Relationship between Characteristic Values of Shear Strength Parallel to Grain and Tensile Strength Perpendicular to Grain for Tropical Woods

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Wood, due to its complex anatomy, requires meticulous characterization that imposes several tests to be carried out to evaluate its properties. Normative codes adopt different specimens to this aim. Geometric specificities proposed by NBR 7190-3:2022 and ASTM D143-22 to specimens used for estimating wood strength in tensile perpendicular to grain (f_{t90}) make them difficult to carry out. Thus it is advisable to consider relating f_{t90} with another mechanical property, for example, the shear strength parallel to the grain (f_{v0}). This paper aims to establish a coefficient relating the characteristic values of f_{t90} and f_{v0}, for strength classes D40 and D60 (frequently used for structural purposes) of Brazilian Code 7190:3-2022. A further aim, if possible, is to determine a single representative coefficient for both classes. Tests made it possible to obtain those properties for four species from each class, following NBR 7190-3:2022 guidelines. The optimal coefficient was determined using the least squares method (MMQ). Ratios $f_{t90,k}/f_{v0,k}$ were 0.22 and 0.19, for classes D40 and D60, respectively. As these ratios don't present a significant difference, it is viable to adopt a single relationship for both classes, thus simplifying characterization procedures.

DOI: 10.15376.biores.19.4.7408-7417

Keywords: Wood properties; Tropical species; Tensile perpendicular to grain; Shear strength perpendicular to grain

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INTRODUCTION

Complexity of wood's anatomy and anisotropy relates to its natural origin. Microscopic elements that compose it, such as fibers, vessels and rays in dicotyledons, are responsible for its strength and stiffness, and present important heterogeneity not only at the genus or species level, but also in individual trees (Fichtler and Worbes 2012). This can cause different batches of the same species to be included in different strength classes (Lima *et al.* 2018), reinforcing the necessity of adequate wood characterization.

The complete wood characterization encompasses a wide range of properties. To estimate each of them, a minimum of 12 samples are necessary for each species and, considering 18 main properties, there are 216 determinations (ABNT NBR 7190-3 2022) to be made. Even though some of these properties are estimated in the same experimental test, several different tests are required to obtain the main properties. Some of them present complex execution and require equipment available only in the few specialized research centers.

One way to avoid carrying out certain tests, whether due to the excessive quantity, complexity, or equipment required, is to establish a relationship between properties. In technical literature, several authors had studied relationships between properties of Brazilian native tropical species. Some of them are cited here: (i) apparent density and dimensional stability (Almeida *et al.* 2017); (ii) longitudinal and transverse modulus of elasticity in static bending (Lahr *et al.* 2017); (iii) characteristic strength in compression parallel to grain and characteristic strength in tension parallel to grain (Wolenski *et al.* 2019); (iv) stiffness in compression and tension parallel to grain (Wolenski *et al.* 2019); (v) stiffness in compression and tension parallel to grain, and in static bending (Almeida *et al.* 2020a, b); (vi) shear strength parallel to grain and strength in compression parallel to grain (Couto *et al.* 2020; Lahr *et al.* 2021a); (vii) apparent density, porosity, shrinkage, strength in compression in parallel and perpendicular to grain (Almeida *et al.* 2022); (viii) density and strength in compression parallel to grain (Lahr *et al.* 2021b); (ix) density and stiffness in compression parallel to grain (Lahr *et al.* 2021c); (x) conventional strength in static bending, strength in compression parallel to grain and strength in tension parallel to grain (Marcolin *et al.* 2021); (xi) shear strength parallel to grain, strength in compression parallel to grain and conventional strength in static bending (Almeida *et al.* 2023); (xii) toughness and strength in compression parallel to grain (Ruthes *et al.* 2023); (xiii) wood colour, apparent density, and anatomical features (Bessa *et al.* 2023); (xiv) apparent density and strength properties (Hussain *et al.* 2023). International Codes, such as ISO 16598 (2015) and EN 384 (2016), also present some correlations between properties (Marcolin *et al.* 2021).

NBR 7190-3 (ABNT 2022) also presents, for simplified characterization, some relations for characteristic strength values, in particular with characteristic value of strength in compression parallel to grain (reference for sizing of structural members). Although their precision must systematically be enhanced, these uncertainties are covered by the ponderation coefficient. This parameter, according to NBR 8681 (ABNT 2003), considers "the effective strength variability; the discrepancies between the effective material strength and that measured conventionally in standardized specimens; and the inconsistencies existing in strength determination requests". Eurocode 5 (EN 1995-1-1 2004) also uses this concept to consider existing uncertainties. By such means, the design value established for strength is reduced to an extreme one with low probability of occurrence.

An example of a complex test proposed by NBR7190-3:2022 is the one carried out to obtain strength in tension perpendicular to grain. The specimen (Fig. 1a) presents geometric specificities analogous to those adopted by ASTM D143-22 (ASTM 2022) for this purpose. Due to the geometry, its manufacture requires high precision so that they can fit properly into the universal testing machine (Fig. 1a) and, thus, achieve reliable test results.

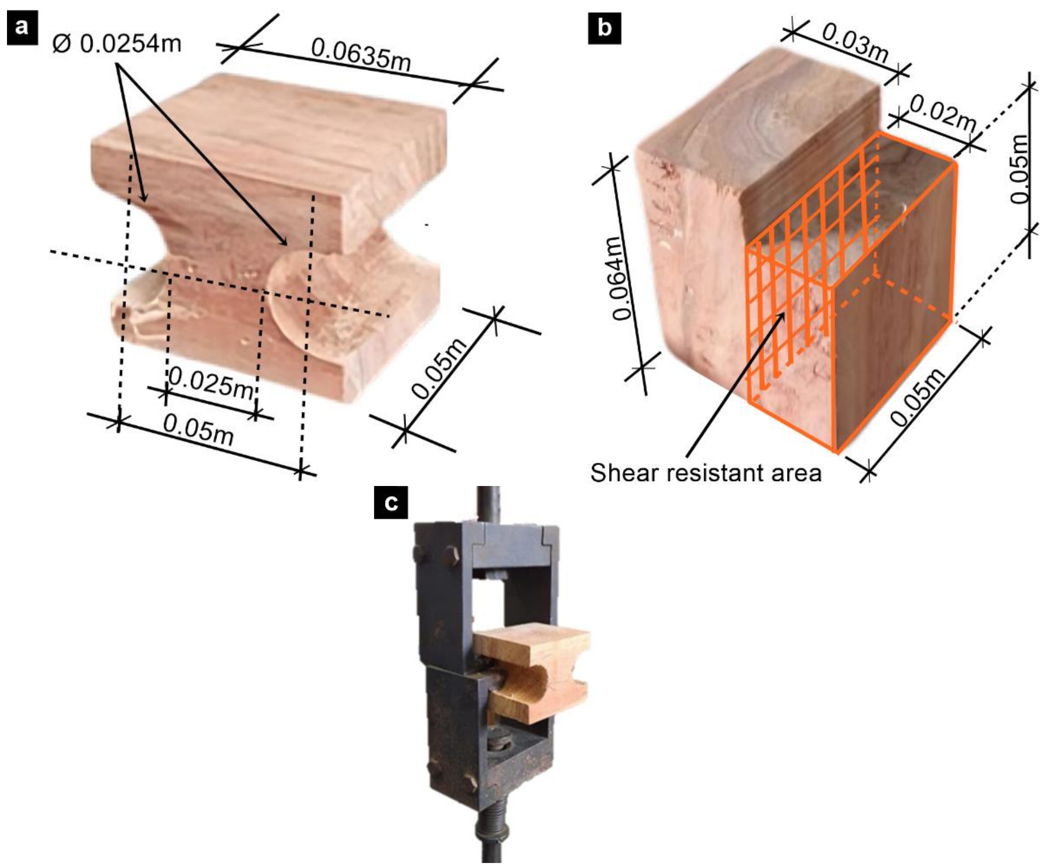

Fig. 1. Test specificities: (a) specimen to determine strength in tension perpendicular to grain; (b) specimen to determine shear strength parallel to grain; (c) difficulty in fitting the arrangement for testing in tension perpendicular to the grain

In this context, the possibility of estimating strength in tension perpendicular to grain by means of another property is considered. Starting from the premise that wood presents an essentially brittle rupture when subjected to tension perpendicular to grain (Amaruddin and Hassan 2022); the authors assumed that an interesting property for this estimation is one determined by a test causing the same brittle behavior: the strength to shear parallel to grain. Furthermore, specimen for estimating this property is simple to perform (Fig. 1b).

Therefore, this paper aimed to propose and evaluate the ratio precision $f_{t90,k}$ / $f_{v0,k}$ = α (model structure considered by ABNT NBR 7190-3:2022) for species belonging to strength classes D40 and D60 (eight wood species), which are commonly used in structural design (Fraga *et al.* 2021; Menezes *et al.* 2022a; Menezes *et al.* 2022b). A further goal was to determine whether it is possible admitting a single coefficient α for both strength classes.

EXPERIMENTAL

Materials

In this study, eight wood species of Brazilian native forest were considered (Table 1). In order to obtain the values of apparent density, strength in compression parallel to grain, strength in tension perpendicular to grain, and shear parallel to grain, 12 samples were made for each test, in accordance with requirements of Code NBR 7190-3 (ABNT 2022). In total, 384 experimental determinations were carried out.

Table 1. Scientific and Common Names of the Wood Species and their Origin

Id	Common Name	Scientific Name	Origin in Brazil (Municipality/State)
1	Goiabão	*Planchonella pachycarpa*	Caracaraí/RR
2	Louro-preto	*Ocotea sp*	Cláudia/MT
3	Maçaranduba	*Manilkara sp*	Vera/MT
4	Mandioqueira	*Qualea albiflora*	Caroebe/RR
5	Oiuchu	*Pradosia sp*	Juína/MT
6	Piolho	*Tapirira sp*	Colíder/MT
7	Quina Rosa	*Chinchona sp*	Cláudia/MT
8	Rabo-de-arraia	*Vochysia haenkeana*	Bonfim/RR

In structural engineering, it is usual that timber procurement follows classification by strength rather than by species. In this case, the utilized pieces have certified origin and fall into strength classes D40 and D60, according to NBR 7190-1:2022. Municipality of origin of each species is indicated in Table 1, concentrating on northern regions of Mato Grosso (MT) State and southern regions Roraima (RR) State, Brazil. Pieces with nominal dimensions 0.06 m x 0.16 m x 4.5 m, from which test specimens were obtained, were properly stored in the yard of Wood and Timber Structures Laboratory (LaMEM), Department of Structural Engineering (SET), School of Engineering of São Carlos (EESC), University of São Paulo (USP), for a period of six to eight months, aiming to stabilize their moisture content.

All tests were carried out at LaMEM. The moisture content of each specimen was obtained following instructions inserted in item 5.1 of NBR 7190-3 (ABNT 2022). The universal testing machine AMSLER, force capacity 250 kN, was used to obtain mechanical properties, with loading applied monotonically, increased according to requirements of the cited Code.

The samples strength values obtained in the tests were corrected for a moisture content of 12%, considered as reference condition prescriptions of item 5.6.1 of NBR 7190-1 (ABNT 2022). Subsequently, the characteristic values were calculated in accordance with the instructions of item 4.6 of NBR 7190-3 (ABNT 2022).

Statistical Method

The optimal coefficient (α) of ratio $f_{t90,k} = \alpha \cdot f_{v0,k}$ between characteristic strength values of tension perpendicular to grain and shear strength parallel to grain was determined by applying the least squares method, as follows:

$$f(\alpha) = \frac{1}{2} \cdot \sum_{i=1}^{n} \left(f_{t90,k_i} - \alpha \cdot f_{v0,k_i}\right)^2 \quad (1)$$

where $f_{t90,k}$ and $f_{v0,k}$ are the characteristic values of strength in tension perpendicular to grain and strength in shear parallel to grain, both given in MPa.

Evaluation of error associated applying Eq. 1 was elaborated considering the mean percentage absolute error (MAPE, Eq. 2) and the coefficient of variation (CV, Eq. 3),

$$MAPE(\%) = 100 \cdot \frac{1}{N} \cdot \sum_{i=1}^{N} \left\| \frac{Ypredict_i - Ydata_i}{Ydata_i} \right\| \quad (2)$$

$$CV(\%) = 100 \cdot \frac{\sqrt{\sum_{i=1}^{N} \frac{(Ypredict_i - Ydata_i)^2}{N}}}{Y_{Mean}} \quad (3)$$

where N is the number of characteristic strength values or the number of species; $Y_{predict,i}$ is the evaluated characteristic value of strength in tension perpendicular to grain (MPa); $Y_{data,i}$ is the characteristic value determined based on experiments (MPa), and Y_{Mean} is the mean of the experimentally determined characteristic values (MPa).

Furthermore, the paired t-test was performed with significance level 5% to further evaluate model accuracy [$f_{t90,k}$ / $f_{v0,k} = \alpha$]. P-value of this test equal to or greater than 0.05 implies the groups means of $f_{t90,k}$ and $\alpha \cdot f_{v0,k}$ are statistically equivalent. This circumstance highlights the appropriate adjustment of constant α, considering both strength classes together.

Topics under investigation in this paper are within a developing research area, justifying exploration of a limited number of species and utilization of statistical methods suitable for reduced availability of datasets. However, for next contributions, considering a broader variety of species, this is indispensable. So, it will be possible to expand and validate the existing results, with the goal of integrating them into future updates of the Brazilian Codes.

RESULTS AND DISCUSSION

Table 2 presents mean and extreme values (minimum – Min; maximum – Max) of coefficients of variation (CV) for: apparent density (ρ_{ap}); strength in compression parallel to grain (f_{c0}); strength in tension perpendicular to grain (f_{t90}); and shear strength parallel to grain (f_{v0}). These values refer to the eight wood species here considered. Wood moisture content ranged from 11.43% to 12.82%, requiring normative correction to the aforementioned 12%. Table 3 presents characteristic values of the strength properties as well as identification of species into the two strength classes (SC).

Table 2. Descriptive Statistics About Physical and Mechanical Properties of Wood Species

Id	Common Name	ρ_{ap} (kg/m^3)	f_{c0} (MPa)	f_{t90} (MPa)	f_{v0} (MPa)
1	Goiabão	911 (±46.46)	52.15 (±7.55)	7.26 (±1.44)	15.20 (±3.39)
2	Louro-preto	630 (±33.83)	51.23 (±7.87)	2.72 (±0.53)	12.47 (±2.69)
3	Maçaranduba	1233 (±62.39)	89.55 (±11.57)	5.54 (±1.21)	25.12 (±5.34)
4	Mandioqueira	894 (±42.20)	65.44 (±9.49)	2.83 (±0.67)	19.76 (±5.12)
5	Oiuchu	955 (±46.22)	75.22 (±9.57)	3.22 (±0.69)	17.57 (±4.37)
6	Piolho	847 (±46.25)	63.96 (±8.99)	4.59 (±0.85)	13.22 (±2.61)
7	Quina Rosa	911 (±50.74)	73.16 (±11.88)	3.67 (±0.89)	17.14 (±3.59)
8	Rabo-de-arraia	755 (±45.83)	64.07 (±7.52)	2.58 (±0.61)	15.33 (±3.19)
CV	**Min**	4.72	11.73	18.41	19.76
	Max	6.07	16.24	24.22	25.93

Note: (±standard deviation)

Table 3. Characteristic Strength Values and Insertion of Wood Species in Strength Classes of Brazilian Code NBR 7190-1 (ABNT 2022)

Id	Common Name	$f_{c0.k}$ (MPa)	SC	$f_{t90.k}$ (MPa)	$f_{v0.k}$ (MPa)
1	Goiabão	45.87	D40	3.26	11.55
2	Louro-preto	40.56	D40	2.26	9.73
3	Maçaranduba	78.69	D60	4.65	19.84
4	Mandioqueira	61.22	D60	2.37	16.40
5	Oiuchu	72.14	D60	2.83	14.76
6	Piolho	48.41	D40	2.83	11.37
7	Quina Rosa	64.76	D60	2.56	15.08
8	Rabo-de-arraia	47.24	D40	1.96	13.80

NBR 7190-3 (ABNT 2022), in item 4.3 (referred to simplified characterization), mentions a maximum coefficient of variation (*CV*) 18% and 28%, for normal and tangential efforts, respectively. As shown in Table 2, CV obtained for all properties are within normative limits, validating the batches' acceptance. Results show, in Table 3, that four species belong to class D40 and another four to class D60, as reported by the company that supplied the wood analyzed. In literature, a comparison was made between 5 of the 8 species investigated here, noting that only Mandioqueira was not classified in the same strength class (Lahr *et al.* 2021d), which may have occurred due to batches being of different origins. In Table 4, α coefficients (ratio $f_{t90,k}/f_{v0,k}=\alpha$) are presented for the set composed of strength values from classes D40, D60, and both classes together. In addition, mean absolute percentage error (*MAPE*) and coefficient of variation (*CV*) are shown.

Table 4. Results of Ratio $f_{t90,k} / f_{v0,k} = \alpha$

SC	α (coefficient)	MAPE (%)	CV (%)
D40	0.22	23.46	26.01
D60	0.19	15.81	19.24
D40 and D60	0.20	22.34	23.18

As shown in Table 4, the α coefficient of the three tested relationships were very close, as MAPE and CV. This evidences that a single coefficient could be adopted for both strength classes, which is an approach that is frequently used in structural design. Regression model results, considering both strength classes, are presented in Fig. 2, together the ratio between characteristic values of strength in tension perpendicular to grain based on experimental results ($f_{t90,k}$), and those approximated by the model ($f_{t90,k\text{-}Ap}$).

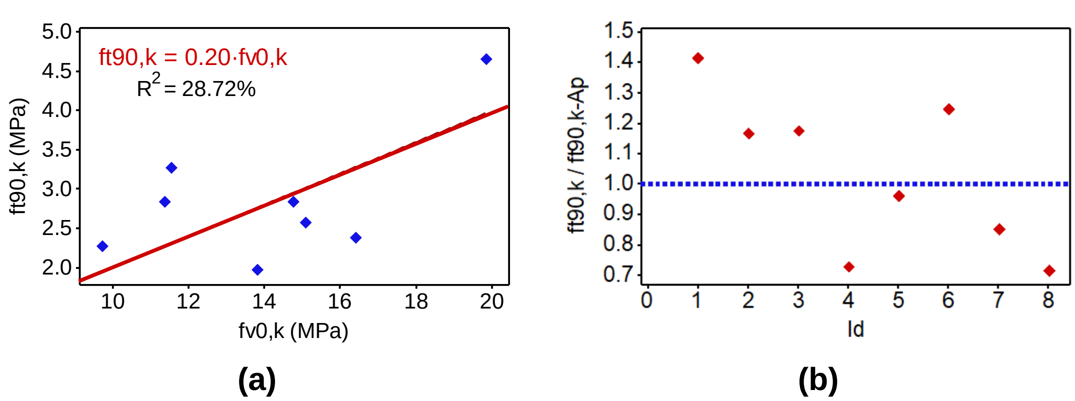

Fig. 2. Regression model results

In Fig. 2b, 50% of $f_{t90,k}$ estimated values ($f_{t90,k\text{-}Ap}$) were lower than those obtained on tests. This reveals a more conservative approach that, from a design perspective, is conducive to structural safety. Therefore, it should be noted that these estimated values must be adequately reduced by considering the coefficient γ_w, reducing the weight of coefficient of determination (R^2) of the regression model (R^2 = 28.72%).

Model precision is inherent to a set of uncertainties, such as edaphoclimatic conditions. Moreover, the anisotropic nature of wood (wherein its properties vary across different directions within the same element) further amplifies uncertainty level.

The paired t test was applied to verify the expected equivalence between $f_{t90,k}$ and $0.20 \cdot f_{v0,k}$, in order to reinforce the good precision achieved (MAPE = 22.34% and CV = 23.18%) using the model obtained. Additionally, for the regression model, the p-value= 0.137 indicates non-significance. However, applying the equation to datasets resulted in statistical equivalence between the experimental and estimated values, as indicated by p-value = 0.917, which is higher than the adopted level of significance.

The proposed equation was applied to data from literature studies that reported tensile strength perpendicular to grain and shear strength parallel to grain, focusing on Brazilian native forests. When comparing the experimental values of $f_{t,90}$ with the values estimated by the equation, the following results were obtained: 1.99 to 3.01 MPa (Morando *et al.* 2019); and 5.79 to 2.43 MPa (Aquino *et al.* 2021), respectively. Note that the proposed model lacks precision. However, the Brazilian Code utilizes other relationships between properties, even without disclosing their precision, and mitigates existing uncertainties by means of coefficients to accommodate variations in wood properties. This approach ensures preservation of safety in structural design.

Ultimately, literature gaps in the field hinder a more thorough results discussion. Nonetheless, given the ratio potential obtained for classes D40 and D60, it is reinforced that inclusion of other species in order to cover the five strength classes (NBR 7190-1:2022) is promising for defining a coefficient that estimates strength in tension perpendicular to grain through strength in shear parallel to grain. This drives new research on the topic, in order to integrate future updates of the Brazilian Code.

CONCLUSIONS

1. Wood's brittle behavior in determining both stresses here considered makes it difficult to achieve a perfect adjustment of ratio between them. Even so, the present results show that it is possible to estimate the strength in tension perpendicular to grain ($f_{t90,k}$) by knowing the shear strength parallel to grain ($f_{v0,k}$).
2. Ratios $f_{t90,k}/f_{v0,k}$ for strength classes D40 and D60 (NBR7190-1:2022) were, respectively, 0.22 and 0.19, indicating similarity between them and making it possible to adopt a single representative coefficient for both classes (α=0.20).
3. The species analyzed, even those belonging to the same strength class, showed significant variations in their physical and mechanical properties, indicating strong differences in their anatomical compositions. This point suggests a need for new studies in this matter, considering other essences of the same classes, to provide more reliability to the quantification of the ratio α.

ACKNOWLEDGMENTS

Authors are grateful to CNPq (National Council of Research), CAPES (Coordination for Improvement of Higher Education) and Pró-Reitoria de Pesquisa, Inovação e Pós-Graduação of Instituto Federal de Rondônia (PROPESP/IFRO) for supporting this research development.

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Article submitted: April 25, 2024; Peer review completed: May 25, 2024; Revised version received; July 31, 2024; Accepted: August 11, 2024; Published: August 22, 2024.
DOI: 10.15376.biores.19.4.7408-7417