate parameter of the Exponential function (Equation 8).

The adhesion tests (at 95% confidence level) used to verify the best distribution model by property (f_{t0}, f_{c0}, and f_{v0}) were obtained by the least squares method using the software Minitab® version 16.

The characteristic strength values were obtained using the probability distribution models and the equation from ABNT NBR 7190 (1997) and the analysis of variance (ANOVA) was used to verify the influence of methodologies used to determine the characteristic values. ANOVA was considered at a 5% significance level. Considering the formulated hypotheses, a probability P (P-value) higher than or equal to the significance level implies in accepting that the means of the characteristic values (considering the five wood species together) by both methods are equivalent, and not equivalent otherwise (P-value < 0.05).

Estimates of the relationships between the characteristic strengths (Equations 3 and 4) were evaluated by the least squares method. The minimization of eqs (9) and (10) allows determining the coefficients α_i of the relationships $f_{c0,k} = \alpha_1 \cdot f_{t0,k}$ and $f_{v0,k} = \alpha_2 \cdot f_{c0,k}$, respectively.

$$f(\alpha_1) = \frac{1}{2}\sum_{i=1}^{n}(f_{c0,k_i} - \alpha_1 \cdot f_{t0,k_i})^2 \tag{9}$$

$$f(\alpha_2) = \frac{1}{2}\sum_{i=1}^{n}(f_{v0,k_i} - \alpha_2 \cdot f_{c0,k_i})^2 \tag{10}$$

From each of the five wood species, 12 samples were manufactured for each of the three studied requests, totaling 180 experimental determinations.

RESULTS AND DISCUSSION

Figure 1 shows the average values, confidence intervals (95% confidence), and the ranges of variance of the coefficient of variation (CV) of the strength properties investigated for the woods of Cambará Rosa (CR), Cedro Amazonense (CA), Cupiúba (Cup), Guarucaia (Ga), and Roxinho (Ro).

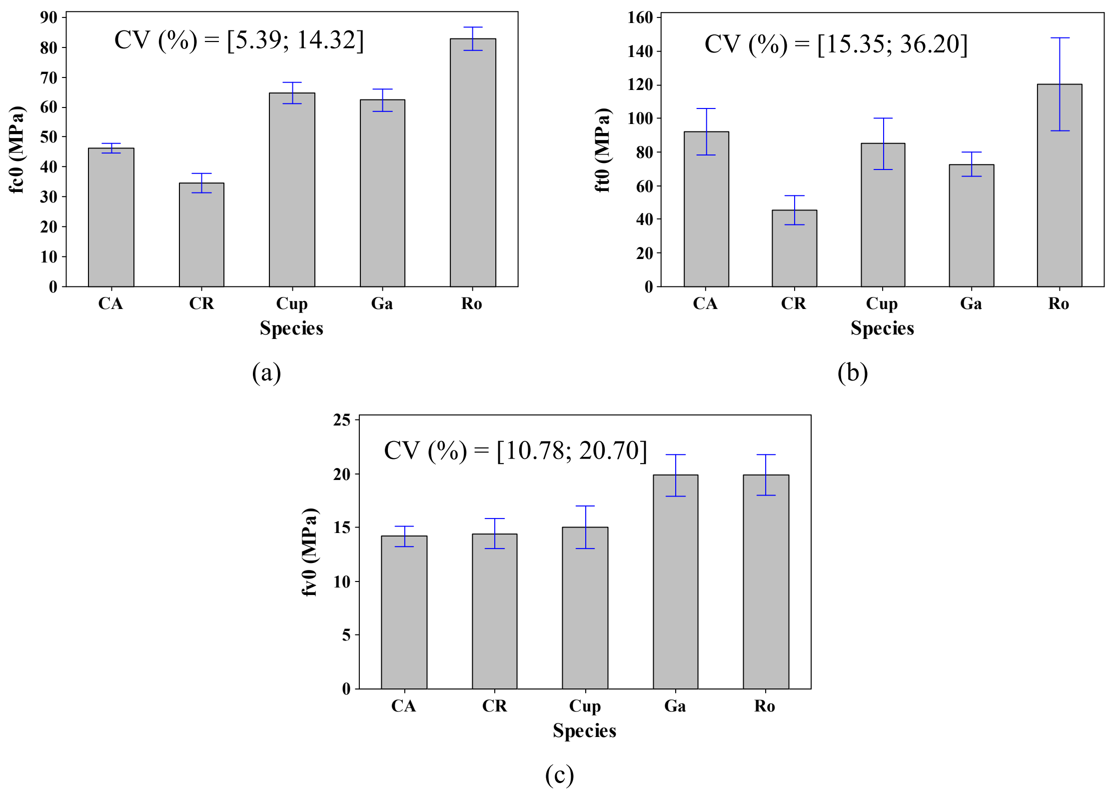


FIGURE 1. Results of strength properties: f_{c0} (a), f_{t0} (b), and f_{v0} (c).

Except for the parallel tensile strength of the Roxinho wood, the values of the coefficients of variation are in accordance with those refereed (18% for normal stresses and 28% for tangential stresses) by the Brazilian document ABNT NBR 7910 (1997).

The average values of compressive (54.4 MPa) and tensile (62.1 MPa) strengths in the direction parallel to the Cupiúba wood fibers cited in Annex E of ABNT NBR 7190 (1997) are close to the values obtained and shown in Figures 1a and 1b, respectively. Likewise, the values of f_{c0} and f_{t0} of the Guarucaia wood contained in this document are equal to 62.4 and 70.9 MPa, respectively, which are in accordance with those obtained in the present study.

Table 2 shows the values of characteristic strengths obtained by wood species and with the use of [eq. (2)].

TABLE 2. Results of the characteristic strength values obtained by [eq. (2)] proposed by ABNT NBR 7190 (1997) for the five wood species.

Species	$f_{c0,k}$ (MPa)	$f_{t0,k}$ (MPa)	$f_{v0,k}$ (MPa)
Cambará Rosa (CR)	27.0	31.9	11.9
Cedro Amazonense (CA)	46.4	64.4	13.2
Guarucaia (Ga)	55.7	64.0	18.0
Cupiúba (Cup)	65.6	63.1	10.8
Roxinho (Ro)	81.2	68.0	15.8

According to Table 2, Cambará Rosa, Cedro Amazonense, Guarucaia, Cupiúba, and Roxinho woods are, according to ABNT NBR 7190 (1997), categorized in the strength classes D20, D40, D50, D60, and D60, respectively.

Table 3 shows the characteristic values associated with the best distribution models by property and wood species and Figure 2 shows the results of adhesion tests for the compressive strength parallel to the wood fibers of Cambará Rosa as an example of the choice of model.

TABLE 3. Results of characteristic values associated with the best distribution models by property and wood species.

Species	$f_{c0,k}$ (MPa)	$f_{t0,k}$ (MPa)	$f_{v0,k}$ (MPa)
Cambará Rosa (CR)	26.4 (N)	26.5 (N)	10.6 (N)
Cedro Amazonense (CA)	41.9 (N)	53.8 (N)	11.6 (N)
Guarucaia (Ga)	55.8 (N)	46.9 (L)	9.6 (N)
Cupiúba (Cup)	52.3 (N)	54.5 (N)	14.7 (N)
Roxinho (Ro)	73.2 (N)	48.2 (N)	14.8 (L)

N – normal; L – lognormal; W – Weibull; E – exponential.

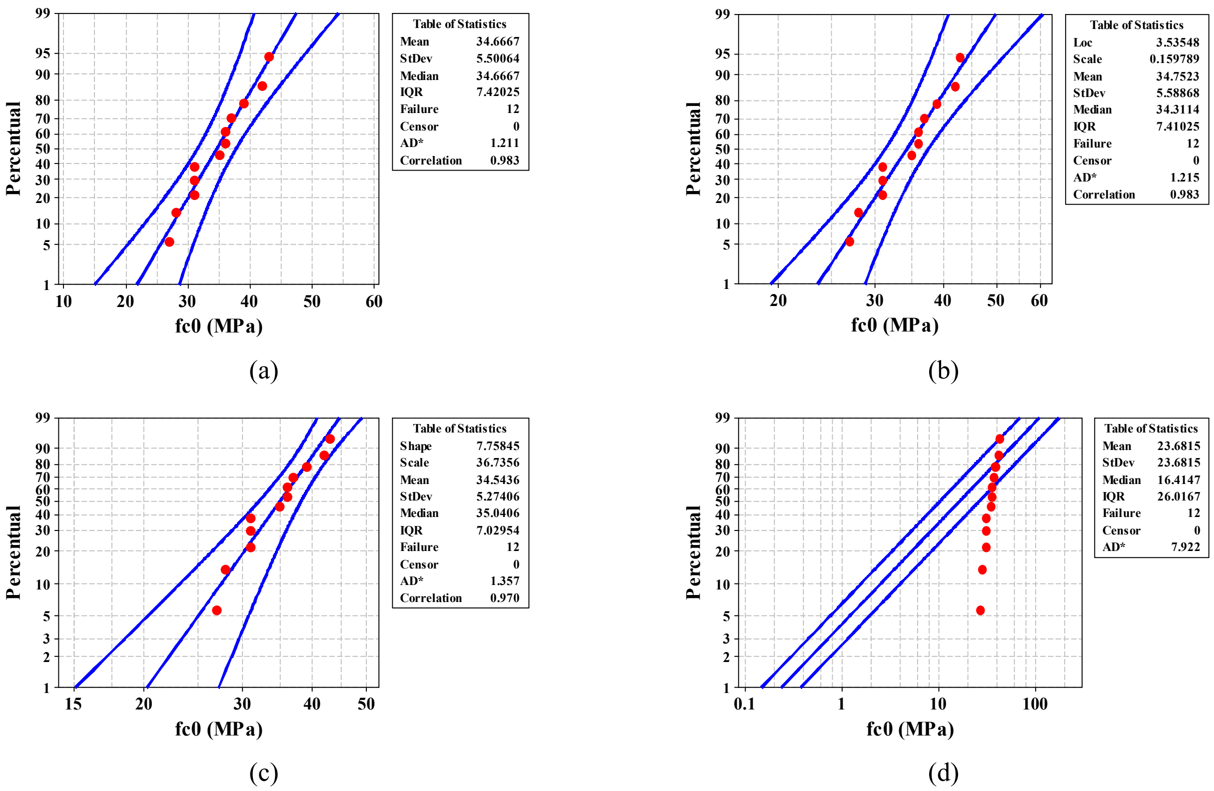
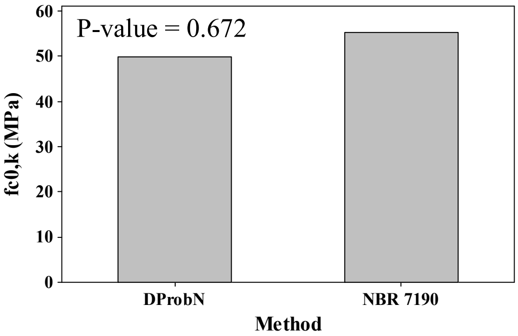


FIGURE 2. Normal (a), lognormal (b), Weibull (C), and exponential (d) distribution models to estimate the characteristic value of compressive strength in the direction parallel to the wood fibers Cambará Rosa.

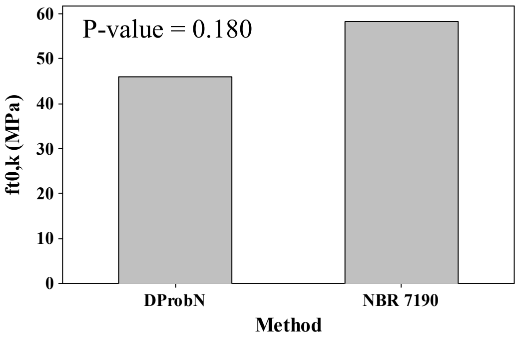
Table 2 shows that the normal distribution model had the best adherence to the results of the investigated strength properties, followed by the lognormal model (results very close to the normal distribution), and the Weibull model. The exponential distribution model had no representativeness in all cases.

Figure 3 shows the results (P-values) of ANOVA regarding the possible differences between the average values of the characteristic strengths obtained using the equation proposed by ABNT NBR 7190 (1997) and the normal distribution model (DProbN).

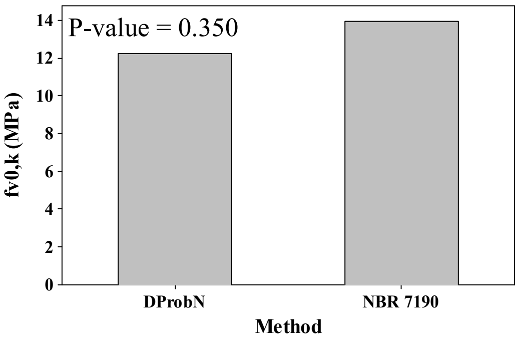
Figure 3 shows that because the P-values were all higher than 0.05, the characteristic values of the three strength properties determined according to ABNT NBR 7190 (1997) or by the normal probability distribution model were statistically equivalent, evidencing the accuracy of the model proposed by this normative document for small samples, suggesting the possibility of using [eq. (1)] also for small samples.



(a)



(b)



(c)

FIGURE 3. Results of ANOVA regarding the characteristic values obtained by the Brazilian standard and the normal distribution model: $f_{c0,k}$ (a), $f_{t0,k}$ (b), and $f_{v0,k}$ (c).

From the use of eqs (9) and (10), the values of the coefficients α_1 ($f_{c0,k}=\alpha_1 \cdot f_{t0,k}$) and α_2 ($f_{v0,k}=\alpha_2 \cdot f_{c0,k}$) of the investigated relationships resulted in 0.96 and 0.23, respectively, being 25 and 92% higher than the coefficients of eqs (3) and (4) indicated by ABNT NBR 7190 (1997), showing they are adequate and favorable to the safety of structures. However, because the differences with the coefficients obtained in this study are significant, these values may overestimate the dimensions of the structure elements, directly affecting the final value of the work to be projected.

CONCLUSIONS

The results obtained in this research allow concluding that:

- Among the tested probability distribution models, the normal model presented the highest adherence to the evaluated characteristic strength values, not being significant the exponential model.

- The equivalence between the characteristic values obtained by the expression of the Brazilian standard and the characteristic values coming from the normal probability distribution models was observed from the statistical analysis, evidencing the accuracy in the estimation of the characteristic value for small samples.

- As observed from the relationships between the characteristic values of the evaluated strength properties, the coefficients obtained in this study were significantly higher when compared to those of the relationships proposed by ABNT NBR 7190 (1997), which implies in more conservative estimates by this document for the evaluated species.

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