Establishing the characteristic bending, compressive, and shear strengths parallel to fiber of *Bambusa blumeana*

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Abstract: Bamboo is known as a sustainable building material. It has been used in building houses in rural areas of the Philippines as a substitute to timber due to its affordability and availability. However, due to the insufficient number of studies on its physical and mechanical properties, there is a lack of design guidelines for using bamboo in building structures. *Bambusa blumeana* is an endemic bamboo specie in the Philippines which is commonly used in construction, concrete reinforcement, and other uses. Using ISO 22157-1 (2017) and ISO 12122-1 (2014), this paper establishes the characteristic bending, compressive, and shear strengths of *B. blumeana*. Resulting average strength values are 92.63, 70.67, and 11.44 MPa and for characteristic strength values are 55.90 MPa, 46.63 MPa, and 5.15 MPa, respectively. *B. blumeana* showed the highest resistance to bending failure. Its density showed significant correlation to both bending and shear strengths, while its moisture content showed significant correlation to compressive strength. The characteristic and average strength values of *B. blumeana* are greater than the high strength group of structural timber with 80% stress grade, thus it is a possible alternative to timber.

Key Words: Bambusa blumeana; bending strength; compressive strength; shear strength; characteristic strength

1. INTRODUCTION

The demand for sustainability in development and human activity has increased through the years, focusing mainly on environmental sustainability, economic sustainability, and social sustainability (Rosen, 2012). In the construction industry, the use of alternative sustainable materials can help lessen the industry's detrimental effects on the environment since it continuously consumes renewable and nonrenewable resources on its on- and off-site activities.

Bamboo is widely known as a sustainable building material due to its natural strength and flexibility. It is used in traditional houses in Asia as it is abundant in tropical rain forests. In the Philippines, houses in rural areas utilize the use of bamboo as a substitute for timber as it is cheaper and easily accessible.

The use of bamboo as a construction material in the Philippines, however, is still limited due to the lack of governing codes and design guidelines. The National Structural Code of the Philippines (NSCP) 2015 only provide chapters for construction materials like concrete, steel, and timber. The physical and mechanical properties of bamboo still need to be determined and established, especially the species that are endemic in the Philippines. The ISO standards for bamboo provide guidelines in determining such properties.

Bambusa blumeana, locally known as Kawayan Tinik, is a commonly used bamboo in the Philippines and is among the list of bamboo species that are most economically important in the country (Aggangan, 2015). It has been used in construction, concrete reinforcement, furniture making, and fences. Base Bahay Foundation, a foundation that offers alternative building technologies, has also used *B. blumeana* in their construction activities, using the work of Salzer et. al (2018) for its mechanical properties. However, the mechanical properties they analyzed in their study is limited to its green condition.

This study analyzes the characteristic bending, compressive, and shear strengths parallel to the fiber of *Bambusa blumeana* in its air-dry condition. It also determines the correlation of its geometric and physical properties to its mechanical properties using simple linear regression.

2. METHODOLOGY

2.1 ISO 22157-1 (2017)

A total of 263 samples were sourced from Base Bahay Innovation Center, 70 of which were tested for bending strength, 93 for compressive strength, and 100 for shear strength. Furthermore, the ISO 22157-1 (2017) by the International Organization for Standardization (ISO) was the fundamental test protocol used to determine the physical and mechanical properties of the bamboo culms.

Each bamboo sample underwent visual inspection to check for initial defects prior to testing. The geometric and physical properties were measured using a digital vernier caliper with a precision of 0.1, in millimeters. These properties include the length, outer diameter, wall thickness, area, mass, mass per unit length, density, and moisture content.

The outer diameter (D) was obtained as the average of two perpendicular measurements made across opposite ends on the outer surface of the sample, as shown in Equation 1.

$$D = \sum_{i=1}^{4} \frac{D_i}{4} \qquad \text{(Eq. 1)}$$

The length (L) measurements of the samples were determined as indicated in the test protocol. For the samples tested under compressive and shear strength, the length of the sample is the lesser of the outer diameter, D, or 10 times wall thickness, 10δ. On the other hand, the test protocol requires a minimum length (L_{min}) of $30D$ for samples tested under flexure. The samples were cut and measured using steel tape following the prescribed minimum length with added allowance to fit the test rig.

The wall thickness (δ) was calculated as the average of four measurements taken around the circumference of the culm at angular spacings of 90° on both ends of the sample, as shown in Equation 2.

$$\delta = \sum_{i=1}^{8} \frac{\delta_i}{8} \qquad \text{(Eq. 2)}$$

The mass (m_e) of the samples were obtained using a weighing scale, in kilograms and grams. The cross-sectional area (A), and mass per unit length (q) were calculated using Equations 3 and 4.

$$A = \frac{\pi}{4} \times [D^2 - (D2 - \delta)^2] \qquad \text{(Eq. 3)}$$

$$q = \frac{m_e}{L} \qquad \text{(Eq. 4)}$$

Each bamboo sample in the testing machine is applied with a continuous and uninterrupted load such that the failure is reached within (300 ± 120) s. Failure in less than 30 s were discarded from the analysis. The maximum applied load, F_{ult}, and failure modes were recorded in each test.

The bending tests of the bamboo culms were performed using SHIMADZU AGX-V Universal Testing Machine with a load rate of 18mm/min and using a four-point loading bending test setup. Trujillo et al. (2017) developed some modifications in the set-up prescribed by ISO, such as the addition of Linear Variable Differential Transformers (LVDT) at the end supports and the replacement of the saddles with steel with nylon straps.

The flexural properties of *Bambusa blumeana* consist of the ultimate bending moment (M_{ult}), in N-mm, bending strength parallel to the fibers ($f_{m,0}$), in N/mm^2, and tangent bending stiffness of the culm ($E_{m,0} \cdot I_B$), which were calculated using Equations 5, 6, and 7, respectively.

$$M_{ult} = \frac{F_{ult} \times \alpha}{2} \qquad \text{(Eq. 5)}$$

$$f_{m,0} = \frac{M_{ult} \times D}{2 \times I_B} \qquad \text{(Eq. 6)}$$

$$E_{m,0} \cdot I_B = \frac{(F_{60} - F_{20}) \cdot \alpha (3L^2 - 4\alpha^2)}{48\,(\delta_{60} - \delta_{20})} \qquad \text{(Eq. 7)}$$

In addition, the external taper (a_e) and internal taper (a_i) can influence the bending and compression capacity of the culm and were calculated using Equations 8 and 9, respectively. The ovality (d_0) refers to the degree of variation of culm cross-section from circular and was computed using Equation 10. The eccentricity (e_c) denotes the measure of deviation from a circle and was computed using Equation 11.

$$\alpha_e = \frac{D_b - D_t}{L} \quad \text{(Eq. 8)}$$

$$\alpha_i = \frac{D_b - D_t - 2(t_b - t_t)}{L} \quad \text{(Eq. 9)}$$

$$d_0 = 2\frac{(D_{max} - D_{min})}{(D_{max} + D_{min})} \quad \text{(Eq. 10)}$$

$$e_c = \sqrt{1 - \frac{{D_{min}}^2}{{D_{max}}^2}} \quad \text{(Eq. 11)}$$

For compressive tests, each sample is placed on the UTM such that its axis is aligned with the loading axis of the machine. The setup of the UTM is in accordance with the test protocol. The compressive strength parallel to fibers was calculated using Equation 12.

$$f_{c,0} = \frac{F_{ult}}{A} \quad \text{(Eq. 12)}$$

For shear tests, the samples were applied with a typical loading rate between 0.15-0.30 mm/min using the set-up prescribed by the test protocol. The specimen is supported at its lower end over two opposing quadrants and loaded at its upper end over the other two opposing quadrants, which will induce shear failure on four shear planes. The load at failure reflected on the UTM is recorded. The shear strength parallel to fibers is calculated using Equation 13.

$$f_v = \frac{F_L}{\sum Lt} \quad \text{(Eq. 13)}$$

After the mechanical tests were performed, a piece of the bamboo culm was extracted from the area where the failure has occurred. The test pieces were weighed and measured to obtain the initial mass (m_i), dimensions, and volume (V_0) of the test piece before they are oven-dried for 24 hours. After oven-drying, the oven-dried mass (m_0) of the test pieces were measured. The density (ρ) and moisture content (ω) of the sample are calculated using Equations 14 and 15, respectively.

$$\rho = \frac{m_0}{V_0} \quad \text{(Eq. 14)}$$

$$\omega = \left[\frac{m_i - m_0}{m_0}\right] \times 100 \quad \text{(Eq. 15)}$$

However, the analysis for bending strength requires further calculations on some of the parameters of the samples. An alternative equation for calculating the density, as shown in Equation 16, was suggested by Trujillo et al. (2017) to address the variation of the density along the length of the bamboo culm.

$$\rho = \frac{m}{L \times \frac{\pi}{4}[D^2 - (D - 2t)^2]} \quad \text{(Eq. 16)}$$

Furthermore, the density and mass per unit length of the bamboo samples for bending strength were normalized at 12% moisture content to allow comparison with reported values as recommended by the test protocol. The values were adjusted by multiplying the oven-dry values by 1.12, as shown in Equations 17 and 18, respectively.

$$\rho_{12} = \rho_0 \times 1.12 \quad \text{(Eq. 17)}$$

$$q_{12} = q_0 \times 1.12 \quad \text{(Eq. 18)}$$

2.2 ISO 12122-1 (2014)

Conforming to the requirements of test protocol ISO 12122-1 (2014), the characteristic strength values for each mechanical property were calculated using 5th percentile-based properties with a 75% confidence evaluation. The basis for evaluation of non-parametric data is AS/NZS 4063.2 fitted in accordance with the bamboo samples. The characteristic strength value, $X_{0.05,0.75}$ (N/mm^2), was calculated using Equation 19, wherein $X_{0.05}$ denotes the 5th percentile value, $k_{0.05,0.75}$ is the constant that considers 75% confidence, V is the variation coefficient calculated as the ratio of sample standard deviation to sample mean, and n represents the sample size.

$$X_{0.05,0.75} = X_{0.05}\left(1 - \frac{k_{0.05,0.75}V}{\sqrt{n}}\right) \quad \text{(Eq. 19)}$$

3. RESULTS AND DISCUSSION

Multiple failure patterns existed for each testing made onto *B. blumeana*. For bending failure modes (Figure 1), these were categorized in 4 types: Type I is the ideal failure, existing in the middle, right into the constant moment zone; Type II is where failure mode occurs in the point of load application;

Type III failure mode happens in the constant moment zone, occurring in where loading was applied extending to the middle; and Type IV, the total collapse of the bamboo culm (Vicencio, 2021). For compressive tests (Figure 2), three failure modes were observed which are splitting, crushing, and combined splitting and crushing failure. Specimens with combined splitting and crushing failure were observed to have splits occurring along the crushing zone. Lastly, in terms of shear (Figure 3), the specimen failed on either 1 or 2 shear failure planes, with 64% of total tests failed on 1 shear failure plane and 34% failing on 2 simultaneous planes (Bautista, Garciano, & Lopez, 2021).

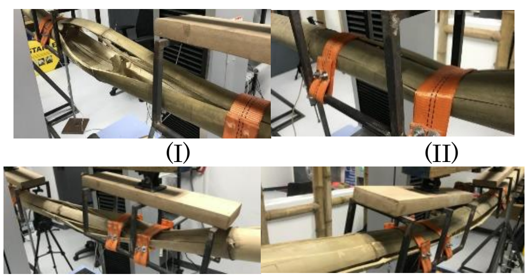

Fig. 1. Bending Failure Modes (by Type)


Fig. 2. Compressive Failure Modes

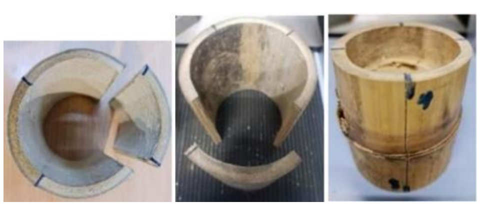
Fig. 3. Shear Failure Modes

Geometric properties determined through measurement through vernier caliper with 0.1% precision are listed in Tables 1, 2, and 3.

Table 1. Geometric Properties for Bending Test (Vicencio, 2021)

Property n = 70	D (mm)	δ (mm)	α_e (x10-3)	α_i (x10-3)	d_0	e_c
Min	75.33	6.01	0.1	0.07	0	0.16
Max	108.08	11.41	7.07	6.06	0.07	0.69
Ave	91.18	7.75	3.39	2.68	0.02	0.49
St dev	7.34	1.03	1.73	1.54	0.02	0.12
V	0.08	0.13	0.51	0.57	0.79	0.24

Table 2. Geometric Properties for Compressive Test

Property n = 93	L (mm)	D (mm)	δ (mm)	A (mm^2)
Min	73.40	76.90	5.58	1255.78
Max	110.40	110.20	10.45	2960.54
Ave	93.08	93.94	7.57	2059.99
St dev	8.62	8.11	1.07	377.45
V	0.09	0.09	0.14	0.18

Table 3. Geometric Properties for Shear Test (Bautista, Garciano, & Lopez, 2021)

Property n = 100	L (mm)	D (mm)	δ (mm)	A (mm^2)
Min	71.43	71.42	5.79	1774.85
Max	111.45	113.56	10.56	4162.85
Ave	92.08	94.56	7.65	2831.8
St dev	7.84	7.56	1.01	522.44
V	0.09	0.08	0.13	0.18

Other physical properties were determined, along with corresponding mechanical properties, which are shown in Tables 4, 5, 6. However, it should be noted that for bending, the values were normalized at 12% moisture content following the recommendation of ISO 22157-1. Average strengths for bending, compressive, and shear, with corresponding coefficient of variation (COV), are 92.63 MPa (0.22), 70.67 MPa (0.19), 11.44 MPa (0.28). From the results, it could be seen that bamboos are most resistant to bending failure, and most vulnerable towards shear failure. Consequently, the highest COV recorded for the strength is for shear, translating to a relatively high dispersion of computed shear strength, evident to the minimum and maximum values, 4.15 and 16.50 MPa, respectively.

Table 4. Other Physical and Mechanical Properties for Bending Test (Vicencio, 2021)

Property n = 70	q_{12} (kg/m)	ω (%)	ρ_{12} (kg/m³)	$f_{m,0}$ (MPa)
Min	1.12	8.89	594.32	43.83
Max	2.60	10.85	1073.08	140.66
Ave	1.67	9.92	823.4	92.63
St dev	0.31	0.44	102.39	20.65
V	0.19	0.04	0.12	0.22

Table 5. Other Physical and Mechanical Properties for Compressive Test

Property n = 93	q (kg/m)	ω (%)	ρ (kg/m³)	$f_{c,0}$ (MPa)
Min	1.00	9.23	465.63	40.46
Max	3.16	14.11	1060.84	136.33
Ave	1.88	10.90	806.85	70.67
St dev	0.48	0.80	130.72	13.70
V	0.25	7.35	0.16	0.19

Table 6. Other Physical and Mechanical Properties for Shear Test (Bautista, Garciano, & Lopez, 2021)

Property n = 100	q (kg/m)	ω (%)	ρ (kg/m³)	f_v (MPa)
Min	0.96	7.5	315.86	4.15
Max	3.35	11.36	945.97	16.50
Ave	2.04	9.36	761.71	11.44
St dev	0.49	0.78	130.33	3.17
V	0.24	0.08	0.17	0.28

Simple linear regressions were used to assess the relationships between the geometric and physical properties to the mechanical strengths of bamboo. The performance of the model was determined based on its r^2 value specifying three levels of correlation (strong for $r^2 > 0.5$; moderately strong for $0.3 < r^2 < 0.5$; and weak for $r^2 < 0.3$). Results of the linear regression analyses, shown in Table 7, presents that the data for bending strength has a strong correlation with density ($r^2 = 0.5612$), while compressive and shear strengths have a moderately strong correlation with moisture content ($r^2 = 0.3199$) and density ($r^2 = 0.4130$), respectively. The geometric characteristics and mass per unit length of the bamboo shows weak correlation, which implies that all three strengths evaluated in this study is relatively independent of the geometric properties of the bamboo samples.

Table 7. Correlations (R^2) of different variables using simple linear regression

	$f_{m,0}$ (MPa)	$f_{c,0}$ (MPa)	f_v (MPa)
L (mm)		0.0005	
D (mm	-0.0509	0.0162	
δ (mm)	0.0036	0.0001	
A (mm²)		0.0093	
q (kg/m)	0.1733	0.1686	
ρ (kg/m³)	0.5612	0.0927	0.4130
ω (%)	-0.0775	0.3199	

According to ISO 12122-1 (2014), the characteristic value is a value of a property taken to represent the property of a designated population using a process of sampling, testing of specimens, and analysis. Using this standard, the computed characteristic bending strength ($f_{m,0,k}$), compressive strength ($f_{c,0,k}$), and shear strength ($f_{v,0,k}$) are 55.90, 46.63, and 5.15 MPa, 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 characteristic values are lower than the average mechanical strengths. Table 8 shows the computations for the characteristic strengths where the multiplier ($k_{0.05,0.75}$) is 1.94 for the bending and compressive strengths since the number of samples (n) is greater than 50 but less than 100. $k_{0.05,0.75}$ for the shear strength is 1.85 due to its 100 samples.

Table 8. Evaluation of 5th percentile value with 75% confidence

Property	n	V	5th Percentile $X_{0.05}$ (MPa)	Multiplier $k_{0.05,0.75}$	Characteristic Value $X_{0.05,0.75}$ (MPa)
[2]$f_{m,0}$	70	0.22	58.95	1.94	55.90
$f_{c,0}$	93	0.19	48.53	1.94	46.63
[1]f_v	100	0.28	5.43	1.85	5.15

[1](Bautista, Garciano, & Lopez, 2021); [2](Vicencio, 2021)

The obtained strength values of *Bambusa blumeana* were compared to the reference values for visually stress-graded unseasoned structural timber of Philippine Woods considering the High Strength Group at 80% Stress Grade (NSCP, 2015). It can be shown that all the mechanical properties studied have far larger values than the indicated reference design capacities. This shows that the bamboo specie, *Bambusa blumeana*, is a possible alternative to wood as a construction material.

Table 9. Comparison of Strength with Structural Timber of Philippine Woods

Source	Species	$f_{m,0}$ (MPa)	$f_{c,0}$ (MPa)	f_v (MPa)
This study:				
Average		92.63	70.67	11.44
Characteristic		55.90	46.63	5.15
Unseasoned Structural Timber - High Strength Group (80% Stress Grade):				
	Agoho	26.30	14.50	2.95
	Liusin	25.00	15.60	2.64
	Malabayabas	28.70	15.80	3.02
	Manggachapui	25.80	16.00	2.78
	Molave	24.00	15.40	2.88
	Narig	21.80	13.70	2.61
	Sasalit	31.30	21.60	3.38
	Yakal	24.50	15.80	2.49

4. CONCLUSIONS

The characteristic strengths parallel to the fiber of *Bambusa blumeana* is determined by conducting tests on 263 bamboo specimens following the protocols in ISO 22157-1 (2017) and ISO 12122-1 (2014). The resulting average strength values show that *B. blumeana* has a high bending strength as compared to its compressive and shear strength. The correlation between the geometric and physical properties of the tested bamboo to its mechanical properties were analyzed based on the r^2 value obtained from simple linear regression. The highest r^2 value shows a strong correlation between density and bending strength. For the shear strength, the density also has the highest value that falls under moderately strong correlation. And lastly, the moisture content showed the highest correlation with compressive strength which is also under moderately strong correlation.

The characteristic bending, compressive, and shear strength of the bamboo was obtained, and the resulting values showed that both the average and characteristic strength values of bamboo are greater than the high strength group of structural timber with 80% stress grade. Therefore, *Bambusa blumeana* can potentially be a substitute to timber as a construction material.

Bambusa blumeana is among the endemic bamboo species in the Philippines which holds great potential as a construction material. As other bamboo species, it still requires further study. Thus, it is recommended to establish its characteristic tensile strength using the ISO. The relationships between these mechanical properties could also be examined such that determining one property could lead to prediction of the other properties.

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