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Establishing the Characteristic Compressive Strength Parallel to Fiber of Four Local Philippine Bamboo Species

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Abstract: Bamboo is considered a sustainable construction material due to its ability to grow quickly and its mechanical properties that are comparable to timber. Contributing to the current effort to establish structural bamboo standards in the National Structural Code of the Philippines (NSCP), this study establishes the characteristic compressive strength of four bamboo species: *Bambusa vulgaris* (36 samples), *Dendrocalamus asper* (36 samples), *Bambusa blumeana* (94 samples), and *Guadua angustifolia* Kunth (30 samples). The samples were subjected to compressive loading following ISO 22157-1 (2017). The characteristic compressive strength values obtained, according to ISO 12122-1 (2014), were 40.35 MPa for *B. vulgaris*, 40.21 MPa for *D. asper*, 46.63 MPa for *B. blumeana*, and 36.99 MPa for *G. angustifolia* Kunth. Simple linear analysis, one-way ANOVA, and Welch's *t*-test were used to analyze the correlation models and establish a comparative analysis of the effects of nodes and geometric and physical properties on the compressive strength of bamboo samples. In comparisons of the characteristic compressive strengths obtained from this study to the strengths of unseasoned structural timber of Philippine woods, all bamboo species showed higher strength values than did other woods, and bamboos thus have great potential as an alternative construction material to timber.

Keywords: *Bambusa vulgaris*; *Dendrocalamus asper*; *Bambusa blumeana*; *Guadua angustifolia* Kunth; characteristic compressive strength; ISO 22157-1; ISO 12122-1

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1. Introduction

Bamboo is a lightweight, naturally renewable, and tree-like plant belonging to the grass family *Poaceae*, and it has about 1482 known species classified under the following three bamboo tribes: *Arundinarieae* (546 species), *Bambuseae* (812 species), and *Olyreae* (124 species) [1]. It is recognized as one of the most rapidly growing perennial plants that is cultivated in tropical to mild-temperate regions [2]. There are a total of 62 bamboo species that can be found in the Philippines and only eight of these are economically important, including *Bambusa blumeana* (kawayan tinik), *Bambusa sp.1* (formerly *Dendrocalamus merrilliamus*) (bayog), *Bambusa sp.2* (laak), *Bambusa vulgaris* (kawayan kiling), *Dendrocalamus asper* (giant bamboo), *Gigantochloa atter* (kayali), *Gigantochloa levis* (bolo), and *Schizostachyum lumampao* (buho). In addition, four more species were identified as having significant potential for economic development and still requiring further research, including *Bambusa oldhamii* (Oldham bamboo), *Dendrocalamus latiflorus* (machiku), *Guadua angustifolia* (iron bamboo), and *Thyrsostachys siamensis* (monastery bamboo). These species are distributed in certain provinces and rural areas around the country such as Abra, Bukidnon, and Davao del Norte [3].

Bamboo is considered a sustainable construction material due to its ability to grow and be harvested in a relatively short amount of time, and its mechanical properties are comparable to that of timber [4]. Depending on the species, bamboo only takes 3–5 years to reach full maturity, in comparison to hardwood trees, which can take about 30–40 years. Moreover, its abundance, workability, and cheap cost have made it a popular construction-material substitute for wood. Considering the availability of numerous Philippine bamboo species, further studies must be conducted to expand the use of our natural resources and shift to more sustainable options. The use of bamboo in the construction industry establishes significant impacts on environmental aspects. It also serves to reduce the rate of deforestation, which also decreases the consumption rate of wood and timber [5]. Furthermore, bamboo plantations are able to aid in carbon sequestration of up to 12 tons of carbon dioxide per hectare, and bamboo produces 35% more oxygen than equivalent areas of trees [6].

The mechanical properties of bamboo such as bending strength, shear strength, compressive strength, and tensile strength are significant in assessing its capacity to support loads, as well as for bamboo-grading purposes. These properties are evaluated in order to generate appropriate structural standards for bamboo in the Philippines for it to be effectively used as a construction material.

Among these mechanical characteristics, the compressive strength of the bamboo species that are readily available in the Philippines requires further research. Available data about economically important bamboo species in the Philippines are mostly limited to their average strength values. For grading and design purposes, the characteristic strength values of the bamboo need to be established as grading considers the strength value at the 5th percentile, which means that 95% of the samples have strength values that are higher than the characteristic strength value. This indicates that it is a better representation of the strength property of bamboo than the average strength value. Additionally, local bamboo users such as the Base Bahay Foundation, Inc. utilize the allowable stress from characteristic strength values supported by safety factors for the design value used in construction.

This lack of engineering data for the mechanical properties of bamboo hinders the establishment of appropriate building codes [7]. To be specific, although there are studies regarding the material characterization of bamboo, data are still insufficient as there exists a wide variety of bamboo species and their strength properties may vary depending on their morphology. In the context of the Philippines, studies characterizing the species *Bambusa blumeana*, *Bambusa vulgaris*, and *Dendrocalamus asper* exist but are only focused on tension [8], shear [9], and bending strength [10].

The National Structural Code of the Philippines (NSCP) 2015 serves as the guidance code for the design of structural members. It includes standards for using conventional building materials such as concrete, steel, and wood/timber. Bamboo is commonly used as a building material, and it can be fully utilized by designers and engineers if it becomes part of the National Structural Code of the Philippines. In addition to this, the Department of Trade and Industry (DTI) recently adopted the International Organization for Standardization (ISO) standards on bamboo structures as Philippine National Standards (PNS) in May 2020 [11]. However, the adopted standards are only focused on the grading of bamboo culms (PNS ISO 19624:2020) and the test methods used to determine its physical and mechanical properties (PNS ISO 22157:2020), not necessarily on bamboo's application to buildings or structures. Thus, there is a need to establish the mechanical properties of bamboo, one of which is the characteristic compressive strength parallel to the fiber.

The main objective of this study is to establish the compressive strength parallel to the fibers of four Philippine bamboo species: *Bambusa vulgaris*, *Dendrocalamus asper*, *Bambusa blumeana*, and *Guadua angustifolia* Kunth. It was hypothesized that would be little to no significant differences between the compressive strength of samples in the node condition and in the internode condition for all bamboo species tested. The compressive strength among the four bamboo species was also expected to have little to no significant differences. It was assumed that the samples satisfy the grading requirement stated in PNS ISO 19624 (2020) [12].

This study only covered the use of bamboo as a construction material, and other aspects such as its medicinal attributes or industrial uses were not discussed. The bamboo samples tested were also limited to the identified four bamboo species being cultivated in the Philippines, excluding any other local or foreign species. Specifically, these samples were outsourced from the Base Bahay Foundation, Inc., and the tests were conducted in the Department of Public Works and Highways—Bureau of Research and Standards (DPWH-BRS) in Quezon City. Other bamboo properties such as its age at harvest were not considered in this study. Its physical properties such as moisture content, basic density, and mass per unit length, however, were considered and determined for each test sample. This study also established the characteristic compressive strength of bamboo; bending, tensile, and shear strengths were not considered. As ISO 22157-1 (2017) guidelines only provide the testing methodology for compressive strength parallel to the fiber, bamboo's compressive strength perpendicular to its fibers is not part of this study [13]. Compression tests were only performed on the bamboo culms in the node and internode part of the bamboo, without considering any branches. Lastly, this study is limited to the determination of the compressive strength based on its location in the culm (top, middle, or bottom).

This study will be significant in developing standards for bamboo as a construction material in the Philippines. Aside from the aforementioned environmental benefits that bamboo has to offer, this research can be used as a guide for engineers, construction firms, and other researchers to support the use of green building materials and the use of bamboo as a structural material.

2. Materials and Methods

2.1. Sample Preparation

A total of 196 bamboo samples were tested, 30 of which were *Guadua angustifolia* Kunth, 36 were *Bambusa vulgaris* and *Dendrocalamus asper*, and 94 were *Bambusa blumeana*. Following the standards of the PNS ISO 22157:2020, 50% of the samples per species were with node and the remaining 50% were without node. Based on the same test protocol, the samples were cut such that the length was the lesser of the outer diameter D or 10 times the wall thickness 10 δ, as shown in Equation (1), and the end planes were approximately parallel to each other and perpendicular to the length axis of the sample.

$$L = \min\begin{cases} D \\ 10\delta \end{cases} \quad (1)$$

where L is the length (mm) of the sample, D is the average outer diameter of the sample (mm); and δ is the average thickness of the sample (mm).

Nodes, if present, were located approximately at mid-height. The bamboo samples were visually inspected and defects such as cracks, holes, and fungal damage were recorded. Severely damaged samples were replaced. The samples were marked by their species (BV, DA, BB, or G), test sample number, node classification (N for with node or WN for without node), and location (T for top, M for middle, or B for bottom). However, the location where the sample was obtained is only known for *G. angustifolia* Kunth.

Using a digital caliper with a precision of 0.1 mm, the dimensions of each sample were measured. Two values of length were measured along the axis of the sample, where two reference points were directly parallel to each other. For the outer diameter D, it was measured from the end planes. Four values of diameter were measured with reference points located from pairs 0° and 180°, and 90° and 270°, referencing the top and bottom faces of bamboo. Eight values of thickness δ were measured, four for each face, located at 0°, 90°, 180°, and 270°. The average diameter and thickness were used for the computation of the cross-sectional area A using Equation (2):

$$A = \left(\frac{\pi}{4}\right) \times \left(D^2 - (D-\delta)^2\right) \quad (2)$$

where A is the cross-sectional area of the sample (mm^2); D is the average outer diameter of the sample (mm); and δ is the average thickness of the sample (mm).

The mass of the sample was also measured using a digital balance with a precision of 0.01 g. Mass per unit length q was subsequently calculated using Equation (3):

$$q = \frac{m_e}{L} \quad (3)$$

where q is the mass per unit length (kg/m) of the sample; m_e is the mass (g) of the sample at green condition; and L is the length (mm) of the sample where L is the average of the two measured length values. The activities performed during the sample preparation are presented in Figure 1.

(**a**) (**b**) (**c**) (**d**)

Figure 1. (**a**) Bamboo cutting, (**b**) placing markings, (**c**) dimension measuring, and (**d**) sample weighing.

2.2. Compression Testing

The bamboo compression tests were performed at the Department of Public Works and Highways of the Bureau of Research and Standards (DPWH-BRS) at Quezon City, Philippines, using an A22C02 Controls compression machine with 2000 kN capacity (Figure 2).

Figure 2. Compression machine.

Following ISO 22157-1 (2017), the samples were placed on the equipment such that their axes were aligned [13]. An initial load not exceeding 1% of the expected failure load was applied to hold the sample in place. The load was then applied where the rate of load application was chosen such that the failure is reached within 300 ± 120 s. Tests with failure in less than 30 s were not considered, and the load was applied continuously throughout the test without being interrupted.

The maximum applied load F_{ult}, time to failure, and the observed location and mode of failure were recorded for each test. The compressive strength $f_{c,0}$ was then calculated using Equation (4). The test set-up is shown in Figure 3.

$$f_{c,0} = \frac{F_{ult}}{A} \tag{4}$$

where $f_{c.0}$ is the compressive strength parallel to the fibers (MPa); F_{ult} is the maximum load at which the sample falls (N); and A is the cross-sectional area of the sample (mm^2).

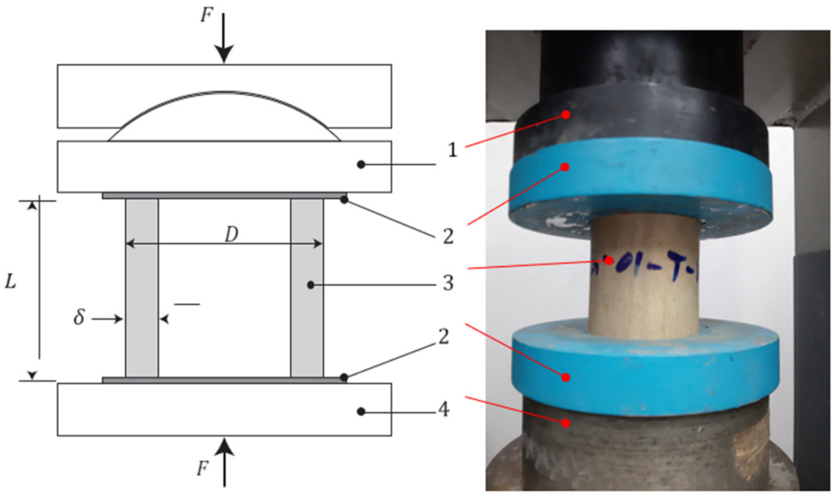


Figure 3. Compression test set-up. D—outer diameter; δ—wall thickness; F—load; L—length of test sample; 1—upper loading platen with spherical bearing; 2—intermediate layer; 3—bamboo sample; 4—lower loading platen.

2.3. Moisture Content Determination

The moisture content of bamboo has a significant effect on its physical and mechanical properties as these are functions of it. It varies with the height of the culm, seasoning period, geographical location, and species [14], as well as the age of the bamboo at harvesting [15]. Test specimens used to determine the moisture content were obtained close to the failure location. The number of specimens was equal to the number of test samples for the compression tests and specimens were approximately rectangular in shape. Shown in Figure 4 are the test specimens for *Dendrocalamus asper* with node and without node, following the sample marking method discussed in Section 2.1. This allows for ease in measuring the specimen volume using the average of four width values (two from each edge), four thickness values (one per corner), and two length values (inner and outer). The volumes of the nodes were not considered in the volume calculations.

(**a**) (**b**)

Figure 4. Test specimens for DA-N (**a**) and DA-WN (**b**).

The specimens were weighed using a digital balance with a precision of 0.01 g and recorded as the initial mass m_i. They were then placed in an oven at a temperature of 103 ± 2 °C for 24 h. The oven-dry mass m_0 was then measured and the moisture content ω was calculated using Equation (5). The basic density ρ was also computed (6).

$$\omega = \left[\frac{m_i - m_0}{m_0}\right] \times 100 \quad (5)$$

$$\rho = \frac{m_0}{V_0} \quad (6)$$

where ω is the moisture content (%) of the specimen; m_i is the initial mass (g) of bamboo specimen (green weight); m_0 is the oven-dried mass (g) of bamboo; ρ is the basic density (kg/m^3) of the specimen; and V_0 is the volume (m^3) of the specimen at green condition.

2.4. Characteristic Strength Calculation

The characteristic compressive strength $f_{c,0,k}$ value was calculated using ISO 12122-1 (2014) and 5th percentile-based properties with a 75% confidence evaluation [16]. The basis of non-parametric data for evaluation, as cited in ISO 12122-1 (2014), is AS/NZS 4063.2, which is used for the determination of characteristic values for structural timber for structural design. The valuation was conducted through data ranking and the 5th percentile was determined by sorting the results from highest to lowest then obtaining the percentile. The characteristic strength value $X_{0.05,0.75}$ was computed using Equation (7).

$$X_{0.05,0.75} = X_{0.05}\ (1 - \frac{k_{0.05,0.75}\ COV}{\sqrt{n}}) \quad (7)$$

where $X_{0.05,0.75}$ is the 5th percentile compressive characteristic strength (MPa) with 75% confidence; $X_{0.05}$ is the determined 5th percentile value interpolated from the test data; $k_{0.05,0.75}$ is the constant multiplier to give the 5th percentile that denotes 75% confidence; COV is the coefficient of variation equivalent to the ratio of sample standard deviation to sample mean; and n is the number of samples tested.

Table 1 shows the corresponding $k_{0.05,0.75}$ constant value used in calculating the characteristic compressive strength depending on the number of samples tested per species as indicated in ISO 12122-1 (2014) [16].

Table 1. Multiplier used to give the 5th percentile with 75% confidence.

Number of Specimens	$k_{0.05,0.75}$
5	-
10	-
30	2.01
50	1.94
100	1.85
>100	1.76

3. Results and Discussion

3.1. Geometric, Physical, and Compressive Properties

The geometric properties of each bamboo species categorized based on the appearance of nodes are listed in Table 2. The length L, outer diameter D, thickness δ, and cross-sectional area A, are the properties measured using ISO 22157-1 (2017) [13].

Table 2. Summary of geometric properties of bamboo species.

Geometric Properties	*L* (mm)	*D* (mm)	*δ* (mm)	*A* (mm^2)
B. vulgaris (Node) (n = 18)				
Min	69.95	71.60	5.55	1192.18
Max	102.20	107.80	11.29	3153.79
Mean	88.75	89.41	7.24	1899.49
St dev	10.26	10.82	1.53	585.69
COV	0.12	0.12	0.21	0.31
B. vulgaris (Internode) (n = 18)				
Min	68.30	71.13	5.85	1199.64
Max	109.60	108.48	9.16	2858.69
Mean	90.30	89.60	7.13	1873.91
St dev	11.06	10.62	1.04	474.83
COV	0.12	0.12	0.15	0.25
B. vulgaris (n = 36)				
Min	68.30	71.13	5.55	1192.18
Max	109.60	108.48	11.29	3153.79
Mean	89.53	89.51	7.19	1886.70
St dev	10.54	10.57	1.29	525.64
COV	0.12	0.12	0.18	0.28
D. asper (Node) (n = 18)				
Min	104.75	109.15	8.20	2723.26
Max	137.25	133.78	15.63	4903.83
Mean	119.92	117.13	10.33	3458.99
St dev	8.43	6.22	2.10	679.19
COV	0.07	0.05	0.20	0.20
D. asper (Internode) (n = 18)				
Min	108.25	109.35	7.74	2772.64
Max	137.35	135.15	15.49	4779.79
Mean	122.89	120.49	10.96	3754.87
St dev	8.22	7.43	2.06	632.03
COV	0.07	0.06	0.19	0.17
D. asper (n = 36)				
Min	104.75	109.15	7.74	2723.26
Max	137.35	135.15	15.63	4903.83
Mean	121.40	118.81	10.65	3606.93
St dev	8.34	6.97	2.08	663.77
COV	0.07	0.06	0.20	0.18
B. blumeana (Node) (n = 46)				
Min	73.45	76.90	5.66	1305.78
Max	110.40	110.20	10.45	2960.54
Mean	94.93	95.03	7.68	2113.08
St dev	8.19	7.35	1.09	372.24
COV	0.09	0.08	0.14	0.18
B. blumeana (Internode) (n = 47)				
Min	73.40	77.28	5.58	1255.78
Max	108.55	108.10	9.94	2796.09
Mean	91.27	92.88	7.46	2008.03
St dev	8.73	8.74	1.06	379.22
COV	0.10	0.09	0.14	0.19

Table 2. *Cont.*

Geometric Properties	*L* (mm)	*D* (mm)	δ (mm)	*A* (mm^2)
B. blumeana (n = 93)				
Min	73.40	76.90	5.58	1255.78
Max	110.40	110.20	10.45	2960.54
Mean	93.08	93.94	7.57	2059.99
St dev	8.62	8.11	1.07	377.45
COV	0.09	0.09	0.14	0.18
G. angustifolia Kunth (Node) (n = 15)				
Min	58.00	57.63	6.28	1012.29
Max	93.70	90.90	13.98	3071.85
Mean	75.13	75.91	9.51	1989.12
St dev	9.63	9.26	2.83	634.72
COV	0.13	0.12	0.30	0.32
G. angustifolia Kunth (Internode) (n = 15)				
Min	52.00	56.25	5.30	869.57
Max	88.20	91.70	12.88	2809.76
Mean	74.05	74.87	8.75	1833.40
St dev	9.47	9.62	2.70	628.84
COV	0.13	0.13	0.31	0.34
G. angustifolia Kunth (n = 30)				
Min	52.00	56.25	5.30	869.57
Max	93.70	91.70	13.98	3071.85
Mean	74.59	75.39	9.13	1911.26
St dev	9.40	9.29	2.74	625.83
COV	0.13	0.12	0.30	0.33

n—number of samples, *L*—length, *D*—diameter, δ—thickness, *A*—area, Min—minimum sample value, Max—maximum sample value, Mean—sample mean μ, St dev—sample standard deviation σ, COV—coefficient of variation (σ/μ).

Table 3 shows the physical properties of the bamboo species considering the mass per unit length q, moisture content ω, and basic density ρ. The mass per unit length values were calculated from the geometric measurements of the samples prior to compression tests, whereas the moisture content and basic density were obtained from the test specimens after the compression tests. *B. vulgaris* and *D. asper* samples, including both nodal and internodal samples, had the lowest and highest average mass per unit length results in this study with values ranging from 1.45 kg/m to 2.71 kg/m, respectively. It can be observed that the mass per unit length was greater for samples with nodes than for samples without nodes, which applies to all four species. In terms of the moisture content, it can be observed that the values for the average moisture content of all species in this study were within the prescribed range of 12 ± 3%. The moisture contents of the species for both nodal and internodal samples ranged from 10.67% to 11.67%, with *D. asper* and *G. angustifolia* Kunth obtaining the lowest and highest moisture contents, respectively. Like the previous property, the moisture content values were greater for samples with nodes compared to samples without nodes for all species in this study. The average basic densities of the species for both nodal and internodal samples ranged from 700.06 kg/m^3 to 806.85 kg/m^3, with *D. asper* and *B. blumeana* obtaining the lowest and highest basic densities, respectively. It is noteworthy that the basic density varied proportionally with the mass per unit length of the samples in which the density increases as the mass per unit length increases, which supports the claim by Nurmadina et al. [17] that a higher mass per unit length results in a higher culm density. The basic density was also greater for samples with nodes in comparison to samples without nodes for all species in this study. However, it should also be noted that mass and volume determine the density of the bamboo. As the diaphragm of the samples with nodes is included when obtaining the mass and it is disregarded in the volume computation, the samples with nodes in this study are more likely to exhibit higher density than samples without nodes [18].

Table 3. Summary of physical properties of bamboo species.

Geometric Properties	q (kg/m)	ω (%)	ρ (kg/m^3)
B. vulgaris (Node) (n = 18)			
Min	1.18	10.12%	585.13
Max	2.23	11.69%	1002.43
Mean	1.61	11.25%	795.24
St dev	0.37	0.00407	121.75
COV	0.23	0.03621	0.15
B. vulgaris (Internode) (n = 18)			
Min	0.91	9.93%	455.67
Max	1.71	11.52%	985.47
Mean	1.30	10.86%	683.63
St dev	0.26	0.00466	144.99
COV	0.20	0.04287	0.21
B. vulgaris (n = 36)			
Min	0.91	9.93%	455.67
Max	2.23	11.69%	1002.43
Mean	1.45	11.05%	739.43
St dev	0.35	0.00473	143.57
COV	0.24	0.04281	0.19
D. asper (Node) (n = 18)			
Min	1.89	9.86%	559.24
Max	4.69	11.68%	979.88
Mean	2.87	10.93%	756.82
St dev	0.83	0.00503	135.15
COV	0.29	0.04600	0.18
D. asper (Internode) (n = 18)			
Min	1.54	9.04%	453.89
Max	3.75	11.55%	858.21
Mean	2.56	10.41%	643.29
St dev	0.72	0.00634	123.88
COV	0.28	0.06090	0.19
D. asper (n = 36)			
Min	1.54	9.04%	453.89
Max	4.69	11.68%	979.88
Mean	2.71	10.67%	700.06
St dev	0.78	0.00622	140.14
COV	0.29	0.05830	0.20
B. blumeana (Node) (n = 46)			
Min	1.33	10.41%	641.93
Max	3.16	14.11%	1060.84
Mean	2.09	11.40%	889.19
St dev	0.45	0.00742	106.69
COV	0.22	0.06505	0.12

Table 3. *Cont.*

Geometric Properties	q (kg/m)	ω (%)	ρ (kg/m^3)
B. blumeana (Internode) (n = 47)			
Min	1.00	9.23%	465.63
Max	2.56	11.66%	881.43
Mean	1.68	10.40%	726.27
St dev	0.41	0.00488	98.12
COV	0.24	0.04694	0.14
B. blumeana (n = 93)			
Min	1.00	9.23%	465.63
Max	3.16	14.11%	1060.84
Mean	1.88	10.90%	806.85
St dev	0.48	0.00801	130.72
COV	0.25	0.07350	0.16
G. angustifolia Kunth (Node) (n = 15)			
Min	0.94	11.16%	730.54
Max	2.70	12.35%	981.35
Mean	1.87	11.81%	859.84
St dev	0.53	0.00360	64.38
COV	0.28	0.03051	0.07
G. angustifolia Kunth (Internode) (n = 15)			
Min	0.70	11.11%	580.80
Max	2.26	12.05%	933.68
Mean	1.45	11.52%	728.26
St dev	0.50	0.002902	83.66
COV	0.34	0.025178	0.11
G. angustifolia Kunth (n = 30)			
Min	0.70	11.11%	580.80
Max	2.70	12.35%	981.35
Mean	1.66	11.67%	794.05
St dev	0.55	0.00354	99.29
COV	0.33	0.03032	0.13

n—number of samples, q—mass per unit length, ω—moisture content, ρ—basic density, Min—minimum sample value, Max—maximum sample value, Mean—sample mean μ, St dev—sample standard deviation σ, COV—coefficient of variation (σ/μ).

The compressive strength parallel to the fibers of each different bamboo species is shown in Table 4, where the loads applied ranged from 0.13–4.19 kN/s. It can be observed that internode samples of *B. blumeana* obtained the highest average compressive strength among the species with 75 MPa, whereas *B. vulgaris* samples taken at the node obtained the lowest average strength value of 55.59 MPa. From the comparison of average strengths of the four main species between node and internode samples, it was common for internode samples to have greater compressive strengths than node samples. Bahtiar et al. [18] noted that the higher compressive strength values exhibited by bamboo samples without nodes may be attributed to the fiber orientation. The fibers on bamboos are parallel to the axial direction and some change direction as they cross the nodes, which may reduce the strength capacity of the bamboo. In comparing the average strengths of the four main species for both node and internode samples, *B. blumeana* and *G. angustifolia* Kunth obtained the highest and lowest strengths with 70.67 MPa and 57.53 MPa, respectively. For the corresponding coefficient of variation (COV) of the compressive strength of the species, *D. asper* internode samples were recorded to have the highest coefficient of variation of 0.21, whereas the *B. vulgaris* and *B. blumeana* samples taken at the node obtained the lowest COV of 0.18. Samples without a node were observed to have greater variance than samples with a node.

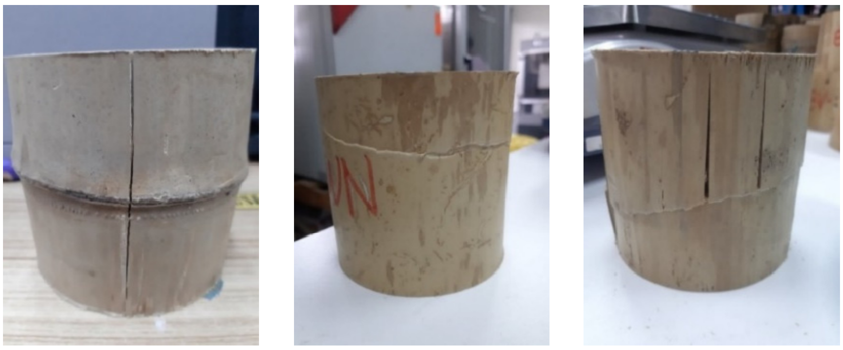
Table 4. Summary of the compressive strength parallel to the fibers of bamboo species.

Species	Mechanical Property $f_{c,0}$						
	n	Min (MPa)	Max (MPa)	μ (MPa)	σ	COV	σ^2
B. vulgaris (Node)	18	39.98	73.56	55.59	10.03	0.18	100.67
B. vulgaris (Internode)	18	44.35	84.96	66.73	13.32	0.20	177.50
B. vulgaris	36	39.98	84.96	61.16	12.92	0.21	167.03
D. asper (Node)	18	39.16	81.75	58.64	11.62	0.20	135.14
D. asper (Internode)	18	41.84	87.08	60.34	12.85	0.21	165.18
D. asper	36	39.16	87.08	59.49	12.11	0.20	146.61
B. blumeana (Node)	46	40.46	86.30	66.24	11.87	0.18	140.89
B. blumeana (Internode)	47	46.51	136.33	75.00	14.10	0.19	198.76
B. blumeana	93	40.46	136.33	70.67	13.70	0.19	187.69
G. angustifolia Kunth (Node)	15	33.43	70.78	56.29	10.82	0.19	117.03
G. angustifolia Kunth (Internode)	15	40.56	79.66	58.76	11.70	0.20	136.79
G. angustifolia Kunth	30	33.43	79.66	57.53	11.14	0.19	124.12

n—number of samples, Min—minimum sample value, Max—maximum sample value, μ—sample mean, σ—sample standard deviation, COV—coefficient of variation (σ/μ), σ^2—sample variance.

3.2. Failure Modes

The failures observed on the bamboo culms after being subjected to compressive loading were recorded. The failure modes are categorized into three types: splitting failure, crushing failure, and combined splitting and crushing. Splitting failure is characterized by cracks parallel to the fiber of the culms (Figure 5a). Due to the fibers of the bamboo running in a single, parallel direction, except at the nodes, splitting is a common failure behavior [19]. The variations in location, frequency, and length of the splitting observed in the culms were also noted. Crushing failure is characterized by a perpendicular or diagonal distortion in the culm due to the applied compressive force (Figure 5b). This can be found on the outer or inner surface of the culm, and it sometimes even penetrates through the entire thickness. In the study of Li et al. [20], they observed that crushing failure commonly happened on short-column samples, whereas long-column samples experienced buckling. The crushing failure in the culms also varied in location, frequency, and length. Combined splitting and crushing is the occurrence of both splitting and crushing in a culm (Figure 5c). Table 5 shows the frequency of each failure mode observed in each species, considering the nodal condition of the culms.



(**a**) (**b**) (**c**)

Figure 5. Typical failure patterns are (**a**) splitting, (**b**) crushing, and (**c**) combined splitting and crushing.

Table 5. Summary of the compressive strength parallel to the fibers of bamboo species.

Failure Type	Figure	Frequency							
		BV (N)	BV (WN)	DA (N)	DA (WN)	BB (N)	BB (WN)	G (N)	G (WN)
Splitting	5a	8	4	8	8	15	0	6	0
Crushing	5b	0	5	3	2	8	11	2	8
Combined	5c	6	6	4	6	21	35	7	4
No Failure		4	3	3	2	2	1	0	3
Total		8	4	8	8	15	0	6	0

BV—*B. vulgaris*, DA—*D. asper*, BB—*B. blumeana*, G—*G. angustifolia*, N—under node conditions, WN—under internode conditions.

Splitting failure was more frequent in *B. vulgaris* under node conditions (BV-N) than under internode conditions (BV-WN). For BV-N, the splits were observed on the outside surface of the culm, with varying frequencies and most were characterized as short splits. For BV-WN, multiple long splits were observed outside the culm surface, with some penetrating the thickness. Crushing failure occurred only in BV-WN, where mostly long, perpendicular crushing outside the culm surface was observed. Combined splitting and crushing failure occurred in both BV-N and BV-WN, where multiple short splits near the crushing were observed for BV-N, whereas larger splits running along the height of the culms were observed for BV-WN. It should also be noted that the crushing on BV-WN samples that experienced combined failure were mostly located inside, either at the top or bottom of the sample, or passing through the splits. Multiple *D. asper* samples under both node (DA-N) and internode (DA-WN) conditions experienced splitting failure. DA-WN samples had mostly single, short splits located either outside or inside the culm surface but never penetrating through the culm thickness. The splitting failure on DA-N behaved quite similarly, having predominantly single splits occurring outside with varying lengths between samples. A few small crushing failures were also observed on both sample types. For the combined splitting and crushing failures observed, the splits were not found near the crushing failure. The failures observed on *B. blumeana* samples were mostly combined splitting and crushing. For *B. blumeana* samples without a node (BB-WN), the crushing failures observed were characterized by perpendicular crushing that runs along the inner circumference, located either on the upper or lower portion of the culm. The splits were observed to be located near the crushing are and they varied in length and frequency. Shorter splits were located outside the culm whereas longer splits tended to penetrate through its thickness. For *B. blumeana* samples with a node (BB-N), the splitting and crushing failures were more varied in terms of frequency, length, and location. The *G. angustifolia* Kunth samples with a node (G-N) had failure modes that were mostly splitting or combined splitting and crushing, whereas *G. angustifolia* Kunth samples without a node (G-WN) had only crushing and combined splitting and crushing. There were multiple short splits observed on G-N samples and they were located on both the inside and outside surfaces of the culm. The crushing failures were oriented perpendicularly, and they varied in length and location. Similar to G-N, the crushing failures in G-WN also varied in length and location, with only one sample recorded as having a diagonal orientation, whereas the rest had splits that were oriented perpendicularly. There were multiple splits observed per sample and they were characterized as long splits located mostly on the outside surface of the culm.

The general trend of failure modes occurring for each species were as follows: in *B. vulgaris*, the presence of nodes had an effect promoting the occurrence of crushing; splitting failure generally governed the failure modes of *D. asper*; combined splitting and crushing were the most prominent among *B. blumeana* samples; and for *G. angustifolia* Kunth crushing was most prominent. Furthermore, results of *D. asper* and *G. angustifolia* Kunth were consistent with the study of Li et al. [20], where they noted that crushing failure commonly occurs in short-column samples, whereas long-column samples experienced buckling. *D.*

asper samples were generally longer, having an average length of 121.40 mm, whereas *G. angustifolia* Kunth samples were relatively short at an average length of 57.53 mm. Although buckling was not possible for the length of the samples, splitting was the failure mode that is most closely related to buckling. In addition to this, in observing average compressive strengths, *B. vulgaris* and *G. angustifolia* Kunth, which have low average $f_{c,0}$ values, are most prone to crushing whereas *D. asper* and *B. blumeana*, which had relatively high average $f_{c,0}$ values, experienced mostly splitting. Hence, it could be inferred that splitting usually occurs with high compressive strength bamboos, whereas crushing is most common for bamboos with relatively low compressive strength.

Samples with pre-existing defects were taken note of before compressive loading, specifically holes, cracks, and fungal infection (Figure 6). It was observed that culms with holes, regardless of the species and nodal condition, were more likely to experience splitting failure along or near the holes (Figure 7a). The pretesting cracks observed on all the samples were parallel to the fiber of the culm. After being subjected to compressive loading, the pretesting cracks were enlarged, resulting to a splitting failure (Figure 7b). Lastly, fungal infection on bamboo was mostly observed on *G. angustifolia* Kunth samples both under node and internode conditions, where failures were observed after being subjected to compressive loading (Figure 7c). It should also be noted that most *G. angustifolia* Kunth samples with fungal infection were observed to also have pretesting cracks parallel to the fiber.

(**a**) (**b**) (**c**)

Figure 6. Pre-existing defects before compression included (**a**) holes, (**b**) cracks, and (**c**) fungal infection.

(**a**) (**b**) (**c**)

Figure 7. Pre-existing defects after compression included (**a**) holes, (**b**) cracks, and (**c**) fungal infection.

3.3. Characteristic Strength

According to ISO 12122-1 (2014) [16], the computed characteristic compressive strength for the species in this study are based on the 5th percentile value with 75% confidence as summarized in Table 6. It can be observed that the highest characteristic strength was 46.63 MPa exhibited by *B. blumeana*, whereas the lowest characteristic strength was 36.99 MPa exhibited by *G. angustifolia* Kunth; *B. vulgaris* and *D. asper* showed characteristic strengths of 40.35 MPa and 40.21 MPa, respectively.

Table 6. Summary of characteristic compressive strengths.

Species	n	COV	5th Percentile $X_{0.05}$ (MPa)	Multiplier $k_{0.05,0.75}$	Characteristic Strength $f_{c,0,k}$ $X_{0.05,0.75}$ (MPa)	Average Strength $f_{c,0}$ (MPa)
B. vulgaris	36	0.21	43.43	2.01	40.35	61.16
D. asper	36	0.20	43.15	2.01	40.21	59.49
B. blumeana	93	0.19	48.53	1.94	46.63	70.67
G. angustifolia Kunth	30	0.19	39.82	2.01	36.99	57.53

n—number of samples, COV—coefficient of variation.

3.4. Effect of Nodes on Compressive Strength

The presence or absence of a node for samples subjected to mechanical testing was evaluated, and its effects on compressive strength f_c were determined using Welch's *t*-test (two-sample *t*-test with unequal variances). Shown in Table 7 is the summary for the statistical analysis of node and internode comparison. The determination of statically significant difference was dependent on satisfying the condition of p-value < 0.05. If this condition was not met, then there was not enough evidence to conclude that there was a statistically significant difference. As is presented in Table 7, node–internode relationships of *B. vulgaris* and *B. blumeana* included statistically significant differences. Hence, it can be determined that the presence or absence of nodes on bamboo culms affects the attained compressive strength f_c values.

Table 7. Node and internode comparisons using Welch's *t*-Test.

Species	*t*-Test Parameters			
	df	*t* Stat	*t* Crit (Two-Tailed)	*p*-Value *
B. vulgaris	32	−2.834	2.037	0.008
D. asper	34	−0.416	2.032	0.680
B. blumeana	89	−3.244	1.987	0.002
G. angustifolia Kunth	28	−0.602	2.048	0.552

df—degrees of freedom, *t* Stat—computed ratio of mean of the two sample sets and variation, *t* Crit—threshold value determining statistical significance, *p*-value—probability that the test data lie between the bounds of the null hypothesis, * p-value < 0.05: reject null hypothesis: $\mu1 = \mu2$, p-value > 0.05: not enough evidence to reject null hypothesis.

3.5. Correlation Models

The correlation between the geometric and physical properties and the compressive strength of the bamboo was analyzed using a simple linear regression technique. The length L, diameter D, wall thickness δ, area A, mass per unit length q, moisture content ω, and basic density ρ of each species were tabulated grouped by nodal condition. There are four levels of correlation used to determine the performance of each variable. $0 < R^2 < 0.3$ indicates no correlation or a very weak correlation, $0.3 < R^2 < 0.5$ indicates weak correlation, $0.5 < R^2 < 0.7$ indicates moderate correlation, and $R^2 > 0.7$ indicates strong correlation. Table 8 shows the R^2 values of each species grouped by nodal condition. It was observed that the geometrical properties of each bamboo species were correlated with its compressive strength only to some small extent. The physical properties, on the other hand, showed higher R^2 values. For the basic density, *D. asper* both with and without nodes showed strong correlation, followed by *B. blumeana* with node and *B. vulgaris* without node, which both showed moderate correlations. The rest of the species showed weak correlations. However, the mass per unit length and moisture content showed correlation to the compressive strength only to some small extent. Among the listed geometric and physical properties, only the basic density showed a weak to strong correlation.

Table 8. Correlation R^2 model of each species per node condition.

$f_{c,0}$	L	D	δ	A	q	ω	ρ
BV-N	0.3293	0.4113	0.1567	0.2525	0.0887	0.1575	0.4600
BV-WN	0.4246	0.4637	0.2502	0.3601	0.0050	0.3286	0.5168
DA-N	0.0309	0.0906	0.0345	0.0767	0.5722	0.4387	0.8857
DA-WN	0.0027	0.0190	0.0048	0.0000	0.4248	0.5695	0.8375
BB-N	0.0775	0.1130	0.0238	0.0812	0.4696	0.2652	0.5753
BB-WN	0.0016	0.0055	0.0018	0.0019	0.3838	0.2652	0.3974
G-N	0.0385	0.0777	0.0022	0.0032	0.0236	0.4754	0.4477
G-WN	0.2469	0.2389	0.0727	0.1374	0.0255	0.3390	0.3703
		$0 < R^2 \leq 0.3$				$0.5 < R^2 \leq 0.7$	
		$0.3 < R^2 \leq 0.5$				$R^2 > 0.7$	

$f_{c,0}$—average strength, L—length, D—diameter, δ—thickness, A—area, q—mass per unit length, ω—moisture content, ρ—basic density, BV-N—*B. vulgaris* under node condition, BV-WN—*B. vulgaris* under internode condition, DA-N—*D. asper* under node condition, DA-WN—*D. asper* under internode condition, BB-N—*B. blumeana* under node condition, BB-WN—*B. blumeana* under internode condition, G-N—*G. angustifolia* under node condition, WN—under internode condition, G-WN—*G. angustifolia* under internode condition, R^2—correlation coefficient.

The correlation of the variables independent of the node conditions were also determined. As seen in Table 9, the geometric properties showed very weak correlations, except for *B. vulgaris*. This suggests that the compressive strength of the bamboo species is independent of its geometric property. For the physical properties of the bamboo, the moisture content showed a consistent weak correlation. Only the basic density of *D. asper* showed a moderate correlation whereas the remaining three species showed very weak correlations. This means that the physical properties of the bamboo may affect its compressive strength to only a small extent. The correlations observed between density and compressive strength, especially for *D. asper*, were comparable to the results of studies cited in Trujillo and López [15].

Table 9. Correlation (R^2) models for each species regardless of node condition.

$f_{c,0}$	L	D	δ	A	q	ω	ρ
BV	0.2707	0.3437	0.1578	0.2434	0.0813	0.3498	0.1665
DA	0.0150	0.0478	0.0040	0.0211	0.4478	0.4573	0.6578
BB	0.0005	0.0162	0.0001	0.0093	0.1686	0.3199	0.0927
GA	0.1257	0.1545	0.0163	0.0529	0.0023	0.3824	0.1498
		$0 < R^2 \leq 0.3$				$0.5 < R^2 \leq 0.7$	
		$0.3 < R^2 \leq 0.5$				$R^2 > 0.7$	

$f_{c,0}$—average strength, L—length, D—diameter, δ—thickness, A—area, q—mass per unit length, ω—moisture content, ρ—basic density, BV—*B. vulgaris*, DA—*D. asper*, BB—*B. blumeana*, G—*G. angustifolia*, R^2—correlation coefficient.

3.6. Comparative Analysis

In comparing the compressive strength $f_{c,0}$ values across all bamboo species tested, the Single-factor Analysis of Variance (ANOVA) test was used, as shown in Table 10. Comparisons were based on the assumption of f_c values having equal values among species (H_o). Rejection of this assumption says otherwise (H_a). As shown in the ANOVA results, at F statistic = 12.56, at p-value = 1.5712×10^{-7}, H_o was rejected, considering F crit = 2.65, and p-value < 0.05, respectively. Hence, there is enough evidence to reject f_c values being equal and suggesting that there is at least one inequality among the species. In addition to this, considering p-value < 0.0001, there is statistically significant difference among sampled groups.

Table 10. Analysis of Variance (ANOVA) results for all bamboo species.

Summary						
Groups	Count	Sum	Average	Variance		
B. vulgaris	36	2201.63	61.16	167.03		
D. asper	36	2141.49	59.49	146.61		
B. blumeana	93	6571.92	70.67	187.69		
G. angustifolia Kunth	30	1725.77	57.53	124.12		
ANOVA						
Source of Variation	SS	df	MS	F stat	*p*-Value	F crit
Between Groups	6281.86	3	2093.95	12.56	1.5712×10^{-7}	2.65
Within Groups	31,843.92	191	166.72			
Total	38,125.78	194				

df—degrees of freedom, SS—Sum of squares, df—degrees of freedom, MS—Mean sum of squares, F stat—F-value, F crit—threshold value of F to determine statistical significance.

As there is at least one inequality among the species, multiple Welch's *t*-Tests were performed, comparing each species to another, as shown in Table 11. If the absolute value of *t* Stat is greater than *t* Crit and $p < 0.05$, then there exists a statistically significant difference among the sampled species; otherwise, there is not enough evidence to reject the null hypothesis. From these results, compressive strengths f_c showing comparable values were observed for (1) *B. vulgaris* and *D. asper*, (2) *B. vulgaris* and *G. angustifolia* Kunth, and (3) *D. asper* and *G. angustifolia* Kunth.

Table 11. Multiple Welch's *t*-Test across all bamboo species.

Species	**Comparison**	***t*-Test Parameters**				
		df	***t* Stat**	***t* Crit (Two-Tail)**	***p*-Value**	**Conclusion**
B. vulgaris						
	D. asper	70	0.566	1.994	0.5732	C
	B. blumeana	67	−3.685	1.996	0.0005	NC
	G. angustifolia Kunth	64	1.226	1.998	0.2249	C
D. asper						
	B. blumeana	72	−4.530	1.994	2.29×10^{-5}	NC
	G. angustifolia Kunth	63	0.684	1.998	0.4964	C
B. blumeana						
	G. angustifolia Kunth	60	5.296	2.000	1.77×10^{-6}	NC

df—degrees of freedom, *t* Stat—computed ratio of mean of the two sample sets and variation, *t* Crit—threshold value determining statistical significance, C—comparable, NC—not comparable.

3.7. Comparison to Other Studies and NSCP Section 6—Wood

Table 12 shows the comparison of the average compressive strength parallel to fiber of the Philippine bamboo species investigated in this study with results from previous studies of the same species based on the presence of a node. It should be noted that the number of samples used, and the origin of the species, may vary between studies, and some of the previous research did not specify the classification of their samples in terms of nodes; hence, they are assumed to include a combination of both node and internode samples.

For *Bambusa vulgaris*, it can be observed that the result of this study was higher than the results obtained by Widjaja and Risyad [21] using the samples from Indonesia and Acma [22], and lower than the strength obtained from the study of Onche et al. [23] that tested a particular variant, *B. vulgaris*-schrad, from Nigeria. This suggests that the compressive strength parallel to fiber of the Philippine *B. vulgaris* is greater than the

Indonesian variant but lower than that of the Nigerian variant. Acma [22] also tested the bamboo in its green condition, which explains the lower compressive strength value.

For *Dendrocalamus asper*, it can be observed that the compressive strength values from this study are close to the results gathered by De Jesus et al. [24]. The results of this study obtained higher strengths for the samples with a node, but lower strength for the internode samples compared to the study mentioned. The similarity in results can also be attributed to the fact that the samples used in both studies were Philippine variants sourced from the same facility. Sompoh et al. [25] produced a slightly higher result than was observed in this study. However, the results from Acma [22] were about twice as high as the results from this study. As stated before, this is due to the green condition of the bamboo during testing.

For *Bambusa blumeana*, the average compressive strength values from this study were within the ranges of the results from the studies of Sompoh et al. [25], Janssen [26], Acma [22], and Candelaria and Hernandez Jr. [27], but this study's strength values were about twice that of the strength values recorded by Espiloy [28] and Salzer et al. [8] in their respective investigations, both of which also used green bamboo samples.

For *Guadua angustifolia* Kunth, the average compressive strength values in this study were higher than the results from the studies of Londoño et al. using *G. angustifolia* samples from Colombia that were in a green condition, and they were slightly greater than the results from Trujillo and López [15]. Comparing the strength values obtained by Omaliko and Uzodimma [29] and Bahtiar et al. [18], the results of this study recorded lower strength values. The variation in the compressive strength values between this study and the study of Trujillo and López [15] may be attributed to the fact that the strength of the former was recorded under a dry condition, whereas the latter was tested under a green condition.

Overall, this study provides the following: an updated average compressive strength value for the bamboos tested such as that for *B. vulgaris* from the study of Widjaja and Risyad [21]; verification of results from recent studies such as that of De Jesus et al. [24]; and results from tests conducted using samples with a 12% moisture content limit as for ISO 22157-1 (2017) in contrast to studies such as Acma [22] and Espiloy [28] that tested this under a green condition.

Table 12. Comparison of average compressive strength parallel to fiber against other studies.

Average Compressive Strength Parallel to Fiber (MPa)				
Species	**This Study**	**Other Studies**		
B. vulgaris		Widjaja and Risyad (1987) [21]	Onche et al. (2020) [23]	Acma (2017) [22]
Node	55.59	-	-	-
Internode	66.73	-	-	44.74 *
Both	61.16	44.62	98 ± 5	-
D. asper		De Jesus et al. (2021) [24]	Sompoh et al. (2013) [25]	Acma (2017) [22]
Node	58.64	55.55	-	-
Internode	60.34	63.42	-	130.40 *
Both	59.49	-	68.67	-
B. blumeana		Sompoh et al. (2013) [25]	Janssen (1981) [26]	Candelaria and Hernandez Jr. (2019) [27]
Node	66.24	-	-	-
Internode	75.00	-	-	-
Both	70.67	66.50	60–176	62.49–76.84
		Espiloy (1987) [28]	Salzer et al. (2018) [8]	Acma (2017) [22]
		36.40 *	-	-
		38.30 *	-	61.75 *
		-	36.40 *	-

Table 12. *Cont.*

Average Compressive Strength Parallel to Fiber (MPa)				
Species	**This Study**	**Other Studies**		
G. angustifolia Kunth		Omaliko and Uzodimma (2021) [29]	Trujillo and López. (2010) [15]	Trujillo and López (2010) [15]
Node	56.29	68–81	-	-
Internode	58.76	60–68	-	-
Both	57.53	-	54.8–56.2	32.00 *
		Bahtiar, Trujillo, and Nugroho (2020) [18]		
		-		
		-		
		78.3		

Note: *—average compressive strength under green condition.

Table 13 shows the comparison of the characteristic compressive strength parallel to the fiber of the bamboo samples. The characteristic compressive strength values ranged from 36.99 MPa to 46.63 MPa with *G. angustifolia* Kunth and *B. blumeana* having the lowest and highest strengths, respectively. Generally, it can be observed that these values were greater than the strengths of the unseasoned structural timber of Philippine woods belonging to the high-strength group with an 80% stress grade as established in the NSCP 2015, with strengths ranging from 13.70 MPa to 21.60 MPa.

Table 13. Comparison of characteristic compressive strength of bamboo species with structural timber of Philippine woods.

This Study		**Compressive Strength (MPa) of Unseasoned Structural Timber High-Strength Group (80% Stress Grade) (NSCP 2015)**							
Bamboo Species	Characteristic Compressive Strength	*Agoho* 14.50	*Liusin* 15.60	*Malabayabas* 15.80	*Manggachapui* 16.00	*Molave* 15.40	*Narig* 13.70	*Sasalit* 21.60	*Yakal* 15.80
		Percent Difference to Characteristic Strength Value of Bamboo (%)							
BV	40.35	94.27	88.48	87.45	86.43	89.52	98.62	60.54	87.45
DA	40.21	93.99	88.20	87.17	86.15	89.23	98.35	60.22	87.17
BB	46.63	105.12	99.73	98.77	97.82	100.70	109.17	73.38	98.77
G	36.99	87.36	81.35	80.28	79.22	82.42	91.89	52.53	80.28

Considering the high percentage differences between the characteristic compressive strength of the bamboo species and the compressive strength of timber, as in the case of *B. blumeana* showing a 216% increase over that of Sasalit, which showed the highest strength among the timber group, this suggests that bamboo species tested in this study have great potential to be used as an alternative to timber, specifically for compressive strength parallel to fiber.

4. Conclusions

The average compressive strengths parallel to the fibers of the four species investigated ranged from 55.59 MPa to 75.00 MPa, from samples of *B. vulgaris* with node to *B. blumeana* without node, respectively. Three modes of failure were noted, which are splitting, crushing, and combined splitting and crushing. The failures observed per species varied in length, frequency, and location. One notable observation was that for a sample that experienced combined splitting and crushing failure, the splits were almost always found passing through the crushing of the culm regardless of the length of the split. The characteristic compressive strength was calculated from 196 tests and resulted in a characteristic strength of 40.35 MPa for *Bambusa vulgaris*, 40.21 MPa for *Dendrocalamus asper*, 46.63 MPa for *Bambusa blumeana*, and 36.99 MPa for *Guadua angustifolia* Kunth.

Through the use of Welch's *t*-test, compressive strength values obtained from nodal and internodal samples were evaluated. There was a statistically significant difference among the node–internode relationships of *B. vulgaris* and *B. blumeana*, whereas for *D. Asper and G. angustifolia* Kunth, compressive strength values were comparable.

Simple linear regression was used to determine the correlations of the geometric and physical properties with the compressive strength of the bamboo. Two analyses were performed as follows: (1) correlations between variables considering node condition and (2) correlation between variables independent of node condition. For the first analysis, the highest correlation for the geometric properties was between 0.3 to 0.5, which denotes a weak correlation, and this was observed for *B. vulgaris*. The physical properties, on the other hand, showed varying correlation strengths, with basic density for *D. asper* both with and without a node showing an R^2 value greater than 0.7, exhibiting strong correlation. For the second analysis that is independent of the node condition, the geometric properties showed very weak to weak correlations, whereas the physical properties showed very weak to moderate strength correlations. It is therefore concluded that the compressive strength of the bamboo is independent of its geometric properties, whereas its physical properties may affect the compressive strength to only a small extent. For *D. asper*, it is evident that its basic density has a significant effect on its compressive strength.

Next, comparative analysis across all bamboo species using Single-Factor ANOVA resulted in the conclusion that there exists at least one inequality among the species. It cannot be concluded that strengths across all species are of equal magnitude or at least comparable to each other. Hence, Welch's *t*-Test was performed for the comparison of pairs of species. Comparable strength values were seen between *B. vulgaris* and *D. asper*, *B. vulgaris* and *G. angustifolia* Kunth, and between *D. asper* and *G. angustifolia* Kunth. In contrast, those pairs with statistically significant differences were *B. vulgaris* and *B. blumeana*, *D. asper* and *B. blumeana*, and *B. blumeana* and *G. angustifolia* Kunth.

Most of the related studies were supported by the results of this study, in which the values were within the ranges of values obtained by other authors. It was evident that the characteristic compressive strengths of the Philippine bamboo species studied in this paper were greater than the compressive strengths of unseasoned structural timber belonging to a high-strength group with an 80% stress grade. Thus, it can be concluded that these bamboo species can provide significant alternatives to timber, and that the average and characteristic compressive strengths provided by this study can be used to characterize the mechanical properties of bamboo and can be adopted by National Structural Code of the Philippines.

This study is limited to investigating only the characteristic compressive strength parallel to the fiber of four local Philippine bamboo species. However, it is recommended that researchers conduct further tests to establish the modulus of elasticity and Poisson's ratio for these bamboo species. Also, other mechanical properties such as flexure, shear, and tensile strength need to be explored further to establish relationships between the different mechanical properties and enable the discrimination of one property from another without the need for additional testing. In addition to this research, quantifying the effects of fungus infection could help to determine possible mitigations and help in repurposing affected bamboos. SEM Analysis of the test specimen for moisture content determination could also be explored to give a better understanding of the samples' failure mechanism. Exploration of other endemic bamboo species such as *Bambusa philippinensis*, *Gigantochloa apus*, and *Bambusa merrilliana* should be studied to further determine the general characteristics of bamboos that are economically important.

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