Strength classes of brazilian hardwoods for structural design

Classes de resistência de madeiras folhosas brasileiras para projeto estrutural

Clases de resistencia de las maderas duras brasileñas para diseño estructural

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ABSTRACT
For the elaboration of projects on timber structures, the Brazilian standard (ABNT, in Portuguese Associação Brasileira de Normas Técnicas) 7190 (ABNT 1997) ensures the correct application of physical-mechanical properties according to strength classes of lignocellulosic materials. This procedure eliminates the need for botanical identification of woods, since these strength classes support the efficient utilization of a wide range of woody varieties available in Brazil. Due to high mechanical resistances, the hardwoods are usually applied for structural projects of timber construction. This Brazilian standard document prescribes four strength classes (C20, C30, C40 and C60) for these woods, which are determined by characteristic value from the compressive strength parallel to the grain ($f_{c0,k}$). But, these classes were obtained from experimental outcomes using a few wood varieties. The reorganization of strength classes should result in the best use of mechanical potentials of woods since the updating of these categories leads to the optimization of structural projects for timber construction in order to reposition this biomaterial at even more competitive levels. In this context, the present study aims to verify the current strength classes of hardwoods and if they lead to a good allocation of the $f_{c0,k}$ characteristic values. Otherwise, new strength classes can be determined for better allocations for efficient structural uses. As a result, 56 hardwoods were considered using 672 experimental determinations. Statistically, the current categories can lead to 12.5% of incorrectly allocated values. The inclusion of C50 and C70 classes allow greater representation for these categories, in order to optimize the use of the hardwoods given the new strength classes. These findings ought to support future revisions of this Brazilian standard document.

Keywords: Mechanical Properties. Timber Structures. Direction Parallel to The Grain. Tropical Woods.

RESUMO
Na elaboração de projetos de estruturas de madeira o documento normativo brasileiro ABNT NBR 7190 (1997) possibilita o emprego de propriedades físico-mecânicas de acordo com classes de resistência do material (CR). Tal procedimento suprime a necessidade da identificação da botânica da espécie, possibilitando a utilização de uma ampla variedade de madeiras disponíveis em uma região. Para as dicotiledôneas, comumente empregadas em projetos estruturais devido a elevada resistência mecânica, a ABNT NBR 7190 (1997) apresenta quatro classes de resistência, (C20, C30, C40 e C60), determinadas por meio da resistência característica à compressão paralela às fibras ($f_{c0,k}$). Todavia, tais classes foram obtidas por meio de resultados experimentais advindos de um número pouco expressivo de espécies de madeira, frente ao
número atual de espécies caracterizadas. Dado que o melhor enquadramento nas CRs acarreta no melhor aproveitamento do potencial mecânico das espécies, a atualização das CRs conduz a otimização de projetos de estruturas de madeira, levando esse material a patamares ainda mais competitivos. Neste contexto, de modo a fundamentar futuras revisões da ABNT NBR 7190 (1997), este trabalho objetivou verificar se as atuais CRs das madeiras do grupo das folhosas conduzem a uma boa alocação dos valores de $f_{c0,k}$ e determinar, em caso contrário, novas CRs com melhores alocações. Para tanto, adotou-se 56 espécies resultando em 672 determinações experimentais. Por meio da análise estatística, observou-se que as CRs atuais conduzem a 12,5% de valores alocados de forma incorreta. Constatou-se que a inclusão das classes C50 e C70 tornou mais representativa a classificação e o emprego da metodologia de classes de resistência.


RESUMEN
En la elaboración de proyectos de estructuras de madera, el documento normativo brasileño ABNT NBR 7190 (1997) permite el uso de propiedades físico-mecánicas según las clases de resistencia del material (CR). Este procedimiento elimina la necesidad de identificar la botánica de la especie, lo que permite el uso de una amplia variedad de maderas disponibles en una región. Para las dicotiledóneas, comúnmente utilizadas en proyectos estructurales debido a su alta resistencia mecánica, la ABNT NBR 7190 (1997) presenta cuatro clases de resistencia (C20, C30, C40 y C60), determinadas por la resistencia característica a la compresión paralela a las fibras ($f_{c0,k}$). Sin embargo, estas clases se obtuvieron a partir de resultados experimentales de un número poco representativo de especies de madera, en comparación con el número actual de especies caracterizadas. Dado que una mejor clasificación en las CRs resulta en una mejor utilización del potencial mecánico de las especies, la actualización de las CRs conduce a la optimización de proyectos de estructuras de madera, llevando este material a niveles aún más competitivos. En este contexto, con el fin de fundamentar futuras revisiones de la ABNT NBR 7190 (1997), este trabajo tuvo como objetivo verificar si las CRs actuales de las maderas del grupo de las frondosas conducen a una buena asignación de los valores de $f_{c0,k}$ y determinar, en caso contrario, nuevas CRs con mejores asignaciones. Para ello, se adoptaron 56 especies, lo que resultó en 672 determinaciones experimentales. A través del análisis estadístico, se observó que las CRs actuales conducen a un 12,5% de valores asignados incorrectamente. Se encontró que la inclusión de las clases C50 y C70 hizo que la clasificación y el uso de la metodología de clases de resistencia fueran más representativos.

1 INTRODUCTION

With a status of “future material” (Kuzman and Sandberg, 2017; Żmijewki and Wojtowicz-Jankowska, 2017), wood has presented with an adequate alternative to the use of traditional structural materials such as steel and reinforced concrete (Baar et al, 2015; Almeida et al 2020a).

Previously, the wood was requested mainly because of the ease of handling and manufacturing of structural elements, but the current choice of this material is attributed to environmental issues (Asdrubali et al, 2017), being defined by natural, biodegradable, recyclable and naturally renewable features (Wang et al, 2014; Souza et al, 2018). Other positive adjective is confirmed by superior levels in carbon fixation as measured by De Araujo et al (2020) either for different construction techniques or wood species.

In addition, wood offers an excellent resistance-to-density ratio (Pries and Mai, 2013; Ramage et al, 2017; Huber et al, 2018; Totsuka et al, 2021). Wood is a smart resource for structural uses (bridges, buildings, etc.), as its weight corresponds to a high proportion of the loads to be resisted.

Physical and mechanical properties vary by species, as wood is a natural raw material. Cruz et al (2021) verified that traditional species are commonly considered in the elaboration of projects for timber structures in Brazil, whose properties are specified by ABNT NBR 7190 (1997); yet, this technical standard habilitates the adoption of physical-mechanical properties from strength classes as an accurate way to simplify the design and preparation of structural projects.

The values of these properties are grouped by lots, which exempts the botanical identification of wood species (Cruz et al, 2021). Due to this consideration, there is the possibility of using a wide variety of wood species from a given territory, as they are not always mechanically characterized in a satisfactory way. In this procedure, it is only necessary to determine the characteristic value from the compressive strength parallel to the grain ($f_{c0,k}$) and verify the ranking of lot in the strength class specified in the project.

Azmi et al (2022) investigate the compressive strength properties of nine structural-sized Malaysian tropical hardwood species. The objective of the study
was to determine the characteristic values of resistance to compression of these tropical woods and compare them with the reference values available in international standards, as a way of providing data for engineers, designers and researchers who work with tropical wood in structural applications.

Around 7700 tree species were catalogued in the Brazilian Amazon forest as suggested by Steege et al. (2016). Due to this very expressive number, the elaboration of structural projects using strength classes facilitates the utilization of non-traditional and little-known species – because about 40 native woods have been applied for the production of timber construction in Brazil as confirmed by De Araujo et al. (2020).

Thus, the use of non-traditional species for several applications worldwide requires specific knowledge of the physical and mechanical properties of wood, such as the $f_{c0,k}$ strength, which have great significance for wood products and construction (Wolenski et al., 2020). For hardwoods, usually applied for structural projects due to high mechanical strengths (Almeida et al., 2020b), the ABNT NBR 7190 (1997) standard document prescribes four homogeneous classes of $f_{c0,k}$:

- a) C20 ($f_{c0,k} < 30$ MPa),
- b) C30 ($30$ MPa $\leq f_{c0,k} < 40$ MPa),
- c) C40 ($40$ MPa $\leq f_{c0,k} < 60$ MPa), and
- d) C60 ($f_{c0,k} \geq 60$ MPa).

As the C40 strength class contemplates a wide range of $f_{c0,k}$ values, the C50 category ($50$ MPa $\leq f_{c0,k} < 60$ MPa), which is not included in the Brazilian standard document cited has been adopted by some literature studies such as Logsdon et al. (2010), Lima et al. (2018), Cruz et al. (2021) and Wolenski (2022). Thus, there is the prerogative to update the standard document.

As a comparative, the European Standard EN 338 (2016) establishes a system of strength classes for general use in design codes and it gives characteristic strength and stiffness properties and density values for strength classes to softwoods and hardwoods. The European standard adopts as its central parameter the characteristic value of the strength bending ($f_{m,k}$) and eight strength classes for hardwoods (D18 to D70), while the Brazilian standard adopts the $f_{c0,k}$ strength and only the four classes mentioned above.
It is noteworthy that the ABNT NBR 7190 (1997) standard has been in force for over 20 years. Their available strength classes were determined through experimental results of a limited number of wood species. Thus, the procedure updating is required to insert additional classes and meet well-defined intervals in order to improve the wood utilization as structural raw material and, therefore, a better destination of financial resources in times of scarcity of the main species. This update can drive hardwoods to even more competitive levels in durable uses, such as construction.

As strategy to support future revisions of the ABNT NBR 7190 (1997) standard document, this scientific contribution aims, through an expressive number of species and determinations, to verify the current strength classes of hardwoods and respective good allocation of $f_{c0,k}$ characteristic values in order to determinate, if necessary, new strength classes from representative sampling.

2 MATERIALS AND METHODS

For the determination of experimental results, 56 hardwoods from the tropical forests were considered (Table 1), which were procured as lumber boards in the local markets. Due to material procurement at the regional level in Brazil, it was not possible to identify respective ages and origins. For all the tests were used homogeneous batches, as it is required by ABNT NBR 7190 (1997). According to the Standard, the batch volume cannot exceed 12 m$^3$, and the specimens should be extracted randomly, limited to one sample per beam.
Table 1. Scientific name and identification number (ID) of 56 tropical hardwoods.

<table>
<thead>
<tr>
<th>ID</th>
<th>Hardwood species</th>
<th>ID</th>
<th>Hardwood species</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vatairea cf. guianensis Aubl.</td>
<td>29</td>
<td>Protium cf. altissimum (Aubl.) Marchand</td>
</tr>
<tr>
<td>2</td>
<td>Cedrela sp.</td>
<td>30</td>
<td>Bertholletia excelsa Bonpl.</td>
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<tr>
<td>3</td>
<td>Handroanthus serratifolius (Vahl) S.Grose</td>
<td>31</td>
<td>Calophyllum longifolium Willd.</td>
</tr>
<tr>
<td>4</td>
<td>Tapirira sp. Aubl.</td>
<td>32</td>
<td>Calophyllum brasiliense Cambess.</td>
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<td>5</td>
<td>Hymenolobium cf. heterocarpum Ducke</td>
<td>33</td>
<td>Parinari excelsa Sabine</td>
</tr>
<tr>
<td>6</td>
<td>Cassia ferruginea (Schrad.) Schrad. ex DC.</td>
<td>34</td>
<td>Vataireopsis araroba (Aguiar) Ducke</td>
</tr>
<tr>
<td>7</td>
<td>Parkia cf. pendula (Willd.) Bent. ex Walp.</td>
<td>35</td>
<td>Andira anthelmia (Vell.) Benth</td>
</tr>
<tr>
<td>8</td>
<td>Dipteryx odorata (Aubl.) Willd.</td>
<td>36</td>
<td>Cedrela odorata L.</td>
</tr>
<tr>
<td>9</td>
<td>Mezilaurus itauba (Meisn.) Taub. ex Mez</td>
<td>37</td>
<td>Cedrela cf. fissilis Vell.</td>
</tr>
<tr>
<td>10</td>
<td>Diplotropis sp. Benth.</td>
<td>38</td>
<td>Cedrelinga cateniformis (Ducke) Ducke</td>
</tr>
<tr>
<td>11</td>
<td>Hymenolobium petraeum Ducke</td>
<td>39</td>
<td>Copaifera multijuga Hayne</td>
</tr>
<tr>
<td>12</td>
<td>Ocotea cf. odorifera (Vell.) Rohwer</td>
<td>40</td>
<td>Goupia glabra Aubl.</td>
</tr>
<tr>
<td>13</td>
<td>Anadenanthera colubrina var. cebil (Griseb.) Altschul</td>
<td>41</td>
<td>Goupia paraensis Huber</td>
</tr>
<tr>
<td>14</td>
<td>Apuleia leiocarpa (Vog.) Macbr.</td>
<td>42</td>
<td>Guatteria sp. Ruiz &amp; Pav</td>
</tr>
<tr>
<td>15</td>
<td>Hymenaea courbaril L.</td>
<td>43</td>
<td>Xylophyllum c. benthamii R.E.Fr.</td>
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<td>16</td>
<td>Tachigali glauca Tul.</td>
<td>44</td>
<td>Planchonella pachycarpa Pires</td>
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<tr>
<td>17</td>
<td>Dinizia excelsa Ducke</td>
<td>45</td>
<td>Peltophorum dubium (Spreng.) Taub.</td>
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<tr>
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<td>Ocotea cf. spixiana (Nees) Mez</td>
<td>46</td>
<td>Ocotea neesiana (Miq.) Kosterm.</td>
</tr>
<tr>
<td>19</td>
<td>Erisma cf. fuscum Ducke</td>
<td>47</td>
<td>Qualea paraensis Ducke</td>
</tr>
<tr>
<td>20</td>
<td>Luetzelburgia cf. guaiassara Toledo</td>
<td>48</td>
<td>Clarisia racemosa Ruiz &amp; Pav.</td>
</tr>
<tr>
<td>21</td>
<td>Sextonia cf. rubra (Mez) van der Werff</td>
<td>49</td>
<td>Pradosia sp. Liais</td>
</tr>
<tr>
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<td>Pouteria cf. guianensis Aubl.</td>
<td>50</td>
<td>Vochysia floribunda Mart.</td>
</tr>
<tr>
<td>23</td>
<td>Sebastiania commersoniana (Baill.) L.B.Sm. &amp; Downs</td>
<td>51</td>
<td>Erisma uncinatum Warm.</td>
</tr>
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<td>24</td>
<td>Pouteria cf. pachyphylla T.D.Penn.</td>
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<td>Geissospermum sericeum Miers</td>
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<td>25</td>
<td>Calycophyllum multiflorum Griseb.</td>
<td>53</td>
<td>Vochysia haenkeana Mart.</td>
</tr>
<tr>
<td>26</td>
<td>Micropholis venulosa (Mart. &amp; Eichler) Pierre</td>
<td>54</td>
<td>Bagassa guianensis Aubl.</td>
</tr>
<tr>
<td>27</td>
<td>Manilkara cf. inundata (Ducke) Ducke</td>
<td>55</td>
<td>Ruizterania retusa (Spruce ex Warm.) Marc.-Berti</td>
</tr>
<tr>
<td>28</td>
<td>Vatairea fusca (Ducke) Ducke</td>
<td>56</td>
<td>Peltogyne lecointei Ducke</td>
</tr>
</tbody>
</table>

1 Flora of Brazil (2020).

Source: prepared by the author.

Hardwood varieties were stored at stable condition close to 12 % moisture content at the Laboratory of Woods and Timber Structures (LaMEM) of the University of São Paulo (USP) in São Carlos, Brazil. This moisture content is a reference parameter prescribed by the ABNT 7190 (ABNT 1997). The values of apparent density at 12% moisture ($\rho_{ap,12\%}$) of the studied woods were determined following the requirements of ABNT NBR 7190 (1997). Twelve specimens were produced by wood species with dimensions of 5 cm × 5 cm × 15 cm, being this...
largest size in the longitudinal direction. Then, 672 experimental determinations were obtained.

The compressive strength parallel to the grain \( f_{c0} \) was obtained from Eq. 1, using a loading applied in a monotonically increasing way at 10 MPa/min through an AMSLER’s universal testing machine (250 kN load capacity). Tests were carried out in compliance with the requirements of the ABNT 7190 (ABNT 1997) to characterize wood properties for structural projects.

\[
f_{c0} = \frac{F_{c0,\text{max}}}{A}
\]  

(1)

Where:

- \( F_{c0,\text{max}} \) is the maximum compression force applied to specimen during the compressive strength parallel to the grain
- \( A \) corresponds to the initial area of transversal section of specimen.

The \( f_{c0} \) values in different moisture contents were corrected to the reference moisture content using Eq. 2, where \( f_{U\%} \) and \( f_{12\%} \) denoted, respectively, the compressive strengths parallel to the grain at two moisture contents (U\% and 12\%):

\[
f_{12\%} = f_{U\%} \cdot \left[ 1 + \frac{3 \cdot (U\% - 12)}{100} \right]
\]  

(2)

From values at 12 \% moisture content, wood varieties were categorized into strength classes for hardwoods according to \( f_{c0,k} \) value, following the recommendation of the Brazilian standard ABNT NBR 7190 (1997). The Eq. 3 gives the \( f_{c0,k} \) value corresponding to the 5 \% percentile of the distribution of strength values:

\[
f_{w,k} = f_m \cdot [1 - 1.645 \cdot \delta]
\]  

(3)
Where:

\[ f_m \] is the average strength value  
\[ \delta \] is the coefficient of variation.

For safety reasons the probabilistic methodology of the Standard supposes that the strength values are normally distributed, and the coefficient of variation is \[ \delta = 18\% \] for compressive strength, as given by Eq. 4:

\[
f_{w,k} = f_m \cdot [1 - 1,645 \cdot \delta] \approx 0,70 \cdot f_m
\]  \( (4) \)

On the other hand, for the direct strength estimation, the Standard provides Eq. 5, which gives the \( f_{w,k} \) value as following:

\[
f_{w,k} = \left[ 2 \cdot \frac{f_1 + f_2 + f_3 + \ldots + f_{(n/2)-1}}{(n/2) - 1} - f_{n/2} \right] \cdot 1,10
\]  \( (5) \)

Where:

\( f_n \) is \( n \) determined strength values, arranged in the ascending order \( f_1 < f_2 < f_3 < \ldots < f_n \); if the number of the specimens is odd, the highest value is disregarded. The equation is based on the estimator \( z_b \), given as:

\[
z_b = \left[ 2 \cdot \frac{x_1 + x_2 + x_3 + \ldots + x_{(m-1)}}{(m - 1)} - f_m \right]
\]  \( (6) \)

for the sample of \( 2m \) values \( x_1 + x_2 + x_3 + \ldots + x_{2m} \).

However, for the distribution centered on the characteristic value, there is a 10 \% increase added to Eq. 3, which, according to Logsdon \textit{et al} (2010), allows avoiding that 50 \% of the estimates is done by the values below the characteristic strength.
On the basis of these equations, \( f_{w,k} \) is given as the highest value among: the strength less than \( f_1 \), the strength less than 70 % of \( f_m \) (Eq. 4) obtained from the tested specimens, and the value computed by Eq. 6, according to ABNT NBR 7190 (1997).

The analysis of variance (ANOVA), by F-test (\( p < 0.05 \)), was regarded to verify the accuracy and validity of this study. From ANOVA, the null hypothesis consisted in the equivalence of strength classes and the class disparity as an alternative hypothesis. By the admitted hypotheses, \( p \geq 0.05 \) implies accepting the null hypothesis (where the average values of compared groups are statistically equivalent to each other) and rejecting them in the \( p < 0.05 \) condition (where those groups exhibited significantly different average values).

The premise of normality in the residue distribution from the ANOVA was evaluated by the Anderson-Darling test as suggested by Weerahandi (1995). By the formulation, \( p > 0.05 \) implies accepting the normality in the residue distribution and thus rejecting this hypothesis otherwise.

3 RESULTS AND DISCUSSION

Table 2 presents the values of apparent density \( (\rho_{ap,12\%}) \) and average values \( (f_{c0,m}) \), characteristic values \( (f_{c0,k}) \) and coefficients of variation \( (C_v) \) of compressive strength parallel to the grain of 56 hardwoods under investigation.

<table>
<thead>
<tr>
<th>ID</th>
<th>( \rho_{ap,12%} ) (kg/m(^3))</th>
<th>( f_{c0,m} ) (MPa)</th>
<th>( C_v ) (%)</th>
<th>( f_{c0,k} ) (MPa)</th>
<th>ID</th>
<th>( \rho_{ap,12%} ) (kg/m(^3))</th>
<th>( f_{c0,m} ) (MPa)</th>
<th>( C_v ) (%)</th>
<th>( f_{c0,k} ) (MPa)</th>
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</tbody>
</table>
Table 3 shows the values of $f_{c0,k}$ for 56 hardwoods (Table 2) allocated in the current strength classes from the Brazilian standard document. Considering the current classification presented in this standard document, 04 (four) values were observed for C20 strength class, 05 (five) for C30, 28 for C40, and 19 for C60 as described by Table 3.

Table 3: Values of $f_{c0,k}$ allocated according to strength classes from the Brazilian standard document.

<table>
<thead>
<tr>
<th>Strength Classes (ABNT 1997)</th>
<th>$f_{c0,k}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C20</td>
<td>27.20 27.30 29.06 29.64 29.99</td>
</tr>
<tr>
<td>C30</td>
<td>36.37 37.71 38.50 38.93</td>
</tr>
<tr>
<td></td>
<td>40.50 41.87 43.10 43.74 44.00 44.13 44.79 45.58 46.00</td>
</tr>
<tr>
<td>C40</td>
<td>46.26 46.51 46.64 47.22 47.52 47.69 48.84 49.14 49.94</td>
</tr>
<tr>
<td></td>
<td>50.91 51.06 51.28 53.02 54.54 55.22 55.58 55.55 56.34</td>
</tr>
<tr>
<td>C60</td>
<td>56.81 58.92 59.84</td>
</tr>
<tr>
<td></td>
<td>60.21 61.53 61.60 62.41 63.38 65.36 67.44 72.34 72.37</td>
</tr>
<tr>
<td></td>
<td>72.73 75.46 78.40 79.57 80.51 89.96 93.02 96.16</td>
</tr>
</tbody>
</table>

Source: prepared by the author.

In order to verify the allocation of these values, a discriminant analysis of observations was performed. From this analysis, the predictions of allocation were put into practice through future values from known allocated values. Thus, the main results obtained in this discriminant analysis of the current Brazilian standard document are identified in the Table 4 for true groups.
Table 4: Discriminant analysis of the current classification of the Brazilian standard document

<table>
<thead>
<tr>
<th>Allocated in the group</th>
<th>True group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C20</td>
</tr>
<tr>
<td>C20</td>
<td>4</td>
</tr>
<tr>
<td>C30</td>
<td>0</td>
</tr>
<tr>
<td>C40</td>
<td>0</td>
</tr>
<tr>
<td>C60</td>
<td>0</td>
</tr>
<tr>
<td>Total observations</td>
<td>4</td>
</tr>
<tr>
<td>Correct observations</td>
<td>4</td>
</tr>
</tbody>
</table>

| Proportion             | 1,000| 1,000| 0,893| 0,789|

Source: prepared by the author.

The statistical model provided by the analysis enabled the correct allocation of all data from C20 and C30 strength classes. For C40 and C60, 89.3% and 78.9% of data were duly allocated, respectively. Considering the global nature of allocations in strength classes, about 87.5% of results were correctly allocated, being 12.5% of incorrect values of allocation. These values are indicators the deficiencies in the current classification procedure of the Brazilian standard document, which were resulted in the existence of $f_{c0,k}$ values with incompatible values in relation to the current scenario under evaluation.

This fact can be clearly analyzed when the dispersion of laboratory results is observed for each current standardized class (Figure 1). The current C20 class includes values below 30 MPa, and the C30 class is based on values between 30 MPa and 40 MPa. Both classes revealed the proximity of occurrence and dispersion of results. For C20 class, the little observation of values less than 20 MPa evinced a low sample dispersion, whose fact was similar to C30 class (Figure 1a).

The range of values allocated in the C40 class was from 40 MPa to 60 MPa (naturally), with a symmetrical distribution of occurrences across the interval. For C60 class, the sample range was from 60 MPa to 110 MPa in an asymmetric distribution of central tendency at 75 MPa (Figure 1b).
Figure 1. Behavior of the current classification of the Brazilian standard document: (a) individual values for strength classes and (b) boxplot values of \( f_{c0,k} \).

An important observation about the current classification procedure by the ABNT NBR 7190 (1997) standard document is given by the average and median values of the intervals, which are at the high limits in all strength classes. While these limits approach 30 MPa in C20 strength class, and they reach something close to 40 MPa in C30. These values are close to 50 MPa in C40, and C60 shows some predominance in the 75 MPa range.

By the analysis of frequency, eleven result values were observed among 50 MPa and 60 MPa, and twelve \( f_{c0,k} \) values were above 70 MPa. These 23 observations are not adequately represented by the current classes (which limit the species resistance), since they correspond to 41 % of underestimated allocations of the 56 different hardwoods in study. These arguments reinforce the need for an update on the current strength classes, whereas an expressive occurrence percentage is present in those regions superior to the inferior limits of the ABNT NBR 7190 (1997). Thus, 50-60 MPa and 70-100 MPa interval values have been frequently observed and, therefore, being limited by 40 MPa and 60 MPa for the Brazilian standard document, respectively.

Whereas the characteristic values are represented by the properties of interest in the wood, with a low probability of not being reached (5%) due to the analysis process, the classification prescribed by the current procedure of the ABNT NBR 7190 (1997) standard document has underestimated the mechanical
potentials of different woods used for structural elements. In this raised scenario, we proposed the creation of additional classes, given by C50 and C70, to mitigate this underestimation and intensify the rational utilization of timber construction, above all, made with non-traditional hardwoods. From this possible replacement, this present proposal should strategically contribute to the reduction of human pressure on the most popular hardwoods from the Brazilian tropical forests – whose environmental problems due to the growing consumption of traditional hardwood varieties have been reported by Barreto et al (2006), Fearnside (2008), Stahel (2016), and other authors.

Figure 2 shows a comparison between the current classification to four strength classes (Figure 2a), and the proposed classification this present study to six classes (Figure 2b).

Figure 2. Diagram of points allocated in strength classes: (a) current classification of the Brazilian standard document, and (b) new classification proposed in this work

Source: prepared by the author.
Figure 3 demonstrates the data behavior after the application of the proposed classification with additional strength classes. From frequency analysis, it was verified a better data distribution of the proposed classes, which reveals a more homogeneous distribution in the observations (Figure 3a). The values of central tendency are predominantly located below the second quartile in the intervals of each strength class (Figure 3b), which allows a more rational process of analysis and project.

![Figure 3. Data behavior after the proposed new classification with additional strength classes: (a) individual values, and (b) $f_{c0,k}$ values of boxplot](image)

Source: prepared by the author.

Through the repetition of discriminant analysis for the new scenario with additional classes, we observed an improvement in the statistical estimation for the classification, where 89.3% of results were correct. Efficient rates of correctness were obtained, which included 94.1% for C40, 90.9% for C50, and 100% for C60. To validate the new proposal of classification, it was necessary to analyze whether the effect of this proposal could be significant for the analyzed data. Therefore, the analysis of variance (ANOVA) was performed using the strength classes with a factor (Table 5) by means of Tukey's paired comparisons (Table 6).

ANOVA results of the Table 5 resulted in “p-value = 0” condition, below the 5% significance level. This situation suggests that null hypothesis (class equality)
can be rejected. Thus, there are at least two different strength classes, whose classification effect is significant.

| Table 5: Results of ANOVA analysis |
| Source | GL | SQAJ | QM4.5 | Value-F | P-Value |
| Strength Classes (MPa) | 5 | 15913 | 3182.26 | 85.29 | 0.000 |
| Error | 50 | 1866 | 37.31 | -- | -- |
| Total | 55 | 17778 | -- | -- | -- |

*GL – freedom degrees; SQAJ – sum of squares; QMAJ – average squares

Source: prepared by the author.

| Table 6: Grouping information using the Tukey method |
| Strength Classes (MPa) | N | Mean | Grouping |
| C70 | 12 | 83.23 | A |
| C60 | 7 | 63.72 | B |
| C50 | 11 | 54.30 | C |
| C40 | 17 | 45.80 | D |
| C30 | 5 | 37.28 | D; E |
| C20 | 4 | 28.37 | E |

* Means with distinct letters are significantly different.

Source: prepared by the author.

The utilization of Tukey’s paired comparisons allowed identifying which strength classes could be different, through a significant classification effect, as it was verified in the Table 6.

From these findings, the proposed classification exhibited good outcomes and applicability to all strength classes, in order to represent the statistical behavior of studied data. Due to low number of specimens of C20 and C30 categories, it was not possible to accurately identify the distinction among these classes by the considered test. But, previously, it is noted the existence and effective demand of these additional strength classes to differentiate species and low-strength woods.

The use of statistical methods requires the corroboration of premises of analyses and data treatment. For the ANOVA, there is the real need to verify the data normality (although this premise can be broken), homogeneity/equivalence of variance, and independence and normality of residues. Essas premissas foram verificadas validando os resultados obtidos pela ANOVA.

Lastly, it is further necessary to validate the results of the compressive strength tests. Figure 4 shows the relationship between the coefficient of variation
for each sample with the $f_{c0,k}$ values. Yet, the points are identified according to strength class, including those additional classes.

Figure 4. Dispersion of the coefficients of variation ($C_v$) in relation to the $f_{c0,k}$ values

The values of $C_v$ are predominantly situated in the 5 % to 20 % interval, which evinced the suitability of laboratory determinations carried out in this scientific study. Also, we observed a smaller dispersion of the obtained results as the characteristic strength increases. This fact is associated to the grain densification, which causes a tendency to standardize the results of the compressive strength tests; the witch is confirmed by Tenorio et al. (2021), where low-density woods modified by densification have presented greater stability in different mechanical properties.

Thereby, the values for the coefficient of variation validate the representativeness of determinations of compressive strength parallel to the grain as well as the fact reinforces the existence of values prudently reclassified for the new C50 and C70 categories.
4 CONCLUSIONS

From the analysis of results of compressive strength parallel to the grain in 56 different tropical hardwoods from Brazil, inadequacies in the current procedure of strength classes were confirmed, since ranges of characteristic values are not adequately addressed in the current recommendations.

Alternatively, there is the effective proposal to include two additional strength classes, given by C50 and C70, in order to reclassify the characteristics results obtained in the analysis. In this way, through the statistical analyses of variance and grouping, a better adjustment in the configuration of this proposal was confirmed, utilizing a more representative classification and providing a more complete standardized methodology about strength classes for timber structures in construction.

Therefore, the present proposal should effectively contribute to the possible reductions in the significant consumption of the more commercially traditional Brazilian hardwoods, since little-known tropical hardwoods could satisfy, with the support of these two new strength classes, the consideration and sequential application of more alternative woody varieties for the construction.

It’s worth noting that the results obtained refer only to hardwoods, commonly used in Brazil for structural projects. This work can be redone using a greater number of wood species, as well as analyzing the allocation of \( f_{c0,k} \) values for softwoods.
REFERENCES


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