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Compression Behaviour of Laminates of Dendrocalamus Asper bamboo and Guadua Angustifolia bamboo

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Abstract

This study presents the experimental results of the compression behaviour of bamboo laminates made of Dendrocalamus asper on the one hand and Guadua angustifolia on the other hand. The construction of these laminates involved using bamboo boards aligned in a singular orientation, as bamboo naturally comprises longitudinal threads. As a result, it was anticipated that the laminates would exhibit orthotropic behaviour. Hence, the current investigation considered three distinct orientations: parallel to the fibres, perpendicular to the fibres and parallel to the boards, and finally, perpendicular to the fibres and perpendicular to the boards. A total of ten tests were conducted for each type of specimen to ascertain the compression strength and elastic modulus in both directions for the two species. The laminates derived from Dendrocalamus asper exhibited comparatively reduced density, compression strength, and modulus of elasticity along the fibre orientation compared to the laminates of Guadua angustifolia. In contrast, the specimens of Dendrocalamus asper exhibited higher resistance and ductility when subjected to compression perpendicular to the fibre. It is essential to clarify that, beyond conducting a direct comparative analysis under identical conditions, this research aims to disseminate and analyze the numerical results of material tests conducted on laminates produced in factories in Colombia and Ecuador.

Keywords: *bamboo laminates; compression parallel to the fibres; compression perpendicular to the fibres; elastic modulus; Guadua angustifolia; Dendrocalamus asper; bamboo.*

1. Introduction

Bamboo has been utilised extensively in housing and building construction for a considerable time in various parts of the world, such as China [1]. However, its use in Latin America has been limited due to various factors [2,3]. Its design as a structural element has recently been included in different Standards like ISO 22156:2021 [4], the Colombian Standard NSR-10 [5], the Peruvian Standard E.100 Bambu [6] and the Ecuadorian Standard NEC Estructuras de Guadua (Gak) [7]. Even though it is a natural [8], renewable [9–11], biodegradable [10], environmentally friendly [5–8], sustainable [12–15] and comfortable material for use in buildings [16], whose mechanical strength concerning its weight is attractive [8,10,14,17] and can be acquired within a few years

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[10,12,18] (compared to wood); its particular characteristics such as its variable circular cross-section along its longitudinal axis [10], the random distribution of nodes, its non-homogeneity [9] and its natural imperfections such as cracks and twists and efficiency make challenging to use on a large-scale construction [19]. Bamboo laminates allow many aspects to overcome the previously mentioned limitations of bamboo culms [9,10,14,19,20]; one of the first steps to take advantage of it is to determine its mechanical characteristics [9] so that with this information, the structural elements under compression can be designed.

The utilisation of bamboo culms in the production of laminate elements has the potential to enhance and streamline its application in the construction of residential, commercial, and other architectural structures [12,21] since it is possible to manufacture elements through an industrialised process standardizing its dimensions [10,22] and its mechanical properties. With materials of these characteristics, it could be possible to have a production line that includes the processing of the material [14] in Ecuador and Colombia, the manufacture of elements and the preparation of connexions that allow an efficient assembly at the final location. In addition, the present study is helpful in the development of numerical simulations [9,18] of bamboo structural elements.

Several investigations have developed studies of bamboo laminates. Barreto [23], Lopez [24], and Cortes et al. [25] studied the behaviour of Guadua angustifolia bamboo laminates; Li et al. [26] and Yeh & Lin [27] tested Phyllostachys pubescens bamboo [Mosso] laminates and Yeh & Lin [27] also worked on Dendrocalamus latiflorus laminates. However, it is essential to deepen the knowledge related to the physical and mechanical behaviour of laminates [28] and its form of failure under different solicitations [29] parallel and perpendicular to the fibre (and between the last one, perpendicular and parallel to the boards) two studies were carried. The initial study [30] was conducted in Colombia, whereas the subsequent investigation [31] was conducted in Ecuador, utilizing specimens obtained from firms in these respective countries.

The lack of diffusion of bamboo laminates in South America is mainly due to the need for more information related to the local species' manufacturing, costs, design, behaviour and mechanical properties, which generates uncertainty among users. In addition, many of the world's design and construction professionals still need to familiarize themselves with the principles of bamboo-based structural design [10]. This research aims to provide information on the behaviour, strength and mechanical characteristics of these two bamboo species to facilitate the process of sizing structural elements, their implementation and dissemination, and to make them potential sustainable commercial options in Ecuador and Colombia.

2. Materials and Methods

2.1. Laminates Manufacture Process using bamboo strips

Generally, the bamboo material's manufacturing process was similar across different countries. Figure 1 illustrates the initial stages of this process, which commenced with extracting strips from round bamboo using a parallel disc saw. Subsequently, a mechanization process was employed to obtain slats. The conditioning of bamboo slats occurs concurrently with the preservation and chamber drying stages. Following removing internal and external knots from the slats, they undergo a pre-drying period that can last anywhere from 5 to 15 days at room temperature. After this, the slats enter a drying chamber where the temperature is regulated from 60°C to 65°C. Throughout this process, the moisture content is reduced to 10%. Additionally, the humidity level within the chamber is carefully monitored and adjusted to prevent the air from becoming excessively dry, which could result in cracks in the slats. These slats were then used to produce boards after adhesive was applied to their edges. Finally, laminate blocks were obtained through the pressing of multiple boards.

The principal differences in the process were the adhesive, which in the case of Guadua angustifolia laminates was urea melamine formaldehyde, and for Dendrocalamus asper laminates was polyvinyl acetate. The temperature of pressing in the first case was the environment temperature. In the second case, it was 60 °C. Consequently, the pressing time differed, being 6 hours in the first case and 15-30 minutes depending on the slat thickness in the second case.

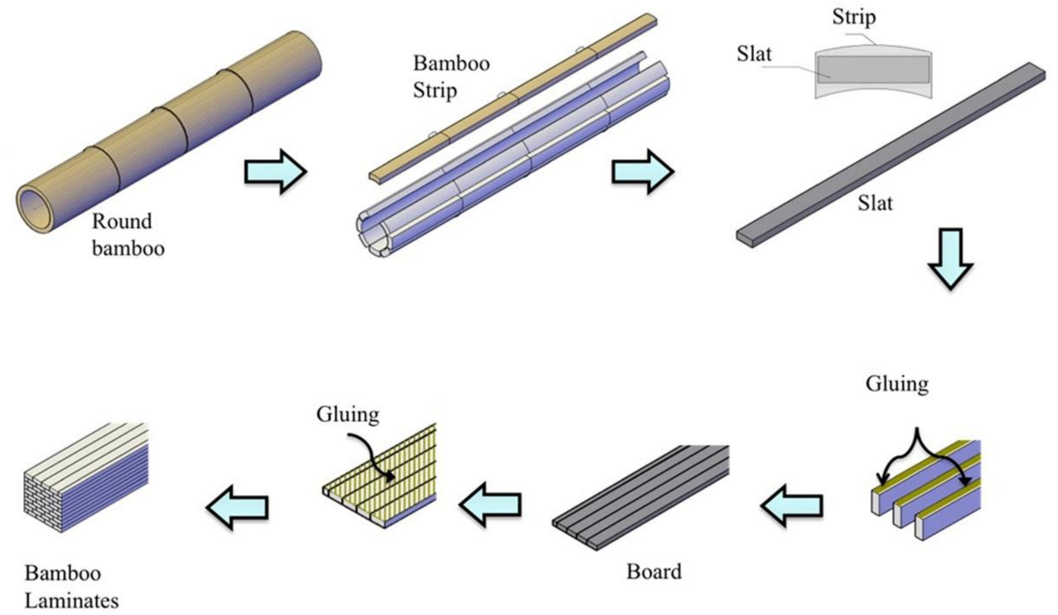


Figure 1. Manufacture of bamboo laminates. Adapted from Figure 1 [32,33].

2.2. Experimental Program

2.2.1. Description of the specimens

The identification of the types of specimens was accord to the rectangular coordinate system shown in Figure 2, where axis 1 is parallel to the fibres, shaft 2 is perpendicular to the fibres and boards, and axis 3 is perpendicular to the fibres and parallel to the boards.

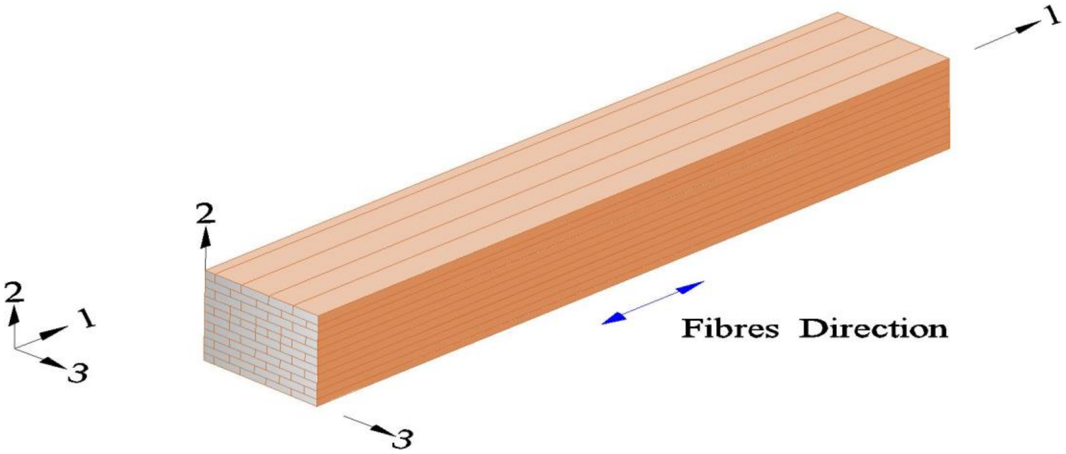


Figure 2. Coordinate system. Adapted from Figure 2 [34].

From each block, three different types of specimens were cut. The nomenclature of the test pieces consisted of a letter C corresponding to compression solicitation and two equal numbers according to the axis of the element to which the compression load is parallel. In this way, the compression load in C11 was parallel to the fibres (axis 1), in C22 specimens was perpendicular to the fibres and the boards (axis 2) and in C33 was perpendicular to the fibres and parallel to the boards (axis 3). Figure 3 shows the three types of specimens. Additionally, each of the test pieces was marked from 1 to 10.

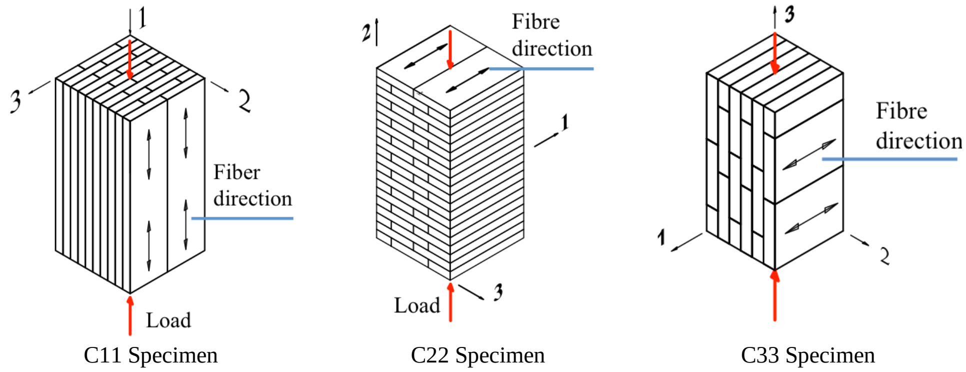


Figure 3. Nomenclature and codes used for specimens. Adapted from Figure 2 [32].

All specimens, except the C33 specimens of Guadua angustifolia bamboo, exhibited 5 cm x 5 cm x 10 cm. On the other hand, the C33 specimens of Guadua angustifolia bamboo measured 3 cm x 3 cm x 6 cm.

2.2.2. Test description

The densities and moisture content of each specimen were weighed and measured. In order to determine the elastic modulus, strain gages were located in the direction parallel to the load, as shown in Figure 4. The specimens were placed directly onto the load plates of the AG-X plus Universal Testing Machine and tested at a speed of 0.01 mm/s (0.6 mm/min).

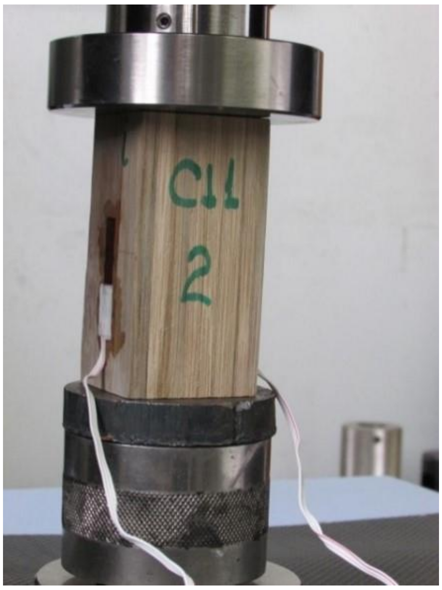


Figure 4. Test assembly. Source: Authors

2.3. Calculations

The volume (V) was calculated based on Equation (1), where l, b and t correspond to each specimen's length, width and thickness.

$$V = l\ b\ t \tag{1}$$

The density (ρ) was calculated based on Equation (2), where m corresponds to mass and V to the volume of the specimen.

$$\rho = \frac{m}{V} \quad (2)$$

The moisture content (MC) was calculated based on Equation (3), where w_i represents the initial weight of the specimen before drying and w_o is the weight of the dried specimen.

$$MC = \frac{w_i - w_o}{w_o} \quad (3)$$

The compressive stress (σc) at each step of the load was calculated with Equation (4), where P is the applied load and A is the cross-section area of the specimen.

$$\sigma_c = \frac{P}{A} \quad (4)$$

The compression strength (Fc) was calculated with Equation (5), where Pmax is the maximum load applied to the specimen.

$$F_c = \frac{P_{max}}{A} \quad (5)$$

The coefficient of variation (CV%) was calculated with Equation (6), where SD is the Standard Deviation, and $\bar{X}$ is the average value of the dataset.

$$CV\% = \frac{SD}{\bar{X}} \quad (6)$$

Concerning Guadua angustifolia laminates [30], the elastic modulus parallel to the fibre in the instrumented C11 tests was determined using the linear regression slope of stress-strain points between 20% and 75% of the maximum stress. For C22 specimens, the range for the calculation was 5% to 30% of the maximum stress and 5% and 55% for C33 specimens. The adopted range for each case was based on the general behaviour of each type of test (where the stress-strain curve exhibits a static-linear behaviour).

For all specimens of Dendrocalamus asper laminates, a unique criterion was applied. The adopted range of data for calculating the elastic modulus for all specimens was 10% to 40% [31,35].

3. Results

Table 1 shows the specimens' mean density and coefficient of variation for all types of laminates of the two species studied. It is possible to observe that for all cases, the coefficient of variation is less than 10%, which indicates that the density of laminates is uniform. Also, it is noted that the laminates of Guadua angustifolia are denser than those of Dendrocalamus asper.

Table 1. Density of specimens (kg/m3)

Code	C11		C22		C33	
Species	Guadua angustifolia	Dendrocalamus asper	Guadua angustifolia	Dendrocalamus asper	Guadua angustifolia	Dendrocalamus asper
Mean density	840	765	800	723	790	728
CV%	4,5	4,3	6,4	7,7	3,9	5,2

The experimental results showed in Table 2 that Guadua angustifolia laminates are more resistant than Dendrocalamus asper laminates under compression parallel to the fibre (C11 specimens), whereas that under compression perpendicular to the fibre are weaker (C22 and C33 specimens). For all cases, the compression strength parallel to the fibre is higher than the compression strength perpendicular to the fibre [19]; for this reason, in the design of connections between elements, the compression perpendicular to the fibres is critical and must be checked [5,7,19,36].

Table 2. Compression strength in the three directions (MPa)

Code	C11		C22		C33	
Species	Guadua angustifolia	Dendrocalamus asper	Guadua angustifolia	Dendrocalamus asper	Guadua angustifolia	Dendrocalamus asper
Mean	65,7	53,2	9,3	16,1	7,1	10,1
CV%	8,2	11,8	8,2	8	5,8	9,9

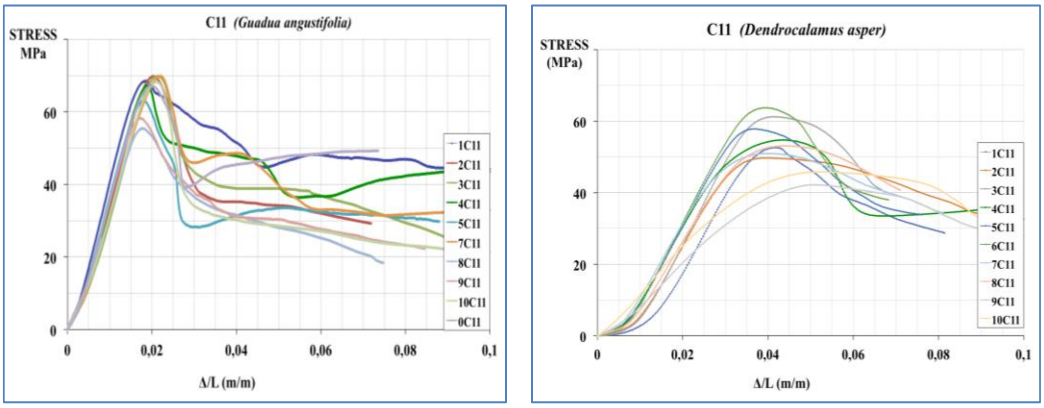
Table 3 shows the elastic modulus. The stiffness of Guadua angustifolia laminates is higher than the corresponding for Dendrocalamus asper when they are under compression parallel to the fibre.

Table 3. Elastic modulus (MPa)

Code	C11		C22		C33	
Species	Guadua angustifolia	Dendrocalamus asper	Guadua angustifolia	Dendrocalamus asper	Guadua angustifolia	Dendrocalamus asper
Mean	30044	19220	265	326	634	530
CV%	21,8	19,6	13	44,8	19,6	23,1

Figures 5, 6, and 7 depict the stress-strain (Δ/L) relationship in compression for three different specimen orientations: parallel to the fibre (C11), perpendicular to the fibres and boards (C22), and perpendicular to the fibres and parallel to the boards (C33).

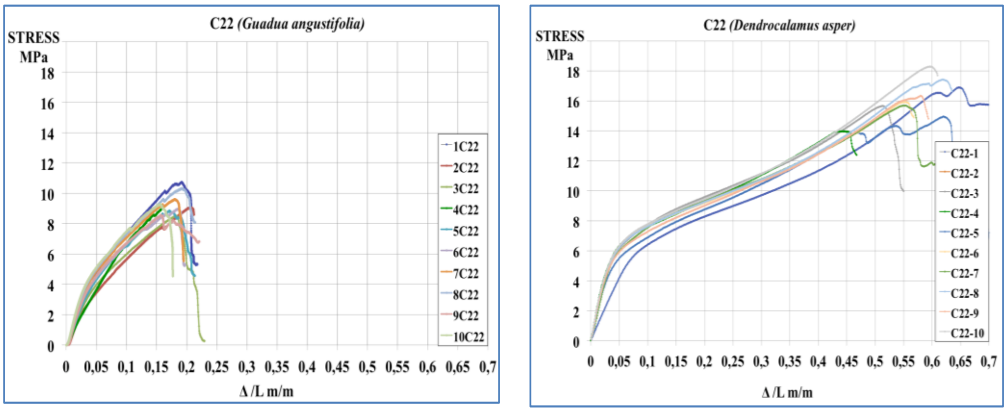
Despite variations in the adhesive type and temperature of the pressing process, the overall characteristics of the laminates exhibited a comparable pattern. A linear behaviour is observed at the beginning, after the accommodation phase. Later, the slope varies gradually, decreasing until it reaches the maximum value. The discharge has two differentiated phases: in the first, the stress decreases quickly, and in the second, the release is more gradual. During the loading and before reaching the maximum stress, the variability is not remarkable except in some specimens of Dendrocalamus asper, but in the discharge phase, there is more dispersion. The stiffness and maximum stress of Guadua angustifolia laminates are higher than in the Dendrocalamus asper. Furthermore, the unit strains at the point of physical fracture exceed the threshold of 0,05. Consequently, it is plausible to classify both materials as exhibiting ductile behaviour.



(a) *Guadua angustifolia* laminates (b) *Dendrocalamus asper* laminates

Figure 5. Stress-strain curves (Compression parallel to the fibre C11). Source: Authors

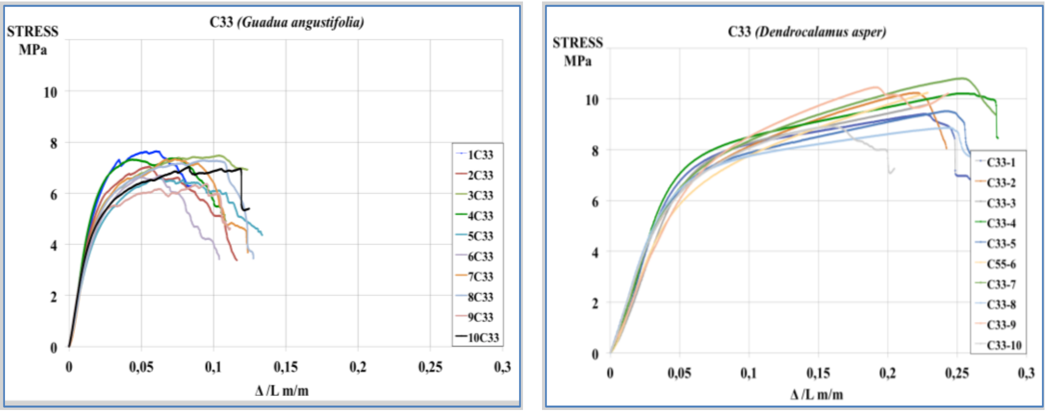
Although C22 specimens of Dendrocalamus asper laminates are more resistant and have more deformation than Guadua angustifolia laminates, their behaviour is similar. The stress-strain curves in the loading phase show a bilinear behaviour before and after the yield stress. A sudden failure is presented after the maximum stress is reached (Figure 6).



(a) *Guadua angustifolia* laminates (b) *Dendrocalamus asper* laminates

Figure 6. Stress-strain curves (Compression perpendicular to the fibre and boards C22). Source: Authors

The shape of stress vs. Δ/L curves for C33 specimens for both materials are approximately similar. The compression strength and ductility of C33 specimens of Dendrocalamus asper laminates are higher than that of Guadua angustifolia laminates (Figure 7).



(a) *Guadua angustifolia* laminates (b) *Dendrocalamus asper* laminates

Figure 7. Stress vs Δ/L (Compression perpendicular to the fibre and parallel to the boards C33). Source: Authors.

3.1. Description of Failures

As depicted in Figure 8, the failure mode of the C11 specimens typically transpired after the maximum load, whereby the fibre bundles underwent separation and buckling. In several instances of laminates, the fibre bundles exhibited signs of separation near the termination point of the specimen.

(a) 2C11 *Guadua angustifolia* (b) C11-2 *Dendrocalamus asper* (c) 1C11 *Guadua angustifolia*

Figure 8. C11 Specimens' failure. Source: Authors

The failure mode of C22 specimens is depicted in Figure 9. The failure can be attributed to diagonal shear cracks in general.

a. 8C22 *Guadua angustifolia* b. C22-3 *Dendrocalamus asper*

Figure 9. C22 Specimens' failure. Source: Authors

Most of the C33 specimens exhibited lateral buckling of the slats, subsequently followed by their separation. Figure 10 illustrates the problems observed in specimens 8C33 and C33-5.

(a) 8C33 *Guadua angustifolia*

(b) C33-5 *Dendrocalamus asper*

Figure 10. C33 Specimens' failure. Source: Authors

4. Conclusions

The primary reason for the restricted utilization of bamboo laminates in Ecuador and Colombia is the lack of sufficient information about indigenous bamboo species' design, behaviour, and mechanical characteristics. This knowledge gap has resulted in uncertainty among potential users. Furthermore, many specialists still lack familiarity with the fundamental principles of structural design with bamboo. This study aims to fill the existing gaps in knowledge by providing significant insights into the behaviour, strength, and mechanical features of the two bamboo species under investigation. Through this approach, the objective is to optimize the sizing, execution, and distribution of structural components, positioning them as viable and enduring commercial choices in both Colombia and Ecuador.

After a more thorough analysis of the laminates derived from these two bamboo species, it becomes apparent that they have discernible differences. One notable discrepancy exists in the density of these materials, as Guadua angustifolia laminates demonstrate higher density properties than Dendrocalamus asper laminates.

The present investigation revealed that the compression resistance and stiffness parallel to the fibres of Guadua angustifolia laminates surpass those of Dendrocalamus asper laminates. It is anticipated that the density of Guadua angustifolia laminates and its proportion of fibres will be higher.

The orientation of the boards significantly influences the compression behaviour of bamboo laminates. It was noticed that the elastic modulus parallel to the fibres exhibited a much greater value compared to the elastic modulus perpendicular to the fibres. The findings presented in this study underscore bamboo's orthotropic characteristics, indicating its significant implications for its utilization in structural contexts.

The analysis reveals that the laminates of both species exhibit the least ductility and strength when subjected to compression perpendicular to the fibre and parallel to the boards along the C33 direction. Therefore, when examining and designing structural elements and their connections, it is crucial to consider this mechanical property.

The failure mode exhibits variability contingent upon the orientation of the applied force. The fibre bundles exhibit separation and buckling when the load is applied parallel to the fibres. Conversely, failure occurs due to diagonal tension when the load is perpendicular to the fibres and boards. In cases where the load is perpendicular to the fibres and parallel to the boards, failure is attributed to the buckling of the specimen.

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