# CHARACTERISTIC STRENGTHS IN THE COMPRESSION AND IN THE STATIC BENDING AS PARAMETERS TO ESTIMATE CHARACTERISTIC SHEAR STRENGTH FOR TIMBER DESIGN

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ABSTRACT – To simplify the characterization of wood species, the Brazilian standard document ABNT NBR 7190-1 (2022) establishes the determination of mechanical properties employing the characteristic strength in the compression parallel to grain ($f_{c0,k}$). This mechanical property is estimated using the linear relation given by the following expression $f_{v0,k} = 0.12 \cdot f_{c0,k}$. Brazilian and European standard documents support the estimation of $f_{v0,k}$ using relations among properties. However, the European guidelines in the EN 384 (2019) have used the conventional characteristic strength in the static bending test ($f_{M,k}$). Thus, this study aimed to investigate the efficiency of the ratio $f_{v0,k} = 0.12 \cdot f_{c0,k}$ for adopting 30 hardwoods. The variance analysis results demonstrate the divergence among the experimental outcomes and those values estimated using the relation cited. Therefore, regression models at two parameters were considered to obtain more accurate estimates of $f_{v0,k}$ by adopting $f_{c0,k}$, and $f_{M,k}$ as independent variables. Regarding the results, the geometric ($R^2$ = 80.80%) and linear ($R^2$ = 74.19%) models were the most accurate for the estimates of $f_{v0,k}$ in terms of $f_{c0,k}$, and $f_{M,k}$, respectively. This fact evinces the good accuracy of the models under consideration, which may provide a more rigorous structural design compared to the correlation currently prescribed by the ABNT NBR 7190-1 (2022).

Keywords: Brazilian hardwood; characteristic strengths; Shear strength estimates.

# *RESISTÊNCIAS CARACTERÍSTICAS NA COMPRESSÃO E FLEXÃO ESTÁTICA COMO PARÂMETROS PARA A ESTIMATIVA DA RESISTÊNCIA CARACTERÍSTICA AO CISALHAMENTO NO PROJETO DE MADEIRA*

*RESUMO – Para simplificar a caracterização de espécies de madeira, o documento normativo brasileiro ABNT NBR 7190-1 (2022) estabelece a determinação de propriedades mecânicas por meio da resistência característica na compressão paralela às fibras ($f_{c0,k}$). Essa propriedade mecânica é estimada utilizando-se da relação linear dada pela expressão a seguir $f_{v0,k} = 0.12 \cdot f_{c0,k}$. Ambos os documentos normativos europeu e brasileiro prescrevem a estimativa da $f_{v0,k}$ empregando-se relações entre propriedades, embora as diretrizes da europeia contidas na EN 384 (2019) utilize a resistência característica convencional obtida no teste de* *flexão estática ($f_{M,k}$). Assim, esse estudo teve o objetivo de investigar a eficiência da relação $f_{v0,k} = 0.12 \cdot f_{c0,k}$ para 30 espécies folhosas. Os resultados da análise de variância demonstram a divergência entre os resultados experimentais e aqueles estimados utilizando-se da relação citada. Portanto, modelos de regressão em função de dois parâmetros foram considerados para se obter estimativas mais precisas da $f_{v0,k}$ através da adoção da $f_{c0,k}$ e $f_{M,k}$ como variáveis independentes. Com relação aos resultados, os modelos geométrico ($R^2$ = 80.80%) e linear ($R^2$ = 74.19%) foram os mais precisos para a estimativa da $f_{v0,k}$ em termos da $f_{c0,k}$ e $f_{M,k}$, respectivamente. Este fato evidencia a boa precisão dos modelos em questão, o que pode proporcionar um dimensionamento estrutural mais rigoroso quando comparado à correlação atualmente prescrita pela ABNT NBR 7190-1 (2022).*

*Palavras-Chave: Madeiras folhosas brasileiras; resistências características; estimativas da resistência ao cisalhamento.*

## 1. INTRODUCTION

Due to the growing demand for efficient and sustainable buildings, wood is being considered as the forthcoming industrial resource due to greater recognitions and broader applications for the civil construction (Araujo et al., 2016; Kuzman and Sandberg, 2017; Wieruszewski and Mazela, 2017; Żmijewki and Wojtowicz-Jankowska, 2017; Nesheim et al., 2021, Niebuhr and Sieder, 2021).

In view of the excellent mechanical-strength and density relation, wood is basically a smart alternative for timber-based tall buildings, whose structure weights correspond to a high proportion of loads to be resisted (Pries and Mai, 2013; Ramage et al., 2017; Lima Jr. et al., 2018; Huber et al., 2018; Araujo, 2021). Buildings with wood-designed structures offer good performance to seismic events, as heavier structures are subjected to greater seismic forces (Ramage et al., 2017).

In addition to the efficiency of wood for structural buildings, this material is still natural, biodegradable, renewable and recyclable and therefore it is effectively an environmentally friendly solution (Wang et al., 2014; Araujo et al., 2016; Souza et al., 2018; Lima Jr. et al., 2018; Araujo, 2021). Due to efficiency of the wood as a structural element, timber construction has become the most popular, economic and practical housing solution in the Northern Hemisphere (Araujo et al., 2016). As a result, the construction of buildings with six or more floors has been observed in the last decade (Ramage et al., 2017). Expressive uses of wood are being confirmed. While wood is the main material in 80% of houses in Scotland and New Zealand, it is also applied for nearly 7% of the Brazilian residences (Mahapatra et al., 2012; Araujo et al., 2018, 2020).

Despite the evident potential for reforestation and the demand for new houses, the use of wood for housing in Brazil is practically insignificant when compared to traditional masonry buildings (Araujo et al., 2018). The lacks of qualified labor and knowledge of species and properties have contributed to the inadequate utilization of wood, resulting in the erroneous production of buildings with unexpected lifespans and misuse of material advantages (Pedreschi et al., 2005).

In this scenario, Almeida et al. (2020) argue about the importance of elaboration of studies to provide, for the Brazilian market, sufficient information about the benefits and features of timber construction and the physical and mechanical properties of lignocellulosic materials to enable the design of rational projects for timber-based structures.

In addition to prescribing procedures for dimensioning of timber structures [ABNT NBR 7190-1 (2022)], the Brazilian standard document ABNT NBR 7190-3 (2022) has established methods for the complete experimental characterization of the physical-mechanical properties of this biomaterial. In order to simplify the characterization of wood, this Brazilian normative allows the determination of mechanical properties as a function of the characteristic compression strength parallel to the grain ($f_{c0,k}$).

Among the prescribed estimates, there is the determination of characteristic shear strength parallel to the grain ($f_{v0,k}$) through the linear relation (Equation 1) between $f_{c0,k}$ and $f_{v0,k}$ values. Concerning hardwoods, the ABNT NBR 7190-1 (2022) implicitly adopts λ equal to 0.12, according to the standard calibration.

$$f_{V0,k} = \lambda . f_{c0,k} \quad \text{(Eq. 1)}$$

Due to expressive volume of native tree species cataloged in the Brazilian Amazon – around 7700 as raised by Steege et al. (2016) – every effective procedure for the characterization of wood species is highly desirable, since the economic resources can be allocated to the characterization of unfamiliar hardwoods as a strategy to promote their uses as well as reduce predatory utilization of the most usual species.

Some researchers have investigated the efficiency of relations between properties prescribed by the standard documents. In Brazil, they have considered the ABNT NBR 7190 (1997), which is the last version before the recent update to ABNT NBR 7190-1 (2022). Thus, there are studies from Lahr et al. (2017), Almeida et al. (2018) and Almeida et al. (2020) about the relations between properties of stiffness of hardwoods.

Regarding $f_{v0,k}$, Matos and Molina (2016) obtained, through tests for *Eucalyptus saligna* species, a λ equal to 0.13, whose value is close to the specifications of the ABNT NBR 7190-1 (2022). On the other hand, Christoforo et al. (2019) obtained a λ equal to 0.23 for a grouping of five hardwood species. This result is according to the experiment of Couto et al. (2020), which verified a λ equal to 0.22 for a set of 10 hardwoods, being a value approximately 80% higher than stated in ABNT NBR 7190-1 (2022). These aforementioned studies highlight the need for a review about the ratio mentioned that is still implicit in the updated Brazilian standard document through its calibration. This justification is motivated by the interest of the academic field on the correlation between mechanical properties. These studies from literature were designed making use of a reduced number of species, in which the aim was to determine only the coefficient λ for the best description of the linear relation between $f_{v0,k}$ and $f_{c0,k}$. Besides, these studies did not investigate the different regression models such as exponential, geometric and logarithmic.

Both Brazilian ABNT NBR 7190-1 (2022) and European EN 384 (2019) standards allow the determination of $f_{v0,k}$ through the correlation of properties. However, $f_{v0,k}$ values are estimated by the conventional characteristic strength in the static bending test ($f_{M,k}$). In this context, making use of a significant number of hardwood species, this study aims to investigate the statistical equivalence among the experimental values of $f_{v0,k}$ and the estimated values (Equation 1) as well as provide, in case of divergence, models of regression as a function of $f_{c0,k}$ and $f_{M,k}$, respectively.

## 2. MATERIALS AND METHODS

### 2.1 Materials

Thirty hardwood species were adopted in this study (Table 1), which were bought as normally acquired in local markets through planks – this

**Table 1 –** Scientific name and identification number (ID) of 30 tropical hardwood species.
***Tabela 1*** *– Nome científico e número de identificação (ID) de 30 espécies de folhosas tropicais.*

| ID | Brazilian Popular Name | Scientific Name | ID | Brazilian Popular Name | Scientific Name |
|---|---|---|---|---|---|
| 1 | Angelim amargoso | *Vatairea fusca* (Ducke) Ducke | 16 | Louro preto | *Ocotea neesiana* (Miq.) Kosterm. |
| 2 | Angelim ferro | *Hymenolobium* cf. *heterocarpum* Ducke | 17 | Louro verde | *Sextonia* cf. *rubra* (Mez) van der Werff |
| 3 | Angelim Saia | *Vatairea* cf. *guianensis* Aubl. | 18 | Maçaranduba | *Manilkara* cf. *inundata* (Ducke) Ducke |
| 4 | Angelim vermelho | *Dinizia excelsa* Ducke | 19 | Mandioqueira | *Qualea paraensis* Ducke |
| 5 | Castanheira | *Bertholletia excelsa* Bonpl. | 20 | Oiticica amarela | *Clarisia racemosa* Ruiz & Pav. |
| 6 | Castelo | *Calycophyllum multiflorum* Griseb. | 21 | Oiuchu | *Pradosia* sp. Liais |
| 7 | Canatudo | *Calophyllum longifolium* Willd. | 22 | Parinari | *Parinari excelsa* Sabine |
| 8 | Cedro amargo | *Cedrela odorata* L. | 23 | Pau-óleo | *Copaifera langsdorffii* Desf. |
| 9 | Cedro doce | *Cedrela cf. fissilis* Vell. | 24 | Piolho | *Tapirira* sp. Aubl. |
| 10 | Copaíba | *Copaifera multijuga* Hayne | 25 | Quarubarana | *Erisma uncinatum* Warm. |
| 11 | Cutiúba | *Goupia paraensis* Huber | 26 | Quina rosa | *Geissospermum sericeum* Miers |
| 12 | Garapa | *Apuleia leiocarpa* (Vog.) Macbr. | 27 | Rabo de arraia | *Vochysia haenkeana* Mart. |
| 13 | Goiabão | *Planchonella pachycarpa* Pires | 28 | Sucupira | *Diplotropis* sp. Benth. |
| 14 | Itaúba | *Mezilaurus itauba* (Meisn.) Taub. ex Mez | 29 | Tachi | *Tachigali glauca* Tul. |
| 15 | Jatobá | *Hymenaea courbaril* L. | 30 | Umirana | *Ruizterania retusa* (Spruce ex Warm.) Marc.-Berti |

Source: Flora of Brazil (2020).
*Fonte: Plantas do Brasil (2020).*

consideration reflected the way in which wood has been used/obtained for structural purposes in the Brazilian construction. Thus, age and origin of the tropical trees were not identified due to the lack of information.

### 2.2 Methods

Experimental tests were carried out in the dependences of the Laboratory of Wood and Timber Structures (LaMEM) of the University of São Paulo (USP), São Carlos, Brazil. For that, it was adopted twelve specimens per species and mechanical property under investigation, which resulted in 1080 experimental determinations. The extraction of specimens was executed with dimensions of specimens in millimeters for testing and obtainment of sampling values of bending ($f_M$), compression ($f_{c0}$) and shear ($f_{v0}$) strength along the direction parallel to the grain.

After testing, values of $f_{c0}$, $f_{v0}$ e $f_m$ were determined (Equations 2, 3 and 4) for each specimen, according to ABNT NBR 7190-3 (2022).

$$f_{c0} = \frac{F_{c0,max}}{A} \quad \text{(Eq. 2)}$$

$$f_{v0} = \frac{F_{v0,max}}{A_{v0}} \quad \text{(Eq. 3)}$$

$$f_M = \frac{M_{max}}{W_e} \quad \text{(Eq. 4)}$$

Where, $F_{c0,max}$, $F_{v0,max}$, $A$, $A_{v0}$, $M_{max}$ and $W_e$, represent, respectively, the maximum force in the compression, maximum shear force, initial area of transversal section of specimen for compression, initial area of critical section of specimen for shear stress, maximum bending moment from static test, and modulus of transversal section of static bending specimen. According to the prescriptions from the ABNT NBR 7190-3 (2022), the load was applied monotonically increasing at 10 MPa/min for static bending and compression tests and at 2.5 MPa/min for shear stress test.

Specimens were tested with moisture content (MC) at 12% since it is prescribed by the ABNT NBR 7190-3 (2022) as the equilibrium moisture content (EMC). However, for those that did not achieve the EMC, the strengths were corrected as recommended by the Brazilian standard (Equation 5).

$$f_{12\%} = f_{MC} \cdot \left[1 + \frac{3 \cdot (MC - 12)}{100}\right] \quad \text{(Eq. 5)}$$

In this equation, $f_{12\%}$ and $f_{MC\%}$ are the strength at 12% and at a certain moisture content, respectively.

To determine the characteristic strength ($f_{w,k}$ - $f_{c0,k}$, $f_{v0,k}$ and $f_{M,k}$), all sampled values at 12% MC were sorted in ascending order ($f1 \leq f2 \leq f3 \ldots \leq f_n = f12$). Then, according to ABNT NBR 7190-1 (2022), $f_{w,k}$ was taken as the highest value among $f1$ and those values obtained through relations (Equations 6 and 7) given by the code.

$$f_{w,k} = f_m \cdot [1 - 1.645.\delta] \approx 0.70 \cdot f_m \quad \text{(Eq. 6)}$$

$$f_{w,k} = \left[2 \cdot \frac{f_1 + f_2 + f_3 + \ldots + f_{(n/2)-1}}{(n/2)-1} - f_{n/2}\right] \cdot 1.10 \quad \text{(Eq. 7)}$$

In which, $f_m$ is the average value of sampled strengths and $\delta$ represents the coefficient of variation of samples. In favor of safety, the ABNT NBR 7190-1 (2022) admits that strengths have normal distributions and $\delta$ does not exceed 18%. Although the present study seeks to estimate $f_{v0,k}$ through $f_{M,k}$ as considered by the European standard document EN 384 (2019), the sample dimensions, laboratory procedures and equations to determine characteristic strengths were used in accordance to the Brazilian standard document ABNT NBR 7190-1 (2022) for purposes of comparing results.

In order to verify the effectiveness of the estimation of $f_{v0,k}$ in terms of $f_{c0,k}$ (Equation 1), the analysis of variance (ANOVA) at 5% significance was adopted. Null hypothesis ($H_0$) was featured by the equivalence among experimental and calculated values ($f_{v0,k}$ and $0.12 \cdot f_{c0,k}$) of the thirty species, while the alternative hypothesis ($H_1$) was based on the no equivalence situation. With P-value greater than or equal to the significance level adopted (P-value $\geq$ 0.05), the $H_0$ is accepted, then the estimate (Equation 1) offers good estimation for $f_{v0,k}$. In the P-valor < 0.05, $H_1$ is adopted otherwise and, therefore, equations that are more precise must be determined.

In case of $H_1$ is true, models of regression (Equations 8 to 11) were further adopted to estimate $f_{v0,k}$ (dependent variable - y) of the thirty species in terms of $f_{c0,k}$ and $f_{M,k}$ (independent variables - x), respectively. Then, these equations were analyzed through analysis of variance at a 5% significance level with respect to the prediction of experimental results.

$$y = a + b.\,x \text{ [Linear]} \quad \text{(Eq. 8)}$$

$y = a \cdot e^{bx}$ [Exponential] (Eq. 9)

$y = a + b \cdot in(x)$ [Logarithmic] (Eq. 10)

$y = a \cdot x^b$ [Geometric] (Eq. 11)

In which, *a* and *b* are parameters of models, which are adjusted by the method of least squares. Thereby, two hypotheses were formulated: null ($H_0$) and alternative ($H_1$). $H_0$ is accepted if P-value is superior to the significance level (P-valor > 0.05), which implies that the model under test is not representative (variations of *x* are not able to explain the variations of *y*). For P-value ≤ 0.05, $H_0$ is accepted otherwise, that is, the tested model is representative.

In order to assess the quality of adjustments, the values of the coefficient of determination ($R^2$) were determined for each model, which allows selecting those representative situations (P-value ≤ 0.05) with better estimates. Finally, normality test of Anderson-Darling was executed to validate the distribution of values.

## 3. RESULTS

Results for characteristic strengths ($f_{v0,k}$, $f_{c0,k}$ and $f_{M,k}$) [Table 2] were obtained in accordance with the ABNT NBR 7190-1 (2022) for thirty hardwoods studied (Table 1).

Hardwood species studied (Table 2) included all strength classes (C20, C30, C40, C50 and C60) prescribed by ABNT NBR 7190-1 (2022), which evinces the broad scope and relevance of the results. Thereby, two hardwoods were classified as C20 (cedro doce and quarubarana), two species as C30 (castanheira and cedro amargo), seven species as C40 (angelim amargoso, copaíba, goiabão, louro verde, pau-óleo, piolho and rabo de arraia), seven as C50 (angelim saia, castelo, canatudo, cutiúba, louro preto, parinari and umirana) and twelve species as C60 (angelim ferro, angelim vermelho, garapa, itaúba, jatobá, maçaranduba, mandioqueira, oiticica amarela, oiuchu, quina rosa, sucupira and tachi).

In the sequence, the results of ANOVA at 5% significance and the normality test of Anderson-Darling to evaluate the $f_{v0,k}$ in terms of $f_{c0,k}$ (Equation 1) are also presented. It was possible to see that the groups of values – $f_{v0,k}$ (experimental values) and $f_{v0,k}$ (Equation 1) – are not equivalent (P-Value = 0.000), indicating an inaccuracy of $f_{v0,k}$ (Equation 1) from the ABNT NBR 7190-1 (2022). Subsequently, results of Anderson-Darling test confirmed the assumption of normal distribution of data with P-value equal to 0.960.

As an alternative to the Brazilian ratio (Equation 1), the adjustments (Figure 1) were obtained through the regression models (Equations 8 to 11) for the estimate of $f_{v0,k}$ in terms of $f_{c0,k}$ considering the thirty hardwoods described (Table 1).

As result, all adjustments (Figure 1) were significant (P-value < 0.05), which suggests that

**Table 2 –** Results of $f_{c0,k}$, $f_{v0,k}$ and $f_{M,k}$ of 30 hardwoods studied.
***Tabela 2*** *– Resultados da $f_{c0,k}$, $f_{v0,k}$ and $f_{M,k}$ das 30 espécies estudadas.*

| ID* | $f_{c0,k}$(MPa) | $f_{v0,k}$(MPa) | $f_{M,k}$(MPa) | ID* | $f_{c0,k}$(MPa) | $f_{v0,k}$(MPa) | $f_{M,k}$(MPa) |
|---|---|---|---|---|---|---|---|
| 1 | 47.52 | 12.76 | 78.76 | 16 | 50.60 | 10.40 | 83.16 |
| 2 | 76.03 | 17.20 | 88.73 | 17 | 49.14 | 9.77 | 85.74 |
| 3 | 51.06 | 12.10 | 76.70 | 18 | 79.46 | 20.77 | 125.80 |
| 4 | 72.73 | 13.35 | 90.24 | 19 | 61.53 | 14.34 | 80.78 |
| 5 | 38.93 | 7.04 | 46.61 | 20 | 62.41 | 15.18 | 90.49 |
| 6 | 54.54 | 15.55 | 99.92 | 21 | 72.34 | 14.63 | 89.17 |
| 7 | 50.91 | 12.30 | 58.17 | 22 | 55.22 | 12.01 | 86.57 |
| 8 | 33.18 | 8.56 | 55.53 | 23 | 45.06 | 10.62 | 63.07 |
| 9 | 29.99 | 7.13 | 39.69 | 24 | 43.74 | 12.39 | 53.05 |
| 10 | 44.13 | 10.25 | 71.65 | 25 | 27.20 | 6.70 | 59.07 |
| 11 | 55.28 | 12.63 | 88.83 | 26 | 61.60 | 11.37 | 99.44 |
| 12 | 65.36 | 16.28 | 103.18 | 27 | 44.79 | 9.30 | 55.43 |
| 13 | 43.10 | 12.14 | 91.12 | 28 | 90.46 | 17.42 | 120.34 |
| 14 | 68.44 | 16.32 | 95.30 | 29 | 75.46 | 14.54 | 98.49 |
| 15 | 89.96 | 23.08 | 133.56 | 30 | 51.28 | 9.83 | 48.09 |

* ID is the identification of each hardwood cataloged in the Table 1 for this representative research.
Source: Author's data.
**ID é a identificação de cada espécie folhosa catalogada na Tabela 1 para a pesquisa de representatividade.*
*Fonte: Dados do autor.*

Source: Author’s data.
*Fonte: Dados do autor.*

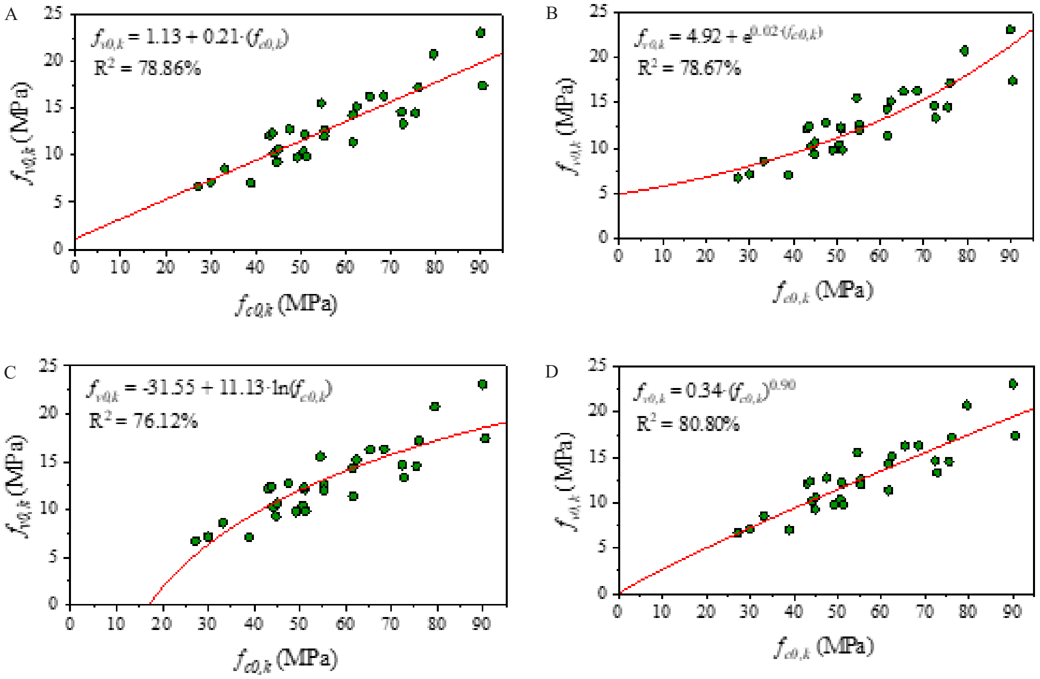


**Figure 1 –** Regression models to estimate $f_{v0,k}$ in terms of $f_{c0,k}$: (a) linear; (b) exponential; logarithmic (c); and (d) geometric.
***Figura 1** – Modelos de regressão para se estimar $f_{v0,k}$ em termos da $f_{c0,k}$: (a) linear; (b) exponencial; logarítmico (c); e (d) geométrico.*

Source: Author’s data.
*Fonte: Dados do autor.*

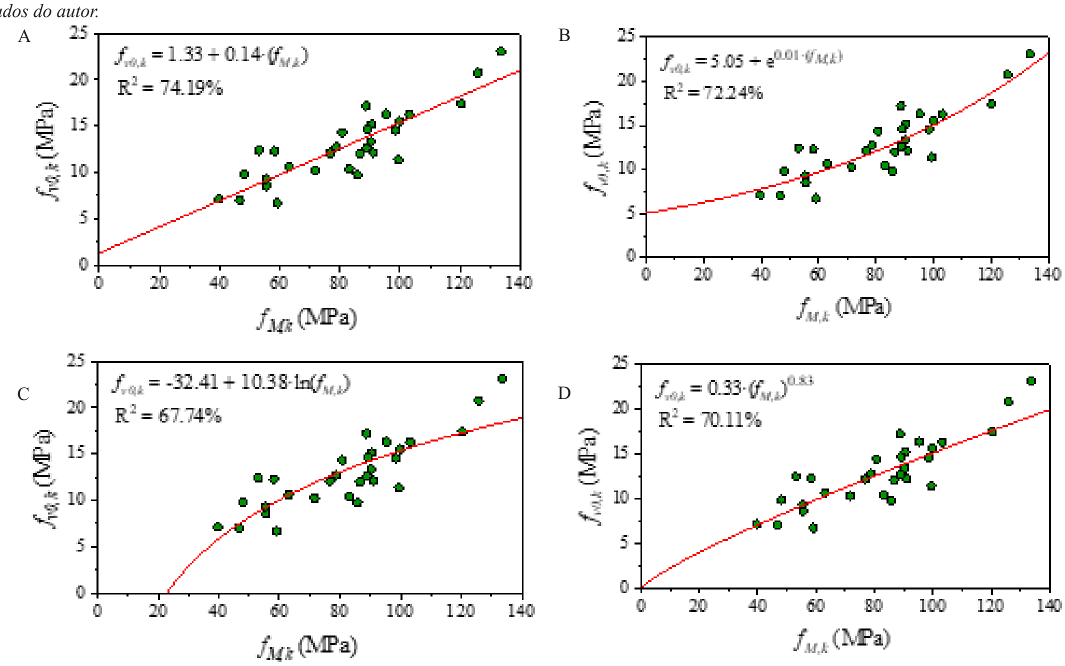


**Figure 2 –** Models of regression to estimate $f_{v0,k}$ from $f_{M,k}$: (a) linear; (b) exponential; logarithmic (c); and (d) geometric.
***Figura 2** – Modelos de regressão para se estimar $f_{v0,k}$ a partir da $f_{M,k}$: (a) linear; (b) exponencial; logarítmico (c); e (d) geométrico.*

variations of $f_{c0,k}$ are able to explain the variations of $f_{v0,k}$. Among the models under consideration, the geometric model (Figure 1D, Equation 12) is the most accurate option, with $R^2$ equal to 80.80%.

$$f_{v0,k} = 0.34 \cdot (f_{c0,k})^{0.90} \quad \text{(Eq. 12)}$$

In the sequence, results of adjustment (Figure 2) were obtained from the models of regression (Equations 8 to 11) in the estimation of $f_{v0,k}$ through $f_{M,k}$.

Analogously to the models of regression considering $f_{c0,k}$ (Figure 1), all tested adjustments through the consideration of $f_{M,k}$ for estimation of $f_{v0,k}$ were significant (P-value < 0.05). Therefore, variations of $f_{M,k}$ are able to explain those variations of $f_{v0,k}$. Concerning the models, the linear one (Figure 2A) is the more accurate, with ($R^2$ = 74.19%).

$$f_{v0,k} = 1.33 + 0.14 \cdot (f_{M,k}) \quad \text{(Eq. 13)}$$

In order to measure any errors from the estimates of $f_{v0,k}$ (Equations 1, 12 and 13), a calculation (Equation 14) was used, since this compared $f_{v0,k}^{(experimental)}$ and $f_{v0,k}^{(estimated)}$. Then, errors (Table 3) were identified for each wood species under consideration. From, the three estimates (1, 12 and 13) demonstrated, in percentage, average errors were of 46.90%, 10.80% e 12.77%, respectively.

$$Er(\%) = 100 \cdot \frac{\left| f_{v0,k}^{(experimental)} - f_{v0,k}^{(estimated)} \right|}{\left| f_{v0,k}^{(experimental)} \right|} \quad \text{(Eq. 14)}$$

## 4. DISCUSSION

With respect to ANOVA result that revealed the Brazilian ratio to be inaccurate to estimate $f_{v0,k}$, this is in line with results presented in Christoforo et al. (2019) and Couto et al. (2020), but not in accordance with Matos and Molina (2016). The reason why this last work does not agree to the results herein found out may be due the fact that only one species was investigated, and given the natural variability of wood, it was not representative.

Regarding the estimate of $f_{v0,k}$ as a function of $f_{c0,k}$, results (Figure 1) pointed to geometric model as the most accurate equation ($R^2$ = 80.80%.). This type of regression is not in accordance to the linear equation adopted in ABNT NBR 7190-1 (2022). It is worth mentioning that even when comparing the normative linear ratio to the linear regression found out ($R^2$ = 78.86%), the second is much more accurate, which emphasizes the poor prediction power of the normative one.

Results presented concerning $f_{v0,k}$ estimated in terms of $f_{M,k}$ (Figure 2) confirms that the linear regression ($R^2$ = 74.19%) was the more accurate equation determined, being in accordance to the regression type prescribed by the European standard EN 384 (2019) that utilizes $f_{M,k}$ as independent variable. Besides, both exponential and geometric regression also presented $R^2$ larger than 70%.

**Table 3 –** Percentage errors from the estimate of $f_{v0,k}$ using models (Equations 1, 12 and 13).
***Tabela 3*** *– Erros percentuais da estimativa da $f_{v0,k}$ ao se utilizar os modelos (Equações 1, 12 e 13).*

| ID | Er (%) (Equation 1) | Er (%) (Equation 12) | Er (%) (Equation 13) | ID | Er (%) (Equation 1) | Er (%) (Equation 12) | Er (%) (Equation 13) |
|---|---|---|---|---|---|---|---|
| 1 | 55.31 | 13.94 | 3.16 | 16 | 41.62 | 11.73 | 24.73 |
| 2 | 46.96 | 2.54 | 20.05 | 17 | 39.64 | 15.84 | 36.47 |
| 3 | 49.36 | 3.18 | 0.26 | 18 | 54.09 | 16.02 | 8.80 |
| 4 | 34.62 | 20.65 | 4.60 | 19 | 48.51 | 3.37 | 11.86 |
| 5 | 33.64 | 30.37 | 11.58 | 20 | 50.66 | 7.54 | 7.78 |
| 6 | 57.91 | 20.05 | 1.49 | 21 | 40.66 | 9.57 | 5.58 |
| 7 | 50.33 | 5.01 | 22.98 | 22 | 44.83 | 4.67 | 11.99 |
| 8 | 53.49 | 7.15 | 6.36 | 23 | 49.08 | 1.43 | 4.33 |
| 9 | 49.53 | 1.78 | 3.41 | 24 | 57.64 | 17.74 | 29.32 |
| 10 | 48.34 | 0.23 | 10.84 | 25 | 51.28 | 0.80 | 43.28 |
| 11 | 47.48 | 0.37 | 9.00 | 26 | 34.99 | 21.99 | 34.14 |
| 12 | 51.82 | 10.13 | 3.10 | 27 | 42.21 | 11.96 | 2.26 |
| 13 | 57.40 | 17.15 | 16.04 | 28 | 37.69 | 12.52 | 4.35 |
| 14 | 49.68 | 6.56 | 10.10 | 29 | 37.72 | 14.51 | 3.98 |
| 15 | 53.23 | 15.49 | 13.22 | 30 | 37.40 | 19.64 | 17.98 |

Source: Author's data.
*Fonte: Dados do autor.*

Concerning errors calculated for estimations (Equations 1, 12 and 13) in comparison to the experimental results, outcome evinces the good accuracy of the estimates of $f_{v0,k}$ using the proposed models of regression, especially when being estimated as a function of $f_{c0,k}$. Then, $f_{c0,k}$ showed to be a more precise variable than $f_{M,k}$, which is recommended by EN 384 (2019).

This better accuracy of $f_{v0,k}$ through $f_{c0,k}$ (Brazilian standard) may be explained by anatomical differences between hardwood and softwood, since the correlation given in EN 384 (2019) is purposely calibrated for the last one, and there is no available estimate for hardwoods. However, as already claimed, the good accuracy of the European estimate makes it useful for Brazilian hardwoods as well.

## 5. CONCLUSION

The analysis of variance revealed the divergence between $f_{v0,k}$ (experimental) and $0.12 \cdot f_{c0,k}$ groups, since the model (Equation 1) currently admitted in the calibration of the Brazilian standard ABNT NBR 7190-1 (2022) does not give accurate estimates of $f_{v0,k}$.

All models of regression applied for the estimate of $f_{v0,k}$ through $f_{c0,k}$ and $f_{M,k}$ were significant. The suggested models (Equations 12 and 13) showed a wider coverage of shear strength due to the very representative number of hardwood species under evaluation in this study.

In the estimate of $f_{v0,k}$, when compared to the model (Equation 1) given implicitly by ABNT NBR 7190-1 (2022), the suggested models (Equations 12 and 13) provide relatively lower errors. This finding indicates the good accuracy of the models proposed, which lead to a more accurate structural design when compared to the current correlation admitted in the Brazilian standard. Therefore, results found out justifies the adoption of these ratios/correlations in the future update of normative recommendations.

## AUTHOR CONTRIBUTIONS

Conceptualization: Almeida JPB, Christoforo AL, Lahr FAR, Wolenski ARV; Performed the experimental tests: Almeida JPB, Molina JC, Rodrigues EFC; Statistical analysis: Christoforo, AL, de Araujo VA, Panzera TH, de Campos CI; Analysis of results: Almeida JPB, Christoforo AL, de Araujo VA, Panzera TH, de Campos CI, Lahr FAR; Writing-review & editing: Almeida JPB, Molina JC, Rodrigues EFC, Wolenski ARV; Supervision and coordination of research; Christoforo AL, Lahr FAR.

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