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A Comparative Study of Static and Dynamic Elastic Modulus Using the Stress Wave Velocity Method in Bamboo

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Keywords:
Bamboo
Modulus of elasticity
Stress wave velocity
Wave spectra
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ABSTRACT

The current grading process of bamboo still relies on visual or conventional observations. Bamboo is a non-prismatic material, so it is challenging to determine its strength accurately without laboratory testing. One crucial parameter for predicting bamboo strength is the modulus of elasticity (MoE). This study focused on 12 stems of Petung Bamboo (Dendrocalamus asper), 12 stems of Wulung Bamboo (Gigantochloa atroviolacea), and 12 stems of Apus Bamboo (Giganthochloa apus) randomly selected from a bamboo store. Before testing, bamboo stalks must be visually inspected to observe bamboo details and ensure there are no defects or damages. In calculating the volume of bamboo (V) have two methods, One, predicted volume, denoted as VP, involves calculating the volume by only measuring the cross-sectional area of the bamboo's tip and the cross-sectional area of the base, which is then multiplied by the bamboo's length (L). Two, detailed Volume, symbolized as VD, refers to the meticulous calculation of bamboo volume. Testing was conducted using the stress wave velocity method to obtain dynamic modulus of elasticity values (MOEd). Bamboo flexural testing (destructive) was performed to obtain static modulus of elasticity (MOEs) and bending strength (MOR) values for bamboo. Regression modelling of the relationship between MOEs and MOEd (using predicted volume) for bamboo, regardless of species, showed a relatively low coefficient of determination, i.e., 0.488. This implies that the longer the bamboo was tested, the lower the precision of its volume. Testing using detailed volume calculations for dynamic modulus of elasticity resulted in a relatively high coefficient of determination, precisely 0.8406.

1. Introduction

Bamboo is a renewable resource with significant potential for application in construction materials, which is attributed to its commendable attributes. Noteworthy are its ease of cultivation, rapid growth cycle, commendable resilience, tensile strength comparable to steel, seismic load resistance, eco-friendliness, and economic viability [1,2]. Bamboo with excellent mechanical properties and great changes in physical properties [3,4]. In structural applications, mechanical properties or material strength play a pivotal role, as bamboo is tasked with safely bearing loa ds over planned durations. The excellent grain orientation mechanical properties can also meet the needs of building materials [5,6,7]. Consequently, each bamboo culm designated for construction necessitates a grading process, commonly known as bamboo grading, to ensure structural reliability.

Up to the present, the common practice in bamboo grading still relies on visual or conventional methods. This encompasses the observation of defects in bamboo, colour changes, the presence of white spots, distinctive aroma, or the sound produced when bamboo is struck. This approach aims to obtain bamboo with the requisite strength, meeting the required standards for field applications. It is noteworthy that bamboo possesses a non-prismatic form, making accurately determining its strength a challenge without laboratory testing.

Another benefit of the grading process is to provide transparent information to sellers and buyers regarding the traded material. According to Divos and Tanaka, the most crucial parameter for predicting strength is the modulus of elasticity (MOE) [8]. While there are methods to determine the MOE of a material, including both dynamic and static approaches, the goal is to

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identify the most efficient and effective way to assess the strength of bamboo.

The ways to determine dynamic modulus of elasticity is through the Stress Wave Velocity method and vibration method [9,10,11]. Experiments using this method on bamboo are still relatively scarce. In a study conducted by Feliana (2014), the method was primarily applied to wooden materials [12]. Consequently, non-destructive testing (without causing damage) was conducted on bamboo using the stress wave velocity method.

At same time, much research has employed probabilistic methods to study the mechanical properties of materials [13,14,15]. In previous research, non-destructive testing using the Stress Wave Velocity (SWV) method demonstrated good predictive capabilities for the static flexural mechanical properties, MOE (Modulus of Elasticity), and MOR (Modulus of Rupture), of cement boards [16]. The elastic constant error of specimen measured by the dynamic and static methods is less than 7%, indicating that the dynamic test has the characteristics of high accuracy and good reliability [17].

This current study aims to compare the results of static modulus of elasticity (MOEs) analysis with dynamic modulus of elasticity (MOEd) in bamboo testing using two bamboo volume measurement methods (predicted volume and detailed volume).

2. Method

2.1 Tools and Materials Preparation

Several instruments in this research include a flexural testing tool, a component of the Universal Testing Machine (UTM) with a capacity of 10 tons, employed to test the flexural strength of bamboo. This flexural testing tool is utilised for destructive tests to determine the Static Young's Modulus of specimens. For non-destructive testing, the Wave Spectra, which is software designed to capture the frequencies generated during the striking process on the specimens, is employed.

The selection of bamboo types is based on the varieties available in the market. The materials used in this study consist of 12 stalks of Bambu Apus (Giganthochloa apus) coded A1 to A12, 12 stalks of Bambu Wulung (Gigantochloa atroviolacea) coded W1 to W12, and 12 stalks of Bambu *Petung* (Dendrocalamus asper) coded P1 to P12. The sampling process is conducted randomly at a bamboo store, and the samples are kept intact for non-destructive testing. Since the selection is done arbitrarily, the samples are diverse, exhibiting distinct dimensions and lengths of bamboo.

Before testing, bamboo stalks must be visually inspected to observe bamboo details and ensure there are no defects or damages. Considering bamboo's non-prismatic nature, the diameter from the tip to the base of the bamboo is not uniform. Therefore, in calculating the volume of bamboo (V) have two methods, One, predicted volume, denoted as VP, involves calculating the volume by only measuring the cross-sectional area of the bamboo's tip and the cross-sectional area of the base, which is then multiplied by the bamboo's length (L). Measurements of the bamboo's diameter and thickness adhere to ISO/TR 22157-2 can be seen in Figure 1.

Two, detailed Volume, symbolized as VD, refers to the meticulous calculation of bamboo volume. This is carried out after static testing (destructive test). Each bamboo is cut between its nodes (internodes), it can be seen in Figure 2.

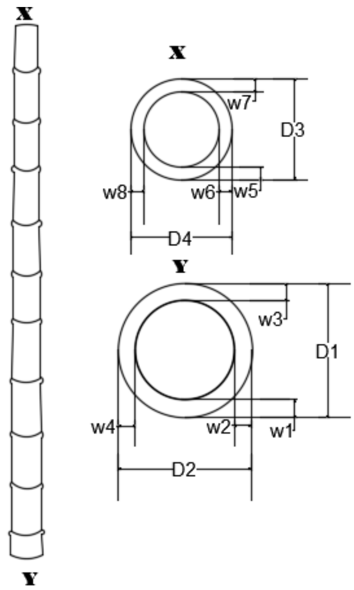

Figure 1. Measurement of bamboo diameter and wall thickness for volume prediction [18].

Figure 2. The bamboo that has been cut between its node

The upper and lower diameters, as well as the thickness of the bamboo at each internode, are then measured. The average cross-sectional area of the bamboo is multiplied by the length of the bamboo internode. As a result, the total volume of bamboo is obtained. Using this method, the calculation of bamboo volume is expected to approximate its original volume closely.

2.2 Nondestructive Testing

Non-destructive testing tools include wave spectra software, a microphone, hitting tools, and buttress tools. The procedure for non-destructive testing is outlined as follows : (1) Measure bamboo's weight, length, diameter, and thickness. (2) Place the bamboo on two supports at each end, as seen in Figure 3 and Figure 4. (3) Give an impulse to side A (the tip of the bamboo) by hitting the shaded area in the following Figure 5.

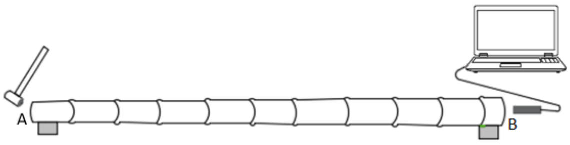

Figure 3. The set-up of Bamboo non-destructive testing

Figure 4. The practice of non-destructive testing

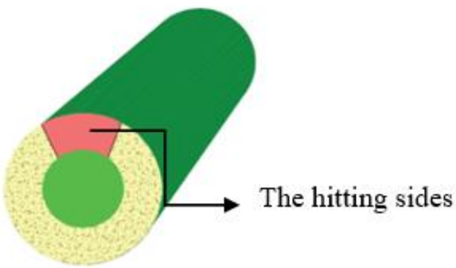

Figure 5. The part of the bamboo that is given an impulse

Waves will arise when the end of the bamboo is impacted. These waves propagate along it as particles from one end to the free end of the bamboo. The depth of the wave or the distance between the end and the base of the wave is determined by the length of the impact applied and the propagation speed of the material. The Data processing with wave spectra can be seen in Figure 6.

The wave moves along the bamboo at a constant speed, but individual particles only undergo small longitudinal motions due to the wave passing through them. After traversing the length of the rod, this moving wave heads towards the free end of the rod and returns in the form of a tensile wave to the rod. The wave speed does not depend on the impact intensity [19]. Sound recording is conducted using a microphone positioned on side B (the base part of the bamboo). The microphone connected to the computer captures the sound signal generated during the striking process. The sound signal in the time domain is transformed into a signal in the frequency domain through wave spectra software. The dynamic modulus of elasticity of bamboo is determined by inputting the natural frequency (f) values from the testing into the following equation.

$$MOE_d = 4 \ . \ L^2 \ . \ f^2 . \frac{m}{V} \quad (1)$$

With MOE_d is the dynamic modulus of elasticity (MPa), f is the internal frequency (kHz), L is the length of the test object (m), m is the mass of the test object (kg), and V is the volume of the test object (m^3)

2.3 Destructive Testing

Destructive testing uses a UTM (universal testing machine) with a capacity of 10 tons with an accuracy of 1%. It is carried out on specimens that have been tested using non-destructive methods. This test was carried out to determine the bending capacity of bamboo based on a three-point bending test, as seen in Figure 7.

This test is carried out until the specimen experiences destruction. The destructive testing procedure is described as follows [20]: (1) To obtain failure due to bending, the minimum free span required is 30 times the outer diameter of the bamboo. (2) Determine the average value of the outer diameter (D) and wall thickness (t). (3) Place the bamboo stick in position in the testing machine, the bamboo is supported on two supports right at the joints. Next, the load is set vertically in the middle of the span and right on the bamboo-segment. (4) The load on the bamboo stem must be carried out uniformly at a constant speed. The testing speed (preferably at a constant speed of movement of the testing machine's loading head, or at a constant speed under loading) is 0.5 mm/s with an accuracy of 1%. (5) Observe the cracks that occur and describe the form of failure that occurs. (6) Draw a load-deflection diagram that occurs. (7) Determine the outer diameter (D) and wall thickness (t), as close as possible to the loading point. The average of the diameter and wall thickness values is used to calculate the moment of inertia (I), with the following equation.

$$I_B = \frac{\pi}{64}\left[D^4 - (D-2t)^4\right] \quad (2)$$

(8) Determine the moisture content with a sample originating from a point near the point of fracture/failure.
(9) Calculate the ultimate strength (σ_{ult}) and static modulus of elasticity (MOE_s) values using the following equation.

$$\sigma_{ult} = F_{max} x\ b\ x\ a\ x\ \frac{D}{2\ x\ L\ x\ I_B} \quad (3)$$

$$E = \frac{F\ x\ a^2 x b^2}{3\ x\ \delta\ x\ I_B\ x\ L} \quad (4)$$

With σ_{ult} is the ultimate strength (N/mm^2), E is the modulus of elasticity (N/mm^2), F_{max} is the maximum load (N), F is the difference in load in the elastic area (N), L is the free span length (mm), a is the distance from the joint support to the loading point (mm), b is the distance of loading point to roller support (mm), D is the outer diameter of bamboo (mm), t is the bamboo wall thickness (mm), δ is the difference in deformation in the elastic region (mm), and I_B is the moment of inertia (mm^4).

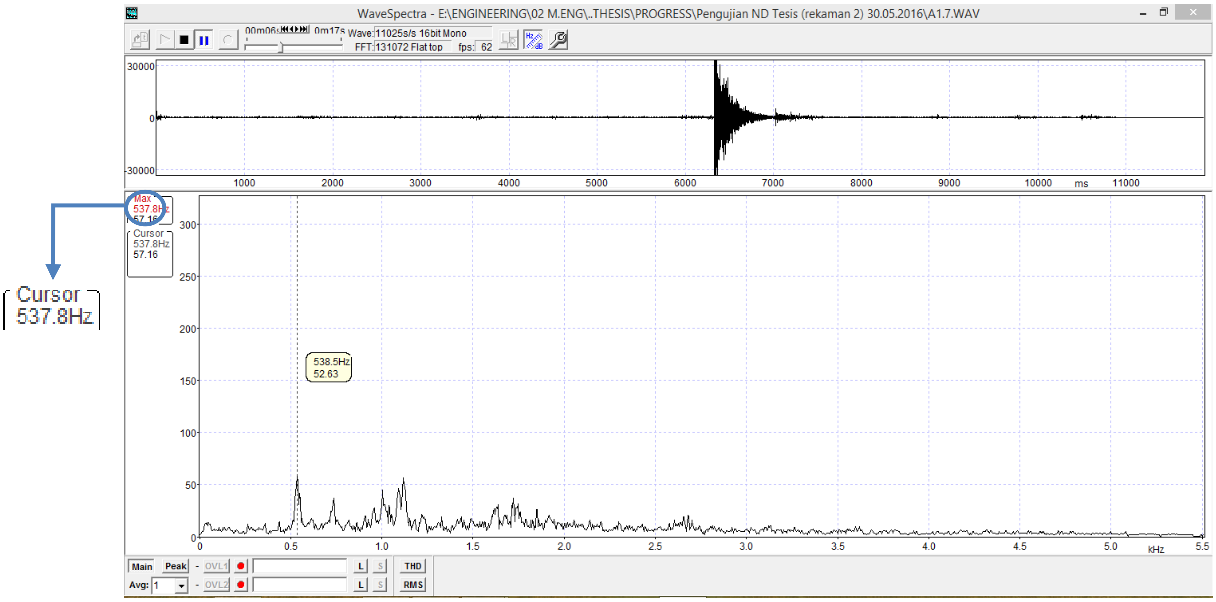

Figure 6. Data processing with wave spectra

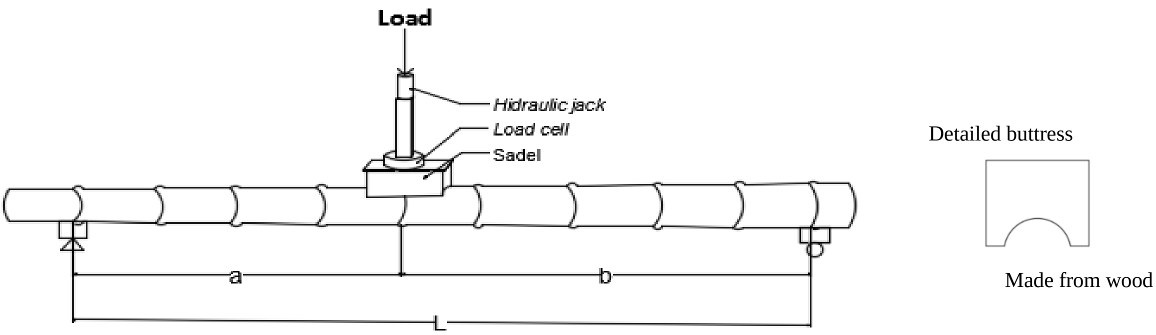

Figure 7. The set-up of bamboo elasticity testing [20]

2.3 Data Analysis Method

The data in this study was processed using linear regression analysis techniques. Regression or correlation is a method to measure the relationship between two or more variables. Both regression and correlation methods are used to measure the degree of relationship between variables that are related or dependent. Regression is a measure of the form of relationship, and correlation is a measure of the closeness of the relationship between variables.

To place a regression line on the data, the least squares method is used as Equation 5.

$$Y' = a + bX \quad (5)$$

The similarities between regression lines and trend lines cannot end with straight line similarities. Regression lines (such as trend lines and arithmetic mean values) have two mathematical properties $\sum (Y - Y') = 0$ and $\sum (Y - Y')^2$ = smallest or lowest value. In other words, the regression line will be placed on the data in the diagram in such a way that the positive deviation (difference) of the points relative to the scatter points above the line will offset the negative deviation of the scatter points located below the line, so that the overall deviation of the points is -point on a straight line is zero.

3. Results

3.1 Nondestructive Testing Results (Predicted Volume)

Table 1 is the results of dimension and weight measurements, predicted volume calculations, as well as non-destructive test on bamboo.

3.2 Non-destructive testing results (Detailed Volume)

Table 2 shows the results of dimension and weight measurements, calculation of predicted volumes, as well as non-destructive test results on bamboo.

Table 1. Results of non-destructive testing of bamboo using the predicted volume of bamboo

Bamboo code	Length (m) L	Frequency (kHz) *f*	Weight (kg) m	Predicted volume (m^3) V_P	Dynamic modulus of elasticity (MPa) MOE_d
A1	4.547	0.538	5.65	0.010	12899
A2	5.552	0.439	9.20	0.015	14612
A3	5.450	0.453	6.15	0.011	15632
A4	5.376	0.469	6.19	0.010	15442
A5	5.538	0.440	10.76	0.015	19069
A6	5.515	0.434	5.36	0.011	11623
A7	5.455	0.457	6.14	0.012	12443
A8	5.430	0.409	7.45	0.011	16524
A9	5.093	0.510	5.26	0.012	12065
A10	5.109	0.474	3.00	0.008	9201
A11	5.003	0.448	3.97	0.007	11380
A12	5.080	0.490	6.90	0.012	14753
W1	5.494	0.485	10.19	0.016	18265
W2	4.501	0.601	8.11	0.014	16860
W3	5.338	0.491	7.89	0.014	15115
W4	5.630	0.451	6.29	0.014	11292
W5	5.116	0.518	9.37	0.015	18106
W6	5.408	0.504	8.56	0.015	17193
W7	5.215	0.496	5.55	0.013	11306
W8	5.089	0.512	10.49	0.017	16428
W9	5.139	0.507	10.30	0.016	17887
W10	5.226	0.513	9.21	0.018	14491
W11	5.136	0.511	10.19	0.017	16210
W12	5.173	0.500	9.54	0.018	14077
P1	5.100	0.318	25.29	0.033	8152
P2	5.112	0.400	19.33	0.022	14989
P3	5.111	0.507	20.33	0.030	18279
P4	5.101	0.474	16.64	0.020	19260
P5	5.094	0.506	17.71	0.035	13581
P6	5.072	0.510	19.64	0.027	19175
P7	5.086	0.521	12.37	0.023	15005
P8	5.058	0.489	12.70	0.027	11656
P9	5.087	0.495	13.37	0.019	17443
P10	5.080	0.454	13.39	0.026	11134
P11	5.141	0.470	13.84	0.015	21674
P12	5.228	0.408	12.25	0.015	14386

Table 2. Results of non-destructive testing of bamboo using the predicted volume of bamboo

Bamboo code	Length (m) L	Frequency (kHz) f	Weight (kg) m	Volume of detailed bamboo (m^3) V_D	Detailed dynamic modulus of elasticity (MPa) MOE_d
A1	4.547	0.538	5.65	0.009	15397
A2	5.552	0.439	9.20	0.012	18280
A3	5.450	0.453	6.15	0.010	17480
A4	5.376	0.469	6.19	0.007	22316
A5	5.538	0.440	10.76	0.014	21398
A6	5.515	0.434	5.36	0.008	15677
A7	5.455	0.457	6.14	0.008	19172
A8	5.430	0.409	7.45	0.008	21241
A9	5.093	0.510	5.26	0.009	15848
A10	5.109	0.474	3.00	0.005	13815
A11	5.003	0.448	3.97	0.006	13544
A12	5.080	0.490	6.90	0.010	17543
W1	5.494	0.485	10.19	0.013	22432
W2	4.501	0.601	8.11	0.009	25716
W3	5.338	0.491	7.89	0.011	20501
W4	5.630	0.451	6.29	0.010	15700
W5	5.116	0.518	9.37	0.011	23937
W6	5.408	0.504	8.56	0.011	23392
W7	5.215	0.496	5.55	0.008	17769
W8	5.089	0.512	10.49	0.011	25642
W9	5.139	0.507	10.30	0.012	23396
W10	5.226	0.513	9.21	0.013	19927
W11	5.136	0.511	10.19	0.012	22575
W12	5.173	0.500	9.54	0.013	19994
P1	5.100	0.318	25.29	0.034	7858
P2	5.112	0.400	19.33	0.023	14145
P3	5.111	0.507	20.33	0.024	22680
P4	5.101	0.474	16.64	0.021	18558
P5	5.094	0.506	17.71	0.031	15355
P6	5.072	0.510	19.64	0.026	20466
P7	5.086	0.521	12.37	0.019	17832
P8	5.058	0.489	12.70	0.023	13676
P9	5.087	0.495	13.37	0.018	19217
P10	5.080	0.454	13.39	0.021	13352
P11	5.141	0.470	13.84	0.014	22853
P12	5.228	0.408	12.25	0.015	14887

3.3 Results of Destructive Testing

The static test results of the bamboo can be seen in Table 3.

Table 3. Results of Bamboo destructive testing

Bamboo code	Span length (m) L	Static modulus of elasticity (MPa) MOE_s	Flexural Fracture Strength (MPa) MOR
A1	2.710	13106	74
A2	3.272	17033	85
A3	3.198	17438	86
A4	3.388	20354	94
A5	3.335	19106	89
A6	3.580	14992	80
A7	3.790	17863	80
A8	2.842	19177	94
A9	2.799	15421	75
A10	3.254	12991	68
A11	3.042	13135	73
A12	2.776	17234	92
W1	3.342	21919	92

Bamboo code	Span length (m) L	Static modulus of elasticity (MPa) MOE_s	Flexural Fracture Strength (MPa) MOR
W2	3.256	22563	94
W3	3.365	20443	92
W4	3.350	15416	80
W5	3.172	20746	91
W6	3.445	21779	92
W7	3.163	15818	62
W8	3.312	21830	96
W9	3.389	19018	89
W10	3.433	18031	80
W11	3.439	21020	89
W12	3.310	19869	88
P1	3.839	7799	49
P2	4.176	12963	41
P3	3.783	18023	67
P4	3.561	17896	70
P5	4.154	14695	52
P6	3.833	13527	37
P7	3.827	16727	71
P8	3.786	11323	44
P9	3.581	18562	72
P10	4.061	15446	93
P11	3.631	22317	108
P12	3.567	13062	42

The relationship between MOE_s and MOR on all tested bamboos can be seen in Figure 8.

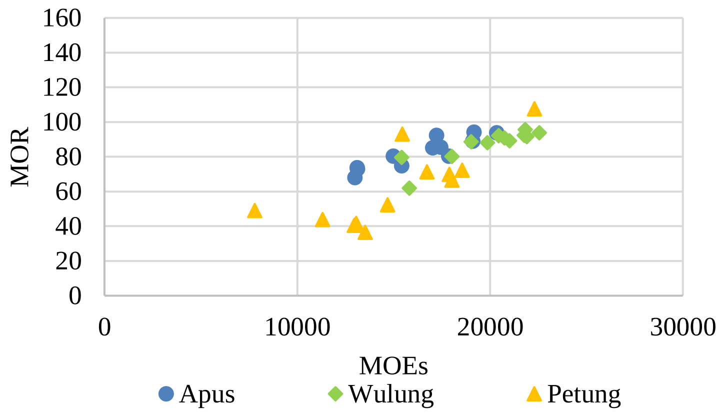

Figure 8. Results of static bamboo testing

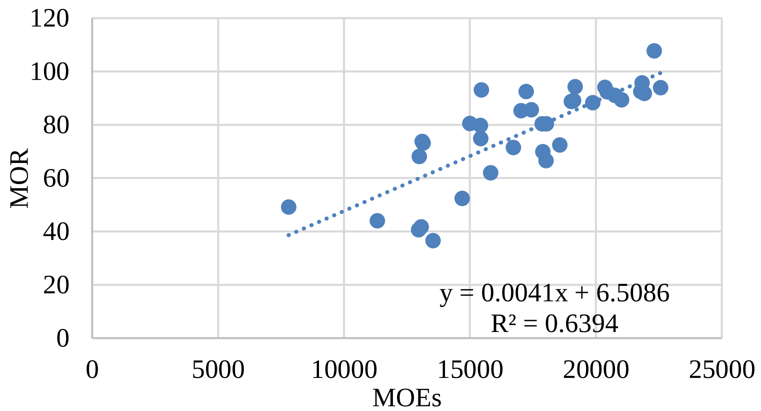

Figure 9. Relationship between static modulus of elasticity (MOE_s) values and flexural strength at fracture (MOR)

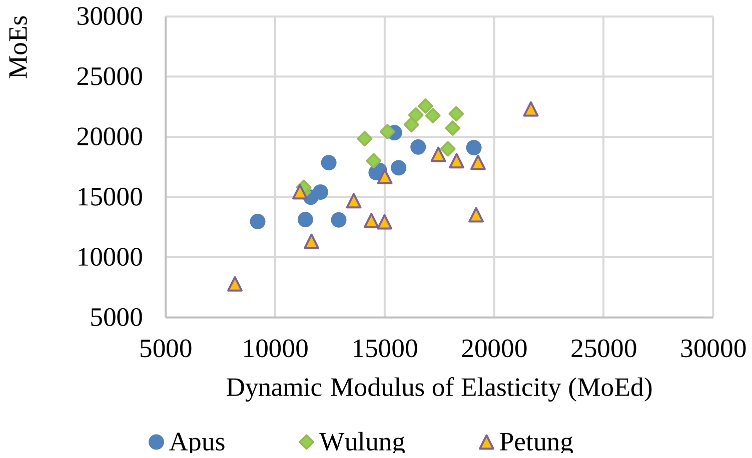

Figure 10.1 Relationship of MOE_d dan MOE_s bamboo scores (predicted volume)

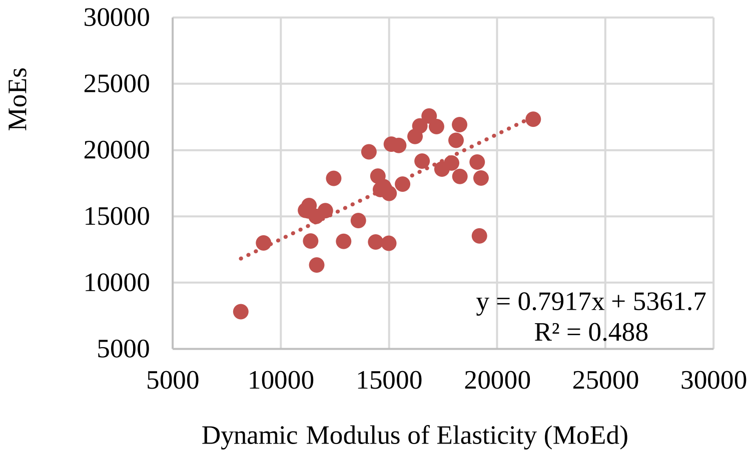

Figure 11. Regression analysis results between MOE_d and MOE_s of the bamboo (predicted volume)

From the results of the regression analysis as shown in Figure 9, the R2 value (coefficient of determination) of the relationship between MOEs and MOR is 0.6394. It means that the MOEs value can be used to predict the MOR value of bamboo using the following equation:

$$MOR = 0.0041\ MOE_S + 6.5086 \quad (6)$$

Figure 10 indicates the relationship of MOE_s and MOE_d bamboo using predicted volume.

In the regression analysis of the relationship between MOE_s and MOE_d of bamboo with predicted volume in Figure 11, the resulting coefficient of determination (R^2) is very small, 0.488.

3.4 The relationship between MOE_s and MOE_d Bamboo with Detailed Volume

Figure 12 shows the relationship of MOE_s and MOE_d bamboo using detailed volume. Figure 13 shows that tests using detailed volumes in the dynamic modulus of elasticity calculations produce a relatively high coefficient of determination (R^2), namely 0.8406.
With this good correlation, the static elastic modulus of bamboo can be predicted using the Equation 2:

$$MOE_s = 0.7951\ MOE_d + 2308.6\ (MPa) \quad (7)$$

Modulus of Elasticity (MOE) is a constant value and is the ratio between stress and strain under the proportion limit. In structural planning, MOE is mainly concerned with changes in shape (deformation) of the structure. The high MOE of the material results in a stiffer structure [21].

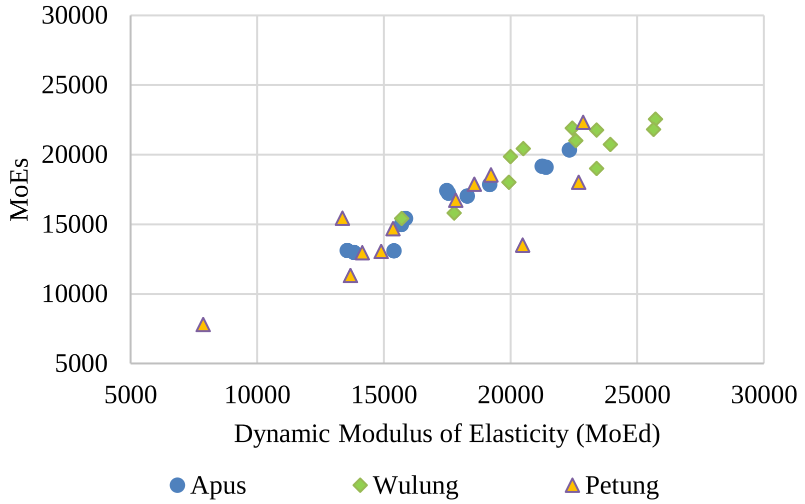

Figure 12. Relationship between MOE_d and MOE_s scores of the bamboo (detailed volume)

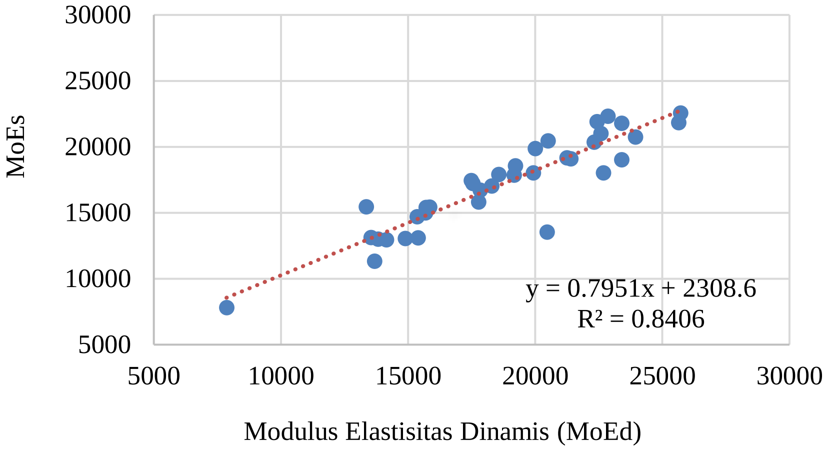

Figure 13. Regression analysis results between MOE_d and MOE_s of the bamboo (detailed volume)

Regression model of the relationship between MOE_s and MOE_d (with predicted volume) bamboo, regardless of species, shows a relatively small coefficient of determination (R^2), namely 0.488 can be seen in Figure 11. This can occur due to various factors, including inaccuracy in calculating the volume of bamboo due to diameter measurements being made on only two sides of the bamboo. The longer the bamboo, the greater the deflection [22]. It means the longer the bamboo to be tested, the lower the accuracy of the bamboo volume.

4. Conclusion

The regression model of the relationship between MOEs and MOEd (using predicted volume) of bamboo without considering the species shows a relatively small coefficient of determination (R^2), i.e. 0.488. Test results using detailed volumes in the dynamic modulus of elasticity calculations produced a relatively high coefficient of determination (R^2), 0.8406. Bamboo's static elastic modulus value can be estimated using the equation: MOEs = 0.7951 MOEd + 2308.6 (MPa).

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