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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 the 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 effect of nodes, and geometric and physical properties on the compressive strength of bamboos. Comparing the characteristic compressive strength obtained from this study to the strength of unseasoned structural timber of Philippine woods, all bamboo species showed higher strength values, and 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

1. Introduction

Bamboo is a lightweight, naturally renewable, tree-like plant belonging to the grass family *Poaceae* and has about 1482 known species classified under three bamboo tribes namely: *Arundinarieae* (546 species), *Bambuseae* (812 species), and *Olyreae* (124 species) [1]. It is recognized as one of the rapidly-growing perennial plants, which are 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 which are economically important, including *Bambusa blumeana* (kawayan tinik), *Bambusa sp.1* (formerly *Dendrocalamus merriliamus*) (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 to have significant potential for economic development and still require further research on, which includes *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 in 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 the environmental aspect. It also draws to reduce the rate of deforestation, which also decreases the consumption rate of wood and timber with the use of bamboo as an alternative [5]. Furthermore, bamboo plantations are able to aid in carbon sequestration of up to 12 tons of carbon dioxide per hectare, plus it 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 the 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 are necessary to be established as it takes 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 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 appropriate building codes to be established [7]. To be specific, although there are studies regarding the material characterization of bamboo, data is still insufficient since there exists a wide variety of bamboo species and its strength properties may vary depending on its morphology. In the context of the Philippines, studies characterizing 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 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 namely; *Bambusa vulgaris*, *Dendrocalamus asper*, *Bambusa blumeana*, and *Guadua angustifolia* Kunth. It is hypothesized that there are 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 is also expected to have little to no significant differences. It is assumed that the samples satisfy the grading requirement stated in PNS ISO 19624 (2020) [12].

The study only covered the use of bamboo as a construction material, and other aspects such as its medicinal attribute or industrial use 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 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 the 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. Since 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 the study [13]. Compression tests were only done on the bamboo culms in the node and internode part of the bamboo, without considering any branches. Lastly, this study is delimited 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 country. 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*. 50% of the samples per specie were with node, and the remaining 50% were without node. The samples were cut such that the length was the lesser of the outer diameter, D, or 10 times the wall thickness, 10δ, as shown in Equation (1), and the end planes were approximately parallel to each other and perpendicular to the length axis of the sample.

$$\mathrm{L} = \min \begin{cases} D \\ 10\delta \end{cases} \tag{1}$$

where:

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

Nodes, if present, were approximately located 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 its specie (BV, DA, BB, G), test sample number, node classification (N for with node, WN for without node), and location (T for top, M for middle, 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 are measured along the axis of the sample, taken 180° apart. The outer diameter, D, was measured from the end planes of the sample, two per plane spaced at 180° for a total of 4 diameter values. Four values of thickness, δ, were measured per plane 90° apart for a total of eight thickness values. The average diameter and thickness were used for the computation of the cross-sectional area, A, using Equation (2):

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

where:

A is the cross-sectional area of the sample (mm^2);
D is the average outer diameter of the sample (mm);
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):

$$q = \frac{m_e}{L} \tag{3}$$

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;
L is the length (mm) of the sample.

where L is the average of the two measured length values. The activities done during the sample preparation are presented in Figure 1.


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

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

2.2. Compression Testing

The bamboo compression tests were done at the Department of Public Works and Highways - 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 its axis was aligned with the loading axis of the machine [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. Failure in less than 30 s were not considered, and the load was applied continuously without being interrupted throughout the test.

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, $f_{c,0}$, is 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);
A	is the cross-sectional area of the sample (mm²).

where:

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

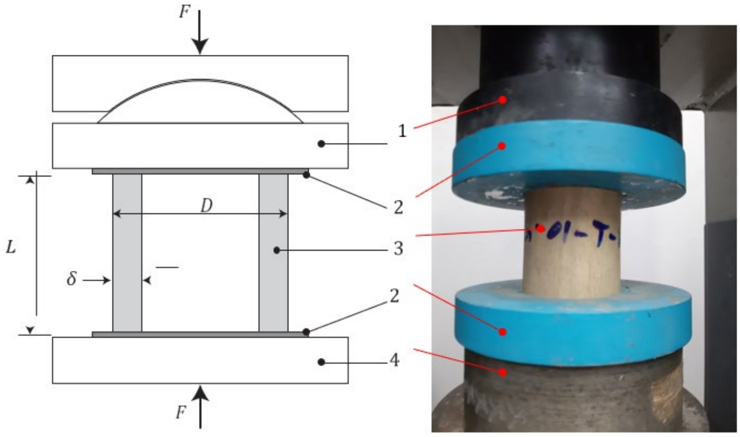

Figure 3. Compression Test Set-up

2.3. Moisture Content Determination

Test specimens used to determine the moisture content were obtained close to the failure location. The number of specimens is equal to the number of test samples for the compression tests and are approximately rectangular in shape (Figure 4). This allows the 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 volume of the nodes was not considered in the volume calculation.

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

Figure 4. Test specimen for DA-N (left) and DA-WN (right).

The specimens were weighed using a digital balance with a precision of 0.01 g and recorded as the initial mass, m_i. It was then placed in an oven at a temperature of (103 ± 2) °C for 24 hours. 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).

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

$$\rho = \frac{m_0}{V_0} \tag{6}$$

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;
V_0 is the volume (m^3) of the specimen at green condition.

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 1. The length, L, outer diameter, D, thickness, δ, and cross-sectional area, A, are the properties measured using ISO 22157-1 (2017) [13].

Table 1. 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, μ	88.75	89.41	7.24	1899.49
St dev, σ	10.26	10.82	1.53	585.69
COV, δ	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, μ	90.30	89.60	7.13	1873.91
St dev, σ	11.06	10.62	1.04	474.83
COV, δ	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, μ	89.53	89.51	7.19	1886.70
St dev, σ	10.54	10.57	1.29	525.64
COV, δ	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, μ	119.92	117.13	10.33	3458.99
St dev, σ	8.43	6.22	2.10	679.19
COV, δ	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, μ	122.89	120.49	10.96	3754.87
St dev, σ	8.22	7.43	2.06	632.03
COV, δ	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, μ	121.40	118.81	10.65	3606.93
St dev, σ	8.34	6.97	2.08	663.77
COV, δ	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, μ	94.93	95.03	7.68	2113.08
St dev, σ	8.19	7.35	1.09	372.24
COV, δ	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, μ	91.27	92.88	7.46	2008.03
St dev, σ	8.73	8.74	1.06	379.22
COV, δ	0.10	0.09	0.14	0.19
***B. blumeana* (n = 93)**				
Min	73.40	76.90	5.58	1255.78
Max	110.40	110.20	10.45	2960.54
Mean, μ	93.08	93.94	7.57	2059.99
St dev, σ	8.62	8.11	1.07	377.45
COV, δ	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, μ	75.13	75.91	9.51	1989.12
St dev, σ	9.63	9.26	2.83	634.72
COV, δ	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, μ	74.05	74.87	8.75	1833.40
St dev, σ	9.47	9.62	2.70	628.84
COV, δ	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, μ	74.59	75.39	9.13	1911.26
St dev, σ	9.40	9.29	2.74	625.83
COV, δ	0.13	0.12	0.30	0.33

n – number of samples, L – length, D – diameter, δ – thickness, A – area, μ = sample mean, σ = sample standard deviation, COV = coefficient of variation (σ/μ).

Table 2 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, while the moisture content and basic density were based on the test specimens obtained after the compression tests. *B.*

vulgaris and *D. asper* concerning both nodal and internodal samples obtained the least and greatest 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 is greater for samples with nodes in comparison to samples taken at the internode, which applies to all four species. In terms of the moisture content, it can be determined that the values for the average moisture content of all species in this study were within the prescribed range of (12 ± 3) %. The moisture content of the species concerning both nodal and internodal samples ranged from 10.67% to 11.67%, with *D. asper* and *G. angustifolia* Kunth obtaining the least and greatest moisture content. Like the previous property, the moisture content values are greater for samples with nodes in comparison to samples taken at the internode for all species in this study. The average basic densities of the species concerning 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 least and greatest basic density. It is noted that the basic density varies 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 of Nurmadina, Nugroho, and Bahtiar [14] that a higher mass per unit length results in a higher culm density. This indicates that the basic density is also greater for samples with nodes in comparison to samples taken at the internode for all species in this study. However, it shall also be noted that mass and volume determine the density of the bamboo. Since the diaphragm of the samples with node is included in obtaining the mass and it is disregarded in the volume computation, the samples with node in this study are more likely to exhibit higher density than samples without node [15].

Table 2. 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, μ	1.61	11.25%	795.24
St dev, σ	0.37	0.00407	121.75
COV, δ	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, μ	1.30	10.86%	683.63
St dev, σ	0.26	0.00466	144.99
COV, δ	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, μ	1.45	11.05%	739.43
St dev, σ	0.35	0.00473	143.57
COV, δ	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, μ	2.87	10.93%	756.82
St dev, σ	0.83	0.00503	135.15
COV, δ	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, μ	2.56	10.41%	643.29
St dev, σ	0.72	0.00634	123.88
COV, δ	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, μ	2.71	10.67%	700.06
St dev, σ	0.78	0.00622	140.14
COV, δ	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, μ	2.09	11.40%	889.19
St dev, σ	0.45	0.00742	106.69
COV, δ	0.22	0.06505	0.12
B. blumeana (Internode) (n = 47)			
Min	1.00	9.23%	465.63
Max	2.56	11.66%	881.43
Mean, μ	1.68	10.40%	726.27
St dev, σ	0.41	0.00488	98.12
COV, δ	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, μ	1.88	10.90%	806.85
St dev, σ	0.48	0.00801	130.72
COV, δ	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, μ	1.87	11.81%	859.84
St dev, σ	0.53	0.00360	64.38
COV, δ	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, μ	1.45	11.52%	728.26
St dev, σ	0.50	0.002902	83.66
COV, δ	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, μ	1.66	11.67%	794.05

St dev, σ	0.55	0.00354	99.29
COV, δ	0.33	0.03032	0.13

n – number of samples, q – mass per unit length, ω – moisture content, ρ – basic density, μ = sample mean, σ = sample standard deviation, COV = coefficient of variation (σ/μ).

The compressive strength parallel to the fibers of the different bamboo species is shown in Table 3, where the loads applied ranges from 0.13-4.19 kN/s. It can be observed that samples of *B. blumeana* taken at the internode obtained the greatest average compressive strength among the other species with 75 MPa, while *B. vulgaris* taken at the node obtained the least average strength of 55.59 MPa. From comparison of average strengths of the four main species between node and internode, it was common that the samples taken at the internode have the greater compressive strength than the samples at the node. Bahtiar et al. [15] noted that the higher compressive strength values exhibited by bamboo samples without node may be attributed to the fiber orientation. The fibers on bamboos are parallel to the axial direction and some change direction as it crosses the nodes, which may reduce the strength capacity of the bamboo. In comparing the average strengths of the four main species concerning both node and internode samples, *B. blumeana* and *G. angustifolia* Kunth obtained the greatest and lowest strength with 70.67 MPa and 57.53 MPa, respectively. On the corresponding coefficient of variation (COV) of the compressive strength of the species, *D. asper* samples taken at the internode was recorded to have the highest coefficient of variation equivalent to 0.21, while the *B. vulgaris* and *B. blumeana* samples taken at the node obtained the least COV equivalent to 0.18. Samples taken at the internode were observed to have greater variance than the samples with node.

Table 3. 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**	**σ²**
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

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: 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 [16]. The variation in location, frequency, and length of the splitting observed in the culms are 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 sometimes even penetrates through its thickness. In the study of Li, Su, Zhang, Deeks, and Hui [17], they observed that crushing failure commonly happened on short column samples, while long column samples experienced buckling.

The crushing failure in the culms also vary in location, frequency, and length. Combined splitting and crushing is the occurrence of both splitting and crushing in a culm (Figure 5c). Table 4 shows the frequency of each failure modes observed in each species, considering the nodal condition of the culms.

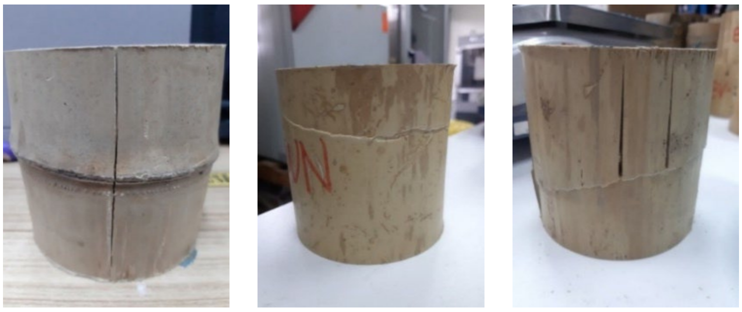
(**a**) (**b**) (**c**)

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

Table 4. 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

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

The general trend of failure modes occurring for each species is that for *B. vulgaris*, presence of nodes has an effect towards the occurrence of crushing; splitting failure generally governs failure modes of *D. asper*; combined splitting and crushing were the most prominent among *B. blumeana*; and *G. angustifolia* Kunth noted crushing to be most prominent. Furthermore, results of *D. asper* and *G. angustifolia* Kunth were consistent with the study of Li et al. [17], where they noted that crushing failure commonly occurs in short column samples, while long column samples experienced buckling. *D. asper* were generally longer having an average length of 121.40 mm while *G. angustifolia* Kunth were relatively short at length of 57.53 mm. Although buckling was not possible for the length of the samples, splitting was the closest failure mode that is relative to buckling. In addition to this, observing average compressive strengths, *B. vulgaris* and *G. angustifolia* Kunth who have low average $f_{c,0}$ values are most prominent to crushing while *D. asper* and *B. blumeana* who have relatively high average $f_{c,0}$ values experience mostly splitting. Hence, it could be inferred that splitting usually occurs with high compressive strength bamboos, while crushing is 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, regardless of the species and nodal condition, with holes are 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 is mostly observed on *G. angustifolia* Kunth samples both under node and internode conditions, where failures were observed after subjecting to compressive loading (Figure 7c). It shall 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: (a) holes, (b) cracks, and (c) fungal infection.


(a) (b) (c)

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

3.3. Characteristic Strength

According to ISO 12122-1 (2014) [18], the characteristic value is a value of a property taken to represent the property of a designated population using a process of sample, testing of specimens, and analysis. Using this standard, the computed characteristic compressive strength for the species in this study are based on the 5th percentile value with 75% confidence and is summarized in Table 5. It can be observed that the highest characteristic strength is at 46.63 MPa from *B. blumeana*, while the lowest characteristic strength is 36.99 MPa exhibited by *G. angustifolia* Kunth, *B. vulgaris* and *D. asper* showed 40.35 MPa and 40.21 MPa characteristic strength, respectively. Since the characteristic strength is computed based on ranking and concentrates on the lower limit (5th percentile) of all the data values, it is expected that the obtained characteristic values are lower than the average strengths.

Table 5. Summary of characteristic compressive strength.

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 to Compressive Strength

Presence and absence of node for samples subjected to mechanical testing were evaluated, determining its effects towards compressive strength (f_c) using Welch’s t-Test (Two-Sample t-Test with Unequal Variances). Shown in Table 6 is the summary for the statistical analysis of node and internode comparison. Determination of statically significant difference is dependent on satisfying the condition of p-value < 0.05. If not met, there is not enough evidence to conclude otherwise. As presented in Table 6, node-internode relationships of *B. vulgaris* and *B. blumeana* present statically significant difference towards its comparison. Hence, can be determined that presence or absence of nodes on bamboo culms affect attained compressive strength (f_c) values.

Table 6. Node and internode comparison using Welch’s *t*-Test.

Species	***t*-Test Parameters**			
	df	**t Stat**	**t Crit (Two-Tail)**	***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 of which test data lies 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 to the compressive strength of the bamboo was analyzed using 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 are tabulated considering the nodal condition. There are four levels of correlation to determine the performance of each variable. $0 < R^2 < 0.3$ indicates no or 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 7 shows the R^2 values of each species considering their node condition. It was observed that the geometrical properties of each bamboo species have a correlation with its compressive strength only to some 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 a strong correlation level, followed by *B. blumeana* with node and *B. vulgaris* without node having moderate levels of correlation. The rest of the species showed weak correlation. However, the mass per unit length and moisture content showed correlation to the compressive strength only to some extent. Among the listed geometric and physical properties, only the basic density showed a correlation of between weak to strong level.

Table 7. 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

⬜	$0 < R^2 \leq 0.3$	🟧	$0.5 < R^2 \leq 0.7$
🟨	$0.3 < R^2 \leq 0.5$	🟥	$R^2 > 0.7$

The correlation of the variables independent of the node condition was also determined. As seen in Table 8, the geometric properties showed very weak correlation level, 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 while the remaining three species showed very weak correlation. This means that the physical properties of the bamboo may affect its compressive strength only to some extent. The density's correlation to the compressive strength, especially to *D. asper*, is like the results of studies cited in Trujillo and López [19].

Table 8. Correlation (R^2) model of each species per 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

⬜	$0 < R^2 \le 0.3$	🟧	$0.5 < R^2 \le 0.7$
🟨	$0.3 < R^2 \le 0.5$	🟥	$R^2 > 0.7$

3.6. Comparative Analysis

In comparing the compressive strength ($f_{c,0}$) values across all bamboo species tested, Single-factor Analysis of Variance (ANOVA) was used, as shown in Table 9. Comparison was based on the assumption of f_c values having equal values among species (H_o). Rejection of assumption says otherwise (H_a). As shown in the results of ANOVA, at F-stat = 12.56, at *p*-Value = 1.5712 x 10-7, rejection region was attained, 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 high significance among sampled groups.

Table 9. 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	*p*-Value	F crit
Between Groups	6281.86	3	2093.95	12.56	1.5712×10^{-7}	2.65
Within Groups	31843.92	191	166.72			
Total	38125.78	194				

df – degrees of freedom, SS – Sum of squares; df – degrees of freedom; MS – Mean sum of squares: SS / df; F stat – F-value: MS (Between Groups) / SS (Within Groups); *p*-Value – probability of data occurring under null hypothesis from ANOVA table; F crit – threshold value of F to determine statistical significance; **p*-Value < 0.05: reject null hypothesis: $\mu_1 = \mu_2$, *p*-Value > 0.05: not enough evidence to reject null hypothesis.

In consideration of determining which species are comparable to each other was greatly highlighted given the ANOVA results shown in Table 10. Hence, multiple Welch's t-Tests were performed, comparing each species to another, as shown in Table 10. At instance of absolute value of t-Stat greater than *t*-Crit, and *p*-Value < 0.05, there exists a statistically significant difference among sampled species. Otherwise, there is not enough evidence to reject null hypothesis (H_o): fc values being equal and could be considered comparable. From results, compressive strengths (f_c) showing comparative values exists within (1) *B. vulgaris* and *D. asper*, (2) *B. vulgaris* and *G. angustifolia* Kunth, and (3*) D. asper* and *G. angustifolia* Kunth.

Table 10. 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 x 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 x 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, *p*-Value – probability of which test data lies between the bounds of the null hypothesis, C – comparable, NC – not comparable, **p*-Value < 0.05: reject null hypothesis: $\mu_1 = \mu_2$, *p*-Value > 0.05: not enough evidence to reject null hypothesis.

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

Table 11 shows the comparison of the average compressive strength parallel to fiber of the Philippine bamboo species investigated in this study against the results from previous studies of the same species based on the presence of the 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 the nodes, hence, they are assumed as a combination of both with node and internode samples.

For *Bambusa vulgaris*, it can be observed that the result of this study is higher than the results obtained by Widjaja and Risyad [20] using the samples from Indonesia and Acma [21], and lesser than the strength obtained from the study of Onche et al. [22] 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 the strength of the Nigerian variant. Acma [21] 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 nearly close with minimal differences to the results gathered by De Jesus et al. [23]. The results of this study obtained higher strength for the samples with node, but lesser strength for the internodal samples in comparison to the study mentioned. The similarity in the 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. [24] produced a slightly higher result than this study. However, the results from Acma [21] 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 close and within the range of the results from the studies of Sompoh et al. [24], Janssen [25], Acma [21], and Candelaria and Hernandez Jr. [26] but were about twice the strength values recorded by Espiloy [27] and Salzer et al. [8] in their respective investigations. Both these studies also used green bamboo samples.

For *Guadua angustifolia* Kunth, the average compressive strength values were relatively higher than the results from the studies of Londoño et al. using *G. angustifolia* samples from Colombia in green condition, and slightly greater than the results from Lozano [19]. Comparing the strength values obtained by Omaliko and Uzodimma [28] and Bahtiar, Trujillo, and Nugroho [15], the results of this study were recorded with lower strength values. The variation in the compressive strength values between this study and the study of Londoño et al. [19] may be attributed to the fact that the strength of the former was recorded in dry condition, while the latter was tested in green condition.

Overall, the study provides: an updated average compressive strength value of the bamboos tested such as in *B. vulgaris* from the study of Widjaja and Risyad [20]; results verification from recent studies such as in the study of De Jesus et al. [23]; and results tested following 12% moisture content limit of ISO 22157-1 (2017) compared to studies such as Acma [21] and Espiloy [27] testing it at green condition.

Table 11. 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 & Risyad (1987) [20]	Onche et al. (2020) [22]	Acma (2017) [21]
Node	55.59	-	-	-
Internode	66.73	-	-	44.74*
Both	61.16	44.62	98 ± 5	-
D. asper		De Jesus et al. (2021) [23]	Sompoh et al. (2013) [24]	Acma (2017) [21]
Node	58.64	55.55	-	-
Internode	60.34	63.42	-	130.40*
Both	59.49	-	68.67	-
B. blumeana		Sompoh et al. (2013) [24]	Janssen (1981) [25]	Candelaria & Hernandez Jr. (2019) [26]
Node	66.24	-	-	-
Internode	75.00	-	-	-
Both	70.67	66.50	60 - 176	62.49 - 76.84
		Espiloy (1987) [27]	Salzer et al. (2018) [8]	Acma (2017) [21]
		36.40*	-	-
		38.30*	-	61.75*
		-	36.40*	-
G. angustifolia **Kunth**		Omaliko & Uzodimma (2021) [28]	Lozano (2010) [19]	Londoño et al. (2010) [19]
Node	56.29	68 - 81	-	-
Internode	58.76	60 - 68	-	-
Both	57.53	-	54.8 - 56.2	32.00*
		Bahtiar, Trujillo, & Nugroho (2020) [15]		
		-		
		-		
		78.3		

Note: *average compressive strength in green condition.

Table 12 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 least and greatest strengths, respectively. Generally, it can be observed that these values are greater as compared to the strengths of the unseasoned structural timber of Philippine woods belonging to the high strength group with 80% stress grade as established in the NSCP 2015, with strengths ranging from 13.70 MPa to 21.60 MPa.

Considering high percentage differences between the characteristic compressive strength of the bamboo species and the compressive strength of timber, such as in the case of *B. blumeana* seeing a 216% increase over Sasalit, the highest strength among the timber group, it 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.

Table 12. 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*	*Liusin*	*Malabayabas*	*Manggachapui*	*Molave*	*Narig*	*Sasalit*	*Yakal*
		14.50	15.60	15.80	16.00	15.40	13.70	21.60	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

4. Conclusion

The average compressive strength 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 and *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 varies in length, frequency, and location. One notable observation is that the splits are almost always found passing through the crushing of the culm, regardless of the length of the split, on a sample that experienced combined splitting and crushing failure. For the characteristic compressive strength, it was calculated from the 196 tests which 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. It was seen that there is a statistically significant difference among node-internode relationships of *B. vulgaris* and *B. blumeana*. While for *D. Asper and G. angustifolia* Kunth, their compressive strength values are comparable.

Simple linear regression was used to determine the correlation of the geometric and physical properties to the compressive strength of the bamboo. Two analyses were done: 1) correlation between variables dependent of the node condition, and 2) correlation between variables independent of the node condition. For the first analysis, the highest correlation for the geometric properties was between 0.3 to 0.5 which exhibits a weak correlation, and it was observed on *B. vulgaris* species. The physical properties, on the other hand, showed varying correlation levels, with basic density of *D. asper* for both with and without node, having 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 weak to very weak correlation, while the physical properties showed very weak to moderate. It is therefore concluded that the compressive strength of the bamboo is independent of its geometric properties, while its physical properties may affect the compressive strength only to some extent. For *D. asper*, it was evident that its basic density has a significant effect on its compressive strength.

Then, 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, pinpointing specific relationships of bamboo species having statistically significant difference and those could be considered comparable among compressive strength values were performed. From this, Welch's *t*-Test was performed for comparison of two species. Comparable strength values were seen between *B. vulgaris - D. asper*, *B. vulgaris - G. angustifolia* Kunth, and *D. asper - G. angustifolia* Kunth comparison. While those with statistically significant difference and are not comparable were *B. vulgaris - B. blumeana, D. asper - B. blumeana, and B. blumeana - G. angustifolia* Kunth.

Most of the related studies were supported and similar to the results of this study in which the values were within the range of values obtained by other authors. It was evident that the characteristic compressive strengths of the Philippine bamboo species studied in this paper was greater than the compressive strength of unseasoned structural timber belonging to high strength group with 80% stress grade. Thus, it can be concluded that these bamboo species can be a significant alternative to timber, and the average and characteristic compressive strength provided by the study can be used to characterize the mechanical properties of bamboo that 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 to conduct further tests to establish the modulus of elasticity and Poisson's ratio. Also, other mechanical properties such as flexure, shear, and tensile strength are needed to be explored further to establish relationships between the different mechanical properties to enable the determination of one property from another without the need for additional testing. In addition to this, quantifying the effects of fungus could help determine possible mitigations and help for repurposing affected bamboos. Exploration of other endemic bamboo species such as *Bambusa philippinensis, Gigantochloa apus, Bambusa merrilliana* should be further studied to further determine general characteristics of bamboos that are economically important.

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References

1. Clark, L. G.; Londoño, X.; Ruiz-Sanchez, E. Bamboo Taxonomy and Habitat. *Liese, W., Köhl, M. (eds) Bamboo. Tropical Forestry* **2015**, *10*. doi:10.1007/978-3-319-14133-6_1.
2. Manandhar, R.; Kim, J.; Kim, J. Environmental, social, and economic sustainability of bamboo and bamboo-based construction materials in buildings. *Journal of Asian Architecture and Building Engineering* **2019**, *18*(2), 49-50. doi:10.1080/13467581.2019.1595629.
3. Virtucio, F. D. General overview of bamboo in the Philippines. *Silvicultural management of bamboo in the Philippines and Australia for shoots and timber* **2009**, 18-23.
4. Nurdiah, E. A. The Potential of Bamboo as Building Material in Organic Shaped Buildings. *Procedia - Social and Behavioral Sciences* **2016**, *216*, 30-38. doi:10.1016/j.sbspro.2015.12.004.
5. Atanda, J. Environmental impacts of bamboo as a substitute constructional material in Nigeria. **2015**, *3*, 33-39.
6. Kassahun, T. Review of Bamboo Value Chain in Ethiopia. *Journal of Biology, Agriculture and Healthcare* **2014**, *4*(27), 179-190.
7. Sharma, B.; Gatóo, A.; Bock, M.; Ramage, M. Engineered bamboo for structural applications. *Construction and Building Materials* **2015**, *81*, 66-73. doi:10.1016/j.conbuildmat.2015.01.077.
8. Salzer, C.; Wallbaum, H.; Alipon, M.; López, L. F. Determining Material Suitability for Low-Rise Housing in the Philippines: Physical and Mechanical Properties of the Bamboo Species Bambusa bluemeana. *BioResources* **2018**, *13*(1). 346-369. doi:10.15376/biores.13.1.346-369.
9. Bautista, B. E.; Garciano, L. E. O.; López, L. F. Comparative analysis of shear strength parallel to fiber of different local bamboo species in the Philippines. *Sustainability* **2021**, *13*(15). doi:10.3390/su13158164.
10. Vicencio, M. A. Developing mechanical properties for flexure and capacity-based grading using measurable indicating properties (IPs) for selected local bamboo species. **2021**. https://animorepository.dlsu.edu.ph/etdm_civ.
11. Bureau of Philippine Standards. DTI-BPS adopts international journal of scientific & engineering research. Available online: http://www.bps.dti.gov.ph/index.php/press-releases/24-2020/214-dti-bps-adopts-international-standards-on-bamboo-structures (accessed on 30 Jun 2022).
12. International Organization for Standardization (ISO). *ISO 19624:2020 - Bamboo structures - Grading of bamboo culms - Basic principles and procedures*, ISO: Geneva, Switzerland, **2020**.

13. International Organization for Standardization (ISO). *ISO 22157-1: Bamboo structures - Determination of physical and mechanical properties of bamboo culms - Test methods,* ISO: Geneva, Switzerland, **2017**.
14. Nurmadina; Nugroho, N.; Bahtiar, E. Structural grading of Gigantochloa apus bamboo based on its flexural properties. *Construction and Building Materials* **2017**, *157*, 1173-1189. doi:10.1016/j.conbuildmat.2017/09.170.
15. Bahtiar, E.; Trujillo, D.; Nugroho, N. Compression resistance of short members as the basis for structural grading of Guadua angustifolia. *Construction and Building Materials* **2020**, *249*. doi:10.1016/j.conbuildmat.2020.118759.
16. Mitch, D.; Harries, K.; Sharma, B. Characterization of splitting behavior of bamboo culms. *Journal of Materials in Civil Engineering* **2010**, *22*(11), 1195-1199. doi:10.1061/(ASCE)MT.1943-5533.0000120.
17. Li, H.-t.; Su, J.-w.; Zhang, Q.-s.; Deeks, A.; Hui, D. Mechanical performance of laminated bamboo column under axial compression. *Composites Part B* **2015**, *79*, 374-382. doi:10.1016/j.compositesb.2015.04.027.
18. International Organization for Standardization (ISO). *ISO 12122-1: Timber Structures - Determination of Characteristic Values - Part 1: Basic Requirements,* ISO: Geneva, Switzerland, **2014**.
19. Trujillo, D. J.; López, L. F. 18 – Bamboo material characterisation. *Nonconventional and Vernacular Construction Materials* **2016**. 491-520. doi:10.1016/B978-0-08-102704-2.00018-4.
20. Widjaja, E.; Risyad, Z. Anatomical properties of some bamboos utilized in Indonesia. *Recent research on bamboos* **1987**, 244-246.
21. Acma, L. M. Comparative mechanical properties of selected bamboo species. *International Journal of Precious Engineering Research and Application* **2017**, *2*(1), 1-8.
22. Onche, E.; Azeko, S.; Obayemi, J.; Oyewole, O.; Ekwe, N.; Rahbar, N.; Soboyejo, W. Compressive deformation of Bambusa vulgaris-Schrad in the transverse and longitudinal orientations. *Elsevier: Journal of the Mechanical Behavior of Biomedical Materials* **2020**, *108*(103750). doi:10.1016/j.jmbbm.2020.103750.
23. De Jesus, A.; Garciano, L. E. O.; López, L. F.; Ong, D.; Roxas, M.; Tan, M.; De Jesus, R. Establishing the Strength Parameters Parallel to Fiber of Dendrocalamus Asper (Giant Bamboo). *International Journal of GEOMATE* **2021**, *20*(81), 22-27. doi:10.21660/2021.81.6253.
24. Sompoh, B.; Fueangvivat, V.; Bauchongkol, P.; Ratcharoen, W. Physical and mechanical properties of some thai bamboo for house construction. *Royal Forest Department, Forest Research and Development Bureau* **2013**.
25. Janssen, J. A. Bamboo in building structures. PhD, Technische Hogeschool Eindhoven, Eindhoven, Netherlands, **1981**. doi:10.6100/IR11834.
26. Candelaria, M. E.; Hernandez, J. Y. Determination of the Properties of Bambusa blumeana Using Full-culm Compression Tests and Layered Tensile Tests for Finite Element Model Simulation Using Orthotropic Material Modeling. *ASEAN Engineering Journal* **2019,** *9*, 54-71.
27. Espiloy, Z. B. Physico-mechanical properties and anatomical relationships of some Philippine bamboos. *Recent Research on Bamboos* **1987**, 257-265. doi:ISBN 9971-84-732-9.
28. Omaliko, I. K.; Uzodimma, U. O. Evaluation of compressive strength of bamboo culms under node and internode conditions. *Saudi Journal of Civil Engineering* **2021**, *5*(8), 251-258. doi:10.36348/sjce.2021.v05i08.001.