Determining material suitability for Low-Rise housing in the philippines: Physical and mechanical properties of the bamboo species Bambusa blumeana

Article *in* Bioresources · February 2018

DOI: 10.15376/biores.13.1.346-369

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Determining Material Suitability for Low-Rise Housing in the Philippines: Physical and Mechanical Properties of the Bamboo Species *Bambusa blumeana*

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The use of cellulosic materials in the construction of low-rise housing in tropical climates has great potential. *Bambusa blumeana* (*B. blumeana*, J.A. and J.H. Schultes), the most abundantly available bamboo species in the Philippines, is a promising alternative material for the construction of cost-efficient buildings. However, to comply with municipal rules and regulations for construction, a comprehensive understanding of the organic raw material is needed to permit its application as a load-bearing structural member. In this study, the physical and mechanical properties of *B. blumeana* bamboo from a typical growth region of the Philippines were tested according to ISO 22157-1 (2004) and ISO 22157-2 (2004). The characteristic strength values of *B. blumeana* were as follows: compressive and tensile strengths parallel to the grain of 20 and 95 MPa, respectively; shear strength of 5 MPa, bending strength of 34.6 MPa, and the mean and fifth percentile modulus of elasticity of 13100 and 8600 MPa, respectively. Based on these results, a recommendation for permissible stresses for structural design was made in line with ISO 22156 (2004).

Keywords: Bambusa blumeana; Bamboo; Philippines; Physical and mechanical properties; Alternative construction materials; Housing

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INTRODUCTION

Two-thirds of the new floor plan area that will be built by 2050 is predicted to be in Asia-Pacific, Africa, and Latin America and the Caribbean (IEA 2016). Affordable, sustainable, climate-adjusted and disaster-resistant housing is an urgent requirement in economies that experience tremendous urban growth, disparity, and extreme weather impacts (UN General Assembly 2015). The New Urban Agenda of the United Nations Human Settlements Program, UN Habitat, identifies the use of local raw materials as one key area for action to address the housing need (UN-Habitat 2015). The tremendous resource hunger and unsustainable consumption patterns for construction and other purposes have caused overexploitation of resources in the past, resulting for example in net forest loss at the scale of 7 million hectares annually in the tropics (FAO 2016). For the Philippines, this magnitude is exemplified at the country level. In 1900, the total land area of the country was 70% covered with forest, with this value declining to 21.8% by 2002 (ESSC 2002). Policy makers in the Philippines have started to react since 2000.

Through a series of policies, the extraction of timber from the natural forests was restricted with only a few exceptions for plantation timber. Since 2011, a national log ban on natural and residual forest has been active (EO23 2011). Global pathways to lessen the resource pressure and contribute to sustainable supply chains must be developed. A large potential lies in the utilization of alternative, renewable raw materials such as bamboo together with sustainable production and consumption patterns for its use. The fast growth and regeneration cycles of bamboo as well as its broad availability in the tropics make it an ecological alternative to conventional construction materials used for low-rise housing such as timber, concrete, and steel (Villegas *et al.* 2003; van der Lugt *et al.* 2006; Liese and Koehl 2015). In the Philippines, the utilization of bamboo for construction has a long tradition in rural areas (Barile *et al.* 2007). However, these rural structures are often considered temporary and not disaster-resistant, as manifested in the vulnerability curves of (Monteverde *et al.* 2014), which relate the intensity of typhoon damage events to the mean damage ratio of bamboo-based houses. The historical mapping of tropical typhoons between 1845 and 2006 indicates that annually approximately 20 typhoons pass the Philippine Area of Responsibility (PAR), which puts it in the category of countries with highest exposure to severe wind impacts (NASA Earth Observatory 2006). Besides typhoons, structures in the Philippines are exposed to earthquakes, as the country is located on the ring of fire (USGS 2017). Both typhoons and earthquakes must be considered as design loads in structural design to provide a sufficient level of safety for their occupants (ASEP 2016). The behavior of alternative structural building materials must be reliable and predictable to formally approve their application for use in construction. Because the latter constraint is not in place for bamboo in the Philippines, it was rarely applied for house construction in the urban centers of the country until recently (Base Builds 2015). The motivation of this paper is thus to contribute to the use of bamboo for cost-efficient and disaster-resistant low-rise housing in the Philippines in compliance with local building regulations.

Globally, more than 1,200 bamboo species have been recorded, and the Philippines Forestry Sector has identified approximately 62 different species (PCARRD 1991). Each bamboo species has characteristic anatomical, chemical, physical, and mechanical properties, which make it more suitable for certain applications than others and often explain its empirical utilization (Liese and Koehl 2015). A shortlist of nine economically relevant species was identified for the Philippines according to the criteria distribution and current utilization (Table 1) (Rojo *et al.* 2000). In addition, Virtucio and Roxas (2003) mentioned the criteria of affordability in comparison to conventional building materials but without further detail on individual species because no standard pricing for bamboo exists in the Philippines. The most common applications considered in the assessment were construction, furniture, handicrafts, edible shoots, and pulp. The potential use of these species for structures such as bridges, scaffoldings, and additional structures was excluded because they are less common locally (Rojo *et al.* 2000; FPRDI 2002).

Among the nine economically relevant species, five have been documented for empirical use in construction (Rojo *et al.* 2000). Similar to application in timber engineering, a careful selection of the species is important for the specific purpose of full-culm load-bearing frame construction. A highly promising species is *Bambusa blumena* (*B. blumeana*), locally called Kauayan-tinik, which is explained in the following according to the criteria of distribution, empiric utilization, affordability, and previous test reports.

Table 1. Economically Relevant Bamboo Species in the Philippines (Rojo *et al.* 2000)

Latin Name	Sub-Species Name	Local Name	Distribution and Utilization
Bambusa blumeana (*B. blumeana*)	J.A. and J.H. Schultes	Kauayan-tinik	Commonly planted across the country in various soils at low and medium altitudes. Frequently used for construction, furniture, farm equipment, kitchen utensils, pulp, and shoot production.
Bambusa vulgaris	Schrader ex. Wendland	Kauayan-kiling	Found across the country but only grows on well-drained sandy loam and clay at low altitudes. Used for light construction, pulp, ornamental purposes, and handicrafts.
Dendrocalamus asper (*D. asper*)	(Schultes f.) Backer ex. Heyne	Giant bamboo	Found in some provinces of the country. Used for construction, laminated bamboo, pulp, and shoot production.
Bambusa merrilliana or *Dendrocalamus merillamus*	(Elmer) Rojo and Roxa or (Elmer) Elmer	Bayog	Endemic species found in areas with deep fertile soil. Its tough and thick walls are preferred for furniture, farming equipment, and construction.
Gigantochloa atter	(Hassk.) Kurz	Kayali	Found mainly in Mindanao and some locations further north. Used for household utensils, handicrafts, banana props, eating, and construction.
Gigantochloa levis	(Blanco) Merr.	Bolo	Endemic species found in selected areas of the country. Used for edible shoots, construction, basketry, and furniture.
Schizostachyum lima	(Blanco) Merr.	Anos	Found across the country. Ideal for woven bamboo mats, edible shoots, and brass metal polishing.
Schizostachyum lumampao	(Blanco) Merr.	Buho	Endemic species found across the country. Ideal for woven bamboo mats, baskets, fences, spears, and flutes.
Bambusa philippinensis or *Sphaerobambos philippinensis*	(Gamble) McClure (Gamble) Dransfield	Laak	Found abundantly in Mindanao near the Davao area. Widely used as banana props.

B. blumeana is the most common raw material used by the rural population to build traditional, vernacular buildings, which indicates its suitability for construction and its affordability for the population, despite its thorny branches which increases the complexity of its harvest. This species is the most widely grown throughout all the regions of the Philippine archipelago, as shown in Fig. 1, from Northern Luzon over Visayas to Southern Mindanao. It is native to Java, Indonesia, and Eastern Malaysia, and beyond the Philippines, and it is cultivated in Southern China, Peninsular Malaysia, the Moluccas, Sumatra, Borneo, India, and Indochina (Rojo *et al.* 2000). This type of bamboo is commonly planted in settled areas at low and medium altitudes; it grows along riverbanks, hill slopes, and freshwater creeks; and tolerates flooding and eroded soils (Espiloy 1986). Researchers from outside of the Philippines have referred to it as priority species but without a description of its frequent empirical use in traditional house construction in the Philippines (Liese and Koehl 2015).

Fig. 1. Map of the Philippines with its main island groups Luzon, Visayas, and Mindanao; author processed based on NAMRIA (2017)

Endeavors have been made to map the geographical distribution and quantify the availability of *B. blumeana* and other economically relevant species by the national and regional offices of the Department of Natural Resources in the Philippines (ERDB 2012). However, it was not possible to develop an updated, consistent, country-wide map of bamboo availabilities. One of the reasons for the knowledge gap in distribution and quantification might be that the bamboo market is highly fluctuating, with uncertain price points and clear cutting of existing stands in favor of one-time income opportunities for temporary utilization (Base Builds 2015). The training and implementation of sustainable harvesting practices is therefore also crucial for bamboo (Virtucio and Roxas 2003). In the Philippines, agriculturally managed clumps yield approximately 800 to 1200 culms per hectare per year, while the unmanaged natural clumps produce approximately 500 to 700 culms per hectare per year (FPRDI 2002). According to local forestry experts, a plantation in a degraded open land plot of 7 m × 7 m has an unfertilized clump yield of 11.6 tons dry weight per hectare per year. The fertilized clumps yield approximately 19.4 tons dry weight per hectare per year (Virtucio and Roxas 2003). Most commonly, the species is available in unmanaged patches, which are not usable for agricultural cash crops. Therefore, its yield has potential to provide a side income for farmers, even though it is not maximized compared with plantation growth (BSI 2015).

In the past and through recent research, major advancements have been achieved in the anatomical, morphological, and chemical characterization of bamboo culms (Liese 1974; Londono 2006; Sharma *et al.* 2011; Liu *et al.* 2014; Sanchez-Echeverri *et al.* 2014). In addition, the mechanical performance of culms from various species around the globe has been subject to scientific research both in the past, such as by Janssen (1980), and in recent years, such as by Luna *et al.* (2012). Because of its relevance and distribution, *B. blumeana* has been studied in the past in Malaysia and the Philippines (Espiloy 1986; Espiloy 1992; Latif *et al.* 1992; Latif and Tamizi 1992). Because of the absence of both national and global bamboo standards at the time of the studies, the Indian Standard IS 6874 (1973), today updated to IS 6874 (2008), and a merger of the Indian Standard IS 6874 (1973) with a modification of the ASTM D143-94 standard (1994), today updated to ASTM D143-14 (2014), have been applied in Malaysia and the Philippines, respectively. The studies support the potential suitability of the species for construction and indicate that three- to four-year-old *B. blumeana* has a high relative density, compressive strength, and modulus of elasticity (MOE) during static bending. The latter are discussed in the Discussion section in comparison with results of the current paper. In summary, the wide distribution, empirical utilization, and promising past scientific findings of *B. blumeana* are considered a good indicator for its economic and technical potential. However, only design values obtained through a standardized, comparable norm will enable its formal approval for the construction of buildings and facilitate its greater acceptance and comparability as a building material (Harries *et al.* 2012).

In 2004, the International Standards ISO 22157-1 (2004) and ISO 22157-2 (2004) were released, which enabled a uniform and transparent strength grading and comparison of bamboo species around the world. This standard has guided subsequent studies for Latin American Guadua species (Correal and Arbeláez 2010; Ordonez-C. and Barcenas-P. 2014; Zaragoza-Hernandez *et al.* 2015). In Asia-Pacific, the standard was applied for testing bamboo species from China, Indonesia, and Thailand (Deng *et al.* 2016, Made Oka *et al.* 2014, Nugroho *et al.* 2013, Sompoh *et al.* 2013, and Suhelmidawati *et al.* 2012). However, no Philippine bamboo species has been examined yet according to this standard. Therefore, the scope of this research was to identify the physical and mechanical properties of the economically and technically relevant Philippine bamboo species *B. blumeana* according to ISO 22157-1 (2004). The documented results include the physical properties of relative density, moisture content (MC), and shrinkage characteristics as well as the mechanical properties of bending strength, shear strength, and compressive and tensile strengths parallel to the grain. The results are set in comparison with results for further bamboo species tested according to the same standard around the globe. The paper concludes by providing a recommendation for permissible stresses of the selected bamboo species for low-rise housing according to ISO 22156 (2004). The research on testing *B. blumeana* strength according to ISO 22157-1 (2004) is expected to incentivize designers, authorities, and people in need of housing to consider round bamboo as a valid alternative to the available but costlier conventional building materials or scarce timber in the country.

EXPERIMENTAL

Materials and Methods

ISO 22157-1 (2004) and ISO 22157-2 (2004) were used to determine the physical and mechanical properties of *B. blumeana*. In the following, the tall grasses with woody jointed stems are referred to as culms (Liese and Koehl 2015). A culm is a single shoot of bamboo that is usually hollow, except at nodes which are often swollen (ISO 22157-1 2004). Culms are further characterized by internode distances, the culm diameter and culm wall thickness, as well as the length along the axis (Lui *et al.* 2016). Twenty-five culms of three- to four-year-old bamboo were collected from the sourcing location at Pagsanjan, Laguna, Region IV in Luzon. Each property was tested in 10 specimens at the Physics and Mechanics Laboratory, Forest Products Research and Development Institute (FPRDI 2015). Each culm was cut into 4-m-long pieces starting from the butt, with a height of approximately 1 m from the ground serving as a reference. Several studies have reported the change of physical and mechanical properties along the culm axis (Kamruzzaman *et al.* 2008; Correal and Arbeláez 2010; Anokye *et al.* 2014; Made Oka *et al.* 2014). Researchers have explained the latter with changes in the anatomical, morphological, and chemical composition in vertical direction. To properly reflect the variation within a culm, testing of the butt, middle, and top portions is a requirement according to ISO 22157-1 (2004). The culms were labeled with a culm number and their height before they were cut. While still in green condition, the culm weight, wall thickness, number of nodes and internodes, diameter, and length were measured before the tests. Testing in dry condition is recommended for commercial purposes, whereas for scientific research, testing may be performed in green condition ISO 22157-1 (2004). For this study, culms were tested consistently in green condition. MC adjustment of results is standardized in timber engineering, as in (EN384 2010). However, similar to timber engineering, values in green condition are considered conservative because the strength properties increase with decreasing MC, particularly below the FSP. Researchers described this behavior and started to set the FSP and evaluate the effect of MC adjustment for selected bamboo species (Jiang *et al.* 2012; Wang *et al.* 2013; Xu *et al.* 2014; Gutierrez *et al.* 2015). Regarding *G. angustifolia* Kunth, Gutierrez *et al.* (2015) observed that the geometric and mechanical properties are not expected to vary considerable with a MC over the fiber saturation point (FSP) of 32% +/−3%. Xu *et al.* (2014) confirmed that no further degradation of mechanical properties was observed above a MC of 30% for *Phyllostachys pubescens* (*P. pubescens*). Wang *et al*. (2013) and Jiang *et al*. (2012) set the FSP for *P. pubescens* lower at approximately 23% MC. Jiang *et al*. (2012) attested that the MC variation influences mechanical properties differently. While below the FSP, compression parallel to the grain and shear strength for *P. pubescens* had a change rate of 3.8% and 3.1% with each 1% of MC increase respectively, tension parallel to the grain and bending strength varied 1.6% and 1.5% respectively. Testing in green condition is considered conservative for this study. Therefore, the MC of *B. blumeana* specimen was consistently clearly above any of the mentioned bamboo FSP during testing.

The tests were conducted at 27 °C ± 2 °C and 70% ± 5% relative humidity (RH). The universal testing machine (UTM) that was used for measuring the bending, shear, and tensile strengths had a loading range of 2 to 10 tons. The UTM for the compressive strength had a maximum load of 90 tons. The MC values after each test were measured for each specimen to appropriately interpret the results. In timber engineering, preservative treatment affects the strength and stiffness properties of timber (Eurocode 5 EN 1995-1-1 2004). The treatment effect was excluded from this study, as untreated bamboo culms were used. Future work is needed to evaluate whether these or other factors are valid for bamboo.

Data Evaluation

The data were processed according to ISO 22157-1 (2004), analysis of variance (ANOVA), and ISO 22156 (2004). The formulas provided in ISO 22157-1 (2004) were used to calculate the physical and mechanical properties from the test readings. ANOVA tests for the statistical relevance were performed. To derive the characteristic strength values, the raw data were transformed into characteristic values according to ISO 22156 (2004) using the following equation,

$$R_k = R_{0.05}\left(1 - \frac{2{,}7\frac{s}{m}}{\sqrt{n}}\right), \tag{1}$$

where R_k is the characteristic value (N/mm^2), $R_{0.05}$ is the 5th percentile value of the sample (N/mm^2), s is the standard deviation of the sample, m is the mean value of the sample, and n is the size of the sample.

Physical Properties

Moisture content

Samples with dimensions of 25 mm in width and height and their natural wall thickness were taken from the bending samples near the location of failure. The samples were weighed to an accuracy of 0.01 g and oven-dried at 103 ± 2 °C. The MC of each sample was calculated using Eq. 2,

$$\text{MC (\%)} = \frac{m - m_0}{m_0} \times 100, \quad (2)$$

where m and m_o are the mass (g) of the test piece before and after drying, respectively.

Relative density

Samples of similar size to those for the MC determination were obtained, and their maximum volume was measured using water immersion or displacement methods. The samples were exposed to room temperature and subsequently placed in a drying oven at 103 °C ± 2 °C until a constant weight was attained. The relative density of each sample was computed using Eq. 3:

$$\rho = \left(\frac{m}{V}\right) \times 10^6, \quad (3)$$

where ρ is the mass volume $[\frac{\text{kg}}{m^3}]$, m is the mass (g) of the test piece in the oven-dry condition, and V is the green volume of the test piece during the test (mm^3).

Shrinkage

To determine the amount of shrinkage, the samples were soaked in water to obtain the initial weight and volume in green condition. Round culms at internode sections with heights of 100 mm were taken from each bending test sample. For each sample, four diameters, four wall thicknesses, and two lengths were measured. These samples were dried in ambient conditions and subsequently oven-dried at 103 °C ± 2 °C until the weight became constant. The shrinkage from the initial condition to the oven dry condition was calculated using Eq. 4,

$$\text{Shrinkage (\%)} = \frac{I - F}{I} \times 100, \quad (4)$$

where I is the initial reading and F is the final reading.

Mechanical Properties

Compressive strength

Specimens without a node were taken from the bending samples with a specimen height equal to the outer diameter. Special attention was made to ensure a precise cut at the end planes that was perpendicular to the grain and a vertically centered placement of the specimen. Melted sulfur was then coated on the ends of the samples to ensure a uniform distribution of the load weight and to reduce the friction between the bamboo and the steel plates. The load was applied continuously during the test at a constant rate of 0.01 mm/s. The compressive strength was determined using Eq. 5,

$$\sigma_{ult} = \frac{F_{ult}}{A}, \quad (5)$$

where σ_{ult} is the ultimate compressive stress (N/mm^2), F_{ult} is the maximum load at specimen failure (N), and A is the cross-sectional area calculated as,

$$\frac{\pi}{4} x(D^2 - (D - 2t)^2) \ (mm^2) \quad (6)$$

where D is the outer diameter (mm) and t is the wall thickness (mm).

Tensile strength

The specimens were wedge-shaped and the cross-sectional dimensions of the gauge portion of the sample were measured to an accuracy of 0.1 mm. The load was applied at a constant rate of 0.6 mm/min until the maximum load was attained. The strain gauges or deflection were read every 0.050 tons. The ultimate tensile strength (σ_{ult}) in N/mm^2 was determined using Eq. 7,

$$\sigma_{ult} = \frac{F_{ult}}{A}, \tag{7}$$

where F_{ult} is the maximum load at specimen failure (N) and A is the cross-sectional area of the gauge portion (mm^2).

Shear strength

The shear strength along the fibers was tested with specimens of length equal to their diameter. An equal number of specimens with and without nodes were tested. Special attention was made to ensure a precise cut at the end planes perpendicular to the grain and a vertically centered placement of the specimen. The wall thickness and height of the samples were measured taken at four shear planes. The load was applied continuously during the test at a constant rate of 0.01 mm/s with a 1-kN stabilizing load. The ultimate shear strength (τ_{ult}) in N/mm^2 was calculated using Eq. 8,

$$\tau_{ult} = \frac{F_{ult}}{\sum(t \ x \ L)}, \tag{8}$$

where F_{ult} is the maximum load at specimen failure (N) and Σ ($t \times L$) is the area of four shear planes as the product of the thickness and specimen height.

Bending strength

The bending strength was determined through four-point bending tests. The outer diameter of the culms multiplied by 30 resulted in the free span of the specimen. On each side of the culm, two wood saddle supports were placed 23-cm apart and mounted onto two steel supports on a wooden beam. Similarly, the load application on top of the culm was arranged. The ultimate strength σ in bending in MPa was computed using Eqs. 9 and 10,

$$\sigma_{ult} = F \ x \ L \ x \ \frac{D/2}{6} \ x \ I_B \tag{9}$$

$$I_B = \frac{\pi}{64}\left(D^4 - (D - 2t)^4\right), \tag{10}$$

where F is the maximum load (N), L is the free span (mm), D is the outer diameter (mm), and I_B is the second moment of area (mm^4).

The MOE was given by the slope of the linear part of the load–deformation diagram. The MOE was calculated using Eq. 11 for the four-point bending test in ISO 22157-1 (2004):

$$E = \frac{23 \ F \ L^3}{1296 \ \delta \ I_B}, \tag{11}$$

where F is the maximum load (N), L is the free span (mm), I_B is the second moment of area (mm^4), and δ is the deflection at mid-span (mm).

RESULTS AND DISCUSSION

The culm diameter of the specimens ranged from 70.6 to 109.2 mm; the maximum diameter of the middle portion was slightly higher than that at the bottom portion. The mean diameter declined from the bottom to the top of the culm by 14%. Because of the conic characteristic of the culms, the wall thickness was highest at the butt, with a significant mean decrease of approximately 70% toward the top, with 24 to 7 mm respectively. The typical length of the *B. blumeana* culms was 16.9 m. The minimum, maximum, and mean geometry of the test specimens are documented in Table 2. In a previous study in the Philippines, the geometric properties of *B. blumeana* culms were comparable in terms of wall thickness, but a 41% decrease in diameter toward the top was documented (Espiloy 1992). This may be explained by the length of the culms considered in the previous study. In Malaysia, Latif *et al*. (1992) found a comparable diameter of 81 mm at the top portion, but a 10% smaller diameter and 40% thinner wall thickness of the butt samples. The latter may again be attributed to the specimen selection process, but also due to the different sourcing location. Overall, diameters and wall thicknesses documented in (Espiloy 1992; Latif *et al.* 1992) can be described as of comparable range to this study and are stated in Table 2.

Table 2. Geometric Characteristics of *B. blumeana* Test Specimens of This and Previous Studies

Species, Country, Source	Diameter (mm)			Wall Thickness (mm)		
	B	M	T	B	M	T
B. blumeana Philippines (authors), *m*	94.0	91.2	80.9	24.0	10.0	7.0
B. blumeana Philippines (authors), range	78.2 to 104.3	81.3 to 109.2	70.6 to 96.5	19.2 to 27.4	7.6 to 14.0	6.2 to 7.6
B. blumeana Philippines (Espiloy 1992), *m*	90.0	84.0	53.1	24.0	11.0	6.0
B. blumeana Malaysia (Latif *et al.* 1992), *m*	85.0	87.0	81.0	14.6	10.3	8.2

B, butt of culm; M, middle of culm; T, top of culm; *m* = mean of sample

Physical Properties

The MC confirmed that all the bamboo specimens were tested in green condition. It was clearly above any FSP set by researchers for other bamboo species. The MC decreased characteristically from the butt to the top, as attested by earlier studies on bamboo, such as Anokye *et al.* (2014) and Wakchaure and Kute (2012). The reduction of MC toward the top can be attributed to the declining share of lignin matrix from the butt to the top (Liese 1974).

The shrinkage of the culm wall thickness from the green condition to oven-dry condition was 6.16%, 8.81%, and 4.01% at the butt, middle, and top, respectively. The decline of the shrinkage from the butt to top of the culms is equally connected to a lower proportion of parenchyma cells at the top of the bamboo culm, as shrinkage is mainly caused by the behavior of the matrix (Liese 1974; Kamruzzaman *et al.* 2008; Huang *et al.* 2014). The mean radial shrinkage of the wall thickness was the largest (6.33%), followed by the tangential shrinkage of the circumference (5.13%), with a ratio of 1.23:1.0. This ratio fell between what Espiloy (1992) reported for *B. blumeana* and Anokye *et al.* (2014) for *Gigantochloa scortechinii* (*G. scortechinii*) and *Bambusa vulgaris* (*B. vulgaris*), where a mean ratio of 1.41:1.0 and 1.15:1.0 was observed, respectively. Longitudinal shrinkage was minimal with 0.5% at the butt and middle and 0.2% at the top of the test culm. The mean result of 0.4% fell between the results of Anokye *et al.* (2014) on *G. scortechinii* and *B. vulgaris*, Correal and Arbelaez (2010) on *Guadua angustifolia* Kunth (*G. angustifolia* Kunth) and Zaragoza-Hernandez *et al*. (2015) on *Guadua aculeata* (*G. aculeata)*, where mean shrinkage values along the longitudinal axis of 0.3%, 0.6%, 0.5%, and 0.1%, respectively, were observed.

The relative density was 517 kg/m^3, 559 kg/m^3, and 634 kg/m^3 at the butt, middle, and top, respectively. It significantly increased from the butt to the top of the culm with a p-value of 0.05. This increase is attributed to the change in percentage of vascular bundles to parenchyma. Liese (1974) specified that the total number of vascular bundles decreases steadily with the height of the culm, whereas at the same time their closeness increases, and the parenchyma content decreases. An increase in fiber to parenchyma ratio explains the increase in density toward the top. With the relative density being an important indicator property for mechanical properties (Janssen 1980; Espiloy 1992; Trujillo 2017), the increase positively affects the mechanical properties toward the top, as will be observed in the results presented below. The average density was observed to be 570 kg/m^3. In previous studies of *B. blumeana*, relative densities of 578 kg/m^3 (Latif *et al.* 1992) and 644 kg/m^3 (Espiloy 1992) were reported. Compared with other tested species reported by Latif *et al.* (1992) and Espiloy (1992), these values were considered high. A density of 852 kg/m^3, which is 49% higher, was reported for *B. blumeana* from Thailand tested in dry condition. In comparison with other bamboo species tested in green condition according to ISO 22157, the relative density of *B. blumeana* is in the medium range. *Guadua velutina (G. velutina)* and *Guadua amplexifolia (G. amplexifolia)* have 25% and 15% lower relative densities, respectively (Ordonez-Candelaria. and Barcenas-Pazos 2014), whereas that of *G. aculeata* is comparable to that of *B. blumeana* (Zaragoza-Hernandez *et al.* 2015). For *G. angustifolia* Kunth and *P. pubescens*, 30% and 26% higher relative densities were reported by Correal and Arbelaez (2010) and Deng *et al.* (2016), respectively. Sompoh *et al.* (2013) compared the relative density of *B. blumeana* with other species tested in dry condition and reported 7% to 10% lower results for *Bambusa bambos* (*B. bambos*), *Dendrocalamus asper* (*D. asper*), and *Dendrocalamus hamiltonii* (*D. hamiltonii*). Compared to the results for *B. blumeana* of this study tested in green condition, the relative densities for *B. bambos*, *D. asper,* and *D. hamiltonii* were 34% to 44% higher, which highlights the change of properties below the FSP of bamboo species.

Examination of the radial distribution of the density has revealed that the weaker interior regions of the bamboo cross section can be attributed to lower fiber density, as identified through nano- and microscale studies such as (Tan *et al*. 2011; Dixon and Gibson 2014; Liese and Koehl 2016). This aspect was not further evaluated in this study, as the construction system uses the full culm.

The raw data of the physical properties of three- to four-year-old *B. blumeana* of this study are presented in Table 3, in comparison with previous test results on the same bamboo species from other sourcing locations and test standards or test conditions. The raw data of the physical properties of other bamboo species tested according to ISO 22157 is compared to the results of this study in Table 4.

Table 3. Physical Properties of *B. blumeana* According to ISO 22157 and Different Test Standards and Sourcing Locations

Species, Country, Source	Moisture Content (%)				Relative Density (kg/m³)				Shrinkage Wall Thickness (%)				Shrinkage Outside Diameter (mm)				Shrinkage Length (mm)			
	B	M	T	All	B	M	T	All	B	M	T	All	B	M	T	All	B	M	T	All
B. blumeana Philippines ISO22157 (2004) (authors), *m*	97.6	75.4	62.1	78.4	517	559	634	570	6.2	8.8	4.0	6.3	3.6	6.6	5.2	5.1	0.55	0.52	0.19	0.42
B. blumeana Philippines ISO22157 (2004) (authors), range	74.2 to 121.5	60.8 to 92.2	36.9 to 84.2		423 to 607	440 to 639	500 to 766		2.5 to 10.3	3.3 to 19.8	0.9 to 9.0		2.4 to 5.0	3.8 to 19.8	4.3 to 6.3		0.14 to 1.74	0.08 to 0.95	0.04 to 0.06	
B. blumeana Philippines IS6874 (1973) (Espiloy 1992), *m*	107.2	90.7	80.4	92.8	587	650	694	644	11.3	13.7	11.0	12.0	8.9	9.9	6.8	8.5				
B. blumeana Malaysia IS6874 (1973) (Latif *et al.* 1992), *m*	95.8	79.5	57.5	77.8	513	603	620	578	8.1	6.1	5.7	6.6	18.0	9.0	6.3	11.1				
B. blumeana ISO22157 Thailand dry MC 10.7% (Sompoh *et al.* 2013), *m*	12.0	11.0	11.0	11.3	784	935	837	852	5.1	4.4	3.8	4.4	5.8	4.5	4.2	4.8	0.20	0.20	0.00	0.13

B, butt of culm; M, middle of culm; T, top of culm; *m*, mean of sample

Table 4. Physical Properties of Other Bamboo Species According to ISO22157

Species, Country, Source	Moisture Content (%)				Relative Density (kg/m^3)				Shrinkage Wall Thickness (%)				Shrinkage Outside Diameter (mm)				Shrinkage Length (mm)			
	B	M	T	All	B	M	T	All	B	M	T	All	B	M	T	All	B	M	T	All
G. angustifolia Kunth Colombia (Correal and Arbelaez 2010)				59.4	659	755	779	721				6.5				5.1				0.6
G. aculeata, Mexico (Zaragoza-Hernandez *et al.* 2015)	>FSP				560	560	660	593	15.5	15.9	10.2	13.9	8.1	7.8	5.5	7.1	0.1	0.1	0.1	0.1
G. amplexifolia, Mexico (Ordonez-C. and Barcenas-P. 2014)	164	140	116	140	427	476	546	483												
G. velutina, Mexico (Ordonez-C. and Barcenas-P. 2014)	183	151	129	154	391	430	492	438												
D. hamiltonii, Thailand dry (Sompoh *et al.* 2013)				23.0	608	808	961	792	4.2	4.5	4.1	4.2	2.8	3.9	2.8	3.2	0.35	0.09	0.12	0.19
B. bambos, Thailand dry (Sompoh *et al.* 2013)				18.7	856	799	804	820	8.5	7.7	6.0	7.4	7.6	7.0	5.8	6.8	0.14	0.15	0.20	0.16
D. asper, Thailand dry (Sompoh *et al.* 2013)				11.3	748	773	779	767	4.5	6.5	2.2	4.4	4.3	5.4	3.9	4.5	0.1	0.0	0.0	0.03
P. pubescens dry China (Deng *et al.* 2016)	8.0 to 12.0				669	723	770	721												

B, butt of culm; M, middle of culm; T, top of culm; *m*, mean of sample

Mechanical Properties

The mean compressive strength parallel to the grain was 36.4 MPa, and the characteristic strength value 20.0 MPa, as documented in Table 5. The characteristic compressive strength compares to the strength class C22 for sawn timber (EN338 2016). The compressive strength increased from the butt toward the top of the culm, similarly to the previously attested increase in density toward the top. The compressive strength according to Espiloy (1992) was 16% higher, while Latif *et al.* (1992) found 26% lower compressive strength of *B. blumeana*. The results of Espiloy (1992) and Latif *et al*. (1992), stated in Table 8, remain difficult to compare to directly, as a merger of the Indian Standard IS 6874 (1973) with a modification of the ASTM D143-94 standard (1994) as well as the Indian Standard IS 6874 (1973) alone was applied for the Philippines and Malaysia, respectively. The results highlight the importance of standardized testing procedures as indicated in (Harries *et al.* 2012), to effectively identify variations among sourcing locations. The compressive strength for *G. angustifolia* was comparable to *B. blumeana* (Correal and Arbeláez 2010), while it was 15% higher than for *G. aculeate* (Zaragoza-hern *et al.* 2015). In previous research, the compressive strength was attested to be most affected by change in MC below the FSP (Xu *et al.* 2014). Testing of this study was conducted in green condition, and results are therefore considered conservative.

For comparison to results of (Deng *et al.* 2016; Made Oka *et al.* 2014; and Somproh *et al.* 2013) on bamboo species tested according to ISO 22157 in dry condition, reference is given to studies on MC adjustment for *G. angustifolia* (Gutierrez *et al.* 2015) and *P. pubescens* (Xu *et al.* 2014). However, MC adjustments are not yet standardized for *B. blumeana* specifically and for bamboo engineering across different strength classes generally; therefore this comparison is made with uncertainty and requires further research. Results of the same species but air-dry samples of 12% MC by Somproh *et al.* (2013) were 83% higher than of this study. This increase is larger than MC adjustments identified for other bamboo species. Xu *et al*. (2014) observed that the compressive strength of *P. pubescens* specimen of air-dry samples was 33% higher than of that at its FSP (Xu *et al.* 2014). In Ordonez-Candelaria and Barcenas-Pazos (2014), an increase of 15% and 52% in compressive strength was found for specimens of *G. amplexifolia* and *G. velutina* comparing green and dry condition. For *G. aculeate*, an increase of 68% was attested by Zaragoza-Hernandez *et al.* (2015). Comparing results tested in dry condition published for *Gigantochloa atroviolacea* (*G. atroviolacea*) (Made Oka *et al.*) and *P. pubescens* (Deng *et al.* 2016) to the current study, 42% and 51% higher results in compressive strength were found respectively.

The delta is lower in comparison to the dry tested results for *B. blumeana* published by Somproh *et al.* (2013). The wide range of MC adjustments between green and dry condition across and within a species, documented in Table 9, highlights that more research on MC adjustment for bamboo is needed. Testing in green condition facilitates comparability for the meantime. A visualization of the compressive strength values is seen in Fig. 2.

The mean tensile strength parallel to the grain was 162.3 MPa, and the characteristic strength value 94.9 MPa. The internode tensile strength significantly increased from the butt toward the top, with a p value of 0.01, whereas in the node the increase was not significant. The increase of tensile strength in vertical direction toward the top can be explained by a higher share of fibers toward the top, as discussed in the section of physical properties above. The tensile strength at the node was lower than that at the internode. According to Janssen (1980), the fibers in a node are interrupted by crossing vessels passing into the diaphragm inside the node. Because the mechanical elasticity is reduced by the shorter, thicker, and forked fibers in the nodule, bamboo culms under tension often break at the node (Liese 1974), which was confirmed by failure at the nodes of the tension specimen of *B. blumeana*. In global comparison, results of tensile strength varied the most across species with a range of 59 to 227 MPa, as documented in Table 9. The tensile testing parallel to the grain with the wedge-shaped specimen caused also in the current study problems with unintended failure mechanisms in shear, which was already indicated in ISO 22157-2 (2004). Consequently, these results caused by unintended failure mechanisms were excluded. In Irawati *et al.* (2012) and Dela Cruz *et al.* (2017), alternative specimen shapes were used that resulted in a higher rate of correct failures; these shapes thus appear worthwhile for consideration in a revision of the standard. Further it was noted that several previous studies did not include tensile strength testing in their publications, such as (Correal and Arbeláez 2010; Ordonez-Candelaria and Barcenas-Pazos 2014; Deng *et al*. 2016). An improved test procedure with a higher rate of intended failures but no increase of complexity for specimen production may incentivize researchers to include tensile strength testing in their test agendas. In addition, it is noted that tensile strength perpendicular to the grain is a largely ignored property of bamboo. However, it is critical for structural performance. To date, perpendicular tension is not included in ISO 22157. In (Sharma *et al.* 2013) and (Dela Cruz *et al.* 2017b), varying recommendations for its test procedure were provided. Further research is recommended to form a baseline for a testing protocol for inclusion in the standard.

The mean shear strength was 7.9 MPa, and the characteristic strength value was 5.1 MPa. The shear strength slightly increased toward the top with a p value of 0.05; however, there was no significant difference between the middle and butt of the culm. The latter was true for specimens with nodes and internodes. The existence of a node did not lead to an increase of the shear or tensile strength but to rather lower results. This finding is in line with previous reports (Made Oka *et al.* 2014). Compared to the current study, (Latif *et al.* 1992) found 39% lower shear strength for *B. bluemeana*, while (Espiloy 1992) did not assess it. Next to the variation of test procedures, also the sourcing location may have caused the lower results. The variation observed between *B. blumeana* testing of this research and that performed by Somproh *et al*. (2013) was in the expected range between green and dry state as also reported by Xu *et al*. (2014) for *P. pubescens* with 55% and 51% increase, respectively. All results of *B. blumeana* are stated in Table 8. The results of five other bamboo species tested in green condition ranged from 3.1 to 7.6 MPa. Test results of nine bamboo species with specimen near or below the FSP and in dry conditions ranged from 5.7 to 13.6 MPa. All results for other bamboo species are stated in Table 9. According to the current study, the shear strength of *B. blumeana* is at the upper end of a previously defined range for green specimen. It is noted that the shear strength calculation assumes the development of four shear planes. However, the failure was mostly observed in one of the planes. It is recommended to conduct tests on alternative specimen shapes for shear strength that delivering failures in all the tested shear planes.

The mean bending strength was 62.8 MPa, and the characteristic strength value 34.6 MPa. The obtained bending strength values were characteristically high, reflecting the flexibility of bamboo. Espiloy (1992) and Latif *et al*. (1992), found 14% lower and 77% higher bending strength, respectively, as displayed in Table 8. Bending strength results were specifically influenced by the variation in test standards, as three point bending tests were applied before. The modulus of rupture increased from the butt towards the top of the culm, which is explained by anatomical changes toward the top (Janssen 1980). The mean results of nine other bamboo species, tested in green and dry condition according to ISO 22157-1 (2004), ranged from 61 to 95 MPa. The mean *B. blumeana* results of the current study were therefore at the lower end of the range, as documented in Table 9. Because of the long internode distance of *B. blumeana* culms, the wooden saddle supports used for testing the bending strength in the current study caused crushing failure in some specimens. These results were consequently rejected from the assessment. The wooden saddles were not always located above or below a node; however, this discrepancy from the ISO recommendation could not be avoided because the symmetric distance between supporting saddles had to be maintained. *G. angustifolia* was superior by approximately one-third in terms of the bending strength (Correal and Arbeláez 2010). Bending testing with belts instead of wooden saddles, as documented in the publication, may have contributed to obtain higher bending strength results.

In summary, the characteristic strength values of *B. blumeana* were as follows: compressive and tensile strengths parallel to the grain ($f_{c,0,k}$ = 20 MPa and $f_{t,0,k}$ = 95 MPa), shear strength ($f_{v,k}$ = 5 MPa), and bending strength ($f_{m,k}$ = 34.6 MPa); in addition, the mean MOE and the MOE at fifth percentile were E_{mean} = 13100 MPa and $E_{0.05}$ = 8600 MPa, respectively. Tables 5 and 6 present the calculated characteristic strength of the current study based on the raw data of *B. blumeana*. Table 7 provides a summary of the characteristic strength values. The mechanical performance of *B. blumeana* can be considered suitable for structural application in low-rise housing. The compressive and tensile strength along the grain and bending strength of *B. blumeana* demonstrate the potential of bamboo for construction. Construction methods must be found, which consider the low shear strength of bamboo culms especially in connections (Latif *et al.* 1992). Table 8 shows the mechanical properties of previous studies on *B. blumeana*, with other sourcing locations and test standards or test conditions. Table 9 documents the mechanical properties published for other bamboo species according to ISO 22157-1 (2004). Overall, the performance of *B. blumeana* was in the expected range of results of previous studies on full bamboo culms used for structural purpose. Figure 2 visualizes selected mechanical properties of various bamboo species, including *B. blumeana*.

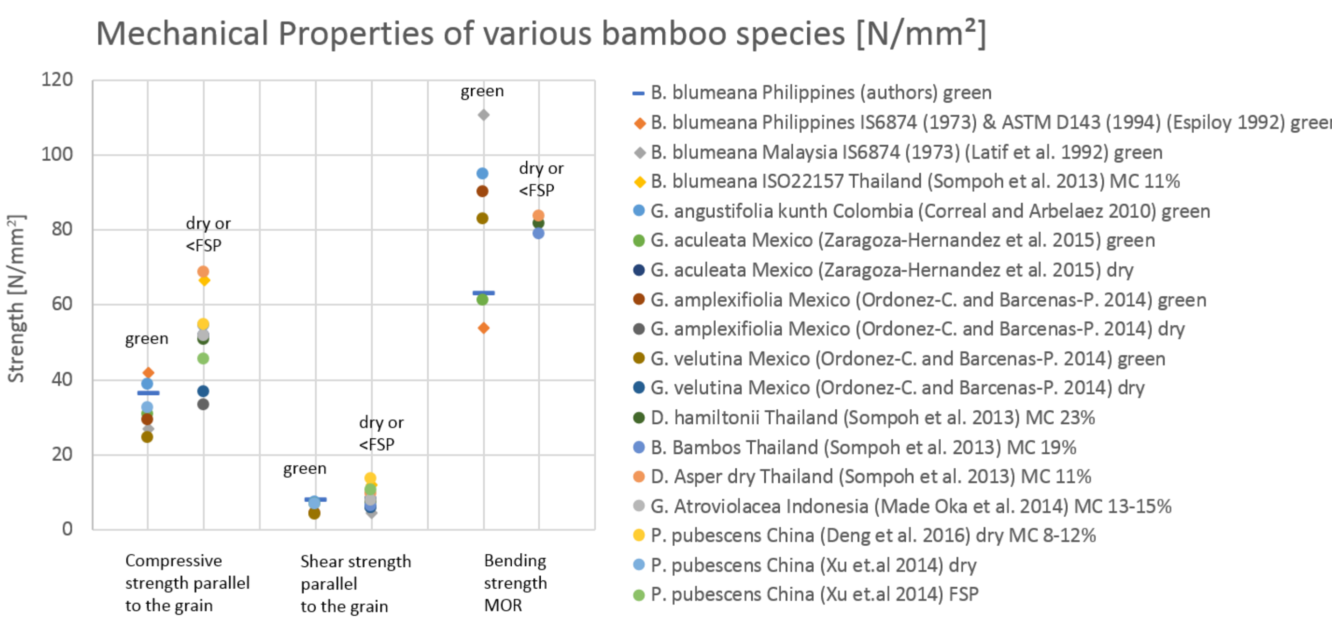

Fig. 2. Mechanical Properties of various bamboo species, including *B. blumeana,* in [N/mm^2]

Table 5. Strength Properties of *B. blumeana*

Property	Compressive Strength Parallel to the Grain (N/mm²)				Tensile Strength Parallel to the Grain (N/mm²)				Bending Strength MOR (N/mm²)				Modulus of Elasticity (Bending) MOE (1000 N/mm²)			
Position	B	M	T	All	B	M	T	All	B	M	T	All	B	M	T	All
m	31.2	37.4	40.6	36.4	126.5	174.1	187.6	162.3	56.7	62.5	69.0	62.8	11.7	14.1	13.5	13.1
s	6.9	9.0	5.4	8.0	22.1	33.1	45.7	43.2	16.1	19.9	14.5	17.2	2.0	4.3	3.7	3.5
$f_{0.05}$	22.0	24.7	34.0	22.5	101	127.5	128.3	104.7	39.9	39.9	52.5	39.9	9.1	7.7	8.6	8.6
n	10	10	10	30	20	20	19	59	10	10	10	30	10	10	10	30
f_k	17.8	19.6	30.1	**20.0**	90.3	112.9	108.9	**94.9**	30.2	29.1	43.1	**34.6**	7.7	5.7	6.5	**7.4**

B, butt of culm; M, middle of culm; T, top of culm; m, mean of sample; s, standard deviation; $f_{0.05}$, 5th percentile value of the sample (N/mm²); n, size of sample; f_k, characteristic value (N/mm²);

Table 6. Shear Strength at Nodes and Internodes

Property	Shear Strength Parallel to the Grain (N/mm²)						
Position	B		M		T		All
	Node	Internode	Node	Internode	Node	Internode	
m	7.1	6.9	7.4	8.1	8.8	9.4	7.9
s	0.8	1.1	1.9	1.5	1.6	1.7	1.7
$f_{0.05}$	6.1	5.5	5.4	6.0	6.8	7.2	5.5
n	10	10	10	10	10	10	60
f_k	5.4	4.7	4.2	5.1	5.8	6.1	**5.1**

m, mean of sample; s, standard deviation; $f_{0.05}$, 5th percentile value of the sample (N/mm²); n, size of sample; f_k, characteristic value (N/mm²)

Table 7. Summary of Characteristic Strength Values for *B. blumeana*

Property	Symbol	Characteristic Strength
Compression strength parallel to grain	$f_{c,0,k}$	20 MPa
Bending strength	$f_{m,k}$	34.6 MPa
Shear strength	$f_{v,k}$	5 MPa
Tension strength parallel to grain	$f_{t,0,k}$	95 MPa
Modulus of elasticity - mean	E_{mean}	13.1 GPa

Table 8. Previous Mechanical Properties of *B. blumeana* According to Other Test Standards or Test Conditions with Varying Sourcing Regions

	Compressive strength parallel to the grain (N/mm²)	Tensile strength parallel to the grain (N/mm²)	Shear strength parallel to the grain (N/mm²)	Modulus of elasticity bending (1000 N/mm²)	Bending strength MOR (N/mm²)
B. blumeana Philippines IS6874 (1973) & ASTM D143 (1994) (Espiloy 1992)	42.2			10.2	54.2
B. blumeana Malaysia IS6874 (1973) (Latif *et al.* 1992)	27.1		4.8		110.9
B. blumeana ISO22157 Thailand MC 10.7% (Sompoh *et al.* 2013)	66.5	253.8	12.3		92.0

Table 9. Previous Mechanical Properties of Other Bamboo Species According to ISO22157

<table>
<tr><th></th><th colspan="2">Compressive strength parallel to the grain (N/mm²)</th><th colspan="2">Tensile strength parallel to the grain (N/mm²)</th><th colspan="2">Shear strength parallel to the grain (N/mm²)</th><th>Modulus of elasticity bending (1000 N/mm²)</th><th>Bending strength MOR (N/mm²)</th></tr>
<tr><td></td><td>>FSP</td><td>dry</td><td>>FSP</td><td>dry</td><td>>FSP</td><td>dry</td><td></td><td></td></tr>
<tr><td>G. angustifolia Kunth Colombia (Correal and Arbelaez 2010)</td><td>38.9</td><td></td><td colspan="2"></td><td>7.6</td><td></td><td>17.4</td><td>94.8</td></tr>
<tr><td>G. aculeata Mexico (Zaragoza-Hernandez et al. 2015)</td><td>30.8</td><td>51.8</td><td></td><td>71.5</td><td>6.7</td><td>8.3</td><td>16.8</td><td>61.1</td></tr>
<tr><td>G. amplexifiolia Mexico (Ordonez-C. and Barcenas-P. 2014)</td><td>29.2</td><td>33.5</td><td colspan="2"></td><td>4.4</td><td>5.8</td><td>18.5</td><td>90.0</td></tr>
<tr><td>G. velutina Mexico (Ordonez-C. and Barcenas-P. 2014)</td><td>24.4</td><td>36.9</td><td colspan="2"></td><td>4.3</td><td>5.7</td><td>17.4</td><td>82.8</td></tr>
<tr><td>D. hamiltonii Thailand (Sompoh et al. 2013) MC 23%</td><td colspan="2">50.8</td><td colspan="2">58.7</td><td colspan="2">7.5</td><td></td><td>81.4</td></tr>
<tr><td>B. bambos Thailand (Sompoh et al. 2013) MC 19%</td><td colspan="2">54.3</td><td colspan="2">131.3</td><td></td><td>6.4</td><td></td><td>78.7</td></tr>
<tr><td>D. asper dry Thailand (Sompoh et al. 2013) MC 11%</td><td></td><td>68.7</td><td></td><td>227.2</td><td></td><td>9.4</td><td></td><td>83.7</td></tr>
<tr><td>G. atroviolacea Indonesia (Made Oka et al. 2014) MC 13-15%</td><td></td><td>51.6</td><td></td><td>182.1</td><td></td><td>7.7</td><td></td><td></td></tr>
<tr><td>P. pubescens China (Deng et al. 2016) dry MC 8-12%</td><td></td><td>54.8</td><td colspan="2"></td><td></td><td>13.6</td><td></td><td></td></tr>
<tr><td>P. pubescens (Xu et al. 2014)</td><td>32.8</td><td>45.4</td><td colspan="2"></td><td>7.0</td><td>10.6</td><td></td><td></td></tr>
</table>

Recommendations

Table 10 presents the characteristic strength values for *B. blumeana*. In accordance with the state design principles, the permissible stresses for using *B. blumeana* in low-rise construction in the Philippines were derived by dividing by the safety factors.

Table 10. Summary of Characteristic Strength and Suggested Permissible Stresses for *B. blumeana* Bamboo

Property	Characteristic Strength		Permissible Stress	
	Symbol	Value	Symbol	Value
Compression Strength Parallel to Grain	$f_{c,0,k}$	20 MPa	$f_{c,0,adm}$	8.0 MPa
Bending Strength	$f_{m,k}$	34.6 MPa	$f_{m,adm}$	7.7 MPa
Shear Strength	$f_{v,k}$	5 MPa	$f_{v,adm}$	1.1 MPa
Tension Strength Parallel to Grain	$f_{t,0,k}$	95 MPa	$f_{t,0,adm}$	21 MPa
Modulus of Elasticity - Mean	E_{mean}	13.1 GPa	E_{mean}	13.1 GPa
Modulus of Elasticity - 5th Percentile	$E_{0,05}$	7.4 GPa	E_{min}	7.4 GPa
Density - Mean	ρ_{mean}	570 kg/m^3	ρ_{mean}	570 kg/m^3

Given the natural variability of bamboo, conservative safety factors are recommended. A safety factor of 4.5 is considered for permanent loads, which is in line with ISO 22156 (2004) and conservative compared with Eurocode 5 EN 1995-1-1 (2004). The latter can be reduced for loads that last for short durations.

Utilization of Test Results

The suggested permissible stresses stated in this work are only applicable for construction for quality-controlled, mature *B. blumeana* bamboo culms from the Philippines. The physical and mechanical properties reported here are only a step toward a more widespread application of bamboo for house construction. Further sourcing regions of the same species or additional bamboo species may be tested in its addition according to ISO22157 (2004) and ISO 22156 (2004). For strategic utilization and entry of bamboo into the low-rise building sector in the Philippines, studies on high-performing, cost-efficient bamboo-based construction systems must be performed. Building methods can use the favorable compressive, tensile and bending strength of bamboo culms, while their weakness in shear strength needs consideration, especially for connection design transferring the loads reliably during the entire lifespan of the houses. An example of such a study from Colombia is that of Lopez Munoz (2000). To facilitate larger scale use of a bamboo species in construction, a strength grading as described by (Trujillo 2017) for *G. angustifolia* Kunth may be implemented to simplify the selection of culms for structural purpose in the Philippines through a rapid selection process. Further, the use of bamboo in construction requires treatment and protection by design as a prerequisite because degradation would otherwise limit its lifespan. Negative implications of insufficient protection against aging have been confirmed both through accelerated laboratory testing (Huang *et al.* 2014) and long-term studies with exposure to outdoor applications (Cardona *et al.* 2002; Beraldo 2016).

The physical and mechanical properties for *B. blumeana* stated in this paper can contribute to address bamboo-based housing in the Philippines holistically. This research informs a participatory, South-South knowledge exchange between Colombia and the Philippines on bamboo-based building. The latter enables an effective, accelerated learning curve to meet multi-stakeholder needs of social housing in the Philippines and elsewhere, while it highlights the importance of local participation, context adaptation and placing people's needs at the center (Base Builds 2015). Next to the characterization of the species, consideration is given to the use-phase of bamboo-based houses, including its durability and maintenance efforts; flexibility for upgrading and expansion; performance under extreme impact events such as fire, earthquakes, or intense winds; and thermal comfort. Through open development and multi-stakeholder feedback loops, science and technology can inform communities, policy makers, professionals and further stakeholder groups effectively. Forming multi-stakeholder partnerships is essential to address the tremendous challenge of social housing in an urban century (UN-ESCAP and UN-Habitat 2011).

CONCLUSIONS

1. This paper elucidates the structural qualities of *B. blumeana* bamboo sourced from a characteristic bamboo growing region of the Philippines. The species exhibited properties of structural quality, and it is generally recommended and suitable for use in low-rise construction. Characteristic strength values were computed based on the test results. A recommendation for permissible stresses was made, which can serve in structural design when using the bamboo species for the construction of low-rise houses. The results of this work are only applicable for construction when the bamboo culms are being quality-controlled and embedded in a suitable building method.
2. The physical and mechanical properties of *B. blumeana* were in the same range as other species around the world, which are used for structural purpose in their full culm such as *G. angustifolia* Kunth, *G. aculeata*, *D. asper*, *G. atroviolacea*, and *P. pubescens.*
3. The standardized assessment of physical and mechanical properties according to ISO22157-1, ISO22157-2, and ISO22156 is recommended for full culm characterization of *B. blumeana* sourced from further locations in the Philippines and Asia-Pacific as well as for further bamboo species around the world. It enables comparability among different regions, test dates, and species. Testing in green condition will facilitate comparability. An update of the ISO standards is recommended, based on available tests results suggesting the revision of existing or the inclusion of additional test protocols.
4. The present research is a starting point to further research and application, higher acceptance and collaboration. For durable results, an effective bamboo treatment and protection by design is required. Research on the use-phase of bamboo-based houses is recommended, tackling the requirements of stakeholder groups in urban social housing. Sustainable harvesting practices are important, to ensure sustainability of using the species in the long term. For an effective use of the test results, participatory application, multi-stakeholder partnerships as well as regional and global knowledge exchanges are recommended.

ACKNOWLEDGMENTS

The authors thank the Hilti Foundation for funding this research. The authors also acknowledge the Chalmers Area of the Advance Built Environment profile "Responsible Use of Resources", which supports affordable building-related research. The authors appreciate the contribution of Bambou Science et Innovation and Fundeguadua triangulating test procedures and acknowledge the Forest Products Research and Development Laboratory Los Banos Philippines, where the testing was conducted. Finally, the authors thank Tiffany Jain, M.S., from Edanz Group for English editing a draft of this manuscript.

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Article submitted: October 12, 2016; Peer review completed: December 29, 2016; Revised version received and accepted: October 30, 2017; Published: November 20, 2017.
DOI: 10.15376/biores.13.1.346-369