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ORIGINAL

Evaluation of mechanical strengths of tropical hardwoods: proposal of probabilistic models

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Abstract

The characteristic value of compressive strength parallel to the grain is used to design structural members in bridges, houses and buildings. Such value is obtained based on experimental tests. The Brazilian standard proposes equations to estimate the strengths by means of probabilistic equations that allow obtaining the characteristic values of different mechanical strengths, such as the compressive ($f_{c0,k}$), tensile ($f_{t0,k}$) and shear ($f_{v0,k}$) properties obtained from a set of experimental results. Considering the results for these strengths in parallel direction to grain of 30 hardwoods, with a total of 1080 experimental determinations, the precision of the relations proposed by this standard was duly evaluated from probability distribution models. The Normal, LogNormal, Weibull and Exponential functions were used in order to determine the best adhesion model. Once the values and respective models had been determined for each species, a multivariate linear regression model, based on analysis of variance (ANOVA) and dependent on the mean value ($\bar{x}$), coefficient of variation ($CV\%$) and lower (LO) and higher (HI) strength values, was adopted to estimate the $f_{c0,k}$, $f_{t0,k}$ and $f_{v0,k}$ adjusted with the most significant terms, in order to infer the quality of the estimator and, consequently, the reliability of such mechanical properties. Finally, the multivariate model proposed here was compared to the empirical proposition of the Brazilian standard, to evaluate the reliability of the model and its adequacy in the estimation of the characteristic strengths values to distinguish the mechanical properties of 30 tropical hardwoods.

1 Introduction

Considering the importance of mechanical properties in the design of timber structures, such as bridges, sheds and timber residences (Dadzie and Amoah 2015), it is of great relevance to evaluate equations that aim to estimate the characteristic strengths of species for structural use. In Brazil, the timber structures have an elevated applicability potential due to a vast number of wood species existing in the Amazonian rainforest, estimated at more than 10,000 species according to Steege et al. (2016). This number induces the development of new research focused on unknown species, which may replace those that are already commonly used in civil construction. Works by Ravenshorst et al. (2004), Ruelle et al. (2011), Mascia and Nicolas (2013), Segundinho et al. (2015), dos Reis et al. (2018), and Silva et al. (2018) can be mentioned as researches that sought to investigate different wood species for structural use.

The use of timber for structural purpose is regulated in Brazil by standard ABNT NBR (1997), which establishes the requirements for project development, construction and control of wood structures, based on semiprobabilistic methods, which assess fracture strength, instability, excessive deformation, and durability of the structure.

Thus, it is important to examine the equations that estimate the mechanical strengths of the species used in

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construction. Such equations are established in the Brazilian standard, which allows obtaining the characteristic values used for structural design for distinct properties (compressive, tensile and shear strengths) of the well-known woods. However, Logsdon et al. (2010) emphasize that these equations should not be the only rule for determination of characteristic wood properties. They sought to benchmark a model for characteristic compression strength ($f_{c0,k}$) estimation for *Dinizia excelsa* species and concluded that NBR equation is more conservative as it provides slightly lower $f_{c0,k}$ values.

Similarly, Matos and Molina (2016) investigated a correlation between compression and shear strength ($f_{c0,k}$ and $f_{v0,k}$) of *Pinus elliotti* and *Corymbia citriodora* species, comparing an experimental relation with the standardized relations of ABNT NBR (1997) and ISO 13910 (2005), and concluded that the values obtained from relations of the Brazilian standard were superior to those of the European standard for both species.

Longui et al. (2017) also researched the shear strength parallel to the grain with tests on four Brazilian wood species. The research evaluated the shear with distinct ray orientation and concluded that specimens with parallel ray orientation to the shear plane did not differ statistically from shear values when compared to specimens having perpendicular and diagonal orientation to shear plane. Already Aicher et al. (2018) studied the shear strength and wood failure of European and tropical hardwoods.

Recently, Christoforo et al. (2019a) evaluated relations based on the probability models to check which model was more adherent and accurate in estimating the characteristic values, $f_{t0,k}$, $f_{v0,k}$ and $f_{c0,k}$, comparing five wood species with the estimates from ABNT NBR (1997). Among the evaluated relationships, the obtained results were significantly higher (up to 92%) when compared to those estimated by the Brazilian standard.

These studies demonstrate the importance of assessing the mechanical properties of wood in order to obtain reliable and safe estimates for structural design. Several authors can be cited for investigating the species studied herein, focusing on physical and mechanical properties for distinct sites: *Mezilaurus itauba* (da Silva et al. 2014), *Parinari excelsa* (Almeida et al. 2015), *Hymenaea* sp. (Icimoto et al. 2015), *Dinizia excelsa* (Ravenshorst 2015), *Cedrela* sp. (Soriano et al. 2015; Tenorio and Moya 2018), *Copaifera* sp. (Aquino et al. 2018), *Goupia* sp. (Almeida et al. 2018), and *Peltophorum* sp. (Christoforo et al. 2019b).

Observing the studies presented here, it may be possible to estimate mechanical properties of distinct wood species for structural purpose using probability models. So, this paper aimed to evaluate, using 30 wood species, the chance to use possibility models to estimate the mechanical properties (compressive, tensile and shear strength) with a set of experimental results. A need for such estimates motivated the present study, thus reinforcing the reliability of the statistical analyses carried out here for tropical hardwoods, enabling their use for structural purpose.

2 Materials and methods

In this work, homogeneous batches, of 30 wood species (Table 1) were used in the experimental tests, as required by ABNT NBR (1997) with a batch volume limited to 12 m^3 and the specimens randomly extracted, limited to one sample per bar for each test, according to the scheme in Fig. 1. In order to carry out the tests, all specimens were stored at 12% moisture level, which corresponds to equilibrium moisture content as defined by this standard. These tests were performed at the LaMEM (Laboratório de Madeiras e Estruturas de Madeiras) of the University of São Paulo, following the procedures of ABNT NBR (1997, Appendix B).

It should be noted that 12 specimens were used for each mechanical property of 30 hardwood species as shown in Table 1, following the Brazilian Standard, resulting in a total of 1080 experimentally obtained values. Two trees per wood species were used to produce the specimens. According to the Brazilian standard, the specimens must be free of defects and extracted far from the end of the bar, randomly chosen along the wood batch.

It can also be highlighted that the statistical equivalence of strength properties between small and defect-free specimens and structurally sized elements has been proven for native forest wood trees, used in this research, and for planted forest wood trees (Lanini 2018).

2.1 Characteristic strength values from Brazilian standard

The characteristic value of the evaluated properties (f_{c0}, f_{t0} and f_{v0}) were calculated from 12 specimens for each species using the equations recommended by ABNT NBR (1997).

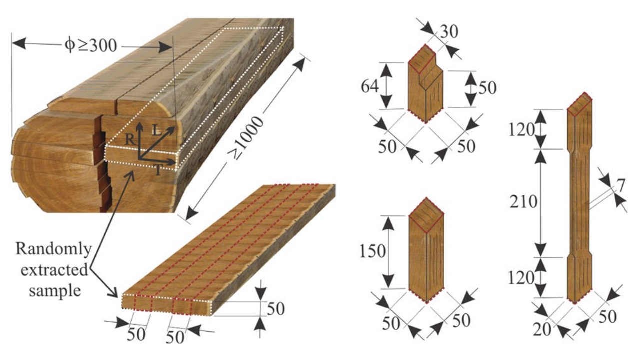

Fig. 1 Extraction scheme and dimensions (in *mm*) of specimens for compressive, tensile and shear tests

Table 1 Scientific name and identification (ID) of 30 tropical hardwoods

ID	Scientific name[a]	ID	Scientific name[a]	ID	Scientific name[a]
1	*Vatairea* cf. *guianensis* Aubl.	11	*Cedrelinga cateniformis* Ducke	21	*Clarisia racemosa* Ruiz & Pav.
2	*Hymenolobium* cf. *heterocarpum* Ducke	12	*Copaifera multijuga* Hayne	22	*Pradosia* sp. Liais
3	*Dinizia excelsa* Ducke	13	*Goupia paraensis* Huber	23	*Parinari excelsa* Sabine
4	*Parkia* cf. *pendula* Benth.	14	*Peltophorum dubium* (Spreng.) Taub.	24	*Copaifera langsdorffii* Desf.
5	*Sebastiania commersoniana* L. & Downs	15	*Mezilaurus itauba* Taub. ex Mez	25	*Tapirira* sp. Aubl.
6	*Cassia ferruginea* Schrad. ex DC.	16	*Hymenaea courbaril* Liais	26	*Erisma uncinatum* Warm.
7	*Bertholletia excelsa* Bonpl.	17	*Ocotea neesiana* Kosterm.	27	*Geissospermum sericeum* Miers
8	*Calycophyllum multiflorum* Griseb.	18	*Sextonia* cf. *rubra* Werff	28	*Vochysia haenkeana* Mart.
9	*Cedrela odorata* L.	19	*Manilkara* cf. *inundata* Ducke	29	*Diplotropis* sp. Benth.
10	*Cedrela* cf. *fissilis* Vell.	20	*Qualea paraensis* Ducke	30	*Tachigali glauca* Tul.

[a]Flora of Brazil (2020)

The characteristic strength value ($f_{w,k}$) is given as the highest value among the values of f_1, the value equivalent to 70% of the value of f_m, and the value equivalent to $1.10 \cdot z_b$, that is:

$$f_{w,k} = \left\{ f_1 ;\, 0.70 \cdot f_m ;\, 1.10 \cdot z_b \right\}, \tag{1}$$

where f_m is the average strength value obtained from the tested samples, and the estimator z_b is given as:

$$z_b = \left(2 \frac{f_1 + f_2 + f_3 + \ldots + f_{\left(\frac{n}{2}-1\right)}}{\left(\frac{n}{2} - 1\right)} - f_{\left(\frac{n}{2}\right)} \right), \tag{2}$$

where f_n is n determined strength values, arranged in ascending order (f_1, f_2, $f_3 \cdots f_n$).

Pinto et al. (2004) emphasize which adoption of Eq. 1 can result in significantly different values (or not) from the characteristic value associated with a given probability density model, considering the diversity of probability functions. This fact contributes to the objectives of this study, with the possibility of adopting new probabilistic models, such as those mentioned in the sequence.

2.2 Probability density functions (PDFs)

The relations proposed by the Brazilian standard (Eq. 1) can be evaluated from the probability distribution function (PDF) obtained for each mechanical property evaluated in this research. The probability function (f) of an aleatory variable (x) is expressed as Normal (N), LogNormal (L), Weibull (W) and Exponential (E) functions, respectively, as follows:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{1}{2}\cdot\left(\frac{x-\mu}{\sigma}\right)^2},\ x \in (-\infty, \infty)\,, \tag{3}$$

where σ is the standard deviation and μ the population mean of normal function;

$$f(x) = \begin{cases} \frac{1}{x\cdot\sigma\cdot\sqrt{2\pi}} \cdot e^{-\frac{1}{2}\cdot\left(\frac{\ln(x)-\mu}{\sigma}\right)^2}, & \text{if x } > 0; \\ 0 & , \text{ if x } \leq 0. \end{cases} \tag{4}$$

where σ is the standard deviation and μ is the log population mean;

$$f(x) = \frac{\beta}{\alpha^\beta} \cdot x^{\beta-1} \cdot e^{-\left(\frac{x}{\alpha}\right)^\beta},\ x > 0\,, \tag{5}$$

where β and α are the shape and scale parameters, respectively;

$$f(x) = \frac{1}{\theta} \cdot e^{-\frac{x}{\theta}},\ x > 0\,, \tag{6}$$

where θ is the scale parameter.

The adherence tests, at the level of 95% of reliability used to verify the best PDF, were obtained via least squares estimation (LSE) and Minitab Software support (Minitab 2018).

The characteristic values ($f_{c0,k}$, $f_{t0,k}$ and $f_{v0,k}$) obtained using the four PDFs (Eqs. 3–6) were related to the mean value of the variable ($\bar{x}$), the coefficient of variation ($CV\%$), and the lowest (LO) and the highest (HI) strength value using a multiple linear regression model based on the analysis of variance (ANOVA); to evaluate the quality of adjustment, the coefficient of determination (R^2) was used:

$$f_{w,k}^{Prob} = \beta_0 + \beta_1 \cdot \bar{x} + \beta_2 \cdot CV + \beta_3 \cdot LO + \beta_4 \cdot HI + \varepsilon\,, \tag{7}$$

where β_i consists of the coefficients adjusted by the LSE and ε is the random error.

Therefore, the ANOVA is adopted to verify the accuracy of probabilistic equations (Eq. 7), when compared to the proposition of the Brazilian standard (Eq. 1). The distribution normality of ANOVA was validated with the normality test by *Anderson-Darling* (Weerahandi 1995), with significance level of 0.05. Given the hypotheses accepted, P-value (probability P) equal to or greater than 5% implies accepting the null hypothesis (H_0—the model is not representative or variations of the factors do not explain the variations in the dependent variable), and rejecting the null hypothesis, if P-value < 0.05 (alternative hypothesis, H_1).

Firstly, the statistical equivalent, between Eqs. 1 and 7, is confirmed by Tukey pairwise comparisons. In this test, *A* and *B* denote, respectively, the first and second group with the highest mean value and the same letters indicate statistically equivalent means. Finally, the coefficient of determination (R^2) was used as a criterion to validate the PDF of better adherence.

3 Results and discussion

Firstly, Fig. 2 shows the mean values, confidence intervals (CI for 95% confidence level) of the strength properties (Fig. 2a (f_{c0}), b (f_{t0}), and c (f_{v0})) of the 30 hardwoods investigated. The individual standard deviations were used to calculate the CIs, being compared with those found in

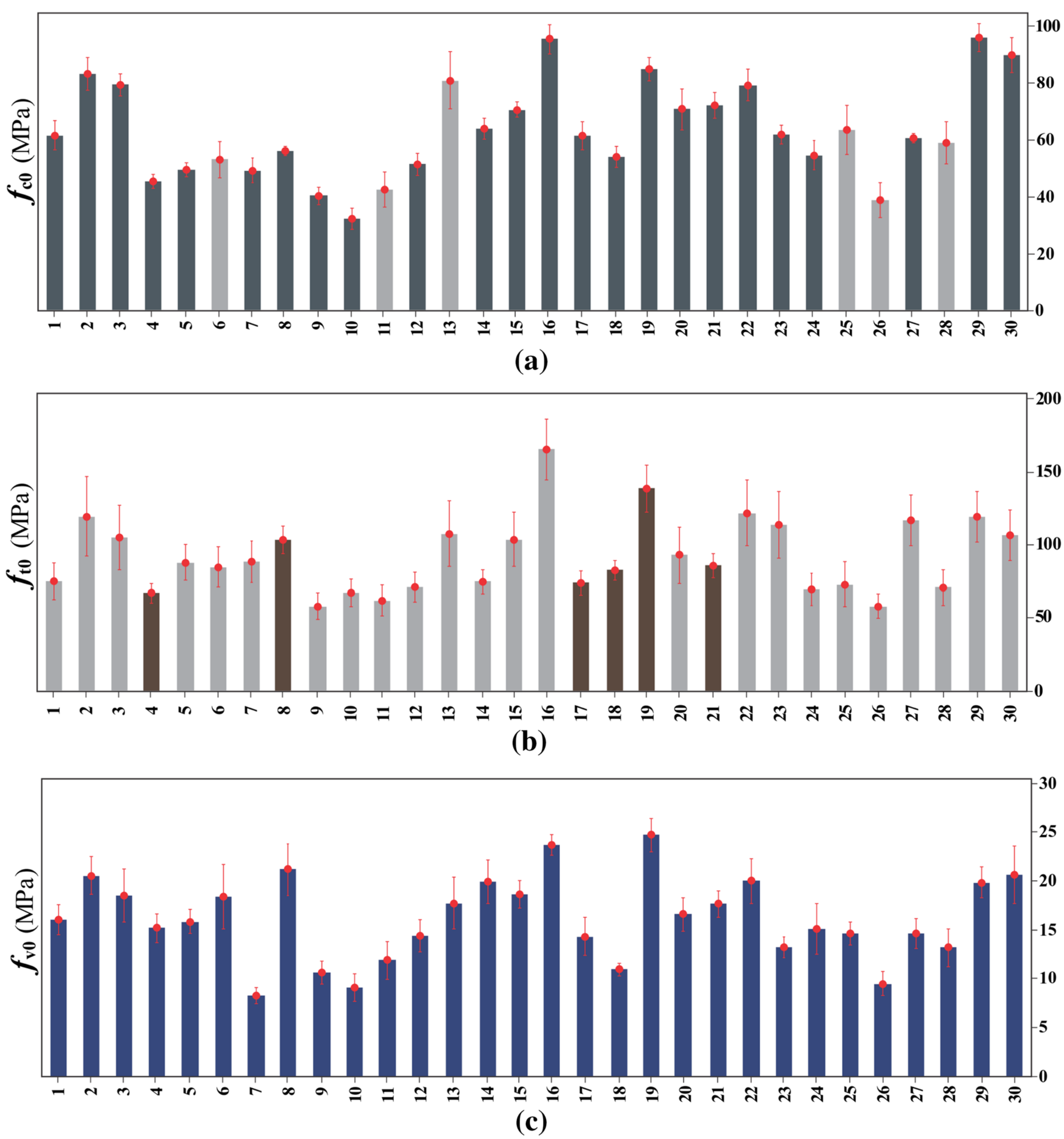

Fig. 2 Results for compressive (**a**), tensile (**b**), and shear (**c**) strengths from the mean values and confidence intervals (95% CI) for the 30 hardwood species

ABNT NBR (1997, Appendix E). Species highlighted in gray exceeded the CI values stipulated by this standard.

The coefficients of variation of f_{c0} (Fig. 2a) reached those referenced by the Brazilian standard with ranges of variance equal to the $CV(\%)$ = (04 to 26). However, for some species this limit was exceeded: Silva et al. (2018) *Erisma uncinatum* (26%), Icimoto et al. (2015) *Cedrelinga cateniformis* (23%), Kollmann and Côté (2015) *Goupia paraensis* (20%), Segundinho et al. (2015) *Tapirira* sp. (22%), Steege et al. (2016) *Vochysia haenkeana* (20%), and Christoforo et al. (2019a) *Cassia ferruginea* (19%) (highlighted in light grey).

Already for the f_{t0} (Fig. 2b), most species reached coefficients of variation above the values recommended by the Brazilian standard. The ranges of variance were equal to the $CV(\%)$ = (13–36). The high values of this coefficient can be explained, according to Kollmann and Côté (2015), by the rupture mode of the material during loading and the intrinsic wood anatomical structure of each species. These aspects include the type of applied stress, grain direction, density, as well as orthotropy, and it demonstrates the importance of more detailed studies on such behaviors. So, only the species *Ocotea neesiana* (18%; Mascia and Nicolas 2013), *Manilkara inundata* (18%; Minitab 2018), *Parkia pendula* (16%; Almeida et al. 2015), *Calycophyllum multiflorum* (15%; Dadzie and Amoah 2015), *Clarisia racemosa* (15%; Ravenshorst 2015), and *Sextonia rubra* (13%; Matos and Molina 2016) reached values of the coefficient as expected, while for other species the values of the coefficients differed from the standard (highlighted in light grey).

For the strength f_{v0} (Fig. 2c), all the species reached coefficients of variation in accordance with those referred to by the standard. The ranges of variance were equal the $CV(\%)$ = (07–28).

To compare the values presented in Fig. 2, the CV = 18% was used for normal stresses and 28% for tangential stresses, according to the Brazilian standard. It is important to emphasize, however, that this standard does not require the difference in the CV, i.e., Eq. 1 is formulated for a CV = 18%, regardless of the mechanical strength to be calculated.

Table 2 shows the characteristic values for compressive, tensile, and shear strengths calculated, following Eq. 1, from 1080 experimental values obtained for the 30 species.

The characteristic values calculated by Eq. 1, the PDF of better adherence is defined by the highest P-value for each of the 30 tropical hardwoods.

Sequentially, the mean values ($\bar{x}$ in MPa), the coefficient of variation ($CV\%$) and the lowest (LO in MPa) and highest (HI in MPa) strength values (f_{c0}, f_{t0}, and f_{v0}) are adopted in the construction of the equation to estimate the probabilistic characteristic value, according to the multivariate linear regression model based on ANOVA (Eq. 7).

3.1 PDFs for compressive strength

Table 3 shows the characteristic values of compressive ($f_{c0,k}^{Prob}$) strength obtained using the PDF of better adherence, among the four distribution functions, following Eqs. 3–6. Note that 57% (17/30) obtained better adjustments by the LogNormal (L), 27% (8/30) by the Normal (N), and 16% (5/30) by the Weibull (W) functions.

From ANOVA of the regression function (Eq. 7), the model is significant given a coefficient $R^2 \approx 99\%$, which results in an error close to < 1%. Therefore, the estimate of $f_{c0,k}^{Prob}$ can be expressed by Eq. 8, as follows:

Table 2 Characteristic values for compressive, tensile, and shear strengths, according to (ABNT NBR 1997) (Eq. 1)

ID	NBR values (Eq. 1)			ID	NBR values (Eq. 1)		
	$f_{c0,k}$	$f_{t0,k}$	$f_{v0,k}$		$f_{c0,k}$	$f_{t0,k}$	$f_{v0,k}$
1	47.52	52.56	12.76	16	89.96	125.29	23.08
2	76.03	83.51	17.20	17	50.60	61.36	10.40
3	72.73	77.02	13.35	18	49.14	69.87	9.77
4	41.87	53.94	12.72	19	79.46	109.40	20.77
5	45.58	67.20	13.75	20	61.53	65.13	14.34
6	36.37	59.44	12.97	21	62.41	74.23	15.18
7	38.93	61.95	7.04	22	72.34	85.29	14.63
8	54.54	86.42	15.55	23	55.22	79.35	12.01
9	33.18	44.04	8.56	24	45.06	50.30	10.62
10	29.99	48.55	7.13	25	43.74	51.14	12.39
11	29.06	50.07	8.37	26	27.20	40.64	6.70
12	44.13	52.67	10.25	27	61.60	81.65	11.37
13	55.28	75.22	12.63	28	44.79	51.39	9.30
14	56.34	63.98	17.47	29	90.46	83.43	17.42
15	68.44	72.60	16.32	30	75.46	74.73	14.54

Table 3 Characteristic values of $f_{c0,k}^{Prob}$ strength, according to PDF of better adherence

ID	$f_{c0,k}^{Prob}$	P-value	PDF	ID	$f_{c0,k}^{Prob}$	P-value	PDF
1	47.45	0.558	N	16	81.09	0.811	L
2	66.99	0.305	L	17	47.50	0.436	N
3	68.31	0.209	L	18	44.30	0.937	L
4	38.35	0.250	W	19	73.14	0.502	L
5	42.51	0.882	L	20	53.16	0.481	L
6	36.39	0.241	W	21	59.03	0.633	N
7	37.17	0.938	N	22	64.41	0.657	L
8	50.31	0.907	L	23	53.51	0.250	W
9	32.35	0.086	W	24	41.59	0.722	L
10	23.75	0.005	L	25	39.95	0.741	N
11	25.96	0.227	N	26	24.72	0.766	L
12	41.13	0.594	L	27	5498	0.513	L
13	53.44	0.715	N	28	40.93	0.477	L
14	53.06	0.905	N	29	81.89	0.406	L
15	62.32	0.985	L	30	71.67	0.203	W

Table 4 Results of ANOVA on the sample sets: $f_{c0,k}^{Prob}$ (probability compressive values)

Source	*DF*	SS_{adj}	MS_{adj}	F-value	P-value
$\bar{x}$	1	47.12	47.12	37.82	0.000
CV	1	24.30	24.30	19.51	0.000
LO	1	47.25	47.25	37.93	0.000
HI	1	1.35	1.35	1.08	0.308
Error	25	31.14	1.25		
Total	29	7254.76			

DF Degrees of Freedom, SS_{adj}/MS_{adj} sum and mean of squares

$$f_{c0,k}^{Prob} = 7.91 + 0.48\bar{x} - 0.56CV + 0.39LO\ [R^2 = 99.5\%] \tag{8}$$

It is observed that three terms are significant ($\bar{x}$, *CV*, *LO*), and the term *HI* is not significant, according to Table 4.

It should be noted that it was possible to exclude the non-significant coefficients without influencing the R^2 value.

3.2 PDFs for tensile strength

Table 5 shows the characteristic values for tensile ($f_{t0,k}^{Prob}$) strength obtained using the PDF of better adherence, among the four distribution functions (Eqs. 3–6). It is noteworthy that 53% (16/30) obtained better adjustments by the

Table 5 Characteristic values of $f_{t0,k}^{Prob}$, according to the best PDF

ID	$f_{t0,k}^{Prob}$	P-value	PDF	ID	$f_{t0,k}^{Prob}$	P-value	PDF
1	46.06	0.668	L	16	111.71	0.508	N
2	49.30	0.907	N	17	54.78	0.511	L
3	62.45	0.045	L	18	66.88	0.867	L
4	50.00	0.318	N	19	101.47	0.334	L
5	61.08	0.423	L	20	43.32	0.796	N
6	52.74	0.250	W	21	64.55	0.250	W
7	54.80	0.159	W	22	73.96	0.848	L
8	80.66	0.768	L	23	54.37	0.935	N
9	38.19	0.347	L	24	45.50	0.292	L
10	45.18	0.764	L	25	39.09	0.214	L
11	34.49	0.030	N	26	36.49	0.527	N
12	48.06	0.227	L	27	72.62	0.831	N
13	59.63	0.268	L	28	44.81	0.319	L
14	56.10	0.676	L	29	74.21	0.893	N
15	55.35	0.603	N	30	61.60	0.815	N

LogNormal (L), 37% (11/30) by the Normal (N), and 10% (3/30) adjusted by the Weibull (W) functions.

From ANOVA of the regression function (Eq. 7), the strength $f_{t0,k}^{Prob}$ can be estimated by Eq. 9:

$$f_{t0,k}^{Prob} = 24.26 + 0.42\bar{x} - 1.01CV + 0.33LO \; [R^2 = 96.3\%] \quad (9)$$

It is observed that three terms are significant ($\bar{x}$, CV, LO), and the term HI is not significant (Table 6), whose model was considered significant given the coefficient $R^2 \approx 96\%$, which results in an error close to < 4%.

3.3 PDFs for shear strength

Table 7 shows the characteristic values for tensile ($f_{v0,k}^{Prob}$) strength obtained using the PDF of better adherence, among the four distribution functions (Eqs. 3–6). It is emphasized that 43% (13/30) obtained better adjustments by the Normal (N), 43% (13/30) by the LogNormal (L), and 14% (4/30) adjusted by the Weibull (W) functions.

Table 6 Results of ANOVA on the sample sets: $f_{t0,k}^{Prob}$ (probability tensile values)

Source	DF	SS_{adj}	MS_{adj}	F-value	P-value
$\bar{x}$	1	261.52	261.52	21.63	0.000
CV	1	252.16	252.16	20.85	0.000
LO	1	147.41	147.41	12.19	0.002
HI	1	0.36	0.35	0.03	0.865
Error	25	302.32	12.09		
Total	29	9114.41			

DF Degrees of Freedom, SS_{adj}/MS_{adj} sum and mean of squares

Table 8 Results of ANOVA on the sample sets: $f_{v0,k}^{Prob}$ (probability shear values)

Source	DF	SS_{adj}	MS_{adj}	F-value	P-value
$\bar{x}$	1	19.413	19.413	56.19	0.000
CV	1	6.844	6.844	19.81	0.000
LO	1	0.027	0.027	0.08	0.782
HI	1	0.118	0.118	0.34	0.564
Error	25	8.637	0.345		
Total	29	416.946			

DF Degrees of Freedom, SS_{adj}/MS_{adj} sum and mean of squares

It is observed from Table 8 that only two terms are significant ($\bar{x}$, CV), whereas the terms LO and HI are not significant, whose model was considered significant given the coefficient $R^2 \approx 97\%$, which results in an error close to < 3%. Therefore, the $f_{v0,k}^{Prob}$ can be expressed by Eq. 10, as follows:

$$f_{v0,k}^{Prob} = 4.27 + 0.74\bar{x} - 0.25CV \quad [R^2 = 97.7\%] \quad (10)$$

Again, the exclusion of non-significant terms (LO and HI) did not have an effect on a high value of R^2 coefficient.

3.4 Synthesis of the results

Table 9 shows the characteristic values estimated from probabilistic functions for compressive ($f_{c0,k}^{Prob}$—Eq. 8), tensile ($f_{t0,k}^{Prob}$—Eq. 9), and shear ($f_{v0,k}^{Prob}$—Eq. 10) strengths.

Finally, the statistical equivalence between Eq. 1 (Brazilian standard approach) and, respectively, Eqs. 8, 9, and 10 was confirmed by Tukey pairwise comparisons, at 95%

Table 7 Characteristic values of $f_{v0,k}^{Prob}$, according to the best PDF

ID	$f_{v0,k}^{Prob}$	P-value	PDF	ID	$f_{v0,k}^{Prob}$	P-value	PDF
1	12.08	0.290	N	16	21.09	0.910	N
2	16.09	0.986	L	17	10.06	0.918	L
3	12.33	0.903	L	18	9.34	0.684	N
4	12.80	0.010	W	19	20.28	0.560	N
5	13.31	0.047	W	20	12.77	0.280	L
6	9.98	0.196	N	21	14.31	0.815	N
7	6.08	0.066	N	22	14.08	0.381	N
8	15.92	0.042	W	23	10.76	0.398	L
9	8.03	0.943	L	24	9.80	0.189	L
10	6.15	0.244	L	25	11.79	0.873	L
11	6.80	0.874	N	26	6.44	0.239	W
12	10.27	0.542	N	27	10.63	0.627	N
13	11.61	0.345	L	28	8.24	0.842	N
14	14.95	0.384	L	29	16.10	0.974	L
15	15.29	0.754	L	30	13.06	0.531	N

Table 9 Characteristic values of the mechanical properties estimated by probabilistic functions (PDFs)

ID	Probabilistic values			ID	Probabilistic values		
	$f_{c0,k}^{Prob}$	$f_{t0,k}^{Prob}$	$f_{v0,k}^{Prob}$		$f_{c0,k}^{Prob}$	$f_{t0,k}^{Prob}$	$f_{v0,k}^{Prob}$
1	48.02	43.89	12.48	16	79.26	108.36	20.26
2	69.03	58.59	16.00	17	46.36	56.87	9.69
3	66.93	54.76	12.37	18	45.00	68.19	10.16
4	38.23	54.78	11.81	19	72.48	100.55	19.98
5	43.65	61.59	13.18	20	53.18	44.26	12.76
6	35.93	47.81	11.09	21	58.96	63.06	14.55
7	38.04	54.71	6.38	22	64.37	72.69	14.70
8	51.09	79.78	15.29	23	50.87	58.05	11.05
9	32.25	35.96	8.05	24	42.17	44.79	8.83
10	23.54	44.32	5.06	25	41.12	35.41	11.97
11	25.66	38.53	6.66	26	22.43	36.81	6.17
12	41.72	47.59	10.65	27	55.42	75.86	11.02
13	54.61	58.44	11.67	28	41.51	42.47	8.42
14	53.67	56.41	14.82	29	81.61	72.80	16.00
15	61.83	58.09	15.27	30	72.44	63.75	14.12

Table 10 Tukey pairwise comparisons for compressive, tensile and shear strengths

Condition	N	$\bar{x}$	StD	95% CI	Grouping	
$f_{c0,k}$ (Eq. 1)	30	54.6	17.5	(48.6; 60.7)	A	
$f_{c0,k}^{Prob}$ (Eq. 8)	30	50.4	15.8	(44.3; 56.5)		A
$f_{t0,k}$ (Eq. 1)	30	68.4	18.9	(61.8; 75.07)	A	
$f_{t0,k}^{Prob}$ (Eq. 9)	30	57.9	17.4	(51.3; 64.6)		B
$f_{v0,k}$ (Eq. 1)	30	12.9	3.9	(11.6; 14.4)	A	
$f_{v0,k}^{Prob}$ (Eq. 10)	30	12.0	3.8	(10.6; 13.4)		A

confidence level. Table 10 presents the grouping information for compressive, tensile and shear strengths.

It is important to highlight the non-statistical equivalence for tensile strength, according to Table 10. This fact reinforces the importance of the revision of the equations proposed in the Brazilian standard, highlighting the probabilistic functions proposed in this study, which can be included in this normative document.

From the results for each of the 30 tropical hardwoods, the mean characteristic values can be calculated by the Brazilian standard equations (Eq. 1) and by regression models proposed in this research (Eqs. 8, 9 and 10). Figure 3 shows the comparison of these values, respectively, for compressive, tensile, and shear strengths.

Finally, it should be pointed out that the probabilistic models herein proposed have mean values below those suggested by the Brazilian standard and, therefore, being in favor of safety in the design of timber structures.

4 Conclusion

The mechanical properties of 30 species were experimentally determined and the obtained values were in accordance with those found in ABNT NBR (1997, Appendix E), with results for a great variety of tropical Brazilian species with structural potential in the civil engineering and possibilities of application in the manufacturing industry of hardwoods.

The probabilistic functions (Eqs. 8, 9 and 10) proposed in this research are an alternative to the equations of the Brazilian standard, with great potential of application to tropical species worldwide, considering the wide set of species herein studied.

The high coefficients of determination (R^2) achieved in this research demonstrate that these probabilistic models are appropriate for estimating the characteristic values of compressive, tensile and shear strengths. This fact reinforces the importance of the revision of ABNT NBR (1997) with the inclusion of the probabilistic models here proposed for tropical hardwood species.

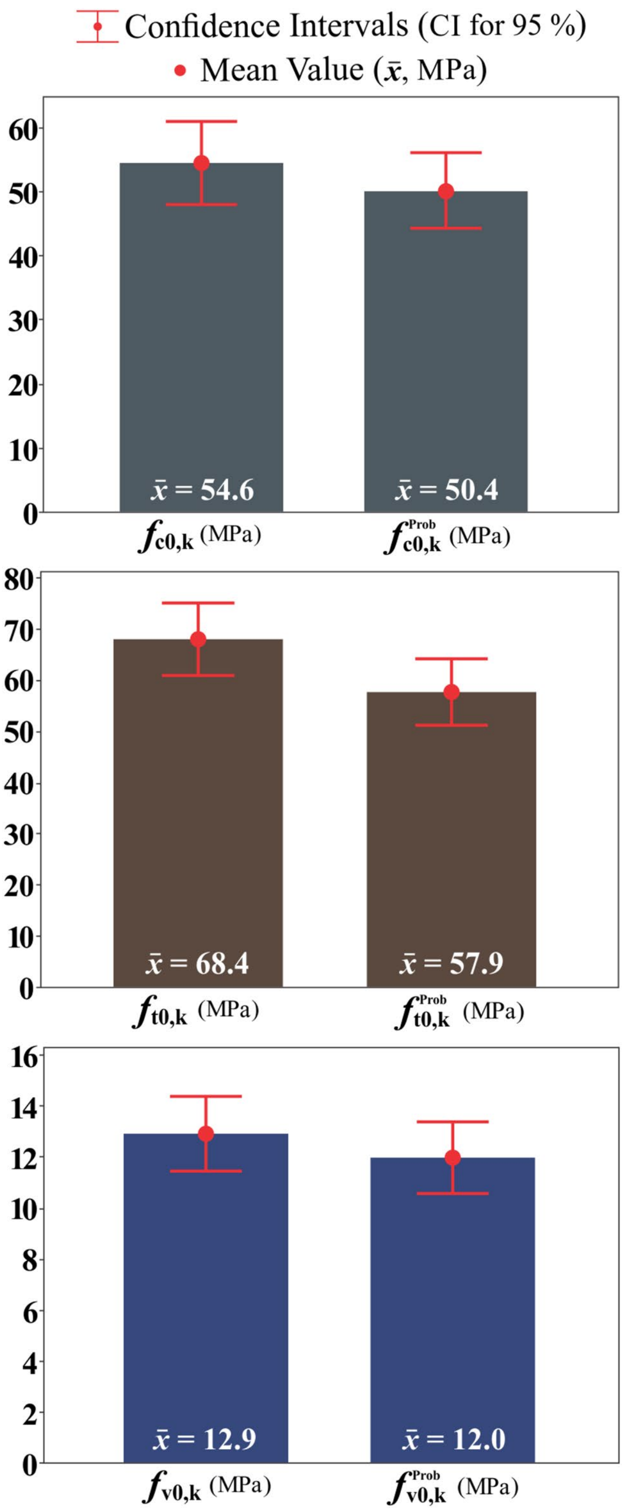

Fig. 3 Characteristic values of compressive, tensile, and shear strength from the mean value of 30 hardwoods—Brazilian standard (left) and probabilistic (right) values

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References

ABNT NBR 7190 (1997) Design of wooden structures. Brazilian Technical Standards Association, Brazil **(in Portuguese)**

Aicher S, Ahmad Z, Hirsch M (2018) Bondline shear strength and wood failure of European and tropical hardwood glulams. Eur J Wood Prod 76(4):1205–1222. https://doi.org/10.1007/s00107-018-1305-0

Almeida AS, Lanini TLS, Caetano JA, Christoforo AL, Lahr FAR (2018) Evaluation of stiffness in compression perpendicular to grain of Brazilian tropical wood species. Curr J Appl Sci Technol 28(5):1–7. https://doi.org/10.9734/CJAST/2018/42945

Almeida DH, Chahud E, Almeida TH, Christoforo AL, Branco LAMN, Lahr FAR (2015) Determination of density shear and compression parallel to the grain strengths of Pariri (*Pouteria* sp.). Int J Mater Eng 5(5):109–112. https://doi.org/10.5923/j.ijme.20150505.01

Aquino VBM, Almeida JPB, Almeida DH, Almeida TH, Panzera TH, Christoforo AL, Lahr FAR (2018) Physical and mechanical characterization of *Copaifera* sp. wood specie. Int J Mater Eng 8(3):55–58. https://doi.org/10.5923/j.ijme.20180803.03

Christoforo AL, Almeida AS, Lanini TLS, Nogueira RS, Lahr FAR (2019a) Estimation of the characteristic value of wood strength. J Braz Assoc Agric Eng 39(1):127–132. https://doi.org/10.1590/1809-4430-eng.agric.v39n1p127-132/2019

Christoforo AL, Aquino VBM, Wolenski ARV, Araujo VA, Lahr FAR (2019) Evaluation of the *Peltophorum vogelianum* Benth. wood species for structural use. J Braz Assoc Agric Eng 39(6):763–768. https://doi.org/10.1590/1809-4430-eng.agric.v39n6p763-768/2019

Dadzie PK, Amoah M (2015) Density, some anatomical properties and natural durability of stem and branch wood of two tropical hardwood species for ground applications. Eur J Wood Prod 73(6):759–773. https://doi.org/10.1007/s00107-015-0925-x

Da Silva F, Higuchi N, Nascimento CC, Matos JLM, De Paula EVCM, Dos Santos J (2014) Nondestructive evaluation of hardness in tropical wood. J Trop For Sci 26(1):69–74. https://doi.org/10.1590/1809-4430-eng.agric.v39n1p127-132/2019

dos Reis PCM, de Souza AL, Reis LP, Carvalho AMML, Mazzei L, Rêgo LJS, Leite HG (2018) Artificial neural networks to estimate the physical-mechanical properties of Amazon second cutting cycle wood, Maderas. Cienc Tecnol 20(3):343–352. https://doi.org/10.4067/S0718-221X2018005003501

Flora of Brazil (2020) Under construction, Rio de Janeiro Botanical Garden, Brazil. floradobrasil.jbrj.gov.br

Icimoto FH, Ferro FS, Almeida DH, Cristoforo AL, Lahr FAR (2015) Influence of specimem orientation on determination of elasticity in static bending, Maderas. Cienc Tecnol 17(2):239–252. https://doi.org/10.4067/S0718-221X2015005000023

ISO 13910 (2005) Structural timber—characteristic values of strength-graded timber—sampling, full-size testing and evaluation, Switzerland, p 30
Kollmann FFP, Côté WA Jr (1968) Principles of wood science and technology: solid wood. Springer-Verlag, Berlin, p 592. https://doi.org/10.1007/978-3-642-87928-9
Lanini TLS (2018) Relation between elastic moduli of structural parts and specimens of tropical hardwoods, Master in Civil Engineering, Federal University of São Carlos, Brazil, pp 64 https://repositorio.ufscar.br/handle/ufscar/9915
Logsdon NB, de Jesus JMH, Penna JE (2010) Evaluation of the estimators of the characteristic strength to compression parallel to the grain, Sci Forestalis, 38:579–587. https://www.ipef.br/publicacoes/scientia
Longui EL, Pires GT, Ballarin AW, Machado JAR (2017) Shear strength parallel to grain with distinct ray orientation on four Brazilian wood species. Eur J Wood Prod 75(4):663–665. https://doi.org/10.1007/s00107-016-1129-8
Mascia NT, Nicolas EA (2013) Determination of Poisson's ratios in relation to fiber angle of a tropical wood species. Constr Build Mater 41(4):691–696. https://doi.org/10.1016/j.conbuildmat.2012.12.014
Matos GS, Molina JC (2016) Shear strength of wood in direction parallel to the grain according to the standards ABNT NBR 7190:1997 and ISO 13910:2005. Revista Matéria 21(4):1069–1079. https://doi.org/10.1590/s1517-707620160004.0098
Minitab (2018) Minitab statistical software. http://www.minitab.com
Pinto EM, Martínez-Espinosa M, Calil Jr C (2004) Methods for determining the characteristic value of strength the compression parallel to the grain of the wood, Madeira: Arquitetura e Engenharia, 4:1–6. www.ipef.br
Ravenshorst GJP (2015) Species independent strength grading of structural timber. Technische Universiteit Delft, Netherlands. https://doi.org/10.4233/uuid:b2243d5d-3275-4d93-9378-b39f97a39f02
Ravenshorst GJP, Van der Linden M, Vrouwenvelder T, Van de Kuilen JWG (2004) An economic method to determine the strength class of wood species. Heron J 49(4):297–326
Ruelle J, Beauchêne J, Yamamoto H, Thibaut B (2011) Variations in physical and mechanical properties between tension and opposite wood from three tropical rainforest species. Wood Sci Technol 45:339–357. https://doi.org/10.1007/s00226-010-0323-9
Segundinho PGA, Lahr FAR, Regazzi AJ, Carreira MR (2015) Variation of modulus of elasticity obtained through the static bending method considering the S/h ratio, Wood Res, 60(2):189–200. www.woodresearch.sk
Silva CEG, Almeida DH, Almeida TH, Chahud E, Branco LAMN, Campos CI, Lahr FAR, Christoforo AL (2018) Influence of the procurement site on physical and mechanical properties of Cupiúba wood species. BioResources 13(2):4118–4131. https://doi.org/10.15376/biores.13.2.4118-4131
Soriano J, Veiga NS, Martins IZ (2015) Wood density estimation using the sclerometric method. Eur J Wood Prod 73:753–758. https://doi.org/10.1007/s00107-015-0948-3
Steege HT, Vaessen RW, Cárdenas-López D, Sabatier D, Antonelli A, Oliveira SM, Pitman NCA, Jorgensen PM, Salomão RP (2016) The discovery of the Amazonian tree flora with an updated checklist of all known tree taxa. Sci Rep 6:1–15. https://doi.org/10.1038/srep29549
Tenorio C, Moya R (2018) Evaluation of wood properties of four ages of Cedrela odorata trees growing in agroforestry systems with Theobroma cacao in Costa Rica. Agrofor Syst 1–16: https://doi.org/10.1007/s10457-018-0194-x
Weerahandi S (1995) ANOVA under Unequal Error Variances. Int Biom Soc 51:589–599. https://doi.org/10.2307/2532947