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Regression Analysis of Bending Perpendicular Property of Guadua Angustfolia (Iron Bamboo)

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***Abstract*—The bamboo is said to be sustainable as it is a renewable and versatile product. The group of giant woody grasses is proven to be the fastest growing plants and extensively in most parts of the world. Guadua angustifolia is one of the most used materials in bamboo construction. Due to its small internode distance and the straightness of long bamboo culms, it allows it to be a versatile material when used in construction. The demand for assessing the mechanical properties of bamboo has also been increasing in the construction industry. Structural codes and standards are limited for some bamboo species since there are insufficient studies regarding the matter. In this study, the bending strength of G. angustifolia 'Kunth' (commonly known as Iron Bamboo) perpendicular to the fibers was established to characterize the bending property of the bamboo species. The latest PNS ISO 22157:2020 test protocol and guidelines from PNS ISO 22156:2021 were used to establish the bending strength from 41 characterized bamboo samples sourced from Cotabato City, Philippines. The results show that the parameter that is relatively significant to the maximum load at bending failure is the wall thickness, t of the bamboo culm. A proposed regression model to estimate the $Fult$ of bamboo using the physical properties derived from the tests is also provided. Through analyses, the average maximum bending strength of G. angustifolia perpendicular to the fibers is 10.13 MPa. The characteristic value of this bending strength for G. angustifolia is 5.57 MPa, with an allowable design capacity of 2.79 MPa.**

Keywords—Guadua angustifolia, bamboo culms, bamboo material, bamboo construction, bending strength perpendicular, PNS ISO 22156:2021, PNS ISO 22157:2020

I. Introduction

Bamboo has proven to be highly productive and versatile. As a renewable source, its culms can be harvested and grow continuously over time without killing the plant. Among the number of bamboo species known worldwide, one of the largest and strongest giant bamboo is the Guadua angustifolia 'Kunth.' The species is commonly known as "Iron Bamboo" and has been widely used and studied in America, particularly in the southern and central regions. In this study, the characteristics and the mechanical property of G. angustifolia, namely the bending perpendicular property, is investigated and discussed, particularly an aspect that would consider the bamboo species as a sustainable construction material.

The use of bamboo for construction has been controversial as the material's properties have been questioned by the average group of people. The professionals in the construction field also lack the acceptance of using bamboo because it is not supported by solid specifications. Working on a material that is inconsistent with and requires complete information is indeed difficult. In this matter, the required information should be concentrated on the strength properties of bamboo influenced by specific applications, the development of a design code for bamboo, and the establishment of consistent engineering data to encourage the use of bamboo in the construction and building industry (Arce, 1993).

With the current trend of sustainability in the construction industry, the search for sustainable materials is of the main interest. Little is known about bamboo, and its usage is controversial as its properties are mostly unfamiliar to some. Housing solutions have been demanding, especially in the Philippines, a country afflicted by severe climate and natural disasters yearly. However, the bamboo species vary in their properties and characteristics due to their physical, anatomical and morphological properties. Therefore, consistent engineering data must be established to encourage the use of bamboo in the construction and building industry.

The Base Bahay Foundation is affiliated with developing a design code of bamboo for the next issue of the National Structural Code of the Philippines (NSCP) which includes specifications for several bamboo species that are commonly found in the Philippines. Base Bahay is studying numerous species of bamboo, and Guadua angustifolia is one of the bamboo species that the foundation is extensively

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investigating. G. angustifolia is one of the most used materials in bamboo construction (Schröder, 2022). Due to its small internode distance and the straightness of long bamboo culms, it allows the material to be versatile when used in construction. However, the species has not yet been characterized in the country due to the limited plantations found in the Philippines.

The International Organization for Standardization (ISO) is known for implementing its own standards in determining the mechanical properties of bamboo. Sample testing and building standards are introduced by the ISO to further approve the use of bamboo materials worldwide. The ISO 22156:2021 Bamboo structures – Bamboo culms – Structural design documents the application of the design of bamboo to structures made of engineered bamboo products. Along with ISO 22157:2019 Bamboo structures – Determination of physical and mechanical properties of bamboo culms – Test methods, the sample testing of different bamboo species can be followed through the guidelines included in the document.

The Department of Trade & Industry Philippines (DTI) and the Bureau of Philippines Standards published the Philippine National Standards that is based on the ISO standards. The PNS ISO 22156:2021 and PNS ISO 22157:2020 issued respective standards regarding bamboo structures.

The bamboo poles of G. angustifolia consist of a small internode distance and the straightness of the poles added to the versatility of the bamboo products, mostly for construction use. As the bamboo is proven to have a moderately high relative density, it is proven to be studied and used for some low-cost structural purposes and engineered bamboo composites as it is highly resistant to tear. Its high strength-to-weight ratio allows it to absorb energy and resist flexibility. However, the bamboo species has the highest dimensional shrinkage results which recommends applying proper treatments or preservation before utilization (Villareal et al., 2020).

In this study, it aims to focus on the bending strength perpendicular to the fiber of the G. angustifolia. The possible sources, plantations, and samples of the said species are also identified. The objectives include characterizing the physical properties of G. angustifolia which underwent several steps and procedures to determine and select the right bamboo species. The sampling method is limited by the type of bamboo treatment which is the "9-Step Treatment Process" using Solignum as a chemical preservative. The results in this study does not define the untreated/raw samples and samples that have undergone another type of treatment. The bending tests perpendicular to the fiber of the bamboo samples were conducted using the guidelines provided in PNS ISO 22157:2020. The bending perpendicular property of G. angustifolia was established using the PNS ISO 22156:2021. There are no structural modeling, analysis of bamboo structures, and other bamboo applications will be found in the study.

II. METHODOLOGY

The bending perpendicular property of *Guadua angustifolia* were characterized by 41 bending test results. In using the PNS ISO 22157:2020 test protocol for bending was used to determine the average maximum bending load at failure. A sample is determined to represent the population in which test results are intended to represent and be appropriate for the testing program's objective. The sample bamboo culms, shown in Fig. 1, represent the total population that is to be used for construction purposes. All culms that are broken, damaged, and discolored are discarded. The bamboo samples used for the study are obtained from various clumps and are cut from unknown locations on the original culm.

Figure 1. *Guadua angustifolia* Bamboo Samples

In conducting a bending test for the bamboo perpendicular to the fibers of the specimens from bamboo culms, the samples are prepared according to the standards provided by PNS ISO 22157:2020. The bending test consists of applying a compression force perpendicular to the axis of a node-free culm segment shown in Fig. 2. For a circumferential compression test, it should be done on specimens without any node. The length, L of the specimen must not exceed the outer diameter, D of the culm. Specimens with a varying diameter that exceeds or is less than $0.05D$ over the length of the samples were not used for the study. The parameters of the specimen such as the weight (q), length (L), outer diameter (D), and wall thickness (t) are recorded prior to testing.

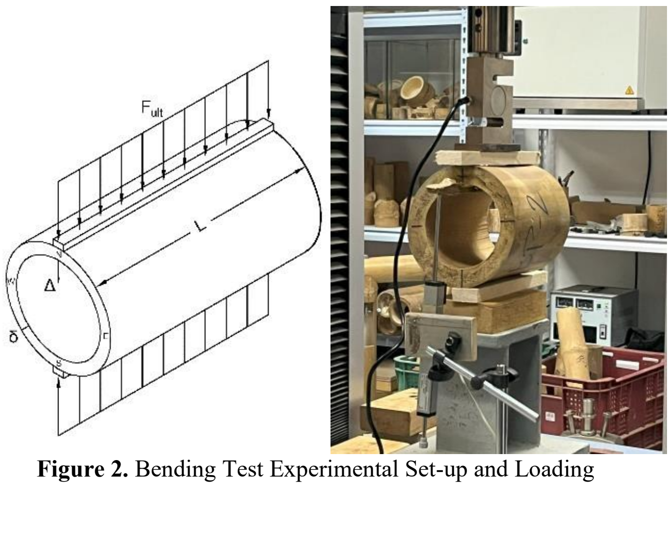

Figure 2. Bending Test Experimental Set-up and Loading

The determination of moisture content by oven-dry method is prepared immediately after the mechanical test. The samples are prepared and cut into strips to fit inside the whole batch in the oven. The moisture content, w of each test sample is calculated with the following formula expressed as a percentage of the oven-dry mass:

$$w = \left[\frac{m_i - m_0}{m_0}\right] \times 100 \quad (1)$$

A bamboo exerts different stress conditions under a load of reaction quadrants (designated as North-South, or N-S) and the orthogonal (East-West, or E-W) quadrants (Fig. 3b), thus separate calculations are required for each location. After the bending test procedures, the maximum failure load, F_{ult} in Newtons (N), the relative deflection (Δ) of the N and S points in millimeters (mm), and the quadrant (N-S or E-W) where the failure(s) was located are recorded. In a case in which the failure occurred at multiple quadrants, the failure recorded is the first failure that occurred. If the failure occurred at neither N-S nor E-W (i.e., Northeast, Northwest, Southeast, Southwest) of the sample, the failure is at the E-W location.

The gathered data are organized in accordance with the PNS ISO 22157:2020 to prepare an analysis for establishing an accurate and precise bending capacity strength of *G. angustifolia* as a code specification in construction. For a specimen that has a uniform culm wall thickness, t along its length, L, has a radius, R to the midline of the culm wall section. For having a solid and curved rectangular section, the estimated h distance from the culm wall midline to the location of the elastic neutral axis measured toward the center of curvature (Fig. 3a) is defined as:

$$h = R - \frac{t}{\ln\left(\frac{2R+t}{2R-t}\right)} \times 100 \quad (2)$$

In bending a through culm-wall, the modulus of rupture is related to the transverse tension properties of the bamboo which performed a splitting behavior. Considering a failure similar to Fig. 3c, a compression force acting at the N-S location will form a hinge at (or near) the locations where the maximum moment around the circumference occurred from the culm section. The maximum moments may occur at the loading and reaction points (N and S) or at the extreme edges (E and W) around the culm circumference. In this case, the culm wall subjected to a positive bending is a failure at the N and S locations. While a negative bending is a failure at the E and W locations. When calculating the bending strength, the failure location is important to be observed as the properties of the bamboo may vary with respect to the critical sections and orientation of the moment. The bending moment perpendicular to the fibers are calculated as:

$$M_{ult} = \left[F_{ult,NS} \times \frac{R}{\pi}\right]\left[1 - \left(\frac{t^2}{12R^2}\right)\right] \quad (3)$$

$$M_{ult,EW} = -\left[F_{ult,EW} \times \frac{R}{\pi}\right]\left[1 - \left(\frac{t^2}{12R^2}\right)\right] - \frac{(F_{ult,EW})(R)}{2} \quad (4)$$

The apparent bending strength perpendicular to the fibers of the culm wall that failed at either N-S or E-W locations is calculated as:

$$f_{m,90,NS} = \left[\frac{M_{ult,NS}}{Lth}\right]\left[\frac{R - R_i - h}{R_i}\right] \quad (5)$$

$$f_{m,90,EW} = \left[\frac{M_{ult,EW}}{Lth}\right]\left[\frac{R - R_o - h}{R_o}\right] - \frac{F_{ult,EW}}{2Lt} \quad (6)$$

The relative deflection or displacement (Δ) between the loaded points (N and S) of the compressed culm is determined by applying a line load (F_{ult}) shown in Fig. 2. The measured displacement is used to determine the circumferential modulus of elasticity, $E_{m,90}$. It is defined as the averaged tension and compression behaviors at the critical sections that are perpendicular to the longitudinal axis of the culm. The calculation for $E_{m,90}$ is:

$$E_{m,90} = \left[\frac{3D^3(F_{60} - F_{20})}{2Lt^3(\Delta_{60} - \Delta_{20})}\right]\left[\frac{\pi k_1}{4} - \frac{2k_2^2}{\pi}\right] \quad (7)$$

To finally establish an accurate and precise bending perpendicular strength of *G. angustifolia* as a code specification in code construction, the gathered data are analyzed by multiple linear regression. This is to present the definition and correlation of the physical properties of *G. angustifolia* with its maximum bending load failure and bending strength perpendicular to the fibers.

In order to properly use *G. angustifolia* bamboo as a structural composite, the 5th percentile of the bending strength perpendicular to the fiber from the tests are computed for as based on PNS ISO 22156:2021. The characteristic value can be used in various applications such as structural engineering and design. To evaluate the characteristic value of the test results, it can be calculated as:

$$X_{0.05,0.75} = X_{0.05}\left[1 - \frac{V(k_{0.05,0.75})}{\sqrt{n}}\right] \quad (8)$$

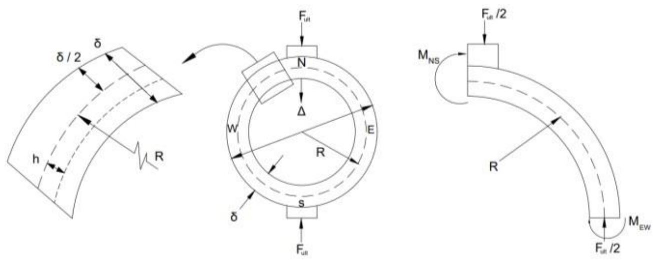

Figure 3. Edge Bearing Test Specimen Geometry and Internal

Reactions (PNS ISO 22157:2020)

The allowable member design load-bearing capacity is determined by applying all relevant adjustment factors. In accordance with PNS ISO 22156:2021, the characteristic component strength is determined by the formula:

$$X_i = X_{0.05,0.75} \times \frac{1}{FS_C} \quad (9)$$

III. RESULTS AND DISCUSSION

The bamboo samples used in the study were treated with *Solignum* as a preservative using the soaking treatment. The specimens were cut from the bamboo poles in which their locations on the original culm are unknown. The total number of specimens used in this study is a total of 41, all with varying shapes and sizes, considering the length is based on the outer diameter of the bamboo culm, as per PNS ISO 22157:2020.

Table 1. Measured Results from Bending Tests on *G. angustifolia*

Species	q (g)	L (mm)	t (mm)	D (mm)	w (%)
G. angustifolia					
$\bar{x}$	438.8	123.5	12.9	121.2	8.51
σ	200.0	22.2	3.9	22.3	0.44
COV (%)	0.46	0.18	0.28	0.18	0.05

From the data collected, summarized in Table 1, it is discovered that the parameter with the highest coefficient of variation (COV) is the weight, q at 0.46. While the moisture content (w), with 0.05 COV, measured the lowest level of variation from the mean of the physical property. These values show that the bamboo samples used in the study vary in shape and size. The weight, q varies the most from these physical properties due to the density of the bamboo samples. The length, L and the outer diameter, D did not show differences in COV since the length of the specimens is based on the outer diameter of the original bamboo pole.

The average load at failure (F_{ult}) is listed in Table 2 to show the calculated results from the bending test procedures. The compression force is applied along the length following the rate of load application of (300 ± 120) seconds to complete the bending test (PNS ISO 22157:2020). Most of the total samples used for the test failed at the NorthSouth (N-S) location, which is approximately 91% of the total samples. There are 4 out of 45 samples that failed at the East-West (E-W) location which is quite insignificant to the study since the calculations for bending strength are separated by the mode of failure. Therefore, a final total of 41 samples were used for the study, all of which failed at the N-S location.

Table 2. Calculated Results and Failure at N-S from Bending

Test on *G. angustifolia*

Species	F_{ult} (N)	$M_{ult,NS}$ (N-mm)	$f_{m,90,NS}$ (MPa)	$E_{m,90}$ (MPa)
G. angustifolia				
$\bar{x}$	2135	37262	10.1	1129.0
σ	859.2	16936	3.03	437.5
COV (%)	0.40	0.45	0.30	0.39

A multiple linear regression analysis was performed to assess the relationships between the physical properties of the bamboo (i.e. weight, length, wall thickness, outer diameter, and shrinkage) and the maximum load at failure (F_{ult}). This is to establish a regression model that can determine the bending strength of *G. angustifolia*.

Based on the regression analyses, the wall thickness, t has proven to be the most significant predictor for estimating the value of F_{ult}. In finding the correlation between the t and F_{ult}, the results from the multiple regression analysis are assessed using the regression statistics. It can be observed that an R, with a value of 81% suggests that there is a strong positive linear relationship between F_{ult} and t. The R^2 is 65% which suggests that the overall model of t for F_{ult} is relatively significant. Additionally, if the predictor is added to the model, whether it increases or decreases the value of the adjusted R^2, the added value is considered useful or useless, respectively. It can be observed in Table 3 that the adjusted R^2 of 64% in Regression Model V, decreases to 61% as shown in Regression Model I. Since it has been proved that the additional parameters are not significant to the model for F_{ult}, the adjusted R^2 decreased accordingly.

Table 3. Multiple Linear Regression Models for $\boldsymbol{F_{ult}}$

	I	II	III	IV	V
	Regression Statistics				
R	0.81	0.81	0.81	0.81	0.81
$R2$	0.66	0.66	0.66	0.66	0.65
Adjusted $R2$	0.61	0.63	0.63	0.64	0.64
	Coefficients				
Intercept	-1.22	-1.05	-1.10	-0.42	-0.35
t	0.21**	0.21**	0.21**	0.20**	0.18**
q	-0.0015	-0.0016	-0.0017	-0.007*	
D	0.013	0.013	0.0084*		
L	-0.0045	-0.0046*			
w	2.50*				

** variable with the highest p-value in the model*

*** p-value < 0.05*

The regression statistics of the model suggest that the regression model with the wall thickness, t as parameter is recommended for usage. The regression model for estimating the maximum load at failure (F_{ult}) is now given as:

$$F_{ult} = 0.18t - 0.35 \quad (9)$$

The thickness, t of a bamboo sample is measured in millimeters and gives an estimated regression coefficient of 0.18 shown in Regression Model V of Table 3. In consideration that the other variables are held constant, it explains that the F_{ult} increases by 0.18 kN, or 180 N, for every corresponding millimeter that is added to the wall thickness of a specimen.

In evaluating the goodness of the fitted model, a residual analysis was performed to assess the correlation between the t and F_{ult} shown in Fig. 4. The data points are randomly scattered around the fitted line which does not contradict the reliability of the regression model.

The line fit plot, shown in Fig. 5, interprets how well the regression line of Eq. (9) fits around the linearity of both the actual and predicted F_{ult}. With a 95% confidence interval, the thickness is relatively significant to that of F_{ult} since the data set performs a good diagonal and linear plot, which means that the mean of variation of the data set, is quite similar to the variation of the predicted data set. In addition, the linearity of the normal probability plot of F_{ult} (Fig. 6) suggests that the data set is normally distributed.

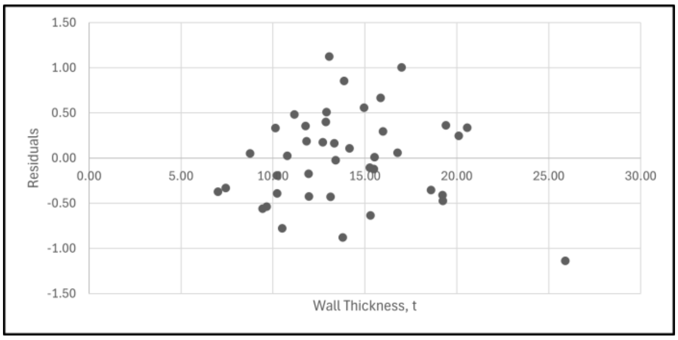

Figure 4. Wall Thickness, t and Residuals Plot

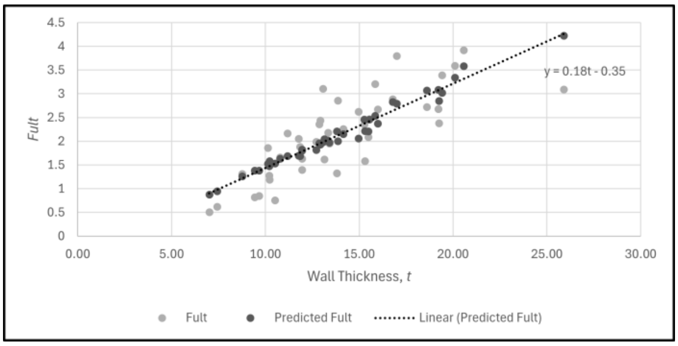

Figure 5. Line Fit Plot for F_{ult} and Wall Thickness, t

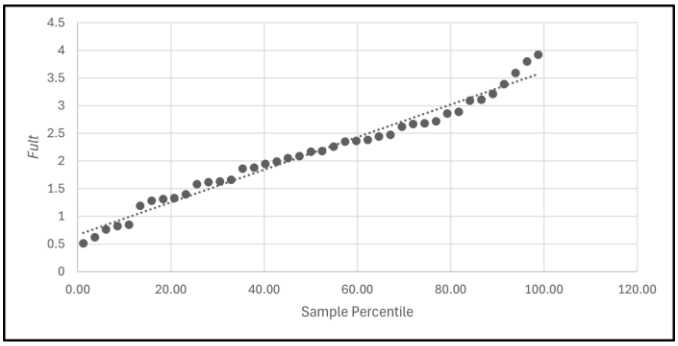

Figure 6. Normal Probability Plot for F_{ult}

In Table 4, the average bending strength (f_m) perpendicular to the bamboo fibers from the test data, and the average bending strength (f_m) using PNS ISO 22157:2020 are listed and compared.

The characteristic values ($f_{m,c}$ and $f_{m,c}$) for each bending strength, using PNS ISO 22156:2021 are also indicated in the table to show the respective comparison.

Table 4. Comparison of Bending Strengths and Characteristic Values

		Actual		Predicted	
Species	n	$f_{m,mean}$ (MPa)	$f_{m,c}$ (MPa)	$\hat{f}_{m,mean}$ (MPa)	$f_{m,c}$ (MPa)
G. angustifolia	41	10.13	5.57	10.52	6.92

The characteristic values are computed using Eq. (7) by evaluating the 5th percentile value with 75% confidence. The allowable design capacity is also computed using Eq. (8) in accordance with PNS ISO 22156:2021. Table 5 shows the process of evaluating the characteristic values and the allowable design capacity.

Table 5. Evaluation of 5th Percentile Values of the Bending Strengths with 75% Confidence

	$X_{0.05}$ (MPa)	$k_{0.05,0.75}$	$X_{0.05,0.75}$ (MPa)	X_i (MPa)
Actual, f_m	6.14	1.97	5.57	2.79
Predicted, f_m	7.41		6.92	3.46

Table 6. One-Way ANOVA between Actual Bending Strength ($\boldsymbol{f_m}$) and Predicted Bending Strength ($\boldsymbol{f_m}$) with 95% Confidence

	Actual, f_m	Predicted, f_m
μ	10.13	10.52
σ	3.03	2.29
σ^2	9.19	5.23
COV (%)	0.30	0.22

Source of Variation: Between Groups

F-stat	F-crit	p-Value	Significance
0.43	3.96	0.51	Fail to reject H_0

To further assess if the actual bending strength from the test data and the predicted bending strength from the regression model have a significant difference, an analysis of variance (ANOVA) is performed. In assessing the ANOVA results, hypotheses testing was performed for the F-value and p-value to check if there are significant differences between the variances and means of the actual and predicted bending strength data set.

For the F-test, it can be concluded that the difference between the variances of the actual and predicted bending data set are not statistically significant. Moreover, the p-value from the ANOVA results claims that the means between the actual and predicted strength are also not statistically significant. In Fig. 7, the comparison of the bending strength values, with respect to their respective wall thickness, between the actual data set and the predicted data set is presented. It also visually suggests how the variances and means between the two data sets are not statistically significant. The linearity of the data plots for the predicted bending data set is also observed.

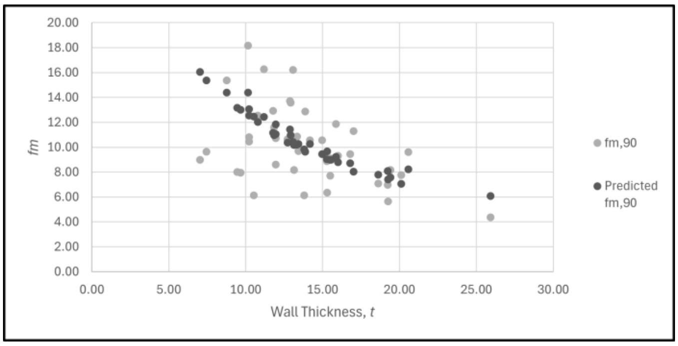

Figure 7. Difference between the Actual Bending Strength (f_m) and Predicted Bending Strength (f_m) with respect to the Wall Thickness, t

Due to the differences in means and variances are proven not to be statistically significant by ANOVA, the actual and predicted bending strengths can be compared and assessed to establish the bending strength of *G. angustifolia*. In most structural codes, the governing value or the critical value for the bending strength of a building material, such as steel and timber, is the lowest. Following this case, the average ultimate bending strength for *G. angustifolia* is 10.13 MPa, taken from the actual bending strength data set. In accordance with the PNS ISO 22156:2021, the characteristic value for the respective data set is 5.57 MPa, with an allowable design capacity of 2.79 MPa.

The apparent bending strength is compared to the reference values from related literatures to show a comparison between *Guadua angustifolia* and other bamboo species. The modulus of rupture (MOR), which can also be called bending or flexural strength, were gathered from different studies under different conditions and test methods shown in Table 7. Some studies generate higher MOR due to different types of test methods. The study from Sharma et al. (2013), uses the same test protocols as this study which used a similar guideline as the PNS ISO 22157:2020. Other types of treatment, age of the bamboo samples, methods of cultivation, localities of the samples, and sample sizes are affecting the values among different bamboo species.

IV. CONCLUSION

The presented study investigated the bending strength perpendicular to the fibers of the bamboo *Guadua angustifolia* 'Kunth' (or commonly known as the Iron Bamboo). A total of 41 bending tests using PNS ISO 22157:2020 test protocol for bending was used to establish the bending strength perpendicular to the fibers of *G. angustifolia*. Using multiple linear

Table 7. Comparison of Bending Strength of *Guadua angustifolia* with Different Bamboo Species

Species	Bamboo Treatment	f_m (MPa)	Reference
	Maximum bending strength from this study		
Guadua angustifolia	*Solignum* Treated	10.13	
	Predicted Value	10.52	
	Reference values from different studies		
Bambusa balcooa	Green	71.46	Kabir et al. (1991)
	Airdry	78.75	
Bambusa bambos	-	35	Gnanaharan (1991)
Bambusa nutans	Green	52.9	INBAR (1998)
	Airdry	52.4	
Bambusa polymorpha	Green	28.3	INBAR (1998)
	Airdry	35.5	
	Green	41.45	Kabir et al. (1991)
	Airdry	47.33	
Bambusa stenostachya	N-S failure	5.8	Sharma et al. (2013)
	E-W failure	3.3	
Bambusa tulda	Green	51.1	INBAR (1998)
	Airdry	66.7	
	Green	60.38	Kabir et al. (1991)
	Airdry	75.15	
Dendrocalamus asper	-	199.9	Chiann et al. (2021)
Dendrocalamus membranaceus	Green	26.3	INBAR (1998)
	Airdry	37.8	
Dendrocalamus strictus	-	118.4	Sekar & Gulati (1973)
Gigantochloa apus	Green	102	Prawirohatmodjo (1990)
	Airdry	87.5	
Gigantochloa atroviolacea	Green	92.3	Prawirohatmodjo (1990)
	Airdry	94.11	
Gigantochloa levis	-	162.7	Nordahlia et al. (2019)
	-	43.4	Virtudazo et al. (2017)
Gigantochloa scortechinii	-	196.7	Salih et al. (2019)
	-	125	Nordahlia et al. (2019)
Melocanna baccifera	-	57.6	INBAR (1998)
Oxytenanthera nigrociliata	Green	46.25	Kabir et al. (1991)
	Airdry	59.85	
Phyllostachys aurea	N-S failure	11.5	Sharma et al. (2013)
	E-W failure	6.5	
Thyrsostachys oliveri	Green	61.9	INBAR (1998)
	Airdry	90	

regression analysis, the recommended parameter for the regression model with the most significant relationship with maximum load at failure (F_{ult}) is the wall thickness, t of the bamboo culm. The correlation model was given to be $F_{ult} = 0.18t - 0.35$ for predicting a data set for F_{ult} with a good fit. The characteristic values and allowable design capacity strength from the actual and predicted bending strength data sets are obtained using a guideline from pns iso 22156:2021. From the anova of the actual and predicted data sets, the maximum bending strength perpendicular to the fibers of *g. Angustifolia* is proven to be 10.13 mpa, which is from the actual bending strength set of data. In accordance with the pns iso 22156:2019, the characteristic value of the bending strength of *g. Angustifolia* is 5.57 mpa, with an allowable design capacity of 2.79 mpa.

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