

## Article

# Influence of Test Method on the Determination of Tensile Strength Perpendicular to Grain of Timber for Civil Construction

Rodrigo de Souza Nogueira <sup>1,\*</sup>, Fabiana Yukiko Moritani <sup>2</sup>, André Luis Christoforo <sup>3</sup>, Sergio Neves Monteiro <sup>4</sup>, Afonso Rangel Garcez de Azevedo <sup>5</sup>, Herisson Ferreira dos Santos <sup>6</sup> and Francisco Antonio Rocco Lahr <sup>1</sup>

- <sup>1</sup> Department of Structural Engineering, São Carlos School of Engineering, University of São Paulo, Av. Trabalhador São Carlense, 400 Centro, São Carlos 13566-590, SP, Brazil; frocco@sc.usp.br
- <sup>2</sup> Department of the Civil Engineering (FCTUC), University of Coimbra, Rua Luís Reis Santos-Pólo II, 3030-788 Coimbra, Portugal; fabianamoritani@gmail.com
- <sup>3</sup> Department of the Civil Engineering—UFSCAR, Federal University of São Carlos, Rodovia Washington Luís, km 235-SP-310, São Carlos 13565-905, SP, Brazil; christoforoal@yahoo.com.br
- <sup>4</sup> Materials Science Department, Military Institute of Engineering (IME), Praça General Tibúrcio, 80 Urca, Rio de Janeiro 22290-270, RJ, Brazil; sergio.neves@ime.eb.br
- <sup>5</sup> Civil Engineering Laboratory (LECIV), Science and Technology Center, North Fluminense State University Darcy Ribeiro, Av. Alberto Lamego, 2000-Parque Califórnia, Campos dos Goytacazes 28013-602, RJ, Brazil; afonso@uenf.br
- <sup>6</sup> Campus of Ariquemes, Federal Institute of Education, Science and Technology of Rondônia (IFRO), Av. Juscelino Kubitschek, 2717-2853 Setor Industrial, Ariquemes 76870-000, RO, Brazil; herisson.santos@ifro.edu.br
- \* Correspondence: rodrigossouzan@hotmail.com

**Abstract:** Tensile perpendicular to grain is an important mechanical property in the design of joints in timber structures. However, according to the standards, this strength can be determined using at least two different methods: uniaxial tensile and three-point static bending. In this context, the present paper aims to investigate the influence of these test methods on the determination of tensile strength perpendicular to grain of wood used in civil construction timber. Three wood species from Brazilian planted forests (*Pinus* spp., *Eucalyptus saligna*, and *Corymbia citriodora*) were used in this investigation. Twelve specimens of each species were used for each test method investigated. Moreover, a statistical analysis was performed to propose an adjustment to the equation of the Code of International Organization for Standardization 13910:2014 for the three-point bending test. Tensile strength values perpendicular to grain obtained from the uniaxial tensile test were significantly higher than those determined by the three-point bending test. It is proposed that the tensile strength perpendicular to grain can be determined more precisely with adoption of coefficient 5.233 in the term  $[(3.75 \cdot \text{Fult})/b \cdot \text{Lh}]$  of the equation specified by the Code of International Organization for Standardization 13910:2014 for the three-point bending test.

**Keywords:** tensile perpendicular to grain; three-point bending test; uniaxial tensile test; species from planted forests; nonlinear regression models



**Citation:** Nogueira, R.d.S.; Moritani, F.Y.; Christoforo, A.L.; Monteiro, S.N.; de Azevedo, A.R.G.; dos Santos, H.F.; Lahr, F.A.R. Influence of Test Method on the Determination of Tensile Strength Perpendicular to Grain of Timber for Civil Construction. *Materials* **2024**, *17*, 4506. <https://doi.org/10.3390/ma17184506>

Academic Editor: Ping Xiang

Received: 8 August 2024

Revised: 7 September 2024

Accepted: 11 September 2024

Published: 13 September 2024



**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

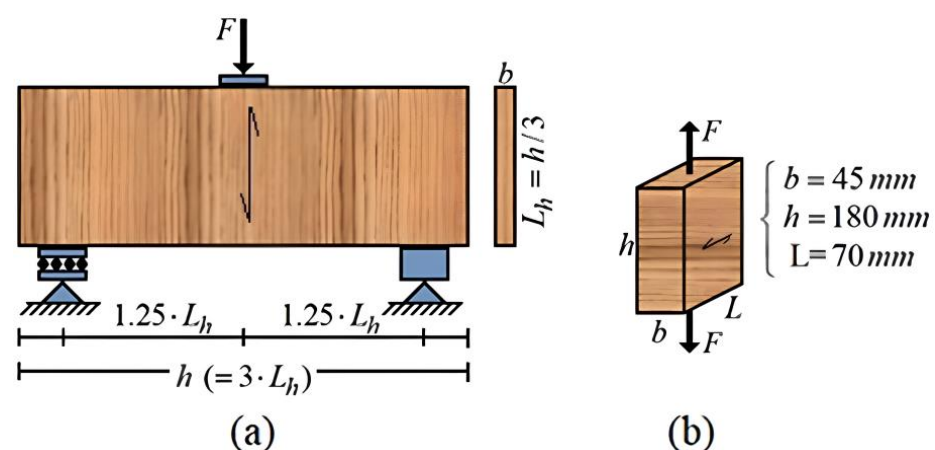
Building materials most commonly used in structural systems are concrete, steel, timber, and masonry (brick or block). However, timber is gaining more attention due to its desirable properties related to sustainability, energy efficiency, speed of construction, and high seismic capacity [1]. In addition, timber contributes to the environment preservation through carbon mitigation. Indeed, carbon is sequestered from atmosphere during the tree's development, and only a portion of the carbon is lost to atmosphere once the tree and its wooden products reach the end of their usage [2]. Timber, as a building material, has a higher strength-to-density ratio than reinforced concrete and steel [3,4]. Moreover,

timber also exhibits a lower energy-to-strength ratio compared to reinforced concrete and steel, with the advantage that the energy used for growing trees comes from sunlight [3].

Planted forests with introduced species, such as pine trees in Brazil, can contribute to carbon sequestration and supply raw materials for civil construction. Globally, planted forests in 2020 represented about 7% of the total forest area (4.06 billion ha) [5]. In South America, 97% of the planted forests in 2020 consisted of introduced species [5]. According to Brazilian Tree Industry (IBÁ) [6], in 2018, *Pinus* and *Eucalyptus* were the genera most cultivated in Brazilian country. In addition, these two genera represented 92.46% of the total planted forest area in Brazil [6]. Therefore, knowledge of mechanical properties of timber is essential for its application as a structural element in construction. Thus, research works were developed in order to characterize the mechanical properties of various wood species [7–12].

Timber exhibits different mechanical properties among its wood grain directions as a result of its anisotropy. However, criteria codes for timber structures are based on load position relative to wood grain in structural elements [13,14]. An important mechanical property in the design of timber structures, which can lead to their collapse due to local stresses perpendicular to grain at certain joints, is the tensile perpendicular to grain [15]. Such failure may occur at a lower force level in joints of joist hangers, glued-in bolts, punched metal plate fastener joints and joints with dowels or rings, as well as shear plate connectors [15]. In addition, this mechanical property is used in the design of double tapered, curved, and pitched cambered beams [13]. Research works determined the value of this mechanical property for various timber species [8,9,12] and engineered wood products [16–18]. The tensile strength perpendicular to grain can be determined by different test methods as uniaxial tensile [19–22] and three-point static bending [20,23,24]. Tannert et al. [25] investigated the tensile strength perpendicular to grain in samples of *Pinus radiata* and laminated veneer lumber made from *Pinus radiata* using various test methods. The test procedures employed were ASTM D143-21 [19], EN 408 [21], and AS/NZS 4063 [23]. The authors also determined the Weibull distribution parameters based on the results of tensile tests perpendicular to grain [25].

Code ISO/FDIS 13910 [20] establishes two test methods for determining the tensile strength perpendicular to grain ( $f_{t,90}$ ): three-point bending (Figure 1a, Method A) and uniaxial tensile (Figure 1b, Method B). Calculation model for obtaining of  $f_{t,90}$  is given in Equation (1) for a three-point bending test (Figure 1a).



**Figure 1.** Test models for determining tensile strength perpendicular to grain ( $f_{t,90}$ ) transcribed from the ISO/FDIS 13910 [20]—(a) method A; (b) method B.

$$f_{t,90} = \left( \frac{3.75 \cdot F_{ult}}{b \cdot L_h} \right) \cdot \left( \frac{0.03 \cdot b \cdot L_h^2}{800^3} \right)^{0.20} \quad (1)$$

In Equation (1),  $F_{ult}$  is the value of the applied force at failure (N), and  $b$  and  $L_h$  the specimen thickness (smaller dimension of the cross-section in mm) and width (larger dimension of the cross-section in mm), respectively. In addition, the relation existing between length and width of the cross-section should be noted, as illustrated in Figure 1a.

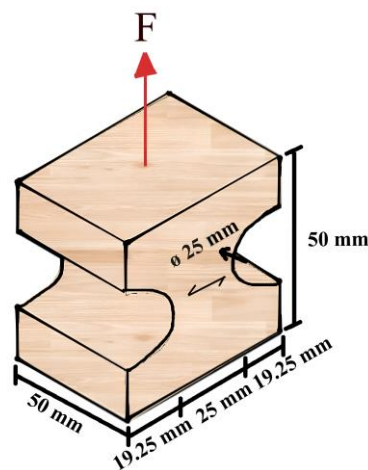
The first term on the right side of Equation (1) represents the shear stress obtained from classical theory of mechanics of materials, adjusted by an amplification factor of five times. Such a factor of shear stress is due to the specimen dimensions, which cannot be considered as a one-dimensional element (long beam—classical theory of the mechanics of materials), but as a bi-dimensional element (deep beam—theory of elasticity) [26].

Since there is no established relationship between thickness and other dimensions of the specimen to be manufactured (only between length and width), its prismatic geometry, Figure 1a, may have a thickness close to one of the other two measurements [27]. Under these conditions, the surface element is now represented as a volume element. In this, the first term on the right side of Equation (1) was multiplied by a factor responsible to normalize the strength to a value similar to that obtained from a timber cube with 800 mm edges.

The  $f_{t,90}$  is determined by means of Equation (2) for uniaxial tensile test or Method B [20]. A similar equation is considered in ABNT NBR 7190-3 [22], ASTM D143-21 [19], and BS EN 408:2010+A1 [21]. In Equation (2),  $F_{t,90,max}$  is the value of the applied force at failure (N), and  $A_{t90}$  is the cross-section area in the central region of specimen ( $\text{mm}^2$ ) (Figure 1b).

$$f_{t,90} = \frac{F_{t,90,max}}{A_{t90}} \quad (2)$$

The main distinction evidenced among ASTM D143-21 [19]; ABNT NBR 7190-3 [22]; and ISO/FDIS 13910 [20] for the uniaxial tensile test is in the format and dimensions of the specimen. Figure 2 shows the specimen format and dimensions adopted for the tensile test perpendicular to grain in accordance with ASTM D143-21 [19] and ABNT NBR 7190-3 [22].



**Figure 2.** Geometry and size of specimens of the uniaxial tensile test according to ASTM D143-21 [19] and ABNT NBR 7190-3 [22].

Brazilian Code ABNT NBR 7190-4 [24] proposes the three-point bending test to determine the tensile strength perpendicular to grain of wood from a planted forest. Thus, studies are required to confirm the accuracy of the expression associated with the test methods to determine wood mechanical properties once the Brazilian Code ABNT NBR 7190-4 [24] is based on ISO/FDIS 13910 [20], which was developed for different wood species and edaphoclimatic conditions.

The purpose of this research was to evaluate the possible differences among the tensile strength values perpendicular to grain obtained from a three-point static bending test recommended by ISO/FDIS 13910 [20] and also by Brazilian Code ABNT NBR 7190-4 [24] (for

planted forest species), as compared to the mechanical property determined by a uniaxial tensile test [19,22]. For this aim, three wood species from Brazilian planted forests (*Pinus* spp., *Eucalyptus saligna*, and *Corymbia citriodora*) were used in the experimental program.

## 2. Materials and Methods

### 2.1. Materials

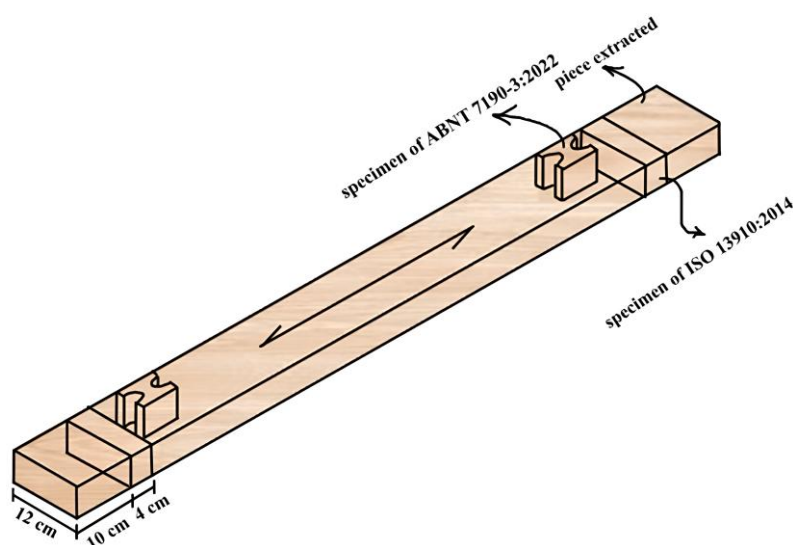
In order to investigate the influence of test methods on tensile strength perpendicular to grain, three timber species from planted forests were selected for this research. The selected timber species were *Pinus* spp., *Eucalyptus saligna*, and *Corymbia citriodora*. Six boards of each species were obtained from a sawmill located in the São Carlos, São Paulo, Brazil, for the production of the specimens. The *Pinus* spp. trees were cut at approximately 16 years, whereas the *Eucalyptus saligna* and *Corymbia citriodora* trees were cut at approximately 20 years. Moreover, the planted forest of *Pinus* spp. was located in the Parana, Brazil, while the planted forests of *Eucalyptus saligna* and *Corymbia citriodora* were located in the São Paulo, Brazil. The green timber boards arrived at the laboratory clear of defects. These green timber boards were stored under ambient temperature and ambient relative humidity to achieve a moisture content close to 12% prior to sample preparation. Table 1 provides information about the timber boards used to prepare the specimens.

**Table 1.** Features and nominal dimensions of timber boards.

Wood Species	Number of Boards	Width (mm)	Thickness (mm)	Length (cm)	Mean Density (kg/m <sup>3</sup> )
<i>Pinus</i> spp.	6	120	50	200	589.96 (64.3) <sup>1</sup>
<i>Eucalyptus saligna</i>	6	120	50	200	738.21 (114.6)
<i>Corymbia citriodora</i>	6	120	50	200	916.64 (40.5)

<sup>1</sup> Values in brackets correspond to the standard deviation.

Two types of specimens were cut from timber boards for tensile tests perpendicular to grain. In total, twelve specimens of each species were prepared for each test method. This sample size was determined based on the Brazilian standard ABNT NBR 7190-3 [22], which allows for this number to characterize the strength of lesser-known species. Initially, a 10 cm length was extracted from each end of the timber boards prior to samples preparation, as shown in Figure 3. After this extraction, the samples were taken from both ends of the timber boards, as shown in Figure 3.



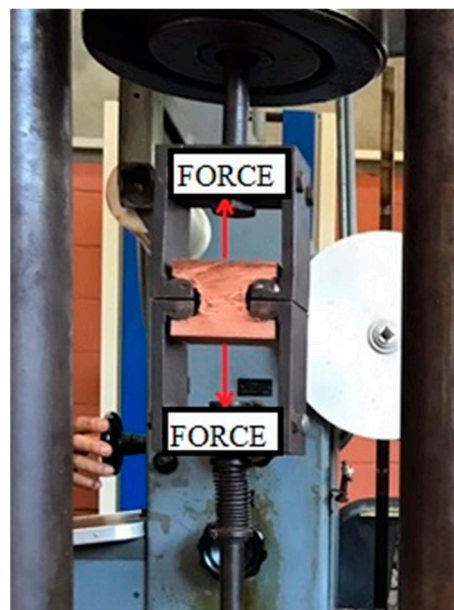
**Figure 3.** Region from extractions of specimens.

## 2.2. Test of Tensile Strength Perpendicular to Grain

Tensile tests perpendicular to grain were carried out according to the ABNT NBR 7190-3 [22] and ISO 13910 [20] in order to verify the difference in the strength values and failure modes of the specimens between these two methods.

### 2.2.1. ABNT NBR 7190-3

In order to determine tensile perpendicular to grain of specimens from the three investigated planted forest species, tests were carried out as per ABNT NBR 7190-3 [22]. Experimental tests were performed at room temperature (RT). A universal testing machine (AMSLER) with a force capacity of 250 kN was used to apply the tensile force. The experimental setup is represented in Figure 4. The force was applied at a constant rate of about 2.5 MPa/min until specimen failure. Tensile strength perpendicular to grain was calculated using Equation (2).



**Figure 4.** Assembly of the tensile test perpendicular to grain according to ABNT NBR 7190-3 [22].

### 2.2.2. ISO 13910

In order to determine tensile perpendicular to grain of specimens from three planted forest species, tests were carried out as per ISO 13910 [20]. According to ISO 13910 [20], the tests shall be performed on specimens obtained from the full cross-section of the timber board. The experimental tests were performed at RT. The EMIC universal testing machine with a load capacity of 30 kN was used to apply the bending load. The force was applied at a constant rate of 1 mm/min until specimen failure. The experimental setup is represented in Figure 5. The tensile strength perpendicular to grain was calculated using Equation (1).

## 2.3. Moisture Content

The moisture content was determined for each specimen tested. First, the specimen weight was obtained with a precision of 0.01 g immediately prior to testing. After the tests, the specimens were placed in an oven at a temperature of 105 °C until a constant mass was reached. According to ABNT NBR 7190-3 [22], the constant mass is achieved when the variation between two weight measurements within a 6 h interval is less than 0.5%. The moisture content was calculated using Equation (3).

$$U = \frac{m_m - m_o}{m_o} \times 100 \quad (3)$$

where  $U$  is the moisture content of the specimen at the time of test (%),  $m_m$  is the initial mass at the time of test (g), and  $m_o$  is the oven-dry mass (g).



**Figure 5.** Assembly of the three-point bending test according to ISO 13910 [20].

#### 2.4. Tensile Strength Perpendicular to Grain with Moisture Content of the 12%

Brazilian Code [14] defines a 12% wood moisture content as a pattern for structural design. Therefore, according to the cited code, the strength value obtained in the characterization test about the moisture content of the specimen must be corrected to a moisture content of 12%. Thus, the tensile strength perpendicular to grain ( $f_{t,90,U}$ ) of each specimen was corrected to the moisture content of 12% ( $f_{t,90,12}$ ) using Equation (4).

$$f_{t,90,12} = f_{t,90,U} \cdot \left[ 1 + \frac{3 \cdot (U - 12)}{100} \right] \quad (4)$$

where  $f_{t,90,12}$  is the tensile strength perpendicular to grain corrected for the moisture content of the 12% (MPa);  $f_{t,90,U}$  is the tensile strength perpendicular to grain at the time of test (MPa); and  $U$  is the moisture content of the specimen at the time of test (%).

#### 2.5. Statistical Analyses

The corrected strength results (Section 2.4) for uniaxial tensile and three-point bending were compared using analysis of variance (ANOVA) with a 5% significance level to identify possible differences.

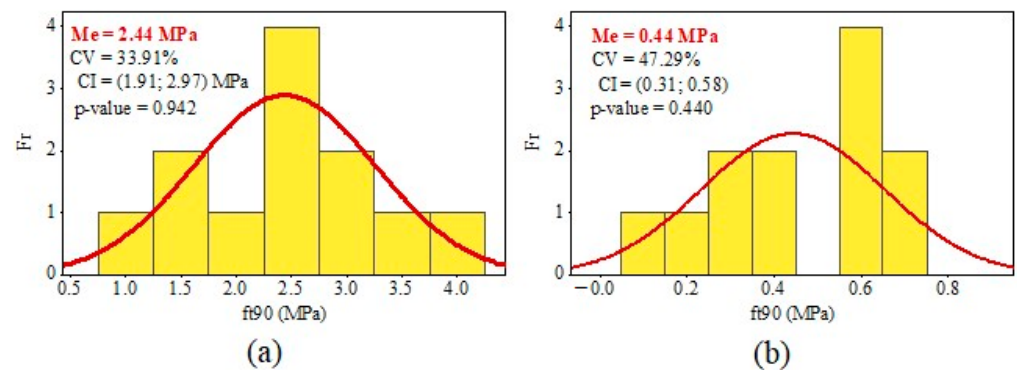
Adjustments in Equation (1) were proposed due to the significant difference in strength obtained from both test methods. Thus, regression models were considered in a way to evaluate the possibility of improvements in the precision of Equation (1). The mean absolute percentage error (MAPE—Equation (5)) was used to compare the results obtained using models adapted to Equation (1) ( $Y_{predict}$ ) with the results of  $f_{t,90}$  determined by a uniaxial tensile test ( $Y_{data}$ ), where  $n$  is the number of specimens considered in generations of models.

$$MAPE(\%) = 100 \cdot \frac{1}{n} \cdot \sum_{i=1}^n \left\| \frac{Y_{predict_i} - Y_{data_i}}{Y_{data_i}} \right\| \quad (5)$$

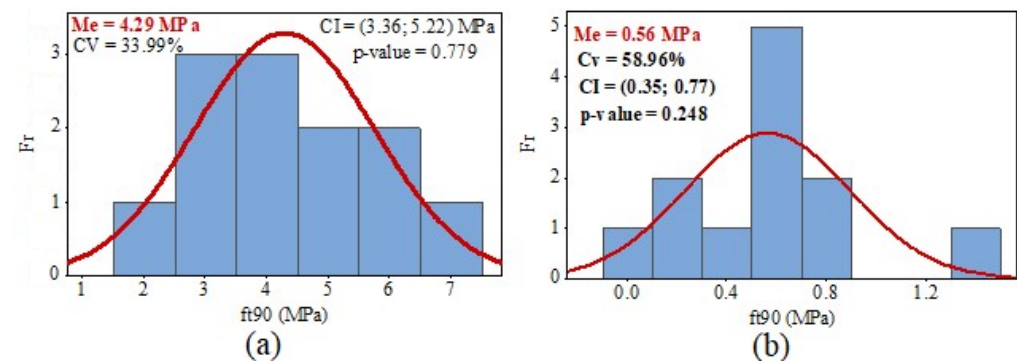
### 3. Results and Discussion

Mean values (Me), coefficients of variation (CV), confidence intervals for the mean (CI, at a 95% confidence level), frequency histograms (Fr), and the  $p$ -values from the Anderson–

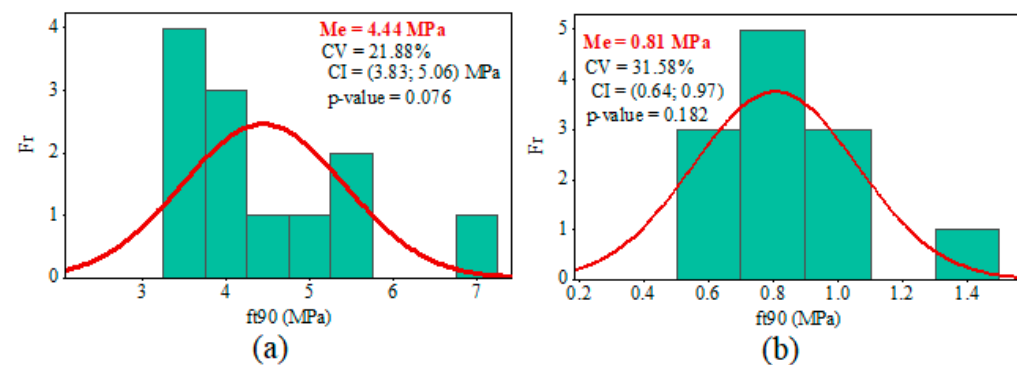
Darling normality test (at a 5% of significance) regarding the  $f_{t,90}$  values obtained from the three-point bending test (Equation (1)) and uniaxial tensile test (Equation (2)) are shown in Figures 6–8.



**Figure 6.** Results of tensile strength values perpendicular to grain ( $f_{t,90}$ ) from *Pinus* spp. wood: (a) uniaxial tensile; (b) three-point bending.



**Figure 7.** Results of tensile strength values perpendicular to grain ( $f_{t,90}$ ) from *Eucalyptus saligna* wood: (a) uniaxial tensile; (b) three-point bending.



**Figure 8.** Results of tensile strength values perpendicular to grain ( $f_{t,90}$ ) from *Corymbia citriodora* wood: (a) uniaxial tensile; (b) three-point bending.

The results of the Anderson–Darling normality test (5% of significance) are greater than the significance level, as shown in Figures 6–8. Thus, the results of the ANOVA and CI for the Me are valid because the distribution of  $f_{t,90}$  values for test methods and, consequently, the wood species, were considered normal.

The CVs obtained from the uniaxial tensile tests for determining the tensile strength perpendicular to grain were lower than the CVs from the three-point bending tests for all the species studied. However, Tannert et al. [25] obtained higher coefficients of variation in uniaxial tensile tests than in three-point bending tests. The CV for *Pinus radiata* samples was

34% for the uniaxial tensile test and 16% for the three-point bending test [25]. Moreover, Tannert et al. [25] also showed that CV for laminated veneer lumber samples from *Pinus radiata* was 37% for the uniaxial tensile test and 34% for the three-point bending test.

The difference between the mean values of  $f_{t,90}$  obtained from the three-point bending tests (Equation (1)) and uniaxial tensile tests (Equation (2)) was significantly elevated ( $p$ -value of the ANOVA  $<0.05$ ). As a result, the difference in the mean strengths of the *Eucalyptus saligna* samples was 766.07%. This discrepancy was the highest observed among all the species investigated. Furthermore, the *Corymbia citriodora* samples differed by 548.15% between the two test methods, whereas *Pinus* spp. samples differed by 554.55%. However, the number of specimens per sample was too small; therefore, additional tests should be performed to verify the discrepancy in strength values between the two testing methodologies.

Some adaptations to Equation (1) from Code ISO 13910 [20] were carried out due to the noted differences in the results between the two calculation methods for the determination of the  $f_{t,90}$ . In such adaptations, the values from the uniaxial tensile tests were regarded as the reference values for  $f_{t,90}$ . First, an attempt was made to determine the coefficients  $\alpha_0$ ,  $\alpha_1$ , and  $\alpha_2$  from Equation (6) using a non-linear regression model (Marquardt algorithm, 2000 iteration and tolerance of  $1.10^{-3}$ ). For this purpose, sampling results from the three wood species examined were combined.

$$f_{t,90} = \left( \frac{\alpha_0 \cdot 3.75 \cdot F_{ult}}{b \cdot L_h} \right) \cdot \left( \frac{\alpha_1 \cdot 0.03 \cdot b \cdot L_h^2}{800^3} \right)^{0.20 \cdot \alpha_2} \quad (6)$$

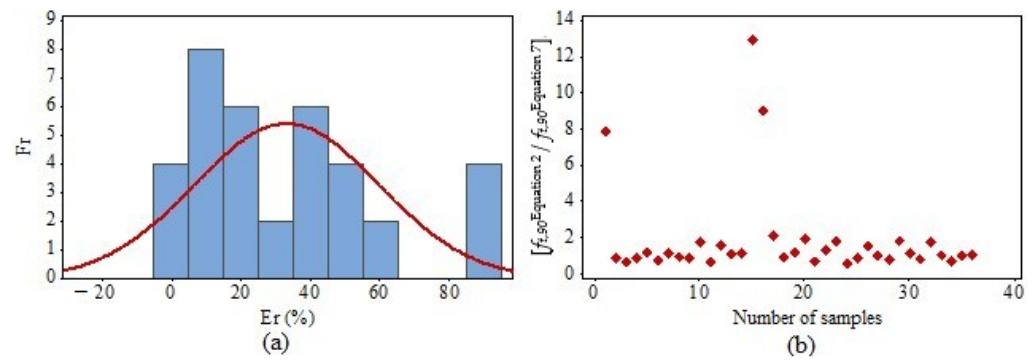
As a result, the coefficients  $\alpha_i$  for Equation (6) consisted of  $\alpha_0 = 0.886$ ,  $\alpha_1 = 0.001$ , and  $\alpha_2 = 0.186$ . These coefficients  $\alpha_i$  resulted in a mean absolute percentage error (MAPE) of 32.85%. An analysis was carried out to assess the influence of the coefficients  $\alpha_i$  in Equation (6). The new values of  $\alpha_0$  and  $\alpha_1$  were 3.301 and 10, respectively, with an associated MAPE of 33.13% after removing the coefficient  $\alpha_2$ . On the other hand, the new values of  $\alpha_0$  and MAPE were 5.233 and 33.14%, respectively, after removing the coefficients  $\alpha_1$  and  $\alpha_2$ . As can be verified, the adjustment that takes into account only  $\alpha_0$  resulted in the same order of MAPE when compared to the models containing two ( $\alpha_0$  e  $\alpha_1$ ) and three coefficients ( $\alpha_0$ ,  $\alpha_1$  e  $\alpha_2$ ). Therefore, determination of tensile strength perpendicular to grain can be estimated just with the adoption of the coefficient  $\alpha_0 = 5.233$ , Equation (7). Moreover, the MAPE obtained using Equation (1) was 82.18%. Thus, it is necessary to calibrate the equation proposed by ISO/FDIS 13910 [20] and ABNT NBR 7190-4 [24].

$$f_{t,90} = \left( \frac{\overset{\alpha_0}{5.233} \cdot 3.75 \cdot F_{ult}}{b \cdot L_h} \right) \cdot \left( \frac{0.03 \cdot b \cdot L_h^2}{800^3} \right)^{0.20} \quad (7)$$

The frequency histogram (Fr) of the errors committed using Equation (7) is shown in Figure 9a, whereas Figure 9b presents a scatter plot of the values obtained from the ratio of  $f_{t,90}$  determined by Equation (7) (three-point bending) and Equation (2) (uniaxial tensile).

Approximately 50% (18 of 36) of the results estimated in Equation (7) have errors less than or equal to 20%, as shown in Figure 9a. In addition, 15 of the 36 estimated values (41.67%) were less than 1; therefore, 58.33% of the results were estimated in favor of safety. Table 2 shows the results (Me and CV) of  $f_{t,90}$  obtained using Equation (7), as well as the corresponding MAPE. Moreover, the wood species evaluated were considered isolated.





**Figure 9.** (a) Frequency histogram (Fr) of error committed with the use of the Equation (7); (b) ratio among the  $f_{t,90}$  [ $f_{t,90}^{\text{Equation (2)}}$ ] obtained by Equation (2), and the  $f_{t,90}$  [ $f_{t,90}^{\text{Equation (7)}}$ ] obtained by Equation (7) [ $f_{t,90}^{\text{Equation (2)}} / f_{t,90}^{\text{Equation (7)}}$ ].

**Table 2.** Results of  $f_{t,90}$  (MPa) obtained with the Equation (7) (adaptation of the Equation (1)).

Wood Species	Equation (7)	Equation (2)	MAPE (%)
<i>Pinus</i> spp.	2.23 (46.27%)	2.44 (33.91%)	34.11
<i>Eucalyptus saligna</i>	3.02 (57.59%)	4.29 (33.99%)	44.82
<i>Corymbia citriodora</i>	4.25 (31.23%)	4.44 (21.88%)	20.48

The ratios of  $f_{t,90}$  values obtained using Equation (7) (three-point bending) to those determined by Equation (2) (uniaxial tensile) for the species of *Pinus* spp., *Eucalyptus saligna*, and *Corymbia citriodora* were 0.91, 0.70 and 0.96, respectively.

Figure 10a shows the failure modes of the specimens tested according to ABNT NBR 7190-3 [22]. Brittle fracture was the predominant failure mode observed in each sample for this test method. In addition, the grains within the fracture surface broke almost at the same time. The crack initially occurred in medullary rays at the edge where the tension stress is maximum in the bending test samples, as shown in Figure 10b. Then, the crack propagated vertically until specimen rupture.



**Figure 10.** (a) typical failure in specimens submitted the axial test of tensile perpendicular to grain based on ABNT NBR 7190-3 [22]; (b) crack in medullary rays in the specimens from ISO/FDIS 13910 [20].

#### 4. Conclusions

The influence of test method on determination of tensile strength perpendicular to grain of timber for civil construction was presented. For this purpose, two different test

methods were analyzed: uniaxial tensile and three-point bending. The main conclusions for this research are:

- Tensile strength values perpendicular to grain ( $f_{t,90}$ ) of the samples obtained from the uniaxial tensile test were significantly higher (around 5.55 and 7.7 times) than the values determined by the three-point static bending test.
- Correction factor for the equation from Code ISO 13910 [20], used to estimate  $f_{t,90}$  based on three-point bending test, was the term that had a significant impact on the obtained results. This impact resulted in much lower bending strength values compared with those obtained from the uniaxial tensile test.
- The values of the mean absolute percentage error were very similar to the results obtained with the adoption of the proposed coefficients for Equation (1). The model with a smaller adaptation of the equation from Code ISO/FDIS 13910 [20] was adopted in this research. Therefore, the coefficient 5.233, inserted into the term  $[(3.75 \cdot F_{ult})/b \cdot L_h]$  of the equation from Code ISO/FDIS 13910 [20] and Brazilian Code ABNT NBR 7190-4 [24], produced results more similar when compared with the uniaxial tensile test results.
- The disparity in outcomes can be attributed to the different stress conditions inherent to each testing method. In the three-point bending test, wood grains and parenchyma cells are subjected to both normal and tangential stresses. In contrast, only normal stress is applied in wood grains in the uniaxial tensile test.
- In the design of timber structures, the tensile strength perpendicular to grain affects the dimensions of double tapered, curved, and pitched cambered beams. Thus, the design of these beams becomes more conservative by taking into account the most unfavorable conditions in the structural design (tensile strength obtained from the three-point static bending test).

The number of specimens was relatively small for each sample, therefore, additional tests with other species should be performed to verify the discrepancy in tensile strength values perpendicular to the grain between the two testing methodologies.

**Author Contributions:** Conceptualization, R.d.S.N., A.L.C. and F.A.R.L.; formal analysis, R.d.S.N. and A.L.C.; investigation, R.d.S.N. and A.L.C.; methodology, R.d.S.N. and A.L.C.; project administration, A.L.C. and F.A.R.L.; resources, S.N.M., A.R.G.d.A., H.F.d.S. and F.A.R.L.; supervision, F.A.R.L.; visualization, R.d.S.N., F.Y.M., A.L.C., S.N.M., A.R.G.d.A., H.F.d.S. and F.A.R.L.; writing—original draft, R.d.S.N. and A.L.C.; writing—review and editing, R.d.S.N., F.Y.M., A.L.C., S.N.M., A.R.G.d.A., H.F.d.S. and F.A.R.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior-Brasil (CAPES)—Finance Code 001.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The raw data supporting the conclusions of this article will be made available by the authors on request.

**Acknowledgments:** The authors thank Wood and Timber Structures Laboratory (LaMEM) of the Department of Structural Engineering (SET) of the São Carlos Engineering School (EESC)—University of São Paulo (USP) for making this work possible. The authors thank Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), process No. CNPq 309058/2019-8—Bolsa PP. The authors thank Federal Institute of Education, Science and Technology of Rondônia (IFRO) for making this work possible.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Follesa, M.; Fragiaco, M.; Casagrande, D.; Tomasi, R.; Piazza, M.; Vassallo, D.; Canetti, D.; Rossi, S. The new provisions for the seismic design of timber buildings in Europe. *Eng. Struct.* **2018**, *168*, 736–747. [[CrossRef](#)]
2. Stocchero, A.; Seadon, J.K.; Falshaw, R.; Edwards, M. Urban Equilibrium for sustainable cities and the contribution of timber buildings to balance urban carbon emissions: A New Zealand case study. *J. Clean. Prod.* **2017**, *143*, 1001–1010. [[CrossRef](#)]

3. Calil Júnior, C.; Dias, A.A. Utilização da madeira em construções rurais. *Rev. Bras. Eng. Agric. Ambient.* **1997**, *1*, 71–77. [[CrossRef](#)]
4. Ramage, M.H.; Burridge, H.; Busse-Wicher, M.; Fereday, G.; Reynolds, T.; Shah, D.U.; Wu, G.; Yu, L.; Fleming, P.; Densley-Tingley, D.; et al. The wood from the trees: The use of timber in construction. *Renew. Sustain. Energy Rev.* **2017**, *68*, 333–359. [[CrossRef](#)]
5. FAO. *Global Forest Resources Assessment 2020: Main Report*, 1st ed.; Food and Agriculture Organization of the United Nations: Rome, Italy, 2020; pp. 1–184. [[CrossRef](#)]
6. Brazilian Tree Industry. Report 2019. Available online: <https://iba.org/datafiles/publicacoes/relatorios/iba-relatorioanual2019.pdf> (accessed on 7 February 2023).
7. Iwuoha, S.E.; Seim, W.; Onyekwelu, J.C. Mechanical properties of Gmelina arborea for engineering design. *Constr. Build. Mater.* **2021**, *288*, 123123. [[CrossRef](#)]
8. Aquino, V.B.M.; de Freitas, M.V.P.; de Vasconcelos, C.Q.; Almeida, J.P.B.; Arroyo, F.N.; Rodrigues, E.F.C.; Christoforo, A.L.; de Almeida, D.H.; Silva, S.A.M.; Silva, D.A.L.; et al. Physical and mechanical characterization of planchonella pachycarpa wood species for use in structural purpose. *Wood Res.* **2021**, *66*, 267–276. [[CrossRef](#)]
9. Teixeira, J.N.; Wolenski, A.R.V.; Aquino, V.B.M.; Panzera, T.H.; Silva, D.A.L.; Campos, C.I.; Silva, S.A.M.; Lahr, F.A.R.; Christoforo, A.L. Influence of provenance on physical and mechanical properties of Angelim-pedra (*Hymenobium petraeum* Ducke.) wood species. *Eur. J. Wood Prod.* **2021**, *79*, 1241–1251. [[CrossRef](#)]
10. Crespo, J.; Majano-Majano, A.; Lara-Bocanegra, A.J.; Guaita, M. Mechanical Properties of Small Clear Specimens of Eucalyptus globulus Labill. *Materials* **2020**, *13*, 906. [[CrossRef](#)] [[PubMed](#)]
11. Derikvand, M.; Kotlarewski, N.; Lee, M.; Jiao, H.; Nolan, G. Characterisation of Physical and Mechanical Properties of Unthinned and Unpruned Plantation-Grown Eucalyptus nitens H.Deane & Maiden Lumber. *Forests* **2019**, *10*, 194. [[CrossRef](#)]
12. Nogueira, M.C.J.A.; de Almeida, D.H.; de Araujo, V.A.; Vasconcelos, J.S.; Christoforo, A.L.; de Almeida, T.H.; Lahr, F.A.R. Physical and mechanical properties of Eucalyptus saligna wood for timber structures. *Ambient. Construído* **2019**, *19*, 233–239. [[CrossRef](#)]
13. EN 1995-1-1; Eurocode 5: Design of Timber Structures—Part 1-1: General—Common Rules and Rules for Buildings. European Committee for Standardization: Brussels, Belgium, 2004.
14. ABNT NBR 7190-1; Timber Structures—Part 1: Design Criteria. Brazilian Association of Technical Standards: Rio de Janeiro, Brazil, 2022.
15. Ehlbeck, J.; Görlacher, R. Tension perpendicular to the grain in joints. Step lecture C2. In *Timber Engineering—STEP 1*, 1st ed.; Blass, H.J., Aune, P., Choo, B.S., Görlacher, R., Griffiths, D.R., Hilson, B.O., Racher, P., Steck, G., Eds.; Salland De Lange: Deventer, The Netherlands, 1995; pp. C2/1–C2/7.
16. Wang, T.; Wang, Y.; Crocetti, R.; Wälinder, M. In-plane mechanical properties of birch plywood. *Constr. Build. Mater.* **2022**, *340*, 127852. [[CrossRef](#)]
17. Nguyen, H.H.; McGavin, R.L.; Gilbert, B.P.; Bailleres, H. Key Mechanical Properties of Cross-banded Laminated Veneer Lumbers Manufactured from Blending Spotted Gum and Hoop Pine Veneers. *BioResources* **2019**, *14*, 9117–9131. [[CrossRef](#)]
18. Gilbert, B.P.; Husson, J.M.; Bailleres, H.; McGavin, R.L.; Fischer, M.F. Perpendicular to grain and shear mechanical properties of veneer based elements glued from single veneer sheets recovered from three species of juvenile subtropical hardwood plantation logs. *Eur. J. Wood Prod.* **2018**, *76*, 1637–1652. [[CrossRef](#)]
19. ASTM D143-21; Standard Test Methods for Small Clear Specimens of Timber. American Society for Testing and Materials: West Conshohocken, PA, USA, 2021.
20. ISO/FDIS 13910; Timber Structures—Strength Graded Timber—Test Methods for Structural Properties. International Organization for Standardization: Geneva, Switzerland, 2014.
21. BS EN 408:2010+A1; Timber Structures—Structural Timber and Glued Laminated Timber—Determination of Some Physical and Mechanical Properties. British Standards Institution: London, UK, 2012.
22. ABNT NBR 7190-3; Timber Structures—Part 3: Test Methods for Characterization of Defect-Free Specimens for Timber of Native Forests. Brazilian Association of Technical Standards: Rio de Janeiro, Brazil, 2022.
23. AS/NZS 4063.1; Characterization of Structural Timber. Standards Australia: Sydney, Australia, 2010.
24. ABNT NBR 7190-4; Timber Structures—Part 4: Test Methods for Characterization of Structural Lumber. Brazilian Association of Technical Standards: Rio de Janeiro, Brazil, 2022.
25. Tannert, T.; Vallée, T.; Franke, S.; Quenneville, P. Comparison of test methods to determine weibull parameters for wood. In Proceedings of the WCTE 2012—World Conference on Timber Engineering, Auckland, New Zealand, 15–19 July 2012.
26. Timoshenko, S.P. *Strength of Materials, Part 2: Advanced Theory and Problems*, 3rd ed.; CBS Publishers & Distributors: New Delhi, India, 2002; pp. 1–563.
27. Christoforo, A.L. *Simulation and Analysis of Deformable Solids—Vol. 1.*, 1st ed.; Lambert Academic Publishing (LAP): Saarbrücken, Germany, 2021; pp. 1–156.

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.