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Prediction of Mechanical Properties of *Bambusa blumeana* Bamboo Culms Using Non-Destructive Indicating Properties

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Abstract: *Growing concern over environmental degradation and the construction industry's damaging contribution raises the need for sustainable materials and methods. Bamboo is recognized as a sustainable construction material that is easily accessible and at a low cost. Bambusa blumeana is a widely used bamboo species that is locally available in the Philippines. The challenges faced by this species are the lack of its understanding and gaps in its standardization. This research studied the influence of non-destructive indicating properties (IP) on its compressive capacity. Through regression analysis, it is identified that linear mass at 12% moisture content was considered highly predictive among other IPs in simple linear regression. Multiple linear regression suggests a 0.635 R^2 value for linear mass at 12% moisture content and wall thickness as its IP. The implementation of computer vision into the grading of bamboo serves as a step towards the development of automated systems and sorting processes.*

Keywords: Regression, Artificial Neural Network. Bambusa blumeana, Computer Vision, Indicating Properties

1. INTRODUCTION

The construction industry has significant environmental impact in terms of fossil fuel energy consumption and CO_2 emissions. Sepehrdoust et al. [1] estimated that an increase of one percent in construction-related activities yields to 0.071 percent in short-term environmental degradation and 0.118 percent in long-term CO_2 emissions. These estimates made in Iran raise awareness to the repercussions of construction to the environment that heightens the need for alternatives to altogether reduce environmental harm.

A study conducted by Mercado et al. [2] promotes sustainability using coffee husk ash and eggshell powder as a partial substitute to cement together with spent coffee grounds as partial alternative for sand. This study explored the compressive strength of concrete with the influence of different ratios of partial replacements. The study was able to find a suitable blend of coffee husk and eggshell powder that garnered higher compressive strength. Jalipa et al. [3] is another study that investigated the use of replacements for conventional cementitious material with the use of poultry sludge. This study observed that the incorporation of poultry sludge decreased compressive and tensile strength while improving flexural strength leading to its recommendation to non-load bearing elements.

Bamboo is another sustainable material identified from various continents that has shown its use in construction for a very long time. This low-cost alternative material possesses strength comparable to high grade hardwood. [4] A study conducted by Adier et al. [5] notes that the changes in species, age, location, and treatment also offer variation in its mechanical properties. With this, it is essential to look into the species that is accessible locally. Within the context of the Philippines, the most used bamboo species is Bambusa blumeana or locally known as Kawayan tinik according to the Department of Environment and Natural Resources Ecosystems Research and Development Bureau [6]. The study of Salzer et al. [7] has investigated the mechanical characteristic values of Bambusa blumeana to develop understanding of the material and its application. The characteristic compressive strength parallel to grain was identified as 20 MPa while the characteristic tensile strength parallel to grain was observed to be 95 MPa. These characteristic values were obtained through tests in accordance with the ISO 22157 [8].

Previous studies suggest the use of capacity is more reliable with indicating properties compared to strength. Tangphadungrat et al. [9] observed that R^2 values are higher in compressive capacity compared to compressive strength with values of 0.859 and 0.596, respectively. In line with this, the study of Correal et al.[10] obtained 0.8 R^2 values for compressive capacities using machine learning methods. These studies present linear mass as the best indicating properties that are easily measured for the prediction of compressive capacity of bamboo. Procedures and standards regarding the grading of bamboo culms are done in accordance with the ISO 19624 [11].

Further development within the construction industry can altogether address emerging sustainability issues. As a developing country, the Philippines, it is essential to take advantage of new technologies to strengthen our growth and meet needs. Emerging technologies such as machine learning and artificial intelligence can further drive innovation. [12] An example of a novel approach is the integration of computer vision techniques with the applications of construction technology. Drawing inspiration from the study of Perez [13], the implementation of computer vision for automated measurement assists in the development and monitoring of projects. With this, computer vision techniques were developed focusing on the cross-section of the bamboo sample to infer mechanical properties. This incorporation of computer vision serves as a step further in the development of an automated system when bamboo is analyzed in bulk.

2. MATERIALS AND METHODS

The standards that are followed regarding the acquisition of materials and methods done are in accordance with ISO 22157:2020 [8] and ISO 19624:2020 [14].

2.1 Bamboo Sample Preparation

The Bambusa blumeana bamboo culms were collected from Nasugbu, Batangas with a total of 19 culms used aged 2-3 years. The collected bamboo was air-dried and protected from weather conditions such as sunlight and rain as seen in Fig 1.

Fig. 1. Bambusa blumeana bamboo culms.

A study conducted by Seixas [15] indicated that the most representative portion of the bamboo culm was found to be in the middle. With this, the location of specimen to be extracted within the culm will be the middle portion for both compression and tension test.

2.2 Measured Indicating Properties

The measured properties are average diameter over culm length (D), average wall thickness over culm length (δ), length (L), and mass (m_e). The average diameter over culm length (D) and wall thickness (δ) was measured with a caliper. To obtain the average diameter over culm length (D), perpendicular measurements at both ends were averaged. On the other hand, the average wall thickness over culm length (δ) was measured by taking the average measurement of both ends taken around the circumference of the culm with angular spacing of 90°.

(a)

(b)

Fig. 2. Measurement of (a) outer diameter and (b) wall thickness.

The moisture content (w) was recorded through the oven-dry method. Samples for the determination of moisture content were collected near the area of failure. The initial mass (m_i) before placing in the oven and final oven-dry mass (m_0) after 24 hours were recorded. The moisture content is then calculated with equation (1).

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

The linear mass (q) of the bamboo culms was also recorded. This is calculated by simply dividing the mass (m_e) to the measured length (L) as seen in equation (2).

$$q = \frac{m_e}{L} \tag{2}$$

The linear mass is then adjusted to 12% moisture content to allow the comparison of results by following equation (3),

$$q_{12} = q\left[\frac{1.12}{1+w}\right] \tag{3}$$

2.3 Mechanical Test

The mechanical tests are conducted in the laboratory of Department of Science and Technology Forest Products Research and Development Institute (DOST-FPRDI) located in Los Baños, Laguna.

A total of 38 specimens for the compression test were prepared, 50% with nodes and 50% internode. The length of these compression specimens follows the requirement of the lesser value between D and 10δ, consistent with ISO 22157. The compression strength ($f_{c,0}$) is obtained through equation (4) where the maximum load at failure (F_{ult}) is divided to the cross-sectional area (A) in square millimeters.

$$f_{c,0} = {}^{F_{ult}}\!/_{A} \tag{4}$$

For tension test, 57 specimens were made since it is required to have at least three tension specimens with a node for each culm. The required gauge length of 50mm to 100mm was followed alongside with the width to be half of wall thickness (δ) and not exceed 20mm in accordance with ISO 22157. The tension strength is then calculated by dividing the maximum load at failure (F_{ult}) to the mean gauge cross-sectional area (Ag) in square millimeters as seen in equation (5).

$$f_{t,0} = {}^{F_{ult}}\!/_{A_g} \tag{5}$$

The characteristic strength of both compression and tension will be taken from the mean in accordance with ISO 12122. As seen in equation (6) where X_i is a test value and n is the number of test values.

$$X_{mean} = \frac{\sum X_i}{n} \tag{6}$$

2.4 Regression Analysis

Regression analysis was done by conducting simple linear regression and multiple linear regression on compression capacity. The focus on the compression capacity is mainly due to tension having a significantly

higher strength making compression more prone to failure. On the other hand, capacity is investigated since it is found to be more reliable and correlated in comparison to strength [7]; [8].
An artificial neural network for regression was trained to develop prediction values. The predictors such as outer diameter (D), wall thickness (δ), and linear mass at 12% moisture content (q_{12}) were selected following previous studies [7]; [8] that show that it has high correlation to compression capacity. This analysis mainly identifies the alignment of these indicating property on the application of a different bamboo species and evaluates its performance in terms of mean square error and R^2 value.

2.5 Computer Vision and Image Processing

The computer vision utilizes a checkerboard calibration to enable the conversion pixel to actual units. The checkerboard has even columns and odd rows for the detection of the x and y axes as seen in Fig 3.

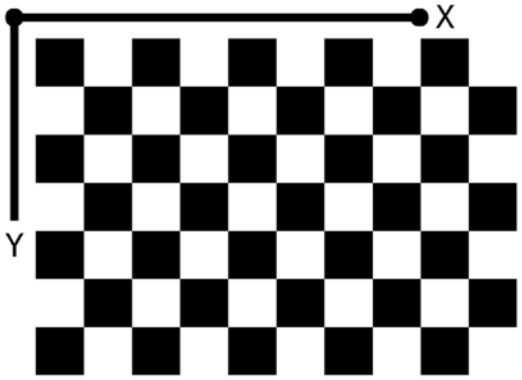


Fig. 3. Checkerboard Calibration.

A total of 10 input images were collected in various angles and positions to provide sufficient spatial information of the object. In reference to Fig 4, the gray area corresponds to the checkerboard and 10 camera angles are shown.

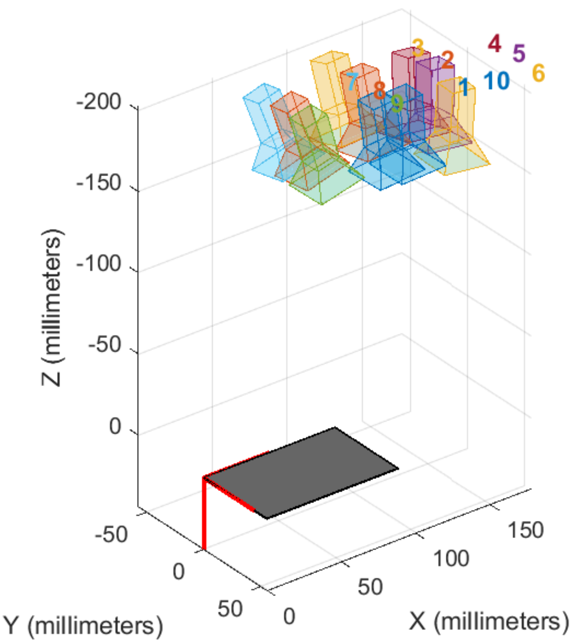


Fig. 4. Checkerboard Calibration.

The enhancement of object segmentation was achieved by doing color detection within the input image. As seen in Fig 5, the cross-section was painted with red to further increase its accuracy and make it more distinguishable.

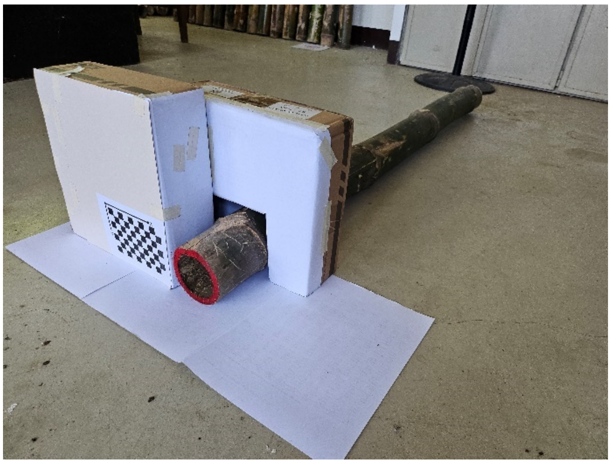


Fig. 5. Actual computer vision set up.

3. RESULTS AND DISCUSSION

3.1 Geometric and Physical Properties

The summary of geometric properties of the collected bamboo culms are presented in Table 1. The geometric properties include the measured average diameter over culm length (D), average wall thickness over culm length (δ), and length (L).

Table 1. Summary of geometric properties

Geometric Property	L (mm)	D (mm)	δ (mm)
Min	1490.000	101.885	7.651
Max	1670.000	132.050	10.424
Mean	1592.630	116.065	9.198
Std. Dev	54.858	8.542	0.818
COV	0.034	0.074	0.089

On the other hand, the summary of physical properties is seen in Table 2 where equations (1), (2), and (3) are applied.

Table 2. Summary of physical properties

Geometric Property	q (g/mm)	q_{12} (g/mm)	w (%)
Min	0.675	0.569	17.09
Max	1.999	1.879	55.66
Mean	1.591	1.326	34.94
Std. Dev	0.388	0.329	11.525
COV	0.244	0.248	0.330

3.2 Mechanical Properties

Considering equation (6), the characteristic strengths of compressive and tensile for Bambusa blumeana based on the mean are 37.040 MPa and 85.177 MPa, respectively as shown in Table 3.

Table 3. Summary of mechanical properties parallel to grain

Mechanical Property	Compressive Strength	Tensile Strength
Number of samples	38	57
Min (MPa)	21.328	45.166
Max (MPa)	63.859	128.544
Mean (MPa)	37.040	85.177

Std. Dev	10.232	20.927
COV	0.276	0.246

3.3 Regression Analysis

The indicating properties that are analyzed to indicate compressive capacities are wall thickness, external diameter, and linear mass at 12% MC. These simple linear regressions are seen in Fig 6, 7, and 8.

The R^2 values observed for the maximum compressive load (F_{ult}) were 0.3319 – 0.5264. With this, it can be inferred that these indicating properties can predict the compressive load from 33.19% to 52.64% with linear mass at 12% MC as the most highly predictive. This result aligns with the trend and most predictive variable of Tangphadungrat et al.[7] and Correal et al.[8].

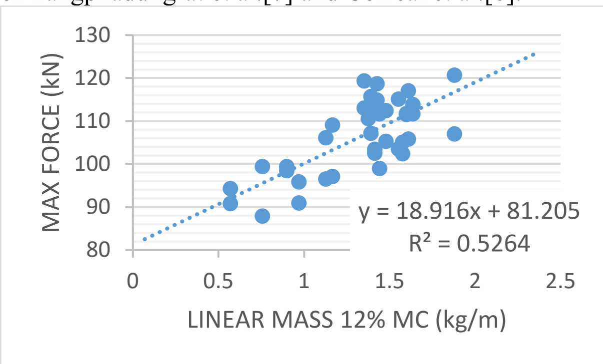


Fig. 6. Simple linear regression of bamboo maximum compressive load (F_{ult}) with linear mass at 12% MC (q_{12}).

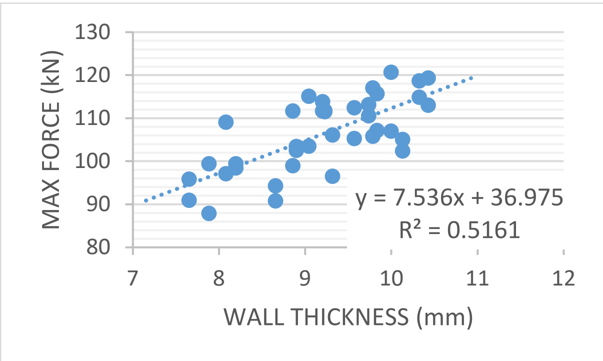


Fig. 7. Simple linear regression of bamboo maximum compressive load (F_{ult}) with wall thickness (δ).

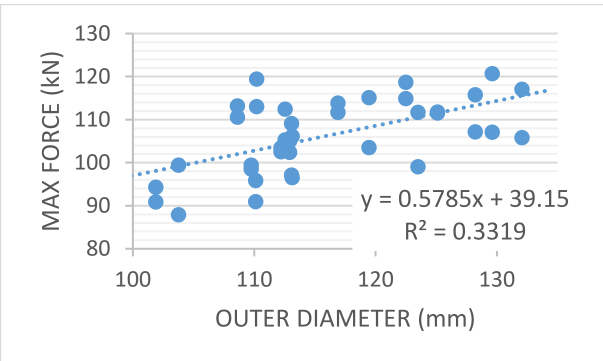


Fig. 8. Simple linear regression of bamboo maximum compressive load (F_{ult}) with outer diameter (D).

The simple linear regression equations for compression capacity obtained are as follows:

$$F_{ult} = 18.916q_{12} + 81.205 \tag{7}$$

$$F_{ult} = 7.536\delta + 36.975 \tag{8}$$

$$F_{ult} = 0.5785D + 39.15 \tag{9}$$

Multiple linear regression further improves accuracy in terms of prediction. However, this approach has the possibility of multicollinearity which entails variables to be statistically insignificant. To address this concern, the p-value should be examined. Table 4 and 5 consider both geometric and physical indicating properties.

As seen in Table 4, the outer diameter (D) was found to be not statistically significant since it has a p-value of greater than 0.05 which also means that there is correlation between the variables. Another multiple linear regression was done excluding the outer diameter (D) as presented in Table 5. The R^2 value obtained has increased to 0.635. In comparison to the simple linear regression R^2 value of 0.5264, this multiple regression analysis has the potential to deliver better and more accurate results.

Table 4. Multiple linear regression of bamboo maximum compressive load (F_{ult}) – model 1

IP	Coefficient	Std Error	*t stat*
q_{12}	13.355	4.729	2.824*
δ	4.390	1.412	3.110*
D	-0.063	0.154	-0.410***
Intercept	55.515	17.942	3.094*
R^2 = 0.626, Std error of estimate = 5.230			
F = 21.677, Significance of F = 4.999 x 10^{-8}			
*p<0.001, **p<0.05, ***p>0.05			

Table 5. Multiple linear regression of bamboo maximum compressive load (F_{ult}) – model 2

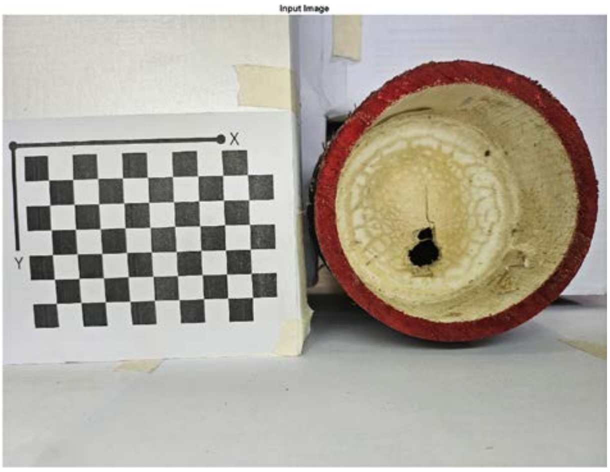
IP	Coefficient	Std Error	*t stat*
q_{12}	12.052	3.458	3.485*
δ	4.431	1.391	3.185*
D	-	-	-
Intercept	49.552	10.365	4.781*
R^2 = 0.635, Std error of estimate = 5.168			
F = 33.222, Significance of F =8.170 x 10^{-9}			
*p<0.001, **p<0.05, ***p>0.05			

The multiple linear regression equation for compression capacity in reference to Table 5 is seen in equation 10.

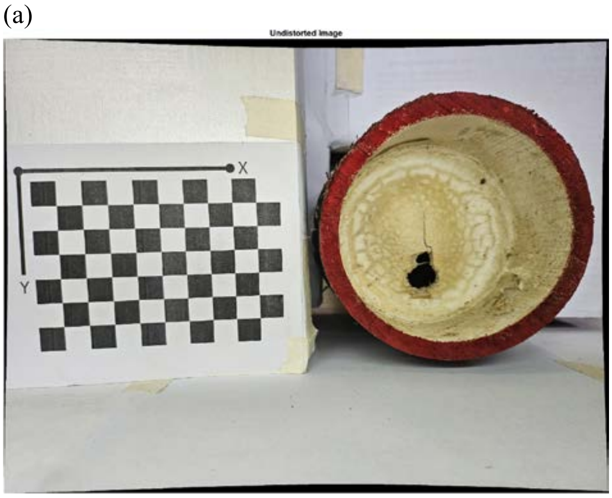
$$F_{ult} = 12.052q_{12} + 4.431\delta + 49.522 \tag{10}$$

3.4 Computer Vision Accuracy

The integration of computer vision to measure the cross-sectional outer diameter (D) and wall thickness (δ) are shown in Fig 9a to 9e. Fig 10a displays one out of the 10 inputted photos. This photo then gets undistorted as seen in 9b to improve its accuracy. Fig 9c provides a visual representation of the cross-section segmentation with the help of color detection. With the segmented image, the computer vision can now easily measure the outer and inner diameters of the bamboo culm. From these measurements, the wall thickness is then calculated in reference to Fig 9d and 9e.

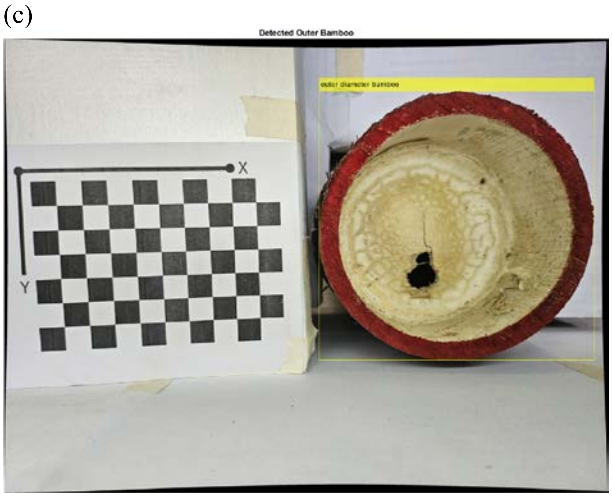


(a)

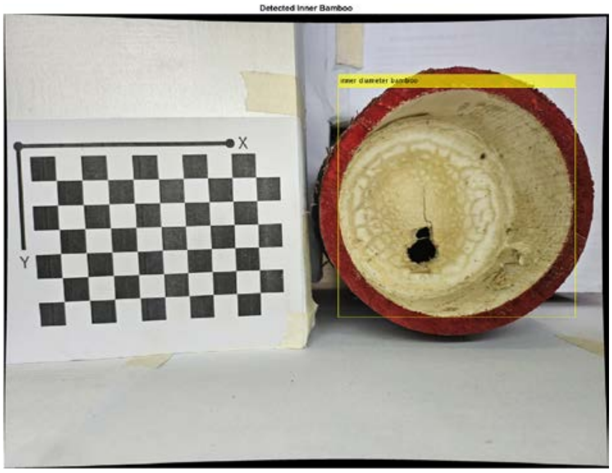


(b)

(c)



(d)



(e)

Fig. 9. Computer vision (a) input image, (b) undistorted image, (c) segmentation, (d) detected outer diameter, and (e) detected inner diameter.

Table 6 presents the performance of the computer vision with its corresponding minimum, maximum, and mean percentage error.

Table 6. Percentage error of computer vision measurement from actual measurement

IP	Percentage error		
	Min	Max	Mean
D	0.08	6.53	2.42
δ	0.01	6.49	3.23

4. CONCLUSION

The observed characteristic compressive and tensile strength for Bambusa blumeana based on the mean are 37.040 MPa and 85.177 MPa. In comparison with the study of Salzer et al. [7] the characteristic strength for Bambusa blumeana is 20 MPa and 95 MPa for compression and tension, respectively. There are differences observed and can be attributed to the differences and variability of the samples tested.

Compressive capacities are seen more reliable and have higher correlation to indicating properties. This is observed from the R^2 values of 0.3319 to 0.5264 of simple linear regression with linear mass at 12%MC (q_{12}) as the most highly predictive. The improvement of these R^2 values lies in the application of multiple linear regression but faces the risk of multicollinearity. It is important to keep the variables to be statistically significant by excluding independent variables that show correlation to other independent variables. The R^2 value of 0.635 was obtained from predictors such as linear mass at 12 % MC and wall thickness only. The accuracy of this regression was kept by monitoring the p-value where it should be lower than 0.001.

The implementation of computer vision into the grading and prediction of compression capacities of Bambusa blumeana serves as a step towards the development of automated systems when it comes to sorting.

5. RECOMMENDATION

Considering the materials and methods done in this research, the researchers recommend to study more sample data and improve the predictability of Bambusa blumeana bamboo, With this, the standardization of bamboo as a sustainable construction material can be developed in the future. It is also recommended to study further on other mechanical properties such as bending and shear strength.

Another recommendation would be to develop a more advanced approach to computer vision and incorporate machine learning techniques.

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