Cross-species bamboo grading based on flexural properties

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Abstract. This experiment studied five species of bamboo culms [e.g. B. vulgaris (ampel), D. asper (betung), G. opus (tali), G. atroviolacea (hitam), and G. pseudourundinaceae (andong)], then analyzed the possibility to develop cross-species bamboo structural grading (both strength and capacity grading) models by mean of dummy variable regression. Since the regression analysis resulted significantly different coefficient values of the dummy variables, any coincided trendline did not found, but some parallel ones were obtained. The non-coincided but parallel trendlines indicated that a linear equation can estimate the average value of the grade determining property (GDP) of cross-species bamboo structural grading, while the constants must be added to consider the species influence. Meanwhile the non-parallel trendlines indicated that the different linear equation must be applied for every bamboo species. The cross-species bamboo structural grading could not reliably justify in this study. Species have a strong influence on bamboo grading. Therefore, the authors suggest considering the species identification in the bamboo structural grading.

1. Introduction

Bamboo has been recognized as an environmentally friendly construction material since ancient time and was traditionally used in culm form. The process for structural properties determination of natural materials such as wood or bamboo differs significantly from that of factory-made materials because their genetics and environment condition during their growth periods are varied and less controlled. Reliable knowledge of the mechanical properties of each structural material forms the basis of any design code or standard [1]. Structural grading is necessary to justify bamboo as construction materials and to guide the designers choosing the adequate bamboo culms for the member resisting the planned design load [2–7]. The initial research on bamboo engineering properties as construction materials was carried out by Janssen in 1981 [8]. The stiffness and maximum moment can be used as indicators in the machine assisted grading of bamboo [1,6,7,9]. Aside from machine assisted grading, visual grading can also be performed on a bamboo culm including observation on its geometry, size, shape, weight, and imperfections to estimate the strength and load-bearing capacity as designated by ISO 19624:2018 [10].

Previous studies [1–7] reported that structural grading is more reliable by applying the capacity grading than the strength grading. Pradhan and Dimitrakopoulos [11] have attempted to implements capacity grading to achieve the capacity-based design for multi culms bamboo axial members. Capacity grading is the process of sorting every piece of material in a sample into grades according its modulus of elasticity and flexural rigidity (EI), while strength grading measure its modulus of elasticity and flexural strength. [6]. Strength grading determines the allowable stress of a material, while capacity grading determines the reference load-carrying capacity of a member.
The first publication on bamboo grading standard was BIS: 6874 - *Methods of tests for round bamboo* [12] introduced by the Indian Standards Bureau in 1973. The first international standards for bamboo were published by the International Standards Organization (ISO 2004a, 2004b and 2004c) [13]. After that, several countries such as China [14], Colombia [15], Ecuador [16] and Peru [17] have developed standards for determining the structural properties of bamboo including their strength and capacity to withstand loads. Indonesian National Standard (SNI) for bamboo construction is limited to general usage in SNI 8020:2014 [18] and the bamboo lamina application in SNI 7944:2014 [19]. International Organization for Standardization (ISO) currently releases ISO 22157:2019 [20] and ISO 19624:2018 [10] to support the bamboo modern construction development, both are recently going on process to be adopted by BSN (The Indonesian National Body for Standardization).

Previous studies have succeeded developing the grading model limited to particular single species (such as *Guadua angustifolia* [1] and *Gigantochloa apus* [6,7]) based on its flexural properties. Several studies on single species bamboo structural grading based on its compressive properties and buckling resistance are also available [2–5]. The aim of this study was to determine the possibility for developing the cross-species bamboo structural grading based on their flexural properties from five bamboo species namely *Bambusa vulgaris* (ampel), *Dendrocalamus asper* (betung), *Gigantochloa apus* (tali), *Gigantochloa pseudoarundinacea* (andong), and *Gigantochloa atroviolacea* (hitam). Both strength and capacity grading methods were also analyzed.

2. Methods

All specimens were 294 pieces of bamboo culms (i.e., 60 pieces of *B. vulgaris*, 59 of *D. asper*, 60 pieces of *G. pseudoarundinacea*, and 58 pieces of *G. atroviolacea*). Furthermore, 59 pieces of *G. apus*, previously research by Nurmadina *et al.* [6], were also cumulatively added to be observed for developing the structural bamboo grading system without regard to species. All data were analyzed to determine whether a reliable cross-species bamboo structural grading can be developed. The specimen lengths were approximately 6 m or 30D (diameter of bamboo). All samples were conditioned using portable fan in indoor environment in Wood Engineering Laboratory – IPB University for 3-5 months to reach air-dry moisture content (w). The indoor temperature was 27 °C and RH was 80% in average. The moisture content of culms was measured using needle type moisture meter (MC-7828T). In addition, the initial conditions of the culm such as defects and cracks were also reported.

2.1. Geometry Measurement

Bamboo geometry measurement referred to ISO 22157:2019 and ISO 19624:2018 [10,20] includes measurements of internode length (Lm), external diameter (D) and culm wall thickness (δ). While bow (b), external taper (αe) and eccentricity (e) referred to the method suggested by previous studies [2,3,6,7].

2.1.1 External diameter (D) and wall thickness (δ) measurement. The external diameter was measured on two perpendicular axes, namely x-axis and z-axis and were measured on each node and mid-internode as seen in Figure 1.a. The average measurements represented the external diameter (D) of a culm. Wall thickness (δ) is the average thickness measured at four positions at each bottom and top section. (Figure 1.b).

2.1.2 External taper measurement (αe). External taper is the ratio between the difference in the top and bottom diameter (Db - Dt) to the length (L) (Equation 1). The taper value in this study was obtained from the average taper in the vertical and horizontal direction when it was placed on a special pedestal (Figure 1.c)

\[
\alpha_e = \frac{D_b - D_t}{L}
\]  

(1)

where:

Db = the bottom diameter (mm); Dt = the top diameter (mm); L = distance between Db and Dt (mm)
2.1.3. Bow \((b_o)\) measurement. Bow measurement steps were:

- Bamboo is placed on a pedestal, then two parallel strings were placed with a constant distance of 30 cm.
- The distances of the furthest culm \((z_1\) and \(z_2\)) to the two strings were measured using a caliper in each node twice on the most curved side then in a 90° rotated position \((x\text{-axis and } z\text{-axis})\). Furthermore, he bows measurement results in \(x\text{-axis}\) and \(z\text{-axis}\) are recorded and plotted in a graph as seen in Figure 2.

\[
\begin{align*}
C_b &= \frac{y_{b1} + y_{b2}}{2} = \frac{z_{b1} + (30 - z_{b2})}{2} = \frac{30 + z_{b1} - z_{b2}}{2} \quad (2) \\
C_t &= \frac{y_{t1} + y_{t2}}{2} = \frac{z_{t1} + (30 - z_{t2})}{2} = \frac{30 + z_{t1} - z_{t2}}{2} \quad (3)
\end{align*}
\]

- Each midpoint of the bottom and top were plotted \((C_b\) and \(C_t\)). The midpoint was the average distance of the two measurement points (Figure 2) according to Equation 2 and Equation 3.

- A centerline, that was a straight line connecting the bottom midpoint \((C_b)\) and the top midpoint \((C_t)\), were drawn.

- The deviation distance at each point is the difference between the midpoint of the measured point and the centerline. The deviation distance is calculated on two axes namely \(x\) and \(z\).

- The Pythagoras equation (Equation 4) was using to calculate the total distance from the center line \((b_{\text{max}})\).
(4)

- The bow value was the maximum distance of a point to the line connecting the center of the bottom and the top divided by the reference length \( L_{\text{ref}} \) (Equation 5). The reference length \( L_{\text{ref}} \) of the culms for bow measurement is the distance from the first to the last measurement point of each specimen.

\[
b_o = \frac{b_{\text{max}}}{L_{\text{ref}}}
\]

2.1.4. Eccentricity \((e_c)\). Eccentricity is a parameter for measuring the roundness of an ellipse. The value of the eccentricity of the culms is obtained from the average value of the eccentricity for each node and internode in the form of the ratio between the distances at each point on the conic side of a focus to the distance in the corresponding direction [21]. In this study, the major axis is the maximum diameter, while the minor axis is the minimum diameter. The eccentricity value of 0 (zero) shows a perfectly round cross section of the bamboo. Eccentricity \((e_c)\) was calculated per Equation 6.

\[
e_c = \sqrt{1 - \left(\frac{d_{\text{min}}}{d_{\text{max}}}\right)}
\]

2.2 Moisture content \((w)\)

Moisture content \((w)\) measurement was carried out using the needle type moisture meter MC7828T soon after the bending test. For calibration purpose, the moisture content measurement by an oven dry method referring to ISO 22157-1 [22] was also conducted. A small piece (1D for each species) was cut from each specimen and weighed to determine the initial weight \((W_1)\), then those small pieces were oven-dried at 103 ± 2 °C for 48 hours to obtain the oven-dry weight \((W_0)\). The moisture content \((w)\) was calculated per Equation 7.

\[
w = \frac{W_1 - W_0}{W_0} \times 100
\]

2.3 Linear mass \((q)\) and density \((\rho)\)

Linear mass \((q)\) is ratio of the mass \((W)\) to the length \((L)\) (Equation 8). Meanwhile, density is determined by assuming the bamboo is a hollow cylinder which results in the density of the bamboo walls \((\rho)\). Density \((\rho)\) is calculated by dividing the mass \((W)\) against the volume \((V)\) of bamboo walls (Equation 9). Linear mass and density values were calculated under two conditions, namely at the air-dry \((q_{12}, \rho_{12})\) and at the 12% moisture content \((q_{12}, \rho_{12})\).

\[
q_{12} = \frac{W_2}{L_{12}}
\]

\[
q_{12} = \frac{1.12}{1 + w} q_a
\]

\[
\rho_{12} = \frac{W_a}{V_{12}} = \frac{4W_2}{\pi(D^2 - (D - 2\delta)^2)}
\]

\[
\rho_{12} = \frac{1.12}{1 + w} \rho_a
\]

2.4 Bending test

The bending test were carried out in two points loading configuration using 30 tons capacity SATROC/Baldwin Universal Testing Machine (Figure 3). The test configuration referred to ISO 22157-1 [22] with some modifications [1,6,7], which are similar with the current ISO 22157:2019 [20]. The modulus of elasticity \((E)\), represented the material stiffness, were calculated within the proportional limit. Two modulus of elasticities were obtained, namely true modulus of elasticity \((E_{\text{true}})\) and apparent modulus of elasticity \((E_{\text{app}})\). In addition, the beam stiffness \((EI)\) values were also obtained, both true beam stiffness \((EI_{\text{true}})\) and apparent beam stiffness \((EI_{\text{app}})\). The values of \(E_{\text{true}}, E_{\text{app}}, EI_{\text{true}},\) and \(EI_{\text{app}}\) are calculated according to Equation. 10, 11, 12 and 13, respectively.
The bending tests were carried out until the bamboo specimen failure. The failure type was identified, and the maximum moment ($M_{\text{max}}$) calculation was carried out if the damage position is in the area between two load points (Equation 14). The flexural strength of bamboo (modulus of rupture/$S_R$) was calculated according to Equation 15.

$$E_{\text{true}} = \frac{4Pa(L_b)^2}{\pi \Delta L_b (D^4 - (D - 2\delta)^4)}$$  \hspace{1cm} (10) \\
$$E_{\text{app}} = \frac{4Pa(3L^2 - 4a^2)}{3\pi \Delta (D^4 - (D - 2\delta)^4)}$$  \hspace{1cm} (11) \\
$$EI_{\text{true}} = \frac{PaL_b^2}{16\Delta L_b}$$  \hspace{1cm} (12) \\
$$EI_{\text{app}} = \frac{Pa(L_b)^3}{48\Delta}$$  \hspace{1cm} (13) \\
$$M_{\text{max}} = \frac{P_{\text{max}} a^2}{2}$$  \hspace{1cm} (14) \\
$$S_R = \frac{16P_{\text{max}} a D}{\pi (D^4 - (D - 2\delta)^4)}$$  \hspace{1cm} (15)

with:
- $a$ = distance between the support to the nearest load point (mm)
- $\Delta$ = deformation measured at the center of the span along the span length ($L$) (mm)
- $\Delta_{Lb}$ = deformation measured at the center of the span along two load points ($L_b$) (mm)
- $L$ = distance between two supports (mm)
- $L_b$ = distance between two load points (mm)
- $P$ = load under the proportion limit (N)
- $P_{\text{max}}$ = maximum load (N)

2.5 Data analysis
2.5.1. Descriptive. Descriptive analysis of data includes mean, standard deviation ($s$), and coefficient of variation (CV).

2.5.2. Ungraded bamboo. The distribution of $E_{\text{true}}$, $E_{\text{app}}$, and $S_R$ data of ungraded bamboo in this study were fitted by the Weibull distribution to obtain the shape ($\alpha$) and scale ($\mu$) parameters. The estimation of the fifth percent exclusion limit ($R_{0.05}$) following parametric tolerance limit (PTL) method referred to ASTM D5457 [23] (Equation 16) while the characteristics value ($R_k$) measurement referred to ISO 22157-19 [22] (Equation 17) with the $k$-factors referring to confident level factor presented in Table 3 ASTM D2915-17 [24]. This $R_k$ value is equivalent to the reference resistance.

$$R_{0.05} = \eta [\ln(1 - 0.05)]^{1/\alpha}$$  \hspace{1cm} (16) \\
$$R_k = R_{0.05} \left(1 - \frac{k_{(0.75, 0.95)}}{m \sqrt{n}} s\right)$$  \hspace{1cm} (17)

with:
- $\eta$ = scale parameter
- $\alpha$ = shape parameter
The geometrical properties of bamboo culms include dimensions and imperfections of the culm. The dimension measurements were the internode length ($L_{in}$), external diameter ($D$) and thickness ($t$). The average diameter of betung is the biggest compared to the other species in this study. Overall, diameter of the bottom is greater than the top. The variation in thickness of five species of bamboo shows similarity with variation in diameter (Figure 5). The largest thickness at the bottom of the culm and decreases with the height of the culm. Thickness is influenced by genetic factors so that the wall’s culms are different in each genus and species [26].
Figure 4. Linear regression analysis for outer diameter (D) vs wall thickness (δ) (a) raw data regression line of each species and all data, (b) mean values regression line (Note: error bars indicate the standard deviations)

Bamboo with 5-20 cm of diameter can be used for structural purposes [27]. Since its big diameter, betung can be applied for a heavy construction material, while the other four species (i.e., ampel, tali, andong, and hitam) are suitable for medium construction material in accordance with SNI 8020:2014 [28]. Outer diameter (D) indicated the flexural moment-carrying capacity ($M_{max}$), beam stiffness (EI) [5,6,9], and ultimate-load ($F_u$) on compression [3,4], while thickness (δ) is an important criterion considered for tension perpendicular and shear capacities. Harries et al. [29] also made a classification of structural bamboos based on the ratio of diameter to thickness (D/δ), which is divided into two classes. Bamboo with D/δ > 8 is classified into thin-walled bamboo, while bamboo with D/δ < 8 is classified into thick-walled bamboo. Based on this classification, ampel and tali bamboo are classified into thick-walled bamboo with D/δ 7.93 and 7.66, respectively, while andong, hitam and betung bamboo are classified as thin-walled bamboo with D/δ respectively 8.71, 8.35 and 11.73. The D/δ classification is found less precise for the species in this study because the ratio of diameter and wall thickness can vary within a species. A species can be classified as both thin-walled and thick-walled (Figure 4).

The correlation between diameter and wall thickness is weak within a species (Figure 4a) but strong for cross-species (Figure 4b) and generally positive. In this study, the diameter is measured at the node and the mid-internode, while the thicknesses were measured at both ends only. The weak positive correlation between diameter and thickness of andong, hitam, and tali were also found [4], while the moderate positive correlation was reported for guadua [3]. Since its positive correlation, the diameter-to-thickness relationship in a specific species may roughly estimate the wall thickness.

The geometric shape of bamboo is always assumed to be a tapered hollow pipe [30]. Geometry of bamboo is influenced by genetic characteristics and the environment in which it grows. Therefore, each bamboo species has different geometric characteristics [31]. The variations of imperfections that affect the geometry of bamboo culm are taper ($\alpha_e$, %), eccentricity ($e_c$) and bow ($b_o$). The imperfections of the culm did not affect the results of two points loading bending test in this study because the resulting $\alpha_e$, $e_c$, and $b_o$ values can still be tolerated for structural purpose. The range of $\alpha_e$, $e_c$, and $b_o$ were 0.09%-0.67%, 0.0321-0.2181, and 0.009-0.015, respectively. Taper does not significantly affect to bamboo flexural properties if the measurement is conducted in third point loading [32] but it reduces modulus of rupture ($S_R$) value in center point loading if its value is greater than 2.3% [30].
3.2 Moisture content

Natural drying process this study was carried out in indoor environment assisted by fan for three to five months. The moisture content of bamboo changes following its ambient temperature and relative humidity, considering that bamboo is a hygroscopic material. Moisture content of the specimens ranged from 14.4% to 16.9%, similar with previous reports [3,5–7]. Mechanical properties of bamboo are better in dry conditions [33,34]. The variation in moisture content between species is not significant because the bamboo culms have uniformly reached equilibrium moisture content [35]. Evaluation of standard procedures for adjusting the properties of wood to changes in moisture content shows that small samples can increase flexural strength along with decreasing moisture content [7,36].

3.3 Linear mass and density

Based on ISO 22157:2019 [21], bamboo moisture content should be standardized to 12% so that the determination of the linear mass and density values is also adjusted. Density value in this study is in accordance with the research of Liese and Tang [26], which is 400 to 900 kg/m³. Sa et al. [37] reported that density can be used to determine flexural strength and stiffness of the raw bamboo culm with reasonable confidence, while several researchers [5,6,38,39] reported that their correlation was weak. Bamboo density is influenced by the volume of the vascular bundles fraction [40–42]. The outer layers of bamboo culms have better stiffness and strength properties [43], because the vascular bundle distribution is denser on the outer than on the inner layers [44,45].

Linear mass is the ratio of the weight to the length of the culms. Tali has the smallest linear mass value ($q_s = 0.86$ kg/m, $q_{12} = 0.82$ kg/m) because its culm is the lightest among others. In contrast, betung has the heaviest culm, so its linear mass value is the highest ($q_s = 2.89$ kg/m, $q_{12} = 2.72$ kg/m). Linear mass is a good predictor for estimating maximum flexural moment ($M_{max}$), flexural stiffness (EI) [5,6,9], and ultimate load ($F_u$) [1–4] because of their strong correlation. Furthermore, estimating the mechanical properties using linear mass provides an advantage, given the tools required and the simple process of measuring it [9].

| Table 1. Descriptive statistics of geometrical properties and physical properties |
|------------------------------------------|----------|----------|----------|----------|----------|----------|----------|----------|
| Species (n=60)                          | Parameter | $L$ (m)  | $L_0$ (cm) | $D$ (mm) | $\delta$ (mm) | $w$ (%)  | $p_o$ (kg/m³) | $p_{12}$ (kg/m³) | $q_s$ (kg/m) | $q_{12}$ (kg/m) | $\alpha_c$ (°) | $e_c$ (%) | $b_o$ (%) |
|------------------------------------------|----------|----------|------------|----------|--------------|----------|----------------|-----------------|-------------|----------------|--------------|-----------|-----------|
| Ampel (n=60)                             | mean     | 3.51     | 33.8       | 62.98    | 8.15         | 15.3     | 718            | 698             | 1.00         | 0.97           | 0.09         | 0.0321    | 0.015     |
| CV (%)                                   |          | 0.05     | 3.44       | 6.95     | 1.45         | 2.10     | 118            | 114             | 0.24         | 0.23           | 0.22         | 0.0123    | 0.0072    |
| Andong (n=60)                            | mean     | 5.94     | 46.4       | 97.75    | 11.48        | 16.7     | 600            | 576             | 1.85         | 1.77           | 0.28         | 0.1392    | 0.0065    |
| CV (%)                                   |          | 0.10     | 4.9        | 8.66     | 1.69         | 0.83     | 144            | 139             | 0.45         | 0.43           | 0.12         | 0.0714    | 0.0033    |
| Betung (n=59)                            | mean     | 6.04     | 42.3       | 116.6    | 13.13        | 14.4     | 678            | 640             | 2.89         | 2.72           | 0.67         | 0.2181    | 0.0099    |
| CV (%)                                   |          | 0.08     | 5.12       | 20.05    | 4.31         | 0.10     | 135            | 137             | 1.13         | 1.06           | 1.71         | 0.0573    | 0.0127    |
| Hitam (n=58)                             | mean     | 6.81     | 50.7       | 73.79    | 8.98         | 15.9     | 648            | 626             | 1.19         | 1.15           | 0.21         | 0.2173    | 0.0089    |
| CV (%)                                   |          | 0.50     | 6.25       | 9.30     | 1.42         | 0.43     | 136            | 132             | 0.39         | 0.38           | 0.09         | 0.0696    | 0.0042    |
| Tali (n=59)                              | mean     | 6.11     | 47.7       | 58.94    | 8.59         | 16.9     | 670            | 642             | 0.86         | 0.82           | 0.23         | 0.187     | 0.0099    |
| CV (%)                                   |          | 0.29     | 7.40       | 14.64    | 3.09         | 0.70     | 188            | 181             | 0.37         | 0.35           | 0.26         | 0.0334    | 0.0043    |

3.4 Flexural resistance

Strength of material is characterized by an ultimate stress ($\sigma_u$) at which failure occurs. Flexural strength, defined by maximum fiber stress in bending just before its failure, is indicated by its modulus of rupture ($S_R$) value. The $S_R$ is calculated as maximum bending moment at failure, divided by the section modulus. The modulus of rupture is an accepted criterion of strength, although it is not an actual stress because the calculation formula is only applying to within the
elastic range, whereas failure occurs beyond the elastic range. Two points loading bending test produces modulus of rupture ($S_R$) and maximum moment carrying-capacity ($M_{max}$). According to Table 2, the average $S_R$ of five species bamboo tested for bending at two points loading was 40.05 to 99.74 MPa, with $S_R$ of andong is the lowest and $S_R$ of betung is the highest. The mean $S_R$ of the bamboo culms in this experiment is greater than that of fast-growing softwood and Pinus merkusii plantation wood [46], Persian silk wood [47], but lower than SR of G. scortechinii [48], LVL and PSL made from softwood [49,50]. The SR and $M_{max}$ of a bamboo culm in this study was calculated if the specimen failure was in the area of maximum moment, which was between the two test load points, and the results is summarized in Table 2.

**Table 2.** Summary of flexural resistance (modulus of rupture and maximum flexural moment-resisting capacity).

| Species | Parameter | $S_R$ (MPa) | $M_{max}$ (N.m) |
|---------|-----------|-------------|-----------------|
| Ampel (n=60) | mean | 40.05 | 673 |
| | $s$ | 18.26 | 352 |
| | CV (%) | 0.46 | 0.52 |
| Andong (n=60) | mean | 63.98 | 3734 |
| | $s$ | 27.39 | 1586 |
| | CV (%) | 0.43 | 0.42 |
| Betung (n=59) | mean | 99.74 | 10274 |
| | $s$ | 31.71 | 5888 |
| | CV (%) | 0.32 | 0.57 |
| Hitam (n=58) | mean | 91.87 | 2471 |
| | $s$ | 31.76 | 1260 |
| | CV (%) | 0.35 | 0.51 |
| Tali (n=59) | mean | 76.9 | 1204 |
| | $s$ | 18.42 | 822 |
| | CV (%) | 0.24 | 0.68 |

3.4.1. Characteristic value of ungraded bamboo. The $S_R$ values of bamboo in this study are varied. The variation in strength is generally caused by the density and defects in the bamboo. The distribution of bamboo strength and capacity was evaluated using the Weibull distribution following ASTM D5457:2004 [22]. The Weibull distribution is the smallest extreme value distribution, and is generally used for materials that have brittle failure properties, and have only positive values [51]. $R_{0.05}$ and $R_k$ indicate the safety limits that can be reliably used for bamboo structural design analysis. Table 3 shows that the structural material quality of betung, hitam, and tali are better than ampel and andong because their modulus of rupture’s ($S_R$) fifth percentile value ($R_{0.05}$) and characteristics value ($R_k$) are much greater than those of the later. Their $R_{0.05}$ and $R_k$ values are higher than softwood in the Douglas-Fir-Larch group [52] and structural timber from hardwood and softwood from natural forest and plantation forest [46]. As natural material, round bamboo culm has higher variability than the engineered bamboo, thus the round bamboo’s $R_{0.05}$ and $R_k$ values in this study are lower than laminated bamboo esterilla sheets (LBES) from ater bamboo [53].

**Table 3.** Characteristic strength of ungraded bamboo’s modulus of rupture ($S_R$)

| No | Species | n | $\mu$ (scale) | $\alpha$ (shape) | $R_{0.05}$ | $R_k$ |
|----|---------|---|--------------|-----------------|-----------|-------|
| 1  | Ampel   | 60| 45.29        | 2.37            | 12.91     | 11.28 |
| 2  | Andong  | 60| 72.28        | 2.51            | 22.16     | 20.56 |
| 3  | Betung  | 59| 111.1        | 3.49            | 47.48     | 43.95 |
| 4  | Hitam   | 58| 103.7        | 3.37            | 43.00     | 39.76 |
| 5  | Tali    | 59| 84.06        | 4.61            | 44.16     | 41.69 |
### 3.4.2. Indicating predictors determination for structural grading.

The coefficient of correlation (r) between indicating-predictor (IP) and flexural-resistance grade-determining-property (GDP) are summarized in Table 4. Density (ρa and p12) was moderately correlated with Sρ for overall specimens. Within species, the coefficient of correlation between density at 12% moisture content (p12) and Sρ of hitam bamboo are moderate (r=0.564), the p12 of betung and tali are strongly correlated to Sρ (r = 0.79 and 0.75), but those of ampel and andong are weakly correlated (r = 0.15 and 0.11). Similarly, Uribe and Durán [54] reported a moderate correlation between the density and SR relationship of guadua bamboo. Meanwhile, Trujillo et al. [9] found a weak correlation between guadua’s density and bending strength, whereas Bahtiar et al. [3] also reported that the relationship between density and compressive strength of three sympodial was weak. Correlation between density and SR of moso (Phyllostachys pubescens), guadua (Guadua angustifolia), Tre gai (Bambusa stenostachya) [41,42], Ampel, Andong, Betung, Hitam and Tali are positive. Density proportionally affects the strength properties with different correlation values for each bamboo species. Density generally mediocrity correlates to biomaterial’s strength e.g. timber [46] and round bamboo [5,6,9,39].

Furthermore, for all species, Mmax correlates strongly with q, qD and qD² and has a weak correlation with density. Similar phenomena were also found within species of bamboo. Mmax strongly correlates with q, qD and qD² within species of Betung, Hitam, and Tali and those within species of Ampel and Andong were moderately correlated. Overall, the correlation coefficient between qD and Mmax was the strongest (0.972) among others, much stronger than the correlation value between ρ and SR. This result supports the previous studies findings [4-6,8,9], which state that the capacity grading is better for round bamboo structural member than the strength grading.

| Species | Ampel (n=60) | Andong (n=60) | Betung (n=59) | Hitam (n=58) | Tali (n=59) | All species (n=296) |
|---------|--------------|--------------|--------------|--------------|-------------|---------------------|
| Sρ      | 0.134        | 0.119        | 0.120        | 0.117        | 0.780**     | 0.564**             |
| Mmax    | 0.134        | 0.119        | 0.120        | 0.117        | 0.780**     | 0.564**             |
| SR      | 0.134        | 0.119        | 0.120        | 0.117        | 0.780**     | 0.564**             |
| Sρ      | 0.134        | 0.119        | 0.120        | 0.117        | 0.780**     | 0.564**             |
| Mmax    | 0.134        | 0.119        | 0.120        | 0.117        | 0.780**     | 0.564**             |
| SR      | 0.134        | 0.119        | 0.120        | 0.117        | 0.780**     | 0.564**             |
| q₁₂     | 0.140        | 0.325**      | 0.578**      | 0.673**      | 0.518**     | 0.750**             |
| qD      | 0.140        | 0.325**      | 0.578**      | 0.673**      | 0.518**     | 0.750**             |
| qD²     | 0.140        | 0.325**      | 0.578**      | 0.673**      | 0.518**     | 0.750**             |

Note: *: Correlation is significant at the 0.05 level (2-tailed)
**: Correlation is significant at the 0.01 level (2-tailed)

### 3.4.3. Structural grading.

Allowable stress (σ’) or reference load-carrying capacity (F’) is used to determine the minimum dimension of materials used for reliable construction. In bamboo construction, the round culms’ geometry is given in non-unison, thus the structural analysis is better approached by capacity-based design rather than strength-based design. The capacity-based design was firstly studied for reinforced-concrete structures [55], and currently applied for wooden structures [56] to increase the robustness and reliability of a building structure. In capacity-based design, the member’s allowable load and moment-resisting capacity (F’ and M’) play more significant role than the material’s allowable stress (σ’). Strength grading determines the allowable stress of a material, while capacity grading determines the reference load-carrying capacity of a member.

The dummy variables regression analysis attempt to fit the flexural resistance’s IP and GDP relationship (Table 5). The IP for flexural strength is density (ρ), and the IP for flexural capacity grading is combination of linear mass and diameter (qD). Although the coefficient of
determinations ($R^2$) were high (0.60-0.91), the parallel or coinciding regression lines were not found. All linear curves between the corresponding IP and GDP of a species are statistically non-parallel and non-coincided. Each species has different density-flexural strength ($\rho-S_R$) relationship. The linear mass and diameter combination to the maximum moment-resisting capacity ($qD-M_{\text{max}}$) relationships are also different between species. Therefore, the concept of grading bamboo regardless to species cannot be reliably applied in this study. Each species requires different specific linear equations. The structural grades should be developed for each bamboo species, with each species having its respective mean value ($\mu$), $R_{0.05}$, and $R_k$ values.

Similar with our previous reports [3], IP at 12% moisture content ($\rho_{12}$ and $q_{12}D$) resulted linear regressions with slightly higher values of coefficient of determination ($R^2$) and adjusted coefficient of determination (Adj-$R^2$), and the lower standard error (SE) than those of IP at air-dry condition ($\rho_a$ and $q_aD$). Therefore, it is worthy to convert the linear mass and density measurement from air-dry condition to the standardized 12% moisture content condition. ISO 19624:2018 [10] also suggested to standardize the density and linear mass into 12% moisture content.

**Table 5. Dummy variable regression analysis for flexural-resistance**

| Species | Dummy variable regression equations |
|---------|------------------------------------|
| Ampel   | $S_R=25+0.022\rho_a$ $S_{12}=23+0.03\rho_{12}$ $M_{\text{max}}=238+6791q_{12}D$ $M_{\text{max}}=227+7170q_{12}D$ |
| Andong  | $S_R=50+0.022\rho_a$ $S_{12}=50+0.02\rho_{12}$ $M_{\text{max}}=-53+20898q_{12}D$ $M_{\text{max}}=-45+21732q_{12}D$ |
| Betung  | $S_R=-24+0.183\rho_a$ $S_{12}=-17+0.18\rho_{12}$ $M_{\text{max}}=675+24675q_{12}D$ $M_{\text{max}}=589+28915q_{12}D$ |
| Hitam   | $S_R=-6+0.132\rho_a$ $S_{12}=-7+0.1\rho_{12}$ $M_{\text{max}}=238+26948q_{12}D$ $M_{\text{max}}=227+28915q_{12}D$ |
| Tali    | $S_R=28+0.073\rho_a$ $S_{12}=28+0.08\rho_{12}$ $M_{\text{max}}=14299+2085q_{12}D$ $M_{\text{max}}=14893+21836q_{12}D$ |

| $R^2$    | 0.597 | 0.600 | 0.903 | 0.905 |
| Adj-$R^2$| 0.585 | 0.588 | 0.900 | 0.902 |
| SE       | 21.64 | 21.56 | 1406  | 1392  |
| coincidence & parallelism test | np, nc | np, nc | np, nc | np, nc |

Note: p=parallel; np=non-parallel; c=coincided; nc=non-coincide

Structural grading produces a different number of classes for each species if the range of each class is fix. Narrow class intervals result in efficient classification because the characteristic values of each bamboo culm justiably close to their approximate values and provide safe and reliable values [5]. Structural grading based of the flexural resistance of five species of bamboo were developed in this study for strength grading (Figure 5a) and capacity grading (Figure 5b).

In strength-based design, structural designers need reference strength value for conducting structural analysis. The strength grading is developed to estimate the characteristic strength value of round bamboo culm by measuring its indicating predictor (IP). The strength grading in Fig. 5a estimates the mean value ($\mu$), the five percent exclusion limit ($R_{0.05}$), and the characteristics value of modulus of rupture ($S_R$) of five bamboo species using the density ($\rho$) as the indicating predictor. Capacity grading provides the reference load-carrying capacity or moment-resisting capacity. Using linear mass and diameter combination ($qD$) as indicating predictor, capacity grading in Fig. 5b estimates the $\mu$, $R_{0.05}$, and $R_k$ of maximum moment resisting capacity ($M_{\text{max}}$) in bending of a round bamboo culm. As seen on Figure 5a and 5b, each species’ regression lines are non-parallel and non-coincided.
Figure 5. (a) Flexural strength grading ($\rho_{12} \text{ vs } S_R$) and (b) flexural moment-resisting capacity grading ($q_{12}D \text{ vs } M_{\text{max}}$) (Note: the regression lines are non-coincided and non-parallel)

3.5. **Flexural stiffness**

The safety of building construction is usually characterized by the maximum load the structure can safely resist without failure. However, in broader perspective, building’s failure implies that collapse has occurred, or the deformation has reached an excessively large value. Reference resistances (allowable stress and load-carrying capacity) are useful to consider the maximum load failure, while stiffnesses (modulus of elasticity and bending stiffness) are useful to predict the deformation. The average value ($\mu$) of modulus elasticity ($E$) and stiffness ($EI$) are usually used in serviceability limit state design, while the near minimum value ($R_{0.05}$) and characteristics value ($R_k$) of $E$ and $EI$ are suitable in safety limit state design.
This experiment measured the flexural stiffness including apparent stiffness \((EI_{app})\) and true stiffness \((EI_{true})\). In addition, the apparent and true modulus of elasticity \((E_{app}\) and \(E_{true}\)) were also calculated. The flexural stiffness was available for three bamboo species. The highest modulus of elasticity \((E)\) was observed in Betung, while the lowest in Andong. Likewise, for culm stiffness \((EI)\), because it is a function of \(E\) and \(I\) (moment of inertia). If compared with several studies, the modulus of elasticity of Andong, Betung and Tali was higher than \textit{B. vulgaris} var striata [57], \textit{Dendrocalamus strictus} [58] and \textit{Guadua angustifolia} [59], and lower than of \textit{M. baccifera} [60] and \textit{Accacia mangium} [46]. According to Javadian et al. [61], modulus of elasticity is not affected by the culm height. \(EI\) is fundamental to the design of any element subject to flexure. Its value shows the amount of deflection that occurs. The lower the \(EI\) value, the higher the deflection.

### Table 6. Summary of flexural stiffness

| Parameter | Andong (n=60) | Betung (n=59) | Tali (n=59) |
|-----------|---------------|---------------|-------------|
| \(E_{app}\) (MPa) | mean 18275 | s 6219 | CV 0.34 | mean 28971 | s 15744 | CV 0.54 |
| \(E_{true}\) (MPa) | mean 10457 | s 5546 | CV 0.53 | mean 17988 | s 11077 | CV 0.62 |
| \(EI_{app}\) (Nm²) | mean 55389 | s 26669 | CV 0.48 | mean 162532 | s 95781 | CV 0.59 |
| \(EI_{true}\) (Nm²) | mean 31724 | s 21013 | CV 0.66 | mean 105257 | s 81408 | CV 0.77 |

### 3.5.1. Characteristic value of ungraded bamboo.

The scale and shape Weibull distribution of modulus elasticity \((E)\) of the three-bamboo species has been obtained and it is shown in Table 7. Moreover, the fifth percentile limit \((R_{0.05})\) and characteristic value \((R_k)\) were calculated. \(R_{0.05}\) of \(E_{app}\) for andong is higher than betung and tali, while \(R_{0.05}\) of \(E_{true}\) of tali is the highest compare with two other species.

### Table 7. Characteristic value of ungraded bamboo.

| Species | \(n\) | \(E_{app}\) | \(E_{true}\) |
|---------|------|------------|-------------|
|        | \(\mu\) (scale) | \(\alpha\) (shape) | \(R_{0.05}\) | \(R_k\) | \(\mu\) (scale) | \(\alpha\) (shape) | \(R_{0.05}\) | \(R_k\) |
| Andong  | 60   | 20424      | 3.09        | 7818       | 7201     | 11861      | 2.03        | 2752       | 2414     |
| Betung  | 59   | 32789      | 1.97        | 7271       | 6348     | 20230      | 1.72        | 3594       | 3077     |
| Tali    | 59   | 22900      | 2.7         | 7619       | 6974     | 17713      | 2.24        | 4704       | 4188     |

### 3.5.2. Indicating predictors determination for structural grading.

The density \((\rho)\) and the modulus of elasticity \((E)\) of bamboo have a moderate correlation (Table 8), similar with the reports of Trujillo et al. [9], Nurmadina et al. [5], and Nugroho et al. [6]. Since their positive correlation value, the \(E\) value proportionally increase with the increasing \(\rho\). Dixon et al. and Sá et al. [37,42] reported that the correlation between density and flexural properties varied between bamboo species. Similar with wood [46,47,62], the correlation between \(\rho\) and \(S_R\) is stronger than the correlation between \(\rho\) and \(E\). Correlation coefficient between beam stiffness \((EI)\) and combination of linear mass and square diameter \((qD²)\) are generally stronger than that of between modulus of elasticity \((E)\) and density \((\rho)\). The strongest correlation coefficient was found between \(EI_{app}\) and \(q_{12}D^2\). Similar with this finding, Nurmadina et al. [5] reported that \(E\) and \(q_{12}D^2\) of Tali resulted the strongest correlation \((r = 0.915-0.980)\).
Table 8. Coefficient correlation ($r$) between indicating predictor (IP) and grade determining property (GDP) flexural stiffness.

|        | $n$  | $\rho_a$ | $\rho_{12}$ | $q_a$ | $q_{12}$ | $q_aD$ | $q_{12}D$ | $q_aD^2$ | $q_{12}D^2$ |
|--------|------|----------|-------------|-------|----------|--------|-----------|----------|------------|
| Andong | 60   | 0.492** | 0.494**     | 0.026 | 0.03     | 0.111  | 0.115     | 0.165    | 0.169      |
| E_app  | 60   | 0.361** | 0.365**     | 0.011 | 0.015    | 0.083  | 0.087     | 0.129    | 0.132      |
| $E_{true}$ | 60   | 0.425** | 0.426**     | 0.177 | 0.18     | 0.429**| 0.431**    | 0.585**  | 0.587**    |
| $E_{true}$ | 60   | 0.344** | 0.346**     | 0.127 | 0.131    | 0.316  | 0.319     | 0.431**  | 0.434**    |
| Betung | 59   | 0.395** | 0.399**     | -0.344 | -0.330  | -0.356 | -0.350     | -0.336    | -0.336      |
| $E_{true}$ | 59   | 0.353** | 0.351**     | -0.260 | -0.252  | -0.272 | -0.268     | -0.255    | -0.262      |
| $E_{true}$ | 59   | 0.147   | 0.144       | 0.636  | 0.641**  | 0.641  | 0.645**    | 0.638**   | 0.637**    |
| $E_{true}$ | 59   | 0.088   | 0.08        | 0.536  | 0.534**  | 0.538  | 0.538      | 0.539**   | 0.525**    |
| Tali   | 59   | 0.595** | 0.599**     | -0.368 | -0.365  | -0.328 | -0.326     | -0.294    | -0.293      |
| $E_{true}$ | 59   | 0.572** | 0.574**     | -0.398 | -0.396  | -0.364 | -0.362     | -0.334    | -0.333      |
| $E_{true}$ | 59   | 0.085   | 0.083       | 0.934  | 0.935**  | 0.970  | 0.970**    | 0.979**   | 0.980**    |
| $E_{true}$ | 59   | 0.206   | 0.204       | 0.883  | 0.885**  | 0.910  | 0.911      | 0.914**   | 0.915**    |

Note: *: Correlation is significant at the 0.05 level (2-tailed)
**: Correlation is significant at the 0.01 level (2-tailed)

3.5.3. Structural grading regardless of species. The dummy regression analysis for structural grading based on the flexural stiffness are summarized in Table 9. The linear lines generated on structural classification based on flexural stiffness are non-parallel and non-coincident for $\rho$ vs $E_{app}$ (Figure 6a), and $q$ vs $E_{true}$, while the other linear lines were parallel but non-coincident (i.e. Figure 6a, 7a, and 7b). The non-parallel and non-coincident regression lines indicate that the structural grading of flexural stiffness should be conducted for each specific species, while the parallel but non-coincident linear curves show that the structural grading can be developed for average of all species and a constant can be added to consider the effect of each bamboo species.

Table 9. Dummy variable regression analysis for flexural stiffness

| IP   | GDP  | Andong   | Betung   | Tali   | $R^2$ | Adj-$R^2$ | SE   | Note |
|------|------|----------|----------|--------|-------|-----------|------|-------|
| $\rho_a$ | $E_{app}$ =5532+21.9\rho_a | =1013+58.9\rho_a | =4724+23.9\rho_a | 0.379 | 0.361 | 9236 np, nc |
| $\rho_a$ | $E_{true}$ =3627+23.9\rho_a | =2062+23.9\rho_a | =644+23.9\rho_a | 0.300 | 0.288 | 7485 np, nc |
| $\rho_{12}$ | $E_{app} =5533+22.\rho_{12}$ | =8757+59.\rho_{12} | =4730+24.\rho_{12} | 0.391 | 0.373 | 9147 np, nc |
| $\rho_{12}$ | $E_{true} =3616+24.\rho_{12}$ | =2344+24.\rho_{12} | =244+24.\rho_{12} | 0.306 | 0.294 | 7427 np, nc |
| $q_a$ | $E_{app} =36043+10460q_a$ | =18005+55696q_a | =9062+2232q_a | 0.738 | 0.730 | 44575 np, nc |
| $q_a$ | $E_{true} =35715+11086q_a$ | =905+59801q_a | =9139+23317q_a | 0.740 | 0.733 | 44340 np, nc |
| $q_{12}$ | $E_{app} =19249+2018947q_{12}D^2$ | =7161+2018947q_{12}D^2 | =2343+2018947q_{12}D^2 | 0.739 | 0.735 | 44172 np, nc |
| $q_{12}$ | $E_{true} =17953+2179584q_{12}D^2$ | =70316+2179584q_{12}D^2 | =2087+2179584q_{12}D^2 | 0.743 | 0.739 | 43858 np, nc |
| $q_s$ | $E_{app} =30818+3384q_s$ | =7673+3384q_s | =2191+3384q_s | 0.577 | 0.570 | 41828 np, nc |
| $q_s$ | $E_{true} =35097+35679q_s$ | =8338+35679q_s | =2221+35679q_s | 0.576 | 0.568 | 41912 np, nc |
| $q_{12}D^2$ | $E_{app} =51995+1544288q_{12}D^2$ | =39919+1544288q_{12}D^2 | =1496+1544288q_{12}D^2 | 0.597 | 0.590 | 40834 np, nc |
| $q_{12}D^2$ | $E_{true} =51995+1544288q_{12}D^2$ | =39919+1544288q_{12}D^2 | =1496+1544288q_{12}D^2 | 0.597 | 0.590 | 40834 np, nc |

Note: p=parallel; np=non-parallel; c=coincident; nc=non-coincident

Similar those of flexural resistance, the structural grading of flexural stiffness round bamboo culm member capacity resulted more reliable value than the structural grading of the material’s modulus of elasticity because of their high values of coefficient of determination ($R^2$) and adjusted coefficient of determination (Adj-$R^2$). Therefore, authors recommend applying the capacity-
based design rather than strength-based design to conduct structural analysis for a building construction using round bamboo culm. The structural grading based on its modulus of elasticity are sketched in Figure 6.

![Figure 6. Strength grading based on ρ₁₂ (Note: regression line of E_{app} vs ρ₁₂ is parallel but not-coincided and regression line of E_{true} vs ρ₁₂ is not-parallel and not-coincided)](image)

This study resulted the non-coincided linear regression line, therefore cross-species structural grading is not reliable. Structural grading of round bamboo culms should consider the species identification. Bamboo identification based on its morphological characteristics [45,63] are considered more conventional and time consuming, and several alternative methods including...
using random amplified polymorphic DNAs (RAPD) technique [64,65] and gene network analysis [66] are also available.

4. Conclusion
Structural bamboo grading based on capacity grading applies to Ampel, Andong, and Betung by using the diameter and linear mass as indicating predictors (IP). Based on the regression analysis conducted, bamboo species had a strong influence on grading because the relationship between the IP and the quality determinants of each species was different. Therefore, it is impossible to build a bamboo grading model without regard to species. Identifying bamboo species is very important before grading. Bamboo morphology is one of the factors that can be used to identify bamboo species.

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Notation

- $b_0$: bow of a piece of bamboo
- $D$: external diameter of the bamboo culm, expressed in mm
- $D_b$: external diameter at the base of a piece of bamboo
- $D_{\text{max}}$: maximum external diameter at a given location on a piece of bamboo
- $D_{\text{min}}$: minimum external diameter at a given location on a piece of bamboo
- $D_t$: external diameter at the top of a piece of bamboo
- $E$: modulus of elasticity, expressed in MPa
- $E_{\text{app}}$: apparent modulus of elasticity
- $e_c$: eccentricity of the bamboo culm
- $EI$: flexural stiffness, expressed in Nm$^2$
- $EI_{\text{app}}$: apparent flexural stiffness
- $EI_{\text{true}}$: true flexural stiffness
- $E_{\text{true}}$: true modulus of elasticity
- $L$: length of a piece of bamboo, expressed in mm
- $L_{\text{in}}$: internode length, expressed in mm
- $L_{\text{ref}}$: reference length of a piece over which the bow of a piece of bamboo is assessed, expressed in cm
- $M_{\text{max}}$: moment maximum, expressed in Nm
- $S_R$: modulus of rupture, expressed in MPa
- $q$: linear mass, expressed in kg/m
- $q_a$: air-dry linear mass
- $q_{12}$: linear mass at 12% moisture content
$w$  moisture content
$W$  weight of the bamboo culm, expressed in kg
$\delta$  culm wall thickness, expressed in mm
$ae$  external taper, expressed as a percentage
$\rho$  density, expressed in kg/m$^2$
$\rho_a$  air-dry density, expressed in kg/m$^2$
$\rho_{12}$  density at 12% moisture content, expressed in kg/m$^2$