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# Compression Resistance of Short Members As the Basis for Structural Grading of *Guadua angustifolia*

Effendi Tri Bahtiar[1)], David Trujillo[2)], Naresworo Nugroho[1)]

1) Faculty of Forestry, IPB University (Bogor Agricultural University), Kampus IPB Darmaga, Bogor, Indonesia.
2) School of Energy, Construction, and Environment - Faculty Research Centre for Built & Natural Environment, Coventry University, Priory St, Coventry CV1 5FB, United Kingdom.

**Abstract**

This study develops the structural grading of Guadua bamboo culms subjected to axial compression. Both strength and capacity grading methods are explored. Several candidates for Indicating Properties (IPs) were measured and calculated. The strongest coefficients of determinations for structural grading were related to densities [e.g.,: (conventional) density ($\rho$) and linear mass ($q$)]. Density ($\rho$) is best IP for strength grading if the culm section is taken as a hollow circle. Alternatively, linear density or linear mass ($q$) provides higher coefficients of determination when used for capacity grading. By using intervals of each indicating property (IP), several structural grades were developed. Each grade has its Grade Determining Properties (GDPs) include mean compressive strength ($f_c$) or load carrying capacity ($F_u$), five percent exclusion limit ($R_{0.05}$), and characteristic structural property ($R_k$). The latter could be used in structural design. As bamboo is a hygroscopic material, the IP should be adjusted into standardized moisture content (12% $M_c$). The moisture content effect on compressive strength and capacity should also be measured to increase the reliability of estimation if densities ($\rho$ or $q$) are chosen as the IPs. Since external diameter can infer the linear mass ($q$) and is also significantly correlated with wall thickness ($t$), average external diameter ($D$) may also be used as the sole IP in capacity grading. Structural grading can reduce the variability of Guadua's structural properties since it classifies the culm into several suitable grades.

Keywords: allowable stress; bamboo construction; capacity grading; characteristics property; regression analysis; strength grading; structural analysis and design.

## Introduction

Natural materials such as timber have significant inherent variability. One way to reduce this variability is to sort a batch of material according to a specified selection criteria. The criteria are known to affect its mechanical properties, for example size and location of knots[1], slope of grain [2], dynamic modulus of elasticity [3], and static modulus of elasticity [4]. This sorting procedure is called 'grading', more commonly referred to as 'strength grading' or 'stress grading'. Bamboo is a similarly variable material, and grading of bamboo is a nascent field of research. In 2018 the International Organization for Standardization (ISO), published ISO 19624:2018[5], an international standard that creates the framework for bamboo grading. The standard proposes two operations that can be adopted to grade material: visual grading and machine grading. The former is defined as "the process of sorting material according to visually measureable characteristics known to affect the mechanical or structural properties of bamboo culms." The latter is defined as "the process of sorting material by means of measuring one or more indicative properties known to correlate to grade-determining properties." Indicating properties (IP) are properties, or measurements, that can be measured non-destructively and that would be sensed by a machine during the grading process. Grade-determining properties (GDP) are mechanical, geometric or physical properties that need to be achieved in order for a piece to be assigned to a given grade. Some GDPs can be measured during the grading process, whilst others can only be inferred from the IPs. Annex A of ISO 19624:2018 provides an example of a grading procedure that uses linear mass as an IP, and flexural stiffness and flexural capacity (bending moment at failure) as GDPs[5].

Trujillo *et al.* [6][7] suggest that structural grading could be undertaken based on external diameter, linear mass, and flexural stiffness, though they also explored density, modulus of elasticity and dynamic modulus of elasticity. The authors identify that 'capacity' grading may be more appropriate for bamboo than 'strength grading', as it provides more reliable predictions. Nurmadina *et al.* [8] and Bahtiar *et al.* [9] considered many more potential IPs in their analysis, including moisture content, density, linear mass, dimensional properties (culm wall thickness and external diameter), geometrical properties (eccentricity, ovality, taper, and out of straightness) Nurmadina *et al.* [8] reported that the product of linear mass and diameter is the best IP when undertaking capacity grading with flexural properties as the GDPs. Bahtiar *et al.*[9] identified that linear mass is the best IP for grading that considers compressive capacity as the GDP. Nurmadina *et al.* and Bahtiar *et al.*[9], also find that capacity grading provides better predictions than strength grading, yet they have included the latter in their analysis, and they identified that density is the best IP for bamboo both bending and compression strength grading.

The objective of this work is to identify the best IPs for estimating the compressive strength and capacity for short columns of *Guadua angustifolia* Kunth, a widely used and studied South American species of bamboo. Though it may be argued that flexural properties are more relevant to frame design, the authors felt that if compressive properties can be reliably inferred for bamboo, it will be possible to provide designers with more design-relevant data. Because the objective is to provide data useful to design, the strength and capacity values for each proposed grade will be presented: mean, five percent lower percentile limit ($R_{0.05}$), and characteristic value ($R_k$).

## Experimental Method

In order to identify candidates to potential indicating properties (IPs), 113 pieces, extracted randomly from 78 culms, of *Guadua angustifolia* Kunth of Colombian origin were tested in compression in accordance with ISO 22157-1:2004[10]. The experimental output would be used to establish a grading procedure based on compressive strength or capacity. All experimental work was undertaken in the structures lab of the Sir John Laing Building at Coventry University, UK. All specimens had been treated with a boron-based preservative and were stored at ambient conditions within the lab. Therefore they were in air-dry condition when all measurements and tests were conducted. The length ($L$) of the specimens were approximately the same as the external diameter ($D$). In accordance with ISO 22157-1:2004[10], some specimens should contain nodes, whilst others should not. The length ($L$), diameter ($D$), wall thickness ($t$), and mass ($m$) of each specimen was measured and recorded. The length and diameter were measured at two separate locations per piece, while the wall thickness was measured at four distinct locations. Digital calipers with an accuracy of 0.01 mm were employed ($L$, $D$, and $t$). Guadua culms may be not perfectly circular, thus the external diameter of each section were measured at the major axis (maximum diameter, $D_{max}$) and its corresponding minor axis (minimum diameter, $D_{min}$). The average of $L$, $D$, and $t$ were used in Equation 2, 3, and 4. The mass was measured three times, which were: before the compression test ($m_a$), after the compression test ($m_{at}$), and after the compression test and oven-drying ($m_{ot}$). The oven drying carried out at 103±2 °C for 4-5 days to evaporate water content in the sample. During the 4th and 5th days, the weighting were conducted every 3 hours and the endpoint of oven-dry mass were recorded when the weight loss constantly less than 0.2 gram. The moisture content ($M_c$) was calculated according to Equation 1.

$$M_c = \frac{m_{at}-m_{ot}}{m_{ot}} \times 100\% \quad (1)$$

Two types of 'densities' were calculated, these were: (conventional) density ($\rho$), and linear mass ($q$). These 'densities' were in turn defined by their moisture content as: air-dried, oven-dried, and 12% moisture content. The densities of air-dried ($\rho_a$ and $q_a$) culms, oven-dried ($\rho_o$ and $q_o$) culms, and 12% moisture content ($\rho_{12}$ and $q_{12}$) culms were approximated based on specimen dimension according to Equation 2, 3, and 4, respectively. 12% moisture content was selected as a standardized moisture content, as per ISO 22157:2019[11]. Table 1 further clarifies the diverse 'densities' concepts recorded and trialed.

Table 1. Definition of the diverse 'density' concepts recorded and trialed

| Moisture content | Type of 'density' | Equation | Equation number |
|---|---|---|---|
| Air-dried | Density | $\rho_a = \frac{4m_a}{\pi L(D^2-(D-2t)^2)}$ | (2a) |
| | Linear mass | $q_a = \frac{m_a}{L}$ | (2b) |
| Oven-dried | Density | $\rho_o = \frac{\rho_a}{(1+M_c)}$ | (3a) |
| | Linear mass | $q_o = \frac{q_a}{(1+M_c)}$ | (3b) |
| 12% | Density | $\rho_{12} = 1.12\rho_o$ | (4a) |
| | Linear mass | $q_{12} = 1.12q_o$ | (4b) |

The compressive tests were conducted following clause 9 ISO 22157-1:2004 [10] And undertaken on a 3000 kN capacity Denison compression machine controlled by Si-Plan servo-controller. The top cross-head of the Denison machine provides a hemi-spherical seating in order to provide concentric loading. In between both steel plates of the machine and both ends of the specimen, an intermediate steel shims layer, resting on PTFE sheets, were applied to minimize friction at the specimen ends and radial restraint of both ends. The ultimate load ($F_u$) attained during testing was recorded. This value is interpreted as the compressive capacity of the culm. The compressive strength ($f_c$) was calculated as per Equation 5:

$$f_c = \frac{F_u}{A_w} = \frac{4F_u}{\pi(D^2-(D-2t)^2)}. \quad (5)$$

Where: $A_w$ = area of culm wall section

As a non-circular section ($A_e$) has a smaller area than that of a perfect circular section of the similar average diameter ($A_c$) (Equation 9), it may be possible that the non-circularity of a section may affect its compressive strength. To assess the effect that non-circularity may have on the overall compressive strength, three geometric measurements were considered in the analysis. The first measure was eccentricity ($e_c$), the second proposed measure is ovality ($o_v$) as simply the ratio between the maximum and minimum diameters. The third measure of ovality is adopted from ISO 19624:2018[5], termed here as ISO ovality ($d_o$). The three were calculated based on Equations 6, 7, and 8, respectively:

$$e_c = \sqrt{1-\frac{b^2}{a^2}} = \sqrt{1-\frac{(D_{min})^2}{(D_{max})^2}}. \quad (6)$$

$$o_v = \frac{(D_{min})}{(D_{max})}. \quad (7)$$

$$d_o = \frac{2(D_{max}-D_{min})}{(D_{max}+D_{min})}. \quad (8)$$

$$\frac{A_e}{A_c} = \frac{0.25\pi D_{max}D_{min}}{0.25\pi\left(\frac{D_{max}+D_{min}}{2}\right)^2} = \frac{4o_v}{(1+o_v)^2} = \frac{4\sqrt{1-e_c^2}}{\left(1+\sqrt{1-e_c^2}\right)^2} = \frac{(2-d_o)(2+d_o)}{4} \quad (9)$$

Where: $D_{max}$ = maximum diameter of a section, $D_{min}$ = minimum diameter of a section

The primary goal of the analysis is to identify whether moisture content ($M_c$), external diameter ($D$), density ($\rho$), linear mass ($q$), eccentricity ($e_c$), ovality ($o_v$) and ISO ovality ($d_o$) – all of which are measured or determined non-destructively – are potential, reliable Indicating Properties (IPs) for compressive strength ($f_c$) or compressive capacity ($F_u$). These latter properties could potentially be used as Grade-determining Properties (GDPs). The adequacy will be determined by correlating the potential predictors ($M_c$, $D$, $\rho$, $q$, $e_c$, $o_v$, $d_o$, and their combination) to the response ($F_u$ and $f_c$). Predictors showing a higher correlation coefficient, hence a stronger correlation, were chosen as potential IPs.

Initially, only linear regression analysis was applied (Equation 10). The 5% exclusion limit ($R_{0.05}$) was calculated using Equation 11. Finally, the characteristic value ($R_k$) was determined in accordance with Equation 13, which was adapted for regression (Equation 14). The adaptation is applied by substituting the standard deviation ($S_D$) with standard error of the prediction at a given value of $x$ ($S_E$) (Equation 12). Current ISO 22156:2004[12] states a scalar 2.7 for confident level factor ($k_{0.05,0.75}$), which was applied in previous studies [9][8][13], however, in this study the authors have chosen to apply a value of 1.751 which is interpolated from confident level factor table in ISO 12122-1[14], ASTM 2915[15], and NZS 4063.2[16] for a sample of 113 specimens.

$$\hat{y}_i = a+bx_i. \quad (10)$$

$$R_{0.05} = \hat{y}_i - t_{(v,0.95)} S_E. \quad (11)$$

$$S_E = \left(1+\frac{1}{n}+\frac{(x_i-\bar{x})^2}{\Sigma(x_i-\bar{x})^2}\right)^{0.5} S_r. \quad (12)$$

$$R_k = R_{0.05}\left(1-\frac{k_{0.05,0.75}S_D}{\mu\sqrt{n}}\right). \quad (13)$$

$$R_k = R_{0.05}\left(1-\frac{k_{0.05,0.75}S_E}{\mu\sqrt{n}}\right). \quad (14)$$

Where: $\mu$ = mean of response ($F_u$ or $f_s$), $n$ = size of samples, $v$ = degree of freedom, $S_D$ = standard deviation, $S_E$ = standard error of prediction at a given value of $x$, $S_r$ = standard error of regression, $x_i$ = predictor value, $\bar{x}$ = mean of predictor, $t_{(v,0.95)}$ = one tail student's t-distribution value with $v$ degree of freedom for 95% probability, $k_{0.05,0.75}$ = confident level factor for 75% confident and 5% probability.

## Results and Discussion

A total of 113 specimens were tested during this study, which consists of 52 specimens without node and 61 specimens with node. The oven-dried weight of several specimens was lost during the testing periods, therefore only the data for 45 specimens without node and 52 specimens with node were available for $M_c$ calculations. This reduced sample also affected the data available for density and linear mass at standard moisture content. Descriptive statistics of the experimental findings are summarized in Table 2. A wide range of diameter, culm wall thickness, densities, and geometrical properties are justified in this study by its coefficient of variation (CV) values of each properties. The dimensional and physical properties variation affected to the high variation of its structural properties ($F_u$ and $f_c$).

A. Moisture content ($M_c$)

In common with timber, bamboo is a hygroscopic material that exhibits improved mechanical properties when in dry condition[17][18]. The moisture content of a bamboo culm changes following its surrounding relative humidity and ambient temperature. The average temperature and relative humidity in the laboratory during this research was 17.3°C and 39.7%, and the moisture content of the sample ranged from 7.3% to 10.9% (Table 2). The moisture content measured for specimens with node was similar to that measured for the specimens without nodes. Moisture content may affect other predictor candidates such as dimension and density. Bamboo culm shrinks when dry and swell when wet. Water content may increase a specimen's mass, and therefore the density is lower the drier the culms are. For these reasons moisture content was measured and noted throughout mechanical testing

B. Dimensions

Guadua is classed as a giant bamboo; this is evidenced by the dimensional properties of the sample: external diameter ($D$ = 59.4-137.2mm) and wall thickness ($t$ = 4.7-22.6mm). As previously discussed, it has been proposed that wall thickness ($t$) may be inferred from external diameter ($D$). To support this idea, a simple linear regression was conducted and it demonstrates that external diameter can be a fairly reliable predictor of the wall thickness, since a relatively and statistically significant value of coefficient of determination was obtained ($R^2 \geq 0.54$) (Figure 1a). Exponential equations resulted in a better prediction ($R^2 \geq 0.68$) (Figure 1b). In addition to the higher $R^2$, the exponential equation changes the funnel form of the residual by scaling the ordinate axis into a logarithmic scale. The fairly high correlation between *D* and *t*, validates the hypothesis that it may be possible to choose only one of these two variables as an IP. The *D* and *t* at the node are commonly bigger than that in internode. The *D*/*t* ratio of the sample nearer to node is smaller than that the farther one which is proved by the higher position of internode line compared to the node line in Figure 1.

Table 2. Descriptive Statistics of short Guadua (*L*=*D*) subject to axial compression

| Properties | without node | | | | | with node | | | | | all samples | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *n* | Min | Max | Mean | CV | *n* | Min | Max | Mean | CV | *n* | Min | Max | Mean | CV |
| moisture content ($M_c$; %) | 45 | 7.3 | 10.9 | 8.4 | 0.09 | 52 | 7.6 | 10.6 | 8.8 | 0.07 | 97 | 7.3 | 10.9 | 8.6 | 0.08 |
| culm wall thickness (*t*; mm) | 52 | 4.7 | 22.6 | 10.6 | 0.43 | 61 | 5.0 | 21.0 | 10.7 | 0.40 | 113 | 4.7 | 22.6 | 10.6 | 0.41 |
| external diameter (*D*; mm) | 52 | 59.4 | 136.1 | 100.5 | 0.18 | 61 | 61.3 | 137.2 | 102.7 | 0.19 | 113 | 59.4 | 137.2 | 101.7 | 0.19 |
| air-dry density ($\rho_a$; kg/m$^3$) | 45 | 507.9 | 968.8 | 768.7 | 0.10 | 52 | 531.8 | 1067.9 | 890.3 | 0.13 | 97 | 507.9 | 1067.9 | 833.9 | 0.14 |
| oven-dry density ($\rho_o$; kg/m$^3$) | 45 | 468.9 | 889.4 | 709.4 | 0.10 | 52 | 489.5 | 981.6 | 818.7 | 0.13 | 97 | 468.9 | 981.6 | 768.0 | 0.14 |
| density at 12%$M_c$ ($\rho_{12}$; kg/m$^3$) | 45 | 525.1 | 996.1 | 794.5 | 0.10 | 52 | 548.2 | 1099.4 | 916.9 | 0.13 | 97 | 525.1 | 1099.3 | 860.1 | 0.14 |
| air-dry linear mass ($q_a$; kg/m) | 45 | 0.74 | 4.35 | 2.11 | 0.47 | 52 | 0.89 | 4.94 | 2.52 | 0.45 | 97 | 0.74 | 4.94 | 2.33 | 0.46 |
| oven-dry linear mass ($q_o$; kg/m) | 45 | 0.68 | 3.94 | 1.95 | 0.46 | 52 | 0.81 | 4.53 | 2.32 | 0.45 | 97 | 0.68 | 4.53 | 2.15 | 0.46 |
| linear mass at 12%*Mc* ($q_{12}$; kg/m) | 45 | 0.76 | 4.42 | 2.18 | 0.46 | 52 | 0.91 | 5.07 | 2.60 | 0.45 | 97 | 0.76 | 5.07 | 2.40 | 0.46 |
| eccentricity ($e_c$) | 52 | 0.02 | 0.36 | 0.15 | 0.55 | 61 | 0.02 | 0.37 | 0.15 | 0.55 | 113 | 0.02 | 0.37 | 0.15 | 0.55 |
| ovality ($O_v$) | 52 | 0.93 | 1.00 | 0.98 | 0.02 | 61 | 0.93 | 1.00 | 0.98 | 0.02 | 113 | 0.93 | 1.00 | 0.98 | 0.02 |
| ISO ovality ($d_o$) | 52 | 0.00 | 0.07 | 0.02 | 1.01 | 61 | 0.00 | 0.08 | 0.02 | 1.05 | 113 | 0.00 | 0.08 | 0.02 | 1.03 |
| ultimate load ($F_u$, kN) | 52 | 97.0 | 427.9 | 237.5 | 0.40 | 61 | 52.7 | 472.7 | 231.7 | 0.45 | 113 | 52.7 | 472.7 | 234.3 | 0.42 |
| ultimate compressive strength ($f_c$; MPa) | 52 | 50.0 | 124.5 | 82.2 | 0.19 | 61 | 44.6 | 97.8 | 75.0 | 0.17 | 113 | 44.6 | 124.5 | 78.3 | 0.18 |

Note: *n* = sample size, Min = minimum value, Max = maximum value, Mean = average value, CV = coefficient of variation

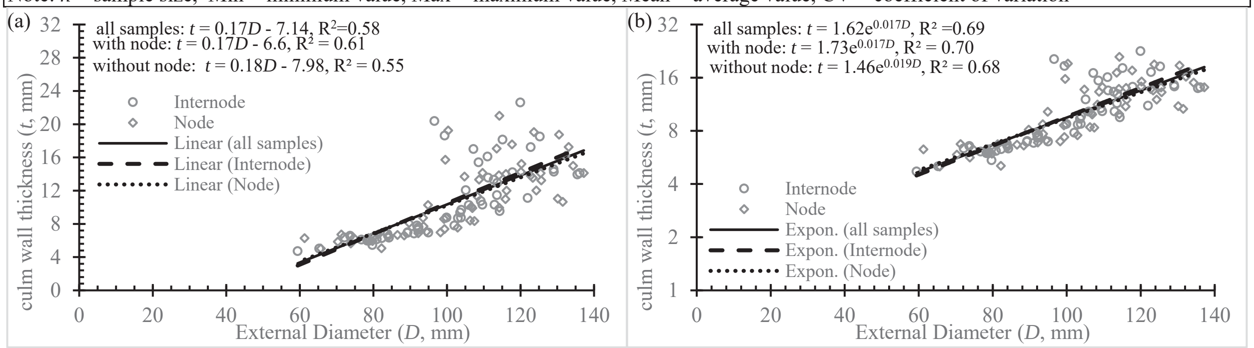


Figure 1. Scatterplot of Guadua culm external diameter vs its culm wall thickness fitted by linear (a) and exponential (b) regression.

C. Density ($\rho$) and Linear Mass ($q$))

As mentioned earlier, two different concepts of densities are postulated here within, as explained in Table 1. The densities of the Guadua sample are presented in Figure 2. Densities ($\rho$ and $q$) are affected by moisture content thus it is necessary to state the standard moisture content. The standard moisture content may be oven-dried (0%) or 12% $M_C$. Density measurements can be conducted at air-dry condition, but the result is reported here in these two standard conditions in order to consider the effect of moisture content and in the interest of comparability. Densities ($\rho$ and $q$) at air-dry, oven-dry, and 12% moisture contents are shown in Figure 2. Densities at 12% moisture content were always smaller that at air-dry condition since average air-dry moisture content was 8.6%. Figure 2 also shows that density of specimens containing nodes is always higher than density of specimens without nodes. This is a trivial observation, because diaphragms contribute to the overall mass but are disregarded in the measurement of volume or length. Figures 3 and 4 support this finding since density and linear mass for specimens with node (denoted by the dashed line) is always higher than the line for specimens without nodes (denoted by the dotted line). As the external diameter and wall thickness increases, density decreases slightly (Figure 3), while linear mass increase (Figures 4). Note that the coefficient of determination for linear mass to external diameter and wall-thickness are very strong ($R^2 > 0.81$), while that for density to external diameter are much weaker ($0.12 < R^2 < 0.32$). Overall specimens with nodes result in weaker predictions; this is to be expected, as the measurement of density for these contains inherent approximations. Linear mass has the strongest correlation with external diameter and culm wall thickness, it therefore is the predictor that offers most promise as an IP.

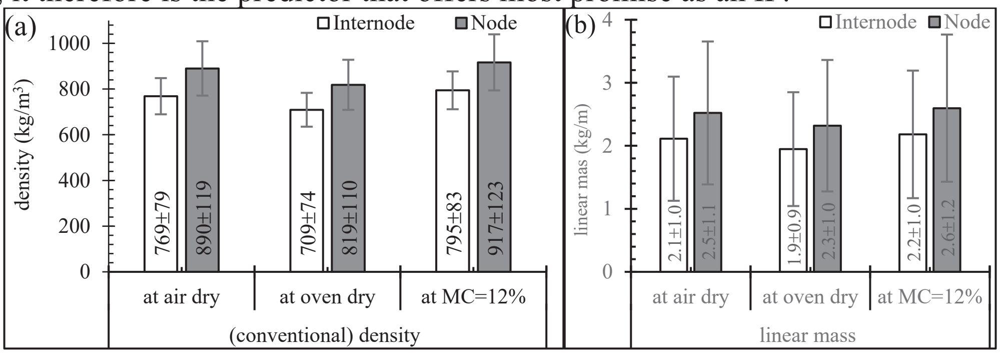


Figure 2. Density (a), and linear mass (b) of Guadua samples

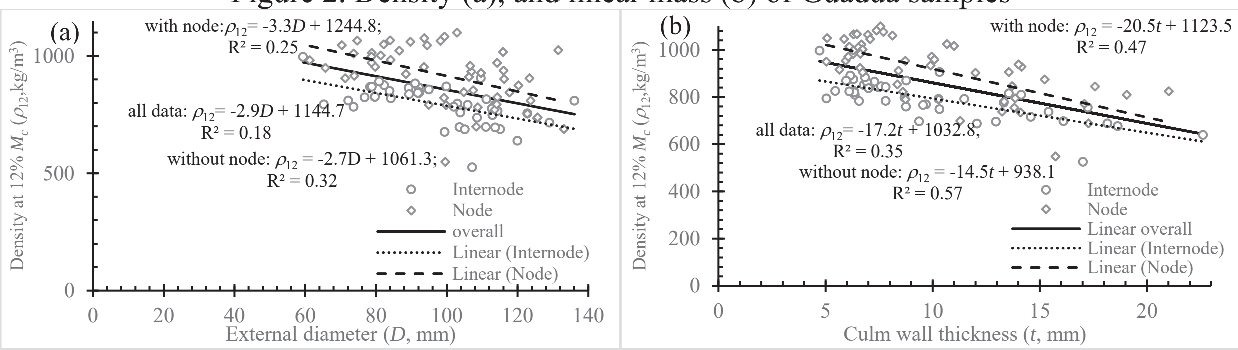


Figure 3. Density at 12% $M_c$ slightly decreases as the diameter (a) and thickness (b) increase.

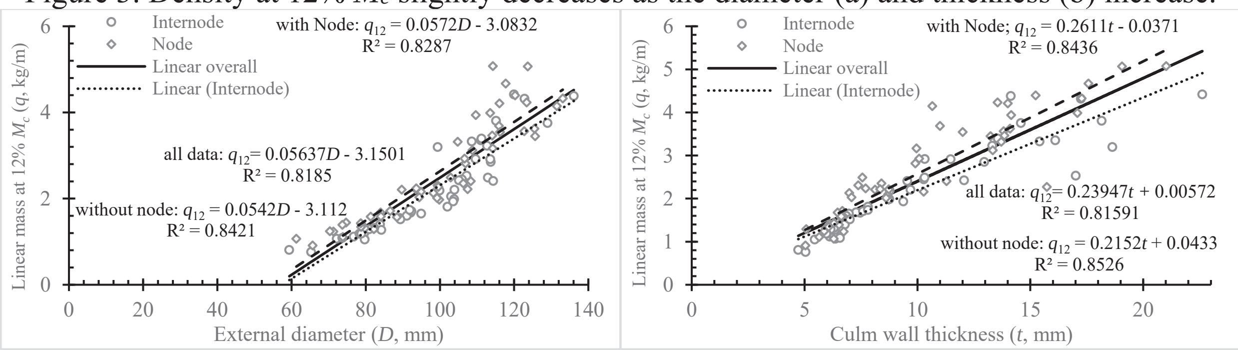


Figure 4. Linear mass at 12% $M_c$ significantly increases as the diameter (a) and thickness (b) increase.

D. Circularity (Eccentricity ($e_c$), Ovality ($o_v$), and ISO ovality ($d_o$))

Eccentricity and ovality describe the circularity of the culm cross-section [19]. A perfectly circular section has 0 eccentricity ($e_c$) and ISO ovality ($d_o$), while it has an ovality ($o_v$) value of 1. The circularity of a cross-section may have an effect in slender column since the smaller radius of gyration, occurring in the minor axis direction, is likely to govern buckling behavior. All of the three parameters ($e_c$, $d_o$, and $o_v$) showed that the Guadua bamboo culms mostly resembled perfectly circular cross-sections (Table 2) ($e_c = 0.15\pm0.08$, $d_o = 0.02\pm0.02$, and $o_v = 0.98\pm0.02$). Due to the circularity of the sample and the short length of the specimens, this measurement is expected to have virtually no incidence on the results, though it is reported for completeness purposes.

E. Compressive capacity ($F_u$) and compressive strength ($f_c$)

Specimens containing nodes and those without nodes displayed similar compressive capacities ($F_u$) (Figure 5a), though specimens without nodes had slightly higher capacities, the difference is not statistically significant. The compressive strength parallel to fibers that were calculated, $f_c$ (Figure 5b), exhibit slightly higher values for specimens without nodes than those with nodes, this may be a consequence of the orientation of the fibers at the nodes. Fibers within the internodes are parallel to the longitudinal (axial) direction, but at the nodes (diaphragms), some fibers change direction and cross into the diaphragm. This loss of longitudinal fibers is possibly reflected in the reduced strength. As discussed, the compressive strength ($f_c$) of specimens with a node is less than that of specimens without nodes (Figure 5b), however the diameter and wall thickness for the specimens with nodes ($D$ = 102.7 ± 19.9mm, $t$ = 10.7 ± 4.3mm) is larger than for specimens without nodes ($D$ = 100.5 ± 18.1mm, $t$ = 10.5 ± 4.5mm) (Table 2). As compressive capacity ($F_u$) is the product of compressive strength ($f_c$) and cross-sectional area, the larger average dimensions may offset the lower strength values for specimens with nodes, and hence explain why there is no significant difference between the compressive capacities for specimens with and without nodes.

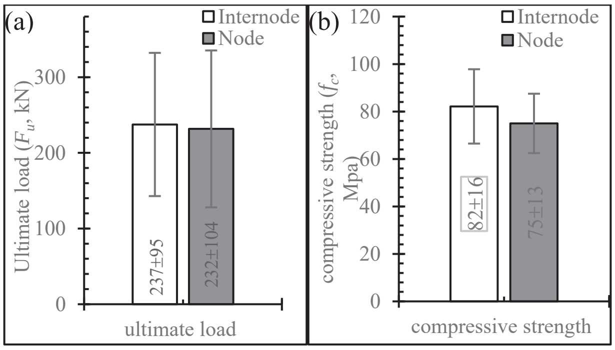


Figure 5. Ultimate compressive load (a) and compressive strength (b) of Guadua samples

F. Correlation between indicating predictor candidate and responses

Several factors may affect the structural properties of Guadua bamboo culms. The coefficient of correlation values ($r$) (Table 3) between those factors and the structural properties can indicate their strong or weak dependencies. Higher correlation values mean stronger dependencies.

Many other researchers [20][21][22] reported that bamboo culm compression strength is inversely proportional to its moisture content, which is in line with the negative value of coefficient of correlation found in this study. Table 3 indicates that moisture content may affect compressive strength and capacity, albeit only to small extent. The small range of moisture contents (Table 2) is likely to affect the conclusiveness of this finding.

Table 3. Coefficients of correlation ($r$) between IP candidates and structural properties

| | Ultimate load ($F_u$, kN) | Compressive strength ($f_c$, MPa) |
|---|---|---|
| Moisture content ($M_c$; %) | -0.06 | **-0.26** |
| Wall thickness ($t$; mm) | **0.90** | **-0.60** |
| External Diameter ($D$; mm) | **0.87** | **-0.55** |
| Air-dry density ($\rho_a$; kg/m$^3$) | **-0.43** | **0.46** |
| Density at standard $M_c$ ($\rho_o$ or $\rho_{12}$; kg/m$^3$) | **-0.43** | **0.47** |
| Air-dry linear mass at ($q_a$; kg/m) | **0.94** | **-0.52** |
| Linear mass at standard $M_c$ ($q_o$ or $q_{12}$; kg/m) | **0.94** | **-0.52** |

| | | |
|---|---|---|
| Eccentricity ($e_c$) | 0.08 | **-0.30** |
| Ovality ($o_v$) | -0.05 | **0.32** |
| ISO ovality ($d_o$) | 0.05 | **-0.33** |

An increase in wall-thickness and external diameter increases compressive capacity (ultimate load, $F_u$), a trivial finding because both represent an increase of cross-sectional area. Diameter and wall thickness are significantly and positively correlated with compressive capacity. This is consistent with the findings of Bahtiar *et al.* [9], others have found that this is also the case for flexural capacity [8]. Whereas for compressive strength ($f_c$), an increase in external diameter or wall-thickness, results in a reduction of strength. Large diameter bamboo culms can resist larger loads (i.e. have a higher capacity), but the smaller diameter and thinner walls generally correspond to higher mechanical properties per unit area, such as ultimate compressive strength. The latter is an observation that has been reported many times for bamboo [9][23].

Coefficients of correlation between density ($\rho$) and compressive strength ($f_c$) are significantly positive, while the correlation value between density ($\rho$) and ultimate load ($F_u$) is significantly negative. This means, the higher the $\rho$ value, the higher the $f_c$ value, but the lower $F_u$ value. This phenomenon can be explained using Figure 3, as a smaller external diameter corresponds commonly to denser culms (Figure 3a), and thicker walls correspond to reduced density (Figure 3b). Higher densities are likely to reflect higher fiber content, hence the increase in compressive strength, but the increase in fibers does not offset the loss in cross-sectional area, hence the reduction in overall compressive capacity. As a consequence of this phenomenon, *density* alone is not a good IP for *capacity grading*, but it is an adequate IP for *strength grading*. This looks like a general phenomenon for bamboo since it is also found on sympodial species [9].

In contrast with density ($\rho$), linear mass ($q$) have significant positive correlation values with compressive capacity ($F_u$), but they have a negative correlation to compressive strength ($f_c$) (Table 3). Similar to the findings of Bahtiar *et al.* [9], the strongest correlation is between linear mass and compressive capacity ($r = 0.94$), therefore linear mass is the best IP for *capacity grading* of Guadua bamboo culms subject to axial compressive loads. It should be noted that linear mass ($q$) [24] or linear mass multiplied by diameter ($qD$) [8] are reliable IPs for flexural capacity (maximum moment carrying capacity, $M_{max}$). Therefore, this finding affirms that *linear mass* is an excellent IP for *capacity grading* and capacity grading provides more reliable predictions than strength grading.

Eccentricity and ovality may affect the compressive strength ($f_c$), but do not significantly affect the compressive capacity ($F_u$) (Table 3). As discussed, in the sample used, the cross-sections was almost circular since the eccentricity ($e_c$) and ISO ovality ($d_o$) value are nearly zero, which means the minor axis is not very different from the major axis. Due to the small range of eccentricities contained within this study, the effect of circularity on the compressive strength and capacity of Guadua culms cannot be detected. The specimens are also short, with lengths similar to the external diameters, therefore buckling could not occur. It may be that wherever buckling can occur, such as in slender columns, eccentricity and ovality play an important role. However, this could not be determined in this investigation.

G. Structural grading

Two types of structural grading for bamboo culms are discussed in this study: capacity and strength grading. Capacity grading is the process of sorting bamboo culms based on their capability to resist an ultimate load, while strength grading is sorting culms based on strength (ultimate load per unit of section area). According to the correlation values (Table 3), the best IP candidates for structural grading of bamboo culms subject to axial compressive load are those that are sensitive to mass, namely:

a) Density ($\rho$) - is suitable for strength grading assuming a hollow circular cross-section,
b) Linear mass ($q$) - is suitable for capacity grading.

Diameter and culm wall thickness are also promising IPs for capacity grading since they have a significant correlation to compressive capacity ($F_c$). Diameter and wall thickness are less sensitive to moisture content variation than mass and density, therefore they could be used as IPs regardless of the moisture content.

To develop a Guadua bamboo structural grading system, the data were plotted in a Cartesian diagram. A 99% normal ellipse band and 95% prediction interval were created (Figure 6). Data that were placed outside both bands were justified as outliers and removed from further analysis.

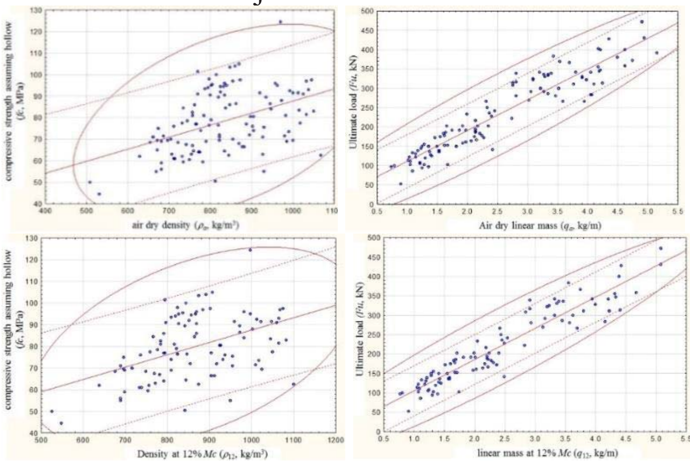


Figure 6. Scatterplot with 99% ellipse normal band and 95% prediction band

G.1. Strength grading assuming a hollow circular cross-section

Bamboo strength grading assuming a hollow circular cross-section may be developed based on the correlation between two or more material intensive properties. This common practice for conventional strength grading of wood [4]. The two variables considered in this type of strength grading for bamboo are culm wall density and compressive strength parallel-to-fibers, which are two physical-mechanical intensive properties that do not depend on the dimensions and amount of bamboo culm. Table 3 indicates that density has the strongest correlation with compressive strength, therefore it may become the most adequate IP for bamboo strength grading (assuming a hollow circular cross-section). A statistical method based on simple linear regression was conducted and successfully used to classify the Guadua culms into several structural grades (Figure 7, Table 4 and 5). Each grade provides a range of density for Guadua culms, with their respective compressive strength expressed as mean, 5% exclusion limit ($R_{0.05}$), and characteristic values ($R_k$) - refer to Tables 4 and 5. The characteristic value ($R_k$) is calculated in accordance to Equation 13.

As a means to assess the efficiency of each grading procedure, the ratio between the mean value and the characteristic value ($R_k$) are presented. The larger the ratio the more inefficient the structural design, although this may result in a higher level of safety. In this instance the ratio ranges from 1.30 to 1.63. The characteristic strength of Guadua culms, for a given structural grade (as summarized in Tables 4 and 5 and Figure 9) could be used directly as a design value in limit-state or Load and Resistance Factor Design (LRFD) design procedures, subject to the adoption of appropriate partial factors of safety for the material. Alternatively, the characteristic strength could be transformed into an allowable (or permissible stress), subject to the adoption of appropriate factors of safety. Either way, in stress basis structural analysis, the bamboo culm geometry is commonly assumed to be a hollow tube. Examples of strength-based bamboo construction designs which assumed hollow cross-sections for the component include Arce [25], Irawati *et al.* [26], Ubolsook and Thepa [27], Uthaipattrakoon [28], Seixal *et al.* [29], etc, while a more complex structural analysis based on a functionally graded layer system of hollow tube bamboo member were conducted by Silva *et al.* [30] and Long *et al.* [31].

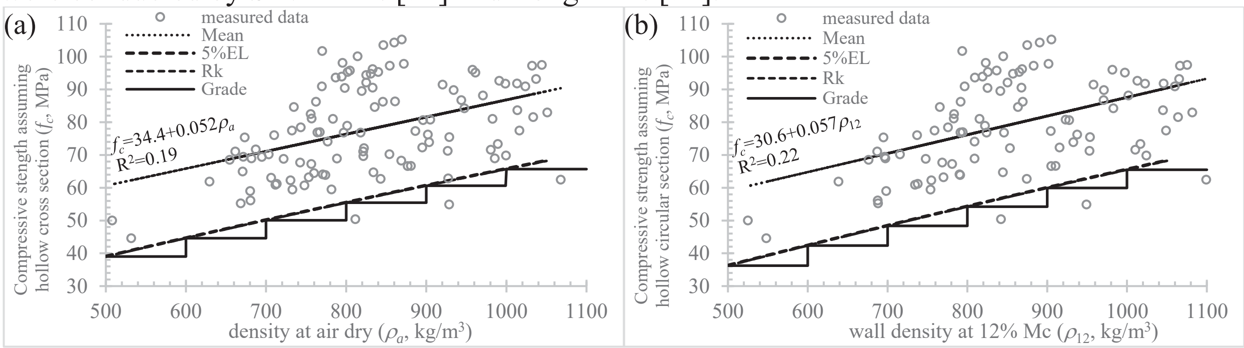


Figure 7. Classification of compressive strength grade of Guadua assuming hollow cross section based on density at air dry (a) and 12% $M_c$.

Table 4. Compressive strength grade classification of Guadua assuming hollow circular section based on density at air-dry.

| Grade ($\rho_a$, kg/m³) | Compressive strength assuming hollow circular cross section ($f_c$, MPa) | | | Mean to $R_k$ Ratio |
|---|---|---|---|---|
| | Mean | $R_{0.05}$ | $R_k$ | |
| 500-599 | 60.6 | 39.1 | 39.0 | 1.55 |
| 600-699 | 65.9 | 44.7 | 44.6 | 1.48 |
| 700-799 | 71.1 | 50.2 | 50.1 | 1.42 |
| 800-899 | 76.3 | 55.6 | 55.4 | 1.38 |
| 900-999 | 81.6 | 60.8 | 60.6 | 1.35 |
| 1000-1099 | 86.8 | 65.8 | 65.7 | 1.32 |
| >=1100 | 92.0 | 70.8 | 70.1 | 1.30 |

Table 5. Compressive strength grade classification of Guadua assuming hollow circular section based on density at 12% $M_c$.

| Grade ($\rho_{12}$, kg/m³) | Compressive strength assuming hollow circular cross section ($f_c$, MPa) | | | Mean to $R_k$ Ratio |
|---|---|---|---|---|
| | Mean | $R_{0.05}$ | $R_k$ | |
| 500-599 | 59.0 | 36.3 | 36.2 | 1.63 |
| 600-699 | 64.8 | 42.5 | 42.4 | 1.53 |
| 700-799 | 70.5 | 48.5 | 48.4 | 1.46 |
| 800-899 | 76.2 | 54.4 | 54.2 | 1.40 |
| 900-999 | 81.9 | 60.1 | 59.9 | 1.37 |
| 1000-1099 | 87.6 | 65.6 | 65.5 | 1.34 |
| >=1100 | 93.3 | 71.1 | 70.9 | 1.32 |

G.2. Capacity grading for Guadua bamboo subjected to axial compressive load

Since linear mass, $q$, as an IP for compressive capacity (i.e. ultimate load, $F_u$) has the highest coefficient of determination value ($R^2$ = 0.88-0.89, Figure 8) from all the correlations explored in this study, capacity grading becomes the most promising procedure for bamboo structural grading. This research finding affirms previous researches [6][9][8][19][32] which suggested capacity grading as a more reliable procedure than strength grading. Tables 6 and 7 present the range of linear mass for each capacity grade alongside the respective mean, 5% exclusion limit ($R_{0,05}$) and characteristic ($R_k$) axial compressive capacities. There is a wider range of compressive load carrying capacities than compressive strengths, so more capacity grades could be created than strength grades. Nine (9) capacity grades and seven (7) strength grades are proposed in this study. However, one aspect that seems counterintuitive is that based on the Mean to $R_k$ ratio for some grades range from very small (1.15) to very large (6.05). This suggests that the level of conservativeness within the proposed linear mass grading procedure varies significantly. This would be undesirable in terms of the safe and efficient use of the resource.

To get a more rational structural property value, a modification to the classification methods was also proposed in this study. The modified procedure is as follow:

a. The 5% exclusion limit of all ultimate load data ($R_{0.05,all}$) were directly measured following Equation 15.

$$R_{0.05,all} = \bar{F}_u - t_{(0.95,n-1)} S_D. \qquad (15)$$

Where: $\bar{F}_u$ = mean value of the ultimate load, $S_D$ = standard deviation of the ultimate load, $t_{(0.95, n-1)}$ = $t$-student value

b. The limit linear mass ($q_{a,0.05}$, $q_{12,0.05}$) which statistically predicts the $R_{0.05;all}$ using Equation 15 is calculated by means of the "goal seek" function in MS Excel. The basic equation for this MS Excel "goal seek" function is Equation 11.

c. A linear function, which is $R_{0.05}$ as a function of linear mass for $q_a \leq q_{a;0.05}$ and $q_{12} \leq q_{12;0.05}$ (Equation 16), is drawn in a graph. This linear function is set to have an intercept through the origin (0 , 0).

$$R_{0.05} = \frac{R_{0.05,all}}{q_{a,0.05}} q_a \quad \text{for} \quad q_a \leq q_{a,0.05} \qquad (16a)$$

$$R_{0.05} = \frac{R_{0.05,all}}{q_{12,0.05}} q_{12} \quad \text{for} \quad q_{12} \leq q_{12,0.05} \qquad (16b)$$

d. The mean ultimate load at $q_{0.05}$ ($\hat{F}_{u,q_{0.05}}$) is calculated using the previous linear regression equation (Figures 8a and 8b) ,

e. A linear function, which is $F_u$ as a function of linear mass for $q_a \leq q_{a;0.05}$ and $q_{12} \leq q_{12;0.05}$ (Equation 17), is drawn in a graph

$$\hat{F}_u = \frac{\hat{F}_{u,q_{0.05}}}{q_{a;0.05}} q_a \quad \text{for} \quad q_a \leq q_{a;0.05} \qquad (17a)$$

$$\hat{F}_u = \frac{\hat{F}_{u,q_{0.05}}}{q_{12;0.05}} q_{12} \quad \text{for} \quad q_{12} \leq q_{12;0.05} \qquad (17b)$$

f. Characteristic value ($R_k$) is calculated following Equation 14.

Classification based on linear mass as IP, as resulted from the modified method, is shown in Figure 8, and Tables 6 and 7. The outcome is that the Mean to $R_k$ ratio now ranges from 1.15 to 1.89, a far more consistent solution. The modification is applied for the 5% lower tail of distribution only, thus the rest of the GDP value which derived from confident method and the modified one are exactly the same.

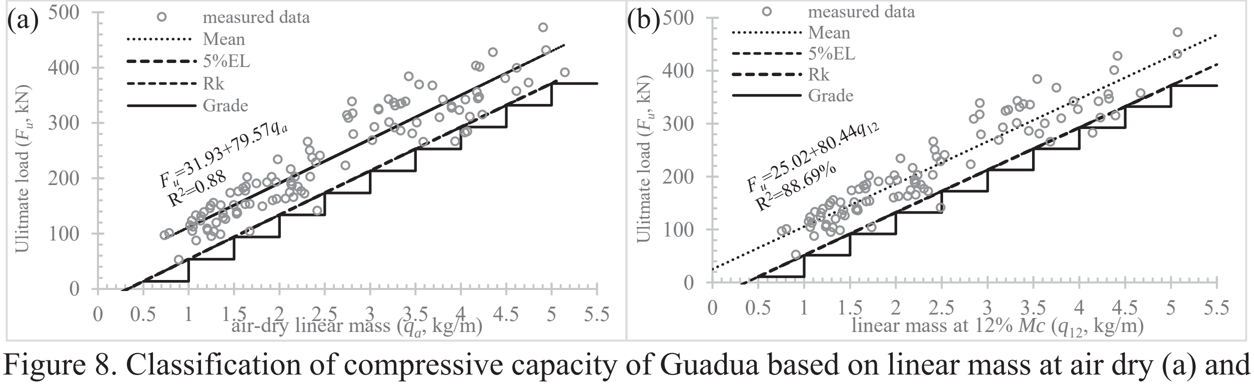


Figure 8. Classification of compressive capacity of Guadua based on linear mass at air dry (a) and 12% $M_c$ developed by confident band method

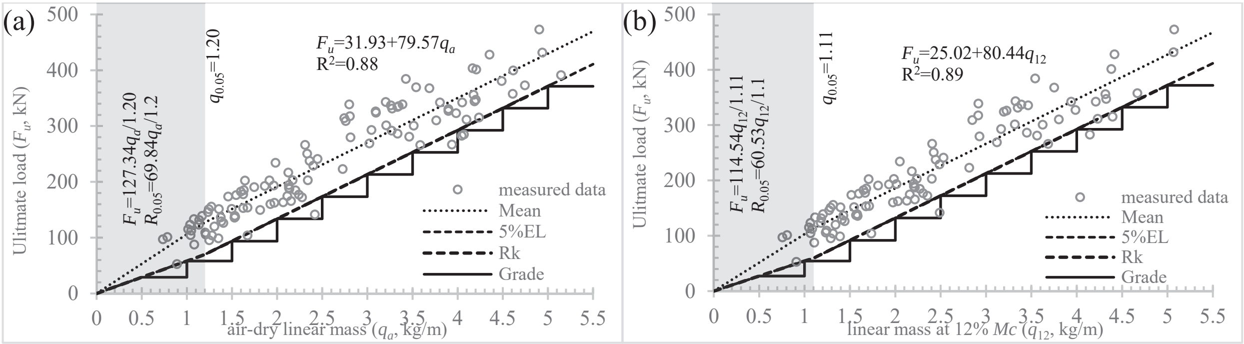


Figure 8. Classification of compressive capacity of Guadua based on linear mass at air dry (a) and 12% $M_c$ which developed by modified method

Table 6. Compressive load carrying capacity grade of Guadua based on air-dry linear mass

| Grade ($q_a$, kg/m) | Confident Band Method | | | | Modified Method | | | |
|---|---|---|---|---|---|---|---|---|
| | Ultimate Load ($F_u$, kN) | | | Mean to $R_k$ Ratio | Ultimate Load ($F_u$, kN) | | | Mean to $R_k$ Ratio |
| | Mean | $R_{0.05}$ | $R_k$ | | Mean | $R_{0.05}$ | $R_k$ | |
| 0.50-0.99 | 71.7 | 13.8 | 13.8 | 5.21 | 53.1 | 29.1 | 29.1 | 1.82 |
| 1.00-1.49 | 111.5 | 53.9 | 53.9 | 2.07 | 106.2 | 58.2 | 58.2 | 1.82 |
| 1.50-1.99 | 115.5 | 57.9 | 57.9 | 2.00 | 111.5 | 61.2 | 61.1 | 1.82 |
| 2.00-2.49 | 191.1 | 133.8 | 133.8 | 1.43 | 191.1 | 133.8 | 133.8 | 1.43 |
| 2.50-2.99 | 230.9 | 173.7 | 173.6 | 1.33 | 230.9 | 173.7 | 173.6 | 1.33 |
| 3.00-3.49 | 270.6 | 213.4 | 213.3 | 1.27 | 270.6 | 213.4 | 213.3 | 1.27 |
| 3.50-3.99 | 310.4 | 253.1 | 252.9 | 1.23 | 310.4 | 253.1 | 252.9 | 1.23 |
| 4.00-4.49 | 350.2 | 292.6 | 292.4 | 1.20 | 350.2 | 292.6 | 292.4 | 1.20 |
| >=5.50 | 429.8 | 371.5 | 371.2 | 1.16 | 429.8 | 371.5 | 371.2 | 1.16 |

Table 7. Compressive load carrying capacity grade of Guadua based on linear mass at 12% $M_c$.

| Grade ($q_{12}$, kg/m) | Confident Band Method | | | | Modified Method | | | |
|---|---|---|---|---|---|---|---|---|
| | Ultimate Load ($F_u$, kN) | | | Mean to $R_k$ Ratio | Ultimate Load ($F_u$, kN) | | | Mean to $R_k$ Ratio |
| | Mean | $R_{0.05}$ | $R_k$ | | Mean | $R_{0.05}$ | $R_k$ | |
| 0.50-0.99 | 65.2 | 10.8 | 10.8 | 6.05 | 51.5 | 27.2 | 27.2 | 1.89 |
| 1.00-1.49 | 105.5 | 51.4 | 51.3 | 2.05 | 102.9 | 54.4 | 54.4 | 1.89 |
| 1.50-1.99 | 109.5 | 55.4 | 55.4 | 1.98 | 108.1 | 57.1 | 57.1 | 1.89 |
| 2.00-2.49 | 185.9 | 132.2 | 132.1 | 1.41 | 185.9 | 132.2 | 132.1 | 1.41 |
| 2.50-2.99 | 226.1 | 172.5 | 172.3 | 1.31 | 226.1 | 172.5 | 172.3 | 1.31 |
| 3.00-3.49 | 266.4 | 212.6 | 212.5 | 1.25 | 266.4 | 212.6 | 212.5 | 1.25 |
| 3.50-3.99 | 306.6 | 252.7 | 252.5 | 1.21 | 306.6 | 252.7 | 252.5 | 1.21 |
| 4.00-4.49 | 346.8 | 292.6 | 292.3 | 1.19 | 346.8 | 292.6 | 292.3 | 1.19 |
| >=5.50 | 427.2 | 372.1 | 371.8 | 1.15 | 427.2 | 372.1 | 371.8 | 1.15 |

As well as linear mass ($q$), external diameter ($D$) may be considered a reliable IP for Guadua capacity grading, because its correlation with ultimate load ($F_u$) is also strong (Table 3). External diameter ($D$) can be readily measured and also strongly correlates with wall-thickness ($t$) and linear mass ($q$). The larger the external diameter, the thicker the culm wall, and obviously the larger the linear mass. External diameter may be chosen as the sole IP for capacity grading of bamboo, as seen in Figure 9a. The associated mean, 5% exclusion limit and characteristic capacities for each diameter-based grade are summarized in Table 8.

Figure 9a shows that the characteristic load carrying capacity of Guadua subjected to compression is negative if the external diameter is smaller than 69 mm. This is a consequence of the higher standard error of the regression ($S_r$) compared to the predicted value. It does not mean that it will have no load-bearing capacity. A previous modification (Equations 15–17) is also proposed to get a more rational structural property value for the lower structural grades, which in this instance is smaller diameters. Classification based on diameter as IP, as resulted from the modified method, is shown in Figure 9b and Table 8. Once again, the mean to $R_k$ was notably homogenized.

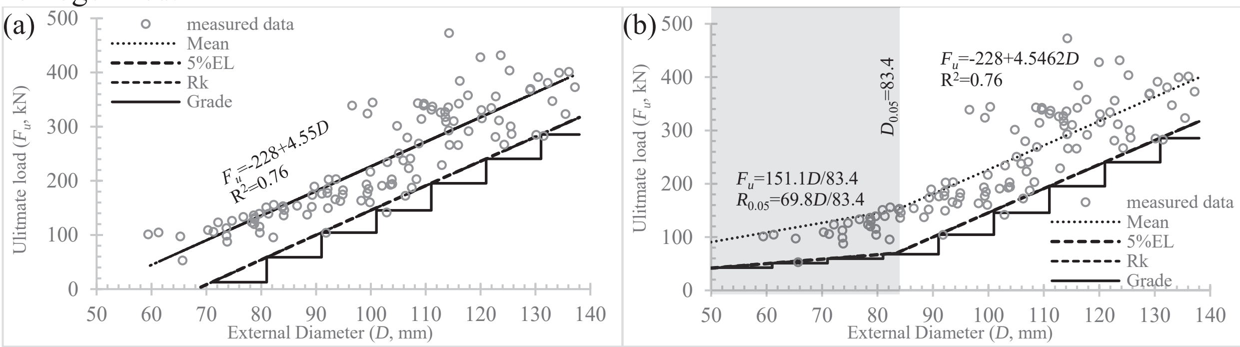


Figure 9. Classification of compressive capacity of Guadua based on its external diameter ($D$) which developed using (a) confident band method and (b) modified method

Table 8. Compressive load carrying capacity grade classification of Guadua based on its external diameter.

| Grade ($D$, mm) | Confident Band Method | | | | Modified Method | | | |
|---|---|---|---|---|---|---|---|---|
| | Ultimate Load ($F_u$, kN) | | | Mean to $R_k$ Ratio | Ultimate Load ($F_u$, kN) | | | Mean to $R_k$ Ratio |
| | Mean | $R_{0.05}$ | $R_k$ | | Mean | $R_{0.05}$ | $R_k$ | |
| 51-60 | n.a. | n.a. | n.a. | n.a. | 92.4 | 42.7 | 42.6 | 2.2 |
| 61-70 | n.a. | n.a. | n.a. | n.a. | 110.5 | 51.0 | 51.0 | 2.2 |
| 71-80 | 94.7 | 12.8 | 12.8 | 7.4 | 128.6 | 59.4 | 59.3 | 2.2 |
| 81-90 | 140.1 | 58.8 | 58.7 | 2.4 | 146.7 | 67.7 | 67.7 | 2.2 |
| 91-100 | 185.6 | 104.6 | 104.5 | 1.8 | 185.6 | 104.6 | 104.5 | 1.8 |
| 101-110 | 226.5 | 145.6 | 145.5 | 1.6 | 226.5 | 145.6 | 145.5 | 1.6 |
| 111-120 | 276.5 | 195.5 | 195.4 | 1.4 | 276.5 | 195.5 | 195.4 | 1.4 |
| 121-130 | 322.0 | 240.7 | 240.5 | 1.3 | 322.0 | 240.7 | 240.5 | 1.3 |
| >=131 | 367.4 | 285.7 | 285.5 | 1.3 | 367.4 | 285.7 | 285.5 | 1.3 |

Note: n.a.: not available

## H. Multiple Regression analysis

This study was conducted in an environment where the average temperature was 17.3°C and the average relative humidity was 39.7%. The proposed structural grades (Tables 4 – 10) are only suitable if Guadua will be used in a similar environment. Since more humid bamboo has lower strength and capacity, it is safer to adjust the characteristic strength and capacity into several moisture content condition. Multiple regression analysis was conducted in this study which resulted in structural grades that have been adjusted for several moisture contents (8%, 9%, and 10%) (Figures 10a, 11a, and 12a). The adjustment factor follows the graph for its corresponding moisture content effects (Figures 10b, 11b, and 12b). The moisture content adjustment factors significantly decrease the structural properties for Guadua bamboo grading when the IPs are densities ($\rho$ or $q$), while it is not necessary when the IP is the external diameter ($D$). The moisture content effect adjustment factor line graph is flat because of the very small gradient value (-0.52) for capacity grading when using the external diameter as the IP (Figure 12b). The $p$-value for that gradient is 0.94 which is statistically not significant. Meanwhile the $p$-value for the gradient adjustment factor is less than 0.05 for each structural grading by using density ($\rho$ or $q$) as the IP, which justifies the need to apply these moisture content adjustment factors. The structural properties for Guadua after being adjusted by the moisture content factor are presented in Tables 9 and 10.

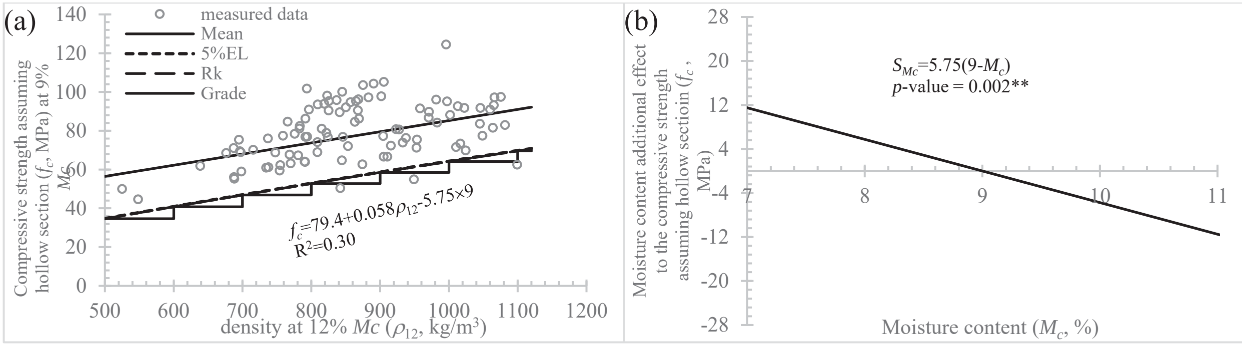


Figure 10. Multiple regression for estimating the compressive strength of Guadua assuming hollow section: density at 12% $M_c$ effect (a), and moisture content effect (b) (Note: ** = very significant)

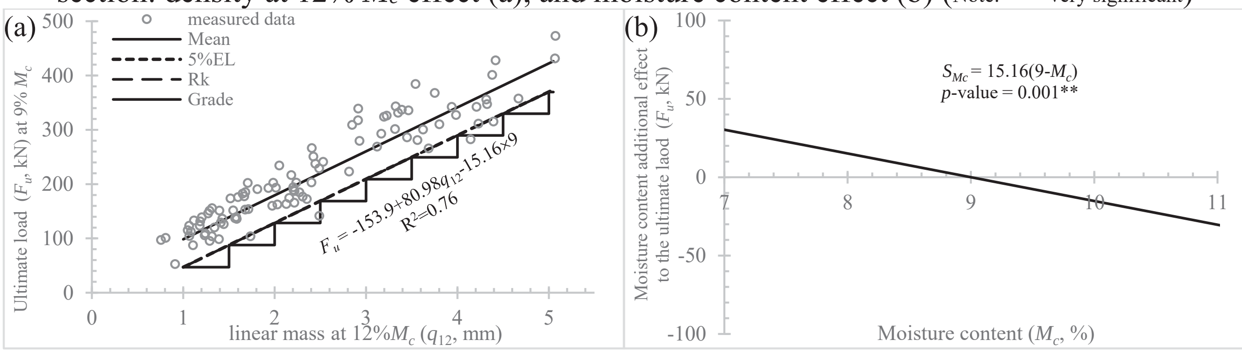


Figure 11. Multiple regression for estimating the compressive load carrying capacity of Guadua: linear mass at 12% $M_c$ effect (a), and moisture content effect (b) (Note: ** = very significant)

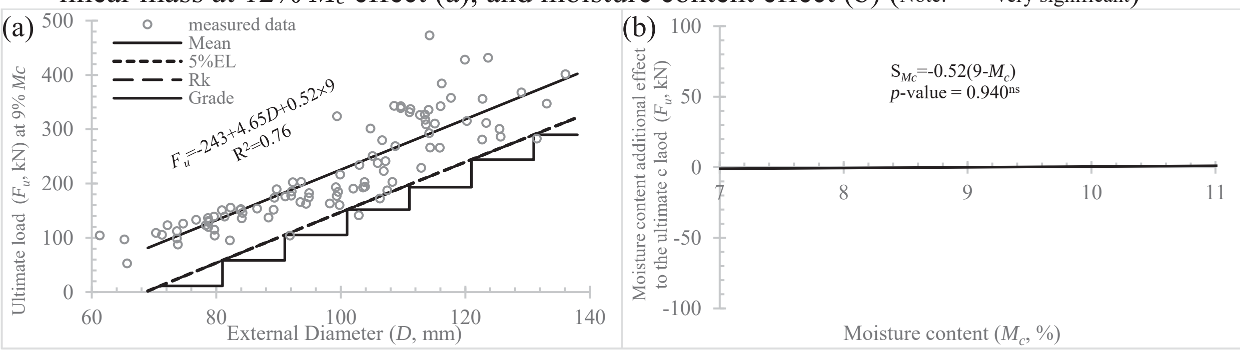


Figure 12. Multiple regression for estimating the compressive load carrying capacity of Guadua: external diameter effect (a), and moisture content effect (b) (Note: ns = not significant)

Table 9. Compressive strength grade classification of Guadua at several moisture content based on density at 12% $M_c$

| Grade ($\rho_{12}$, kg/m$^3$) | Compressive strength assuming hollow cross section ($f_c$, MPa) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | at 8% $M_c$ | | | at 9% $M_c$ | | | at 10% $M_c$ | | |
| | Mean | $R_{0.05}$ | $R_k$ | Mean | $R_{0.05}$ | $R_k$ | Mean | $R_{0.05}$ | $R_k$ |
| 500-599 | 62.2 | 40.5 | 40.4 | 56.5 | 34.7 | 34.6 | 50.7 | 29.0 | 28.9 |
| 600-699 | 68.0 | 46.7 | 46.6 | 62.2 | 40.9 | 40.8 | 56.5 | 35.2 | 35.1 |
| 700-799 | 73.7 | 52.7 | 52.6 | 68.0 | 47.0 | 46.9 | 62.2 | 41.2 | 41.1 |
| 800-899 | 79.5 | 58.6 | 58.5 | 73.7 | 52.9 | 52.8 | 68.0 | 47.1 | 47.0 |
| 900-999 | 85.2 | 64.4 | 64.3 | 79.5 | 58.6 | 58.5 | 73.7 | 52.9 | 52.8 |
| 1000-1099 | 91.0 | 70.0 | 69.9 | 85.2 | 64.3 | 64.1 | 79.5 | 58.5 | 58.4 |
| >=1100 | 96.8 | 75.5 | 75.4 | 91.0 | 69.8 | 69.6 | 85.3 | 64.0 | 63.8 |

Table 10. Compressive load carrying capacity grade classification of Guadua at several moisture content based on linear mass at 12% $M_c$

| Grade ($q_{12}$, kg/m) | Compressive load carrying capacity ($F_u$, kN) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | at 8% $M_c$ | | | at 9% $M_c$ | | | at 10% $M_c$ | | |
| | Mean | $R_{0.05}$ | $R_k$ | Mean | $R_{0.05}$ | $R_k$ | Mean | $R_{0.05}$ | $R_k$ |
| 1.00-1.49 | 113.6 | 62.2 | 62.2 | 98.4 | 47.1 | 47.0 | 83.2 | 31.9 | 31.9 |
| 1.50-1.99 | 154.0 | 102.9 | 102.9 | 138.9 | 87.8 | 87.7 | 123.7 | 72.6 | 72.6 |
| 2.00-2.49 | 190.5 | 139.5 | 139.4 | 175.3 | 124.4 | 124.3 | 160.2 | 109.2 | 109.1 |
| 2.50-2.99 | 226.9 | 176.0 | 175.9 | 211.7 | 160.8 | 160.7 | 196.6 | 145. 7 | 145.5 |
| 3.00-3.49 | 263.3 | 212.4 | 212.2 | 248.2 | 197.2 | 197.1 | 233.0 | 182.1 | 181.9 |
| 3.50-3.99 | 295.7 | 244.7 | 244.5 | 280.6 | 229.5 | 229.3 | 265.4 | 214.3 | 214.2 |
| 4.00-4.49 | 332.2 | 280.9 | 280.7 | 317.0 | 265.7 | 265.5 | 301.8 | 250.6 | 250.4 |
| 4.50-4.99 | 372.6 | 321.1 | 320.8 | 357.5 | 305.9 | 305.6 | 342.3 | 290.7 | 290.5 |
| >=5 | 409.1 | 357.1 | 356.8 | 393.9 | 342.0 | 341.7 | 378.8 | 326.8 | 326.5 |

Relationship between moisture content and mechanical properties of bamboo is generally similar to that of wood. The moisture content effect adjustments proposed in Figures 10-11 and manifest in Tables 9-10 are similar with sugi wood board, but greater than small clear specimen of softwood. Ido *et al*. [33] reported that the average increase in compressive strength parallel to the grain due to a 1 % decrease in moisture content of small clear specimen softwood is 5.2% [34] and that of sugi wood board is 5.8% [35], while this research resulted 4 – 9% and 6 – 11% of that of Guadua capacity grading and strength grading, respectively. The lower structural grade of Guadua culms seem more sensitive to moisture content change than the higher grade. Similar with this research's results, Jiang *et al*. reported that compressive strength parallel to grain of 4.5 years old Moso Bamboo at 5% and 10% $M_c$ are 110 MPa and 80 MPa, respectively[21], so that the sensitivity is approximately 6.3% for every 1% $M_c$ change.

I. Variability Reduction Because of Structural Grading

Structural grading successfully reduces the material variability as it classifies the material into several structural grades which is shown by the decrease of the coefficient of variation value (CV) (Table 11). The variability reduction is higher for the higher coefficient of determination ($R^2$), as it counts the proportion of the variance in the response variable which is predictable from the predictor variable – the IP in this instance. Unexplained variability is decreased when the model can be a better fit to the experimental data. As seen in Table 11, structural grading reduces the coefficient of variation value of the response variables (Grade-determining properties - $F_u$ and $f_c$) with respect to the non-graded data.

J. Comparison with Structural Grading of Other Bamboo Species

Similar to previous research on Hitam (*Gigantochloa atroviolacea*), Andong (*Gigantochloa pseudoarundinacea*), and Tali (*Gigantochloa apus*) bamboo subjected to axial compressive load [9], this study consistently found that linear mass ($q$) is also the best IP for capacity grading, while density ($\rho$) is the best ones for strength grading of Guadua. The regression equations of structural grading for each species are summarized in Table 11. For comparison, these regression equations are plotted in Figures 13a and 13b, for capacity grading and strength grading assumed hollow, respectively. As seen in Figure 13, Guadua always has better structural properties than Hitam, Andong, and Tali which is demonstrated by the higher position of the line compared to the other species. This may be a consequence of the moisture content, as Guadua strength and capacity were measured at 8.6% average moisture content, while the others were measured at 16% average moisture content. If the adjustment factor value for moisture content effect were applied, there may be universality in the trends. This gives rise to the possibility of allowing cross-species grading methods. This possibility is beyond the scope of this paper, as it needs to be studied more thoroughly by means of an appropriate statistical method, such as that proposed by Firmanti *et al.* [4] in order to confidently apply a structural grading of bamboo without regard to species.

K. Next work: Bucking Reduction Factor ($\psi$)

This study successfully develops structural grading for short Guadua member subjected to axial compression load. Buckling is not occurred in short column, but it is usually become critical incident in long and slender column. The column tends to buckle if the length-to-diameter-ratio ($L/D$) or slenderness ratio ($\lambda$) is more than a critical slenderness ratio ($\lambda_{lim}$). Long column subjected to compression is shorten while deflection is also occurred which significantly reduce the compressive load carrying capacity. The buckling critical load to ultimate compressive load ratio ($F_{cr}/F_u$) is introduced a buckling reduction factor ($\psi$) which consider as compression load carrying capacity reduction of long and slender column. The buckling reduction factor may also be defined as ratio of critical buckling stress to yield stress in compression ($\psi=f_{cr}/f_c$). The actual strength and load carrying capacity characteristic of long Guadua subjected to compression ($R_{k,\,cr}$) should be the characteristics value of short column which adjusted by this buckling reduction factor ($R_{k,cr} = R_k\psi$). The buckling behavior of Guadua long column will be discussed in our next paper.

Table 11. Guadua variability reduction as a result of structural grading

| Structural grading methods | Grade-determining properties (GDP) | | | Indicating Property (IP) | $S_r$ | Coefficient of variation (CV) | |
|---|---|---|---|---|---|---|---|
| | Property | Mean | $S_D$ | | | Graded | Non graded |
| Capacity grading | $F_u$ | 218.40 | 95.04 | $q_{12}$ | 32.13 | 0.147 | 0.435 |
| | $F_u$ | 218.40 | 95.04 | $q_{12}$ and $M_c$ | 30.49 | 0.140 | 0.435 |
| | $F_u$ | 218.40 | 95.04 | $D$ | 48.57 | 0.222 | 0.435 |
| Strength grading | $f_c$ | 79.60 | 14.73 | $\rho_{12}$ | 13.05 | 0.164 | 0.185 |
| | $f_c$ | 79.60 | 14.73 | $\rho_{12}$ and $M_c$ | 12.48 | 0.157 | 0.185 |

Table 12. Regression equation for structural grading of bamboo subjected to compressive load

| Type | Species | GDP | IP | Regression Equation | $R^2$ |
|---|---|---|---|---|---|
| Capacity Grading | *Guadua* (this study) | $F_u$ (kN) | $q_{12}$ (kg/m) | $F_u$=80.44$q_{12}$+25.02 | 0.89 |
| | | $F_u$ (kN) | $q_a$ (kg/m) | $F_u$=79.57$q_a$+31.93 | 0.88 |
| | | $F_u$ (kN) | $D$ (mm) | $F_u$=4.55$D$-228 | 0.76 |
| | Hitam[9] | $F_u$ (N) | $q_a$ (kg/m) | $F_u$=68843$q_a$−5525 | 0.95 |
| | Andong[9] | $F_u$ (N) | $q_a$ (kg/m) | $F_u$=49128 $q_a$ +7842 | 0.82 |
| | Tali [9] | $F_u$ (N) | $q_a$ (kg/m) | $F_u$=57055 $q_a$+692 | 0.95 |
| Strength grading | Guadua (this study) | $f_c$ (MPa) | $\rho_{12}$ (kg/m$^3$) | $f_c$=0.057$\rho_{12}$+30.558 | 0.22 |
| | | $f_c$ (MPa) | $\rho_a$ (kg/m$^3$) | $f_c$=0.052$\rho_a$+34.432 | 0.19 |
| | Hitam[9] | $f_c$ (MPa) | $\rho_a$ (g/cm$^3$) | $f_c$ = 82.24$\rho_a$ – 14.06 | 0.74 |
| | Andong [9] | $f_c$ (MPa) | $\rho_a$ (g/cm$^3$) | $f_c$ = 81.24$\rho_a$ – 18.3 | 0.68 |
| | Tali [9] | $f_c$ (MPa) | $\rho_a$ (g/cm$^3$) | $f_c$ = 63.29$\rho_a$ – 4.48 | 0.55 |

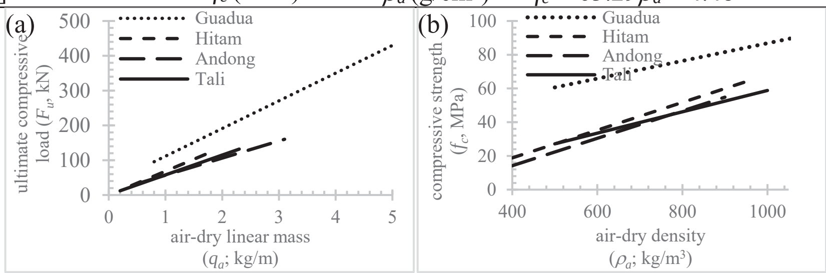


Figure 13. Regression analysis for capacity grading (a), and strength grading (b) for Hitam, Andong, Tali [9], and Guadua

## Conclusion

Several candidates to Indicating Properties (IPs) were measured in this study to develop structural grading for Guadua. Due to their stronger correlation values, density ($\rho$) and linear mass ($q$) were deemed the best IPs for structural grading of Guadua subject to axial compressive load. Density ($\rho$) is reliable for estimating the compressive strength if the cross-sectional area is assumed to be a hollow cylinder, while linear mass ($q$) is reliable for estimating the compressive load carrying capacity. Structural grading may be undertaken on the basis of strength grading or capacity grading. The study identifies that capacity grading is more reliable than strength grading due to its higher coefficient of determination values ($R^2$). As bamboo is a hygroscopic material, the IP should be adjusted into standardized moisture content (12% $M_c$). The moisture content effect on compressive strength and capacity should also be measured to increase the reliability of estimation if densities ($\rho$ and $q$) are chosen as the IPs. Since external diameter can infer the linear mass ($q$) and is also significantly correlated with wall thickness ($t$), average external diameter ($D$) may also be used as the sole IP in capacity grading. Structural grading can reduce the variability of Guadua structural properties since it classifies the culms into several suitable classes. The prospect of cross-species structural grading method seems viable but needs further investigation.

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