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Mechanical properties of bamboo: a research synthesis of strength values and the factors influencing them

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Bamboo is a rapidly renewable resource, used in many countries as a viable building construction material. It is not widely used in the U.S. or other western countries however, partly because it is not yet included in building codes or safety standards. To develop these, the mechanical properties of bamboo must be fully understood and documented. Studies have been published by many different researchers, but they have not yet been aggregated or compared. From this literature 43 publications (in English, Portuguese, and Spanish) presenting mechanical properties for bamboos were selected and analyzed. Five mechanical properties were reviewed: shear strength, compressive strength, tensile strength, modulus of rupture (MOR), and modulus of elasticity (MOE). Properties were found to have a wide range, so major variables were investigated: age, bamboo species, density, moisture content, post-harvest treatment, and the testing standards employed. The findings suggest no consistent correlations exist between mechanical property values reported and these variables, although substantial variation was attributable to species, moisture content, and the test standard used, and we present overall average values. We propose that for practical purposes the inherently high variability in mechanical properties of bamboo suggested by this analysis can be accounted for by the use of appropriately high safety factors, but further research is clearly required.

INTRODUCTION

Currently, dynamic changes are occurring in the world from rapid increases in population, affluence, and associated consumption of resources (Zimmerman et al. 2008) with many natural material reserves being stressed. This has led to water scarcity, deforestation, and mineral depletion. One path forward to a more sustainable future is through wider adoption of an underutilized natural and renewable plant material: bamboo, of the grass family Poaceae. Bamboo is an advantageous and sustainable material mainly due to its fast growth, reaching maturity in 2 - 4 years, when some species become ready for use in engineering applications (Limay 1952; Liese 1991; Liese 2004). Cusak (1999) noted: "there could never be enough silver flutes to give one to everybody in the world. There could, easily, be enough bamboo for all 50 billion fingers on the earth to make and play their own."

Since bamboo grows natively, is cultivated, and is naturalized in many countries, it also has the potential to improve community well-being for a variety of peoples of different cultures. Parts of many species of bamboo can be used: its shoots as a nutritious food (Zheng et al. 2013; Badwaik et al. 2014), its leaves as improved chicken and cattle feed (Ogunwusi & Onwualu 2013), and its culm (the focus of this paper), which can number 5,000–10,000 per hectare, as a sturdy, inexpensive, and readily available building material (Lipangile 1991). Traditionally, bamboo is also used as a home building material as well as for repelling insects, flooring, and basket making (Laha 2000; Arinasa & Bagus 2010; Teron & Borthakur 2012). Commercially, bamboo is used in part as a material to manufacture paper, clothing, corrugated roofing, and walls (Verma & Chariar 2012; Sathish et al. 2017). In fact, bamboo housing has been found to be more resistant to earthquakes than unreinforced masonry (Edwards & Doing 1995; Macdonald 1999). It has additionally been used as outdoor piping for water supply (Lipangile 1991) and as fast-producing biomass (Liese 1987). More recent science has taken a new look at bamboo, using it in research for improved wastewater treatment (Colin et al. 2007) and in its nanoparticle form for cancer research (Xie et al. 2017). Bamboo therefore presents itself as a viable material for a wide variety of uses for high-income as well as economically-marginalized areas. However, it has not received global attention as a common building material.

Compared to the global use of conventional building materials such as steel, cement, and timber, bamboo use is significantly smaller. In fact, it is reported that in 2012, the export of manufactured bamboo products was approximately 1,500 times less than steel, 700 times less than concrete, and 400 times less than timber (Trujillo 2018). Nevertheless, bamboo has a great potential for global use. Unfortunately, there is a general lack of information, understanding of the material properties, or research findings to advance the use of bamboo.

Current literature demonstrates there are large gaps in knowledge regarding bamboo mechanical properties (Valero et al. 2005; Fabiani 2015). Liese (1992) stated that "a thorough understanding of the relations between structure, properties, behavior in processing and product qualities is necessary for promoting the utilization of bamboo." Supporting this notion, Wang et al. (2014), wrote "to promote the widespread application of bamboo in construction and other engineering fields, far more knowledge and understanding of its mechanical properties is required." This lack of knowledge extends to building codes for bamboo which are likewise in need of development (Lugt et al. 2006). Kaminski et al. (2016) noted "bamboo will be as well understood as timber is, but we have some way to go before that happens."

Although the mechanical properties of bamboo have been tested by different researchers, the data has not been collectively synthesized. Here, these values have been compiled to obtain average values and analyzed by variable to see which are most determinant. Variables analyzed are: age, species, density, moisture content, post-harvest treatment, and testing standard employed.

METHODS

A critical review of the literature identified 43 publications that provided mechanical property values of bamboo to be used for this analysis (see Appendix 1). Considerations for inclusion in this study were: (1) focus on externally peer-reviewed publication, (2) publications that provided access to well-presented data, (3) collecting information that spanned a period of 1981 to 2018, (4) a focus on collecting information that represented the diversity of global contributors (publications from authors of 25 countries are included, including papers published in English, Spanish, and Portuguese).

The five mechanical properties analysed were: shear strength, compressive strength, tensile strength, modulus of rupture (bending strength, MOR), and modulus of elasticity (MOE). From each publication one or more average mechanical property value was extracted per study (i.e. species of bamboo, treatment condition, etc.). These individual mechanical properties were used to derive overall averages and statistical ranges as well as dependency on variables reported in the literature: age, bamboo species, density, moisture content, post-harvest treatment, and testing standard employed. Although this meta-analysis uses only an average value per study so that it weighs all studies equally regardless of sample size, this was determined to be the most appropriate method to compare multiple studies in this case, as many studies only report average values. Accordingly, a goal of this paper was to present and review mechanical property values reported in the literature by different researchers working with different species and testing methods.

Table 1 presents the definitions and symbols used to represent each property. F_v, F_c, F_b, F_t and E_c, E_b, E_t, and E have been adopted from timber specification for comparison and uniformity (Parker 1979).

The mechanical property value data were compiled as follows: shear strength, 18 results conducted by 9 researchers; compressive strength, 59 results from 24

Table 1. Mechanical properties studied and their definitions

Mechanical Property	Symbol	Units	Definition
Shear strength	F_v	MPa	Strength of material when fails in shear
Compressive strength parallel to grain	F_c	MPa	Maximum compressive load divided by initial cross-sectional area
Bending Strength / Modulus of rupture (MOR)	F_b	MPa	Tensile strength at bending failure
Tensile strength	F_t	MPa	Ultimate tensile strength, maximum tensile stress at failure
Compressive Modulus of Elasticity (MOE)	E_c	GPa	Compressive force per unit area divided by change in length over initial length
Bending Modulus of Elasticity (MOE)	E_b	GPa	Ratio of stress to strain in flexural deformation
Tensile Modulus of Elasticity (MOE)	E_t	GPa	Ratio of tensile stress to tensile strain
Combined Modulus of Elasticity (MOE)	E	GPa	Compressive, bending, and tensile MOE values combined

researchers; modulus of rupture (bending strength), 52 results from 18 researchers; tensile strength, 21 results from 7 researchers; compressive MOE, 19 results conducted by 10 researchers; bending MOE, 34 results from 16 researchers; tensile MOE, 10 results from 6 researchers; combined MOE data, 63 results from 32 researchers. To clarify, per published study, one or more average values was obtained, depending on whether the published data was separated by bamboo species, moisture content, or other grouping parameters which the author defined. Data in various sections are shown per mechanical property only if enough data were available (>6 data points).

Other test methods have been performed on bamboo, such as microscopic nano-indentation and non-destructive tests (Yan-hui et al. 2012; Yang et al. 2014; Lin et al. 2006), but only conventional destructive mechanical property tests were considered for this review. Additionally, although mechanical testing has been performed on bamboo composites (e.g., Huang et al. 2014; Bahari et al. 2017; Sathish et al. 2017; Wistara et al. 2017), only studies that tested the bamboo in its original whole or split culm state were assessed.

The main bamboo species reported were *Bambusa vulgaris, Guadua angustifolia, and Phyllostachys pubescens,* and less common species were *Bambusa balcooa, B. blumeana, B. oldhamii, B. pervariabilis, B. salarkhanii, B. tulda, Dendrocalamus asper, D. giganteus, D. strictus, Gigantochloa apus, G. scortechinii, Guadua aculeata, Melocanna baccifera, Phyllostachys aurea, P. bambusoides, P. edulis, P. viridiglaucescens,* and *Schizostachyum brachycladum*.

RESULTS

Mechanical properties of bamboo

The shear, compressive, and tensile strength, along with the bending modulus of rupture are shown in Figure 1 (F_v, F_c, F_t and F_b, respectively). For each test type, the box represent the middle 50% of data and the whiskers represent the upper 25% and lower 25%. The middle line represents the median and the middle "X" is the mean.

The average values shown are: shear strength, 9 MPa; compressive strength, 52 MPa; modulus of rupture, 120 MPa; and tensile strength, 159 MPa.

Figure 2 provides the results for the modulus of elasticity, in compression (E_c), bending (E_b), and tension (E_t). The combined MOE (E), similar to timber, has a consistent MOE regardless of test method used to acquire it (i.e. E_c, E_b, and E_t all have consistent values). The MOE values of timber (Parker 1979) were included in Figure 2 for comparison. The range of values obtained were for the following timber species: California Redwood, Douglas Fir, Larch, Engelmann Spruce, and Southern Pine.

The average values of MOE are: compressive, 16 GPa; bending, 17 GPa; tensile, 14 GPa; combined, 16 GPa.

From Figures 1 and 2, it can be seen that the mechanical properties have a wide range. These studies included many species of bamboo, and similar variability exists for different species of structural timber.

Although the mechanical property values of bamboo range as high as 61% for shear strength, 65% for compressive strength, 60% for MOR, 90% for ultimate tensile strength, and 75% for MOE, these values are comparable to the average deviation of structural timber of different varieties: 23% for shear strength, 52% for compressive strength, 33% for ultimate tensile strength, and 20% for MOE (Parker 1979) for structural timber species, including: California Redwood, Douglas Fir, Larch, and Southern Pine.

It was also found that several mechanical properties are quite understudied for bamboo. These are: impact energy, toughness, and compression perpendicular to grain. Each was only found to be reported in 1–2 publications; those values are presented in Table 2. If bamboo is to be used conventionally, these understudied properties need to be better understood.

Table 2. Mechanical properties and values understudied for bamboo.

Mechanical Property	Value(s)	Average Value	Publication
Compression perpendicular to the grain	1.7 MPa	1.7 MPa	Luna *et al.* 2014
Impact energy	7.6-8.9 J	8 J	Omobowale & Ogedengbe 2008
Poisson's Ratio	0.23-0.35	0.3	Cruz 2002; Ghavami & Marinho 2005
Toughness	17-22 J	20 J	Manalo & Acda 2009

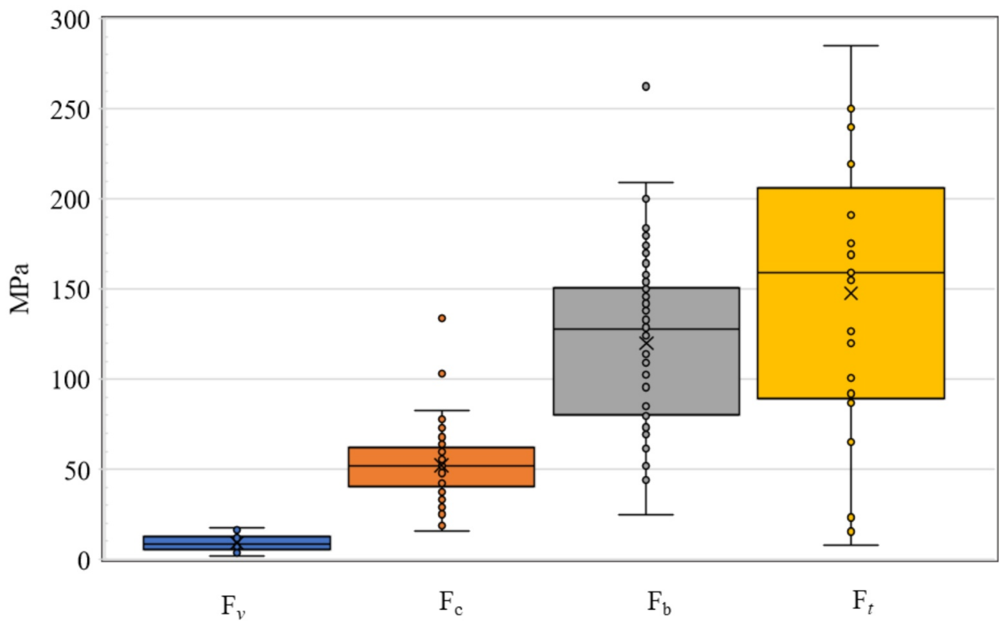

Figure 1. Shear strength (F_v), compressive strength (F_c), modulus of rupture (F_b), and tensile strength (F_t) values. Sample size: F_v (18), F_c (59), F_b (52), F_t (21).

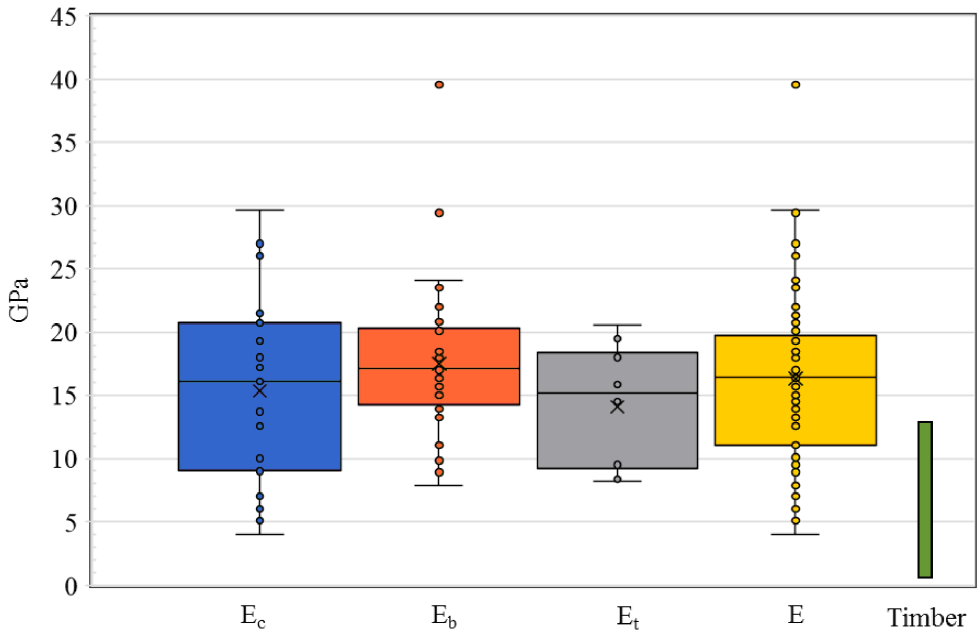

Figure 2. Compressive modulus of elasticity (E_c), bending MOE (E_b), tensile MOE (E_t), and combined MOE (M) values alongside timber values for comparison. Sample size: E_c (19), E_b (34), E_t (10), E (63).

Variables affecting mechanical properties

As one method of explaining variations in mechanical properties, the values for properties were considered in light of different bamboo variables, or factors.

The variability of mechanical properties has been linked to: age, species, density, moisture content, position in culm, post-harvest treatment, and whether or not the node was included in the test specimen. These are individually explored. Although initial defects is a major variable for timber (Parker 1979), it is hardly mentioned as an explanation for bamboo variability in the literature.

1. Age

The literature supports cutting bamboo between 3–4 years old (y.o.) for use as an engineering material. It is well

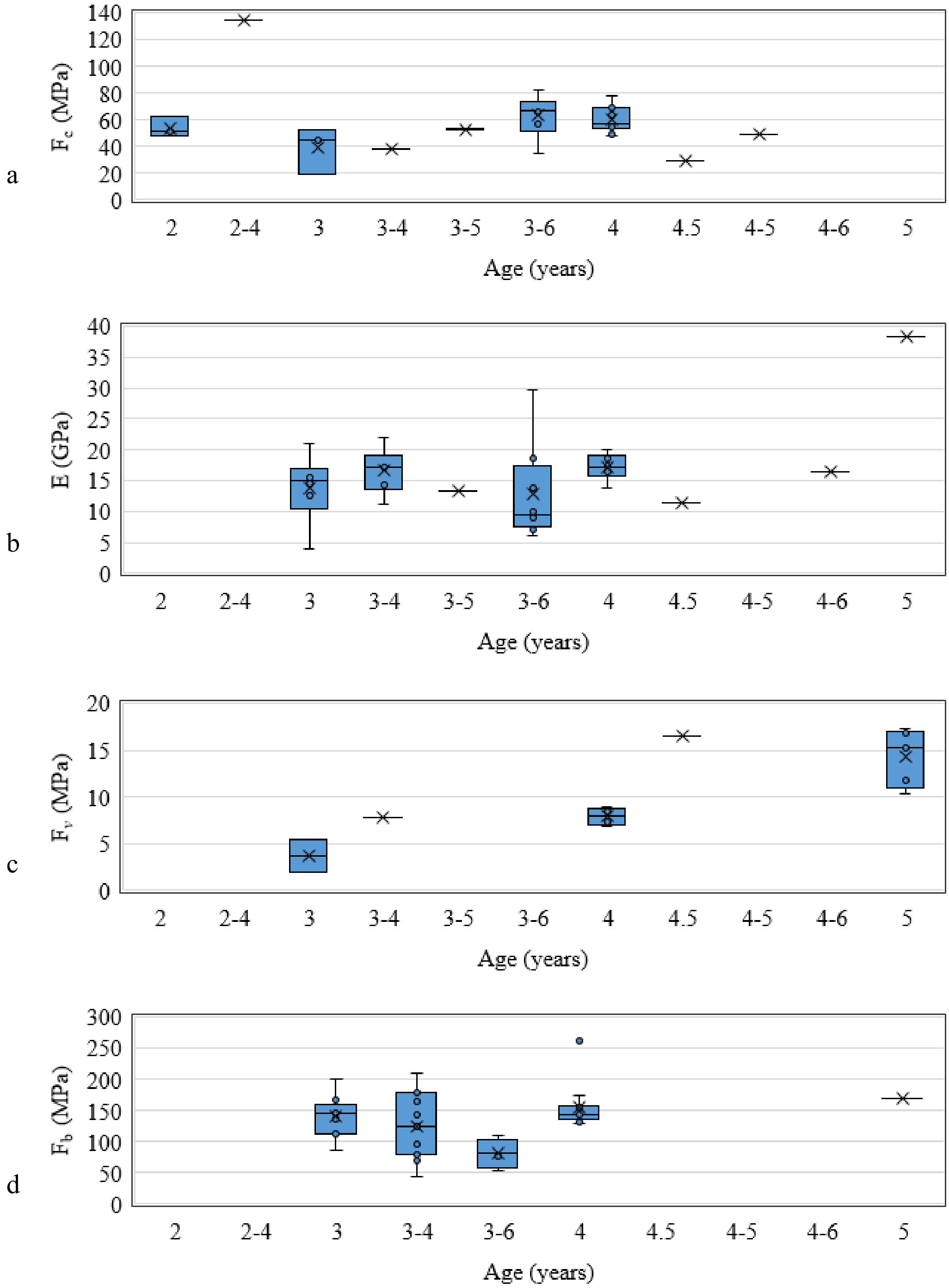

Figure 3. Mechanical strength data sorted by age of the tested bamboo: **a**) comprehensive strength (F_c), **b**) modulus of elasticity (E), **c**) shear strength (F_v), **d**) modulus of rupture (F_b). Sample size: F_c (28), E (19), F_v (13), F_b (37).

known that very young culms (age <1 y.o.) should never be used, and it has been reported that culms aged <3 y.o. are more susceptible to termite attack (Dhawan et al. 2008); that mature bamboo (age 3–4 y.o.) is at the optimum age for the highest value of strength properties (Liese 1992; Kabir et al. 1993); and that old bamboo (age >5 y.o.) becomes less dense, increasingly brittle, and lower in starches (Zhou 1981). The decrease in starches, especially for very old and flowering bamboo, is stated to render the bamboo nearly immune to post harvest pest attack (Liese & Tang 2015). Accordingly, old brittle bamboo could be used in situations that do not require high material properties (e.g., decorative items), having the advantage of natural pest resistance.

This raises the question of how to identify the age of bamboo upon cutting from wild sources or nurseries. In a

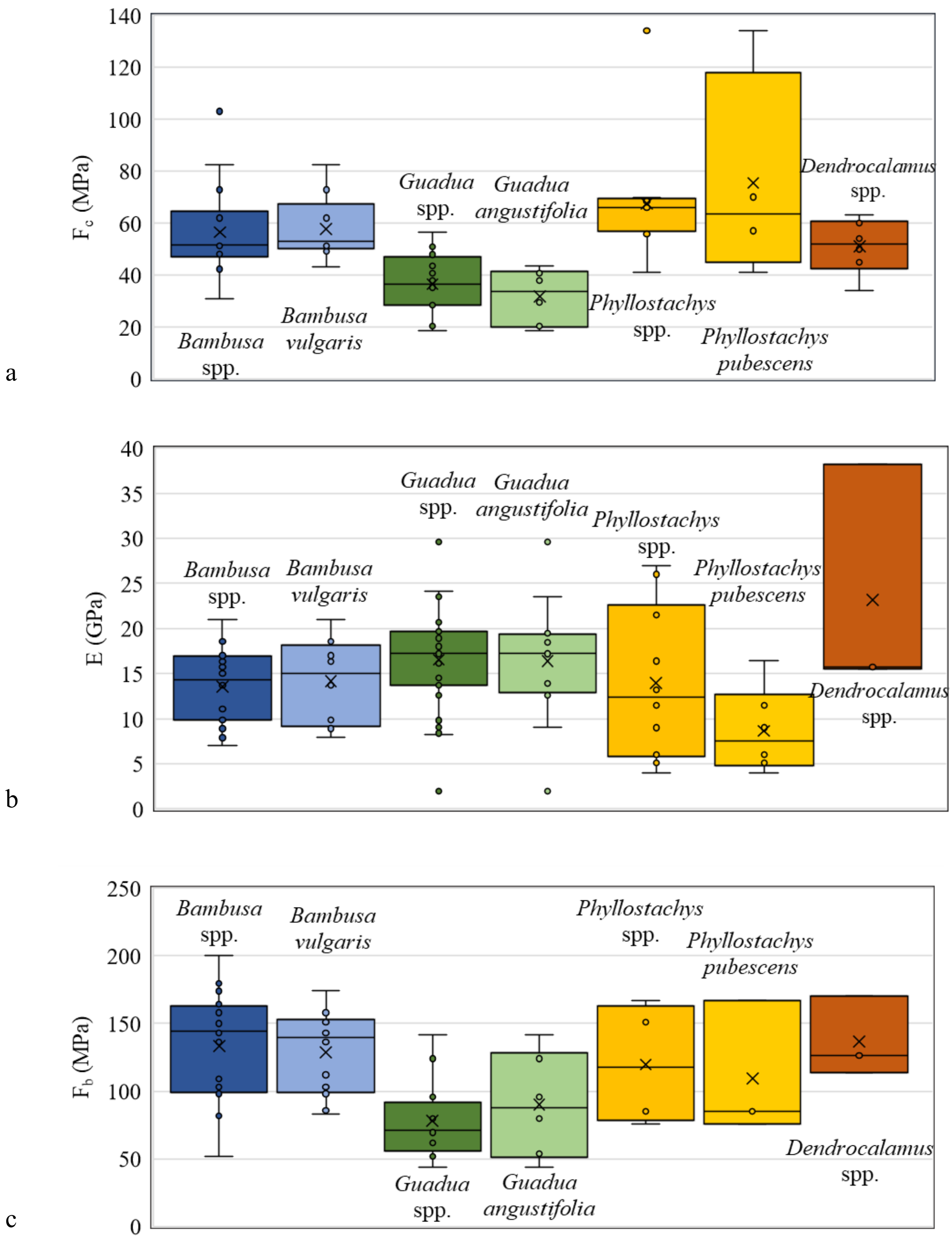

Figure 4. Mechanical strength data sorted by bamboo species and genera: **a**) compressive strength (F_c) **b**) modulus of elasticity (E), **c**) modulus of rupture, the bending strength (F_b). Note that spp. is an abbreviation meaning two or more species. Sample size: F_c (43), E (55), F_b (36).

nursery setting, new shoots can be labeled each year and the age of the culms accurately monitored. For bamboo acquired from wild sources, the estimation of age is less precise although there are some ways to estimate age. While there are no quantitative parameters currently established to identify the age of the bamboo (Londoño et al. 2002), there are qualitative parameters, such as outer color and presence of mold (Ubidia 2002). One study recently found the surface temperature was successful in estimating the age of the culm before cutting (Nölke et al. 2015).

Figure 3 shows that only the shear strength (Figure 3c) showed appreciable effect from the age of the material when it was tested. In many cases, the age was reported vaguely (e.g. 2–4, 3–6 y.o.) which did not aid in establishing clearer trends. Additionally, in the studies that

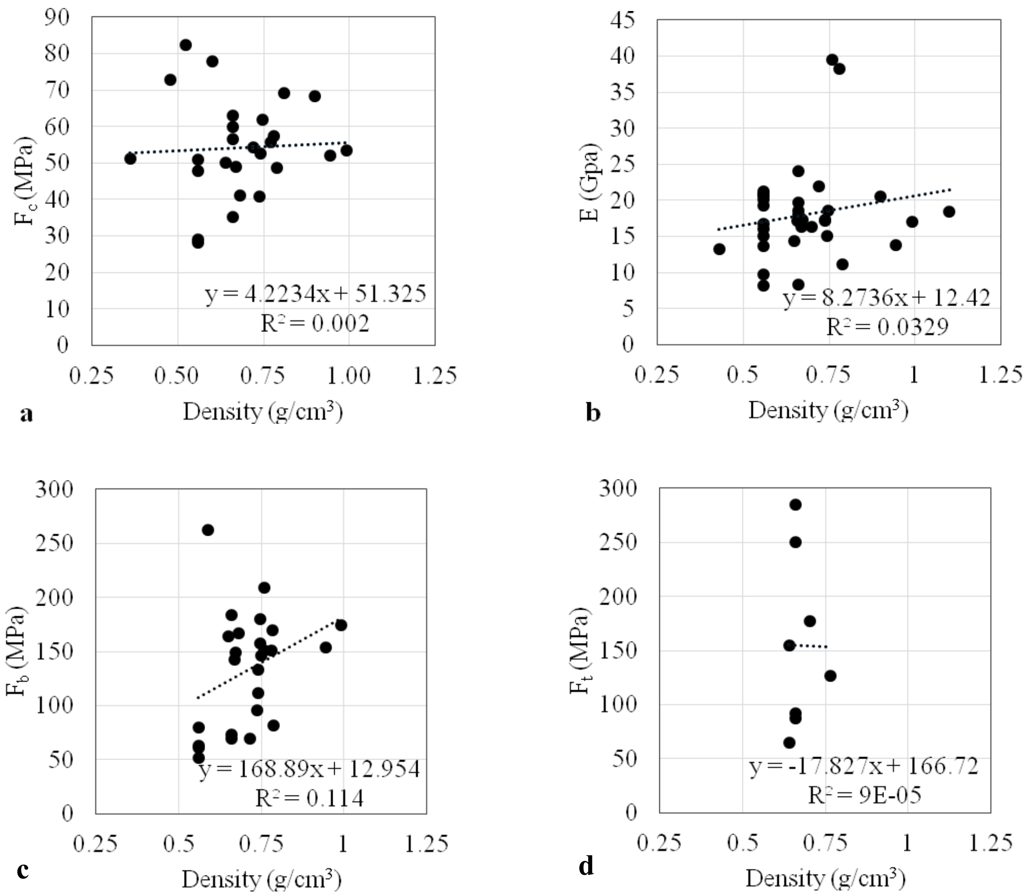

Figure 5. **a**) Density vs. compressive strength (F_c), **b**) density vs. modulus of rupture (F_b), **c**) density vs. modulus of elasticity (E), **d**) density vs. tensile strength (F_t). Sample size: F_c (26), E (34), F_b (26), F_t (8).

reported age, the bamboo was at an age which is recommended by bamboo literature (3–5 y.o.).

2. Species

The most commonly tested species of bamboo found in the literature by species were: *Bambusa vulgaris* (pantropical), *Guadua angustifolia* (found in Latin America), and *Phyllostachys pubescens* (found in Asia). And by genera were: *Bambusa* (including species: *B. balcooa*, *B. blumeana, B. oldhamii, B. pervariabilis, B. salarkhanii*, and *B. tulda*), *Dendrocalamus* (including species: *D. asper*, *D. giganteus*, and *D. strictus*), *Guadua* (including species: *G. aculeata* and *G. angustifolia*), and *Phyllostachys* (including species: *P. aurea*, *P. bambusoides*, *P. edulis*, and *P. viridiglaucescens*). Figure 4 shows the effect of species and genera on compressive strength (F_c), MOE (E), and MOR (bending strength) (F_b), respectively.

While structural timber shows a strong dependence on species when considering mechanical properties (Parker 1979), less influence was noted with bamboo. Theoretically, it is expected that bamboo mechanical properties will also vary with species and therefore this potential relationship should continue to be studied. Some bamboo studies, however, have found density to be a stronger indicator than species for modulus of rupture in three different bamboo species of similar density (Dixon 2016).

3. Density

Erakhrumen & Ogunsanwo (2010) suggested that density is the major factor that influences mechanical properties of bamboo. However, density values versus mechanical properties (Figure 5) show no correlation for the 91 data points plotted. Typically, a correlation, (R^2) value of 0.27 is the threshold for a moderate association (Pfeiffer & Olson 1981). Higher R^2 values indicate stronger relationships; these were all significantly less. It must be noted that the data used in this study were all average values of different bamboo mechanical property tests. Therefore, no clear correlation between mechanical property values and density was observed as is seen on the raw data of other studies (Berndsen et al. 2013; Zaragoza-Hernandez et al. 2015; Srivaro et al. 2018). Additionally, as this study compares average sample values that were tested using different testing methods, density may have been a comparatively less significant variable.

Research has also reported a positive linear correlation for density vs. E_b and F_b values (Berndsen et al. 2013; Srivaro et al. 2018); the highest R^2 value (0.114) correlation found in this study was also for F_b. According to one study, by using density and the bamboo outer diameter, in combination, the MOR and MOE values can be estimated (Gnanaharan et al. 1994). The densities reported in this study ranged from 0.36 to 1.1 g/cm^3 which is wider in range than values of 0.5–0.9 g/cm^3 for bamboo stated in the literature (Liese 1991; Harries et al. 2017). Additionally, density has been noted to vary along the culm height of the bamboo and generally, a positive correlation with height was seen (Sattar et al. 1990; Gnanaharan et al. 1994; Nordahlia et al. 2011).

4. Moisture Content

Moisture content has also been reported as the most important physical property governing the mechanical properties of bamboo, by Chung & Yu (2001), and as an important property by others (Limay 1952; Liese 1987; Lee et al. 1994). The collective moisture content versus property values were plotted and show that when divided into greater than or less than 15% MC, a bimodal relationship, which has been previously noted (Chung & Yu 2002; Jiang et al. 2012a), can be identified for Fb, and to some extent, for F_c, E, and F_v (Figure 6). The relationships were as follows: (1) for MC ~15% or less (shown circled in red) properties are fully independent of moisture, (2) for MC ~15% or higher, properties follow an increasing, decreasing, or stable relationship; which have also been reported (González et al. 2007; Okhio et al. 2011; Jiang et al. 2012a; Xu et al. 2014).

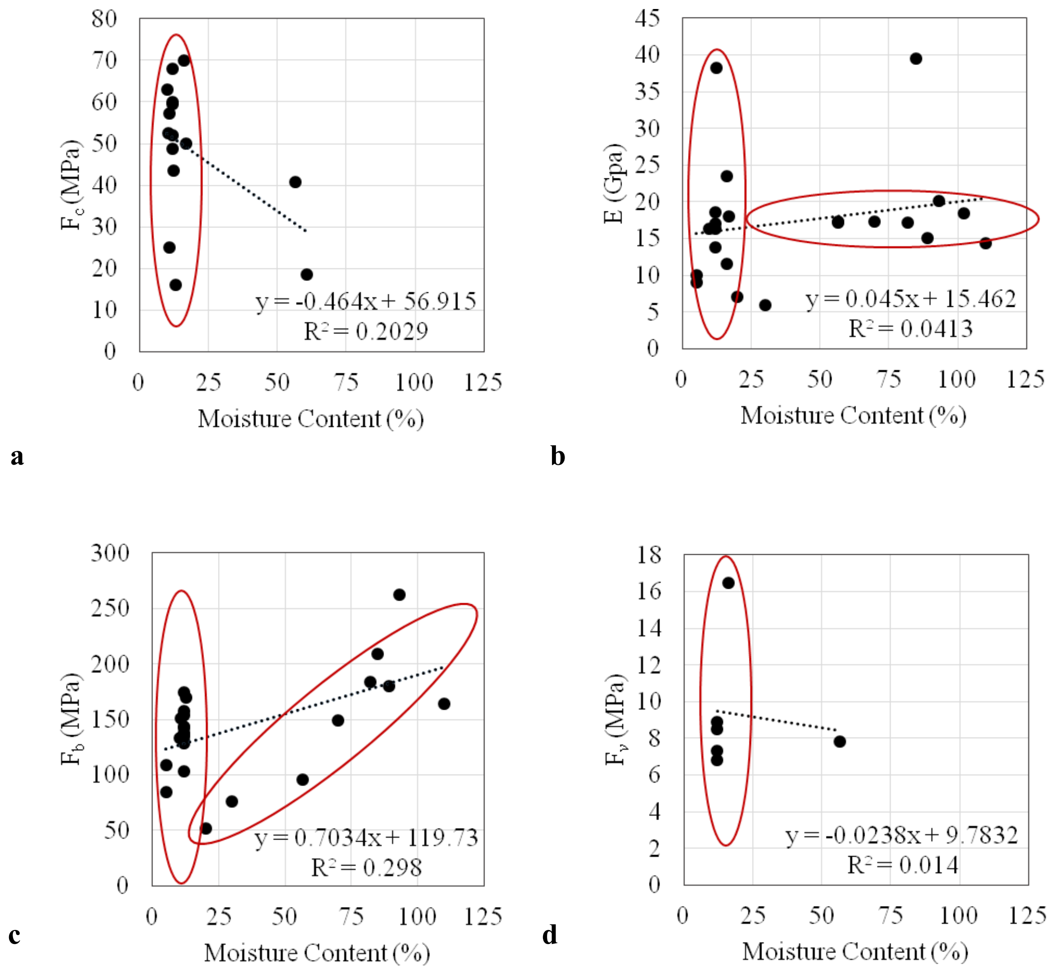

Figure 6. **a**) Moisture content vs. compressive strength (F_c), **b**) Moisture content vs. combined modulus of elasticity (E), **c**) Moisture content vs. modulus of rupture (F_b), **d**) Moisture content vs. shear strength (F_v). Sample size: F_c (15), E (22), F_b (25), F_v (6).

Regardless of the correlation between mechanical property values and moisture content of the bamboo, it should ideally be dried to a moisture content less than 20% to prevent fungal attack (Schmidt et al. 2013; Liese & Tang 2015). Bamboo can be either air dried or heat treated by solar drying, the latter being more effective. Improved solar dryers achieve final bamboo moisture contents of 10–22% (Ong 1996; Verma & Chariar 2012); the different values depend mainly on bamboo species and drying methods, bamboos with lower densities having higher drying rates (Tang et al. 2012).

For timber, moisture content is noted to have a significant influence on strength properties and it is therefore stated that it should be dried to constant weight before testing (ASTM 143). In design, moisture content is stated to be one of the three most important properties that influence the strength of timber and a strength reduction factor for wet service conditions of 0.667–0.875 is applied to the mechanical property values (Parker 1979). Given the importance of moisture content to timber characteristics, and bearing in mind the currently contradictory data regarding bamboo, the relationships between moisture content and mechanical property values should continue to be studied for bamboos.

Moisture content (MC) versus density was also compared for the compiled data (Figure 7). Though several studies did not report the method used to measure density, those that do provide more details report this parameter as dry density. Accordingly, it was assumed that all reported density values provided in Figure 7 are dry density.

Similarly to Figure 6, Figure 7 shows two trends: (1) for dry bamboo of MC <20% (in blue oval), and (2) for MC >20% (in red rectangle). The density and MC are inversely related for MC >20%. This again suggests the reported MC values reflect lab/dry conditions (<20%) and as-received (>20%) where specimens with higher void volumes were reflected in lower density even when still containing moisture within the voids.

5. Position along culm (base, middle, top)

The density and other variables have been reported to vary along the culms of bamboos (Limay 1952; Liese 1987). Literature generally separates the bamboo culm into three parts: base, middle, and top. Once again there is conflicting evidence on the relationship between culm position and mechanical properties. Many studies report increased mechanical property values from base to top of culm, specifically for compressive strength and MOR (Gnanaharan et al. 1994; Lee et al. 1994; González et al. 2008; Bahari & Ahmad 2009; Chung & Yu 2001; Tomak et al. 2012; Berndsen et al. 2013). Other studies report decreased mechanical property values from base to top of culm, specifically MOR and tensile MOE (Gnanaharan et al. 1994; Ghavami & Marinho 2005; Wahab et al. 2006; González et al. 2007). One study reports the highest tensile strength at the middle section (Wakchaure & Kute 2012). And yet others, specifically some for compressive strength and one shear study, report no difference in mechanical property values attributable to position along the culm (Ghavami & Marinho 2005; Correal & Albeláez 2010; Wakchaure & Kute 2012; Zaragoza-Hernandez et al. 2015). If position along the culm produces a difference in mechanical property values, it is an easy variable to control practically. The data presented in all of the graphs in this study generally use top third, middle third, and bottom third sections for mechanical property tests as required by most standards.

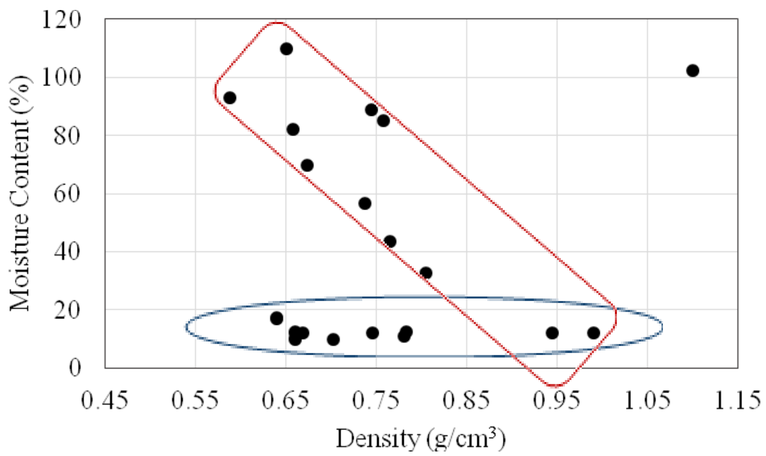

Figure 7. Density vs. moisture content (MC). Sample size: 23.

6. Post-harvest treatment/testing condition

Treatment is performed to extend the service life of bamboo by protecting it from pests that attack the bamboo after cutting. The common treatments identified in the literature were borax/boric acid immersion, metal-based chemical treatments, heat treatment, natural oil treatments, and water immersion. The two conditions of bamboo at the time of mechanical property testing were green (raw / freshly-cut) state and air-dried state. The treatment or testing condition is plotted versus mechanical property values (Table 3 and Figure 8) and the results seem inconclusive with regards to correlating trends between mechanical property values and post-harvest treatment.

A trend observed in Figure 8 is that green bamboo mechanical properties are consistently less than or equal to those of the air-dried bamboo samples (except for Figure 8b). This difference observed in Figure 8b may be due to the less accurate ways of obtaining modulus of elasticity (E) data from bamboo specimens as we have observed in our laboratory when performing bamboo compression tests and obtaining compressive modulus of elasticity data using axial extensometers. Additionally, some researchers use strain gauges instead of axial extensometers to obtain this data and there is no standard written in any bamboo manual as to how this data should be accurately acquired. Regardless of this, it should be noted that it is recommended that green bamboo should never be used

Table 3. Statistical data of bamboo treatment mechanical property values. Values reported: maximum value (max.), minimum value (min.), average value (avg.), standard deviation (STD), coefficient of variation (COV). Sample size: F_c (60), E (63), F_v (17), F_b (42), F_t (20).

		Air-dried	Green	Borax	Chemical	Heat	Oil	Water
F_c (MPa)	Max.	134	82.4	-	63.7	68	52	68.5
	Min.	18.6	16	-	48.8	68	49	45
	Avg.	54.1	42.7	-	56.2	68	50.5	56.8
	STD	21.9	18.5	-	7.5	-	2.1	16.6
	COV	0.41	0.43	-	0.13	-	0.04	0.29
E (GPa)	Max.	39.6	18.6	29.6	15.7	26.0	21.0	21.5
	Min.	1.9	9.5	23.5	15.7	26.0	7.9	5.1
	Avg.	15.9	16.1	26.6	15.7	26.0	14.2	13.3
	STD	7.9	2.6	4.3	-	-	4.5	11.6
	COV	0.50	0.16	0.16	-	-	0.3	0.9
F_v (MPa)	Max.	17.2	8.5	5.5	-	4.5	7.3	9.2
	Min.	4.2	7.8	5.5	-	4.5	6.8	3.5
	Avg.	12.2	8.1	5.5	-	4.5	7.1	6.4
	STD	4.5	0.5	-	-	-	0.4	4.0
	COV	0.37	0.06	-	-	-	0.05	0.63
F_b (MPa)	Max.	262.5	209.2	-	135.3	-	200.0	-
	Min.	44.0	51.9	-	126.4	-	83.0	-
	Avg.	120.4	122.4	-	130.2	-	134.6	-
	STD	50.5	61.1	-	3.8	-	39.6	-
	COV	0.42	0.50	-	0.03	-	0.29	-
F_t (MPa)	Max.	285.0	169.1	-	-	-	-	250.0
	Min.	8.1	15.4	-	-	-	-	250.0
	Avg.	153.6	77.1	-	-	-	-	250.0
	STD	72.7	72.4	-	-	-	-	-
	COV	0.47	0.94	-	-	-	-	-

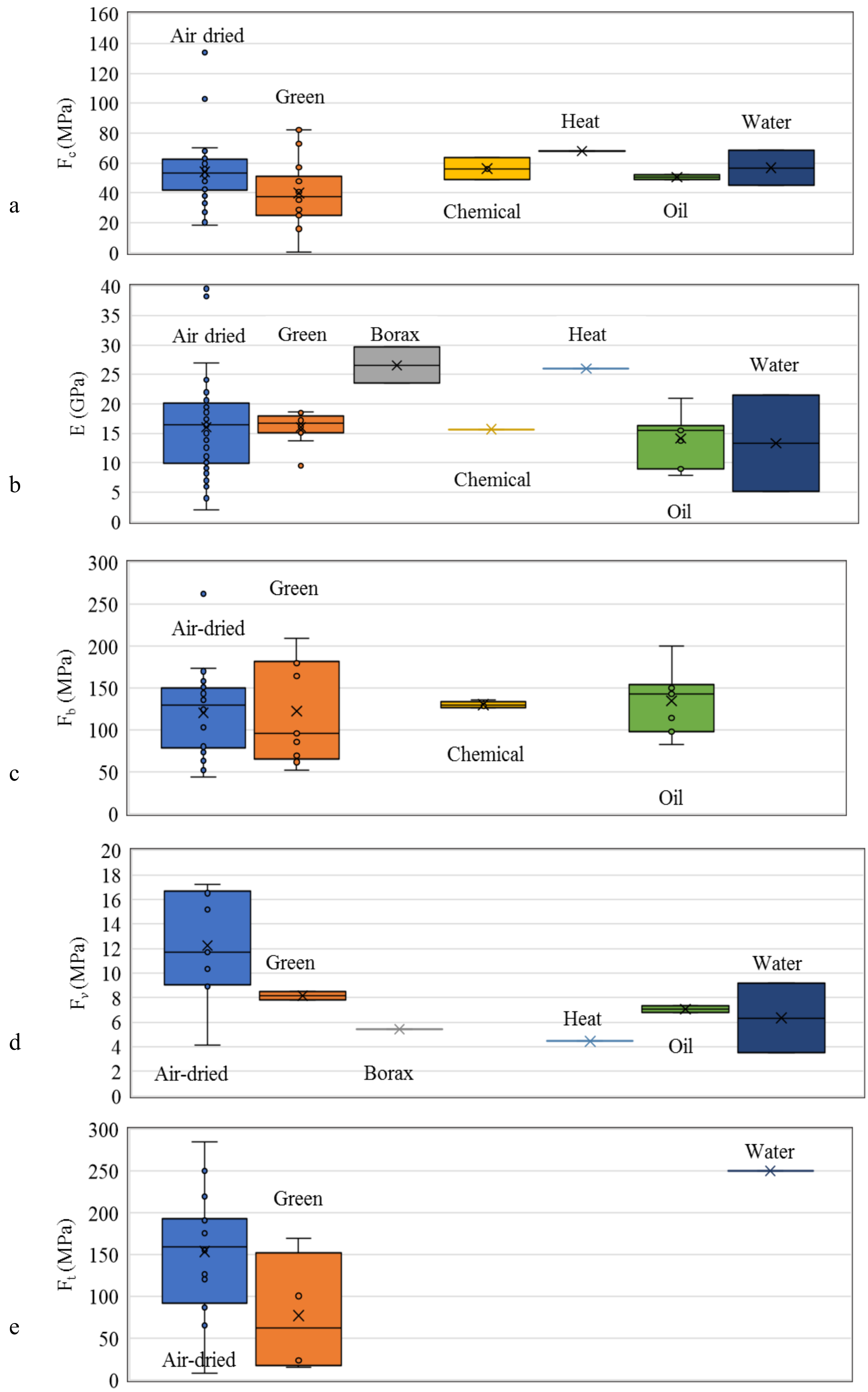

Figure 8. Property vs. treatment **a)** Compressive Strength (F_c), **b)** Modulus of Elasticity (E), **c)** modulus of rupture (F_b), **d)** Shear (F_v), **e)** Tensile strength (F_t). Sample size: F_c (60), E (63), F_v (17), F_b (42), F_t (20).

structurally because it shrinks radially over time as it dries (Kaminski et al. 2016). Additionally, any green bamboo used will eventually dry, and therefore, mechanical property values of air-dried bamboo should be assumed. Despite this, a large proportion of the data found in the literature (used herein) reporting bamboo mechanical property tests was obtained from green, or undried, bamboo. Others have also concluded that type of bamboo treatment did not significantly change the mechanical property values of the bamboo (Gupta et al. 2015).

In contrast, other studies have found a correlation between bamboo mechanical property values and post-harvest treatment and are as follows, from highest to lowest mechanical property values: (1) green or water treated bamboo samples (Wahab et al. 2007; Amatosa & Loretero 2016), (2) air dried samples (Manalo & Acda 2009; Wahab et al. 2007; Erakhrumen 2010), (3) oil treated samples (Manalo & Acda 2009). For samples treated with oils, the higher the treatment oil temperature, the lower the mechanical property values (Wahab et al. 2007; Erakhrumen & Ogunsanwo 2010; Colla et al. 2011; Jiang et al. 2012b).

Regarding the effectiveness of bamboo post-harvest treatments: (1) metal-based chemical treatments such as copper compounds are the most effective treatments, although they present environmental concerns. (2) Borax/boric acid treatment is the current conventional treatment used in the industry with proven effectiveness yet has the disadvantage of being water-soluble (Trujillo 2018) which limits its use in outdoor settings because environmental moisture and rain can leach it away. Additionally, the concentration of borax/boric acid is different in many bamboo guides and one publication reports that it did not adequately protect from fungi and bamboo borers (Jayanetti & Follet 1998), (3) Natural treatments, such as camphor oil, bamboo vinegar (Lin & Shiah 2006; Shiah et al. 2006), camphor and resin treatments (Xu et al. 2013), coconut oil (Manalo & Acda 2009), neem oil (Erakhrumen 2009), cedar oil, and Lantana and Jatropha leaves (Perminderjit et al. 2014), have also been shown to function effectively although they have mainly been used in scientific studies and rarely used in practical applications.

7. Node vs. internode

Although most bamboo mechanical property tests are performed on bamboo internodes, with the exception of tensile tests, there is no mention in the scientific literature of how the presence of nodes impacts mechanical properties. Some studies report that the presence of a node in mechanical property tests did not alter the mechanical property values significantly (Gnanaharan et al. 1994; Ghavami & Marinho 2005; González et al. 2008). Other studies reported that having a node in the mechanical property test did reduce the values (Lee et al. 1994; Omobowale & Ogedengbe 2008; Bahari & Ahmad 2009; Tomak et al. 2012). Despite this, it has also been noted that the presence of nodes is the least important factor from a practical point of view (Limay 1952; Prawirohatmodjo 1990). Although the presence of nodes affects the end-product of bamboo, it is not technically or economically feasible or justifiable to remove the nodes (Nordahlia et al. 2011).

Testing standards

The formal testing of mechanical properties of bamboo is limited when compared to materials such as concrete or steel. Testing standards are still not widely adopted/unified for bamboo and, in this review, it was found that the testing fell under the guidelines of 18 different standards: some timber standards, some plastic standards, and some relatively recently established bamboo standards. The most commonly used and recently established bamboo standards are ISO 22157 (2004) and NTC 5525 (2007). Bamboo standards have been previously documented and compared as it is known that changes in the standard testing procedure used will influence the resulting mechanical property values (Gnanaharan et al. 1994; Harries et al. 2012; Trujillo 2018). Accordingly, average data were compared for common testing standards over nine studies undertaken applying each standard (Figure 9). The results show reported measurements can vary by up to 29% for compressive strength, 19% for MOE, 23% for MOR, and 31% for shear strength. Figure 9 generally shows that the highest mechanical property values were for the following standards from highest to lowest: (1) N/A (no testing standard used); (2) ISO 22157: International Standards Office, determination of physical and mechanical properties of bamboo; (3) ASTM 143: standard methods of testing small clear specimens of timber; and (4) NTC 5525: Norma Técnica Colombiana (Colombian Technical Standard), determination of physical and mechanical properties for the *Guadua angustifolia* Kunth.

Compression testing information comparing the different most common testing standards is presented in Table 4. The ASTM 143 standard uses a possibly longer sample (depending on how the researcher adapts the standard to fit bamboo). This may explain the lower compressive strength values for that standard. Compression failures are classified according to criteria in standards for wood (ASTM 2003), and these criteria are not present in the recently established bamboo testing standards.

Bending test information comparing the different most common testing standards is presented in Table 5. The large variation between testing standards can largely be

Table 4. Compression test data. Length is reported as L, diameter as D.

	Loading Rate	Length	Node vs. Internode	Misc.
ASTM 143	N/A	50 x 50 x 200 mm	N/A	No intermediate layer
NTC 5525	0.01 mm/s	L = D	Internode	Intermediate layer
ISO 22157	0.01 mm/s	L = D	internode	Intermediate layer

Table 5. Bending test data. Diameter is reported as D.

		Loading Rate	Length	Node vs. Internode Misc.
ASTM 143	Primary: 0.0416 mm/s, Secondary: 0.0216 mm/s	Primary: 50 x 50 x 760 mm. Secondary: 25 x 25 x 410 mm	N/A (wood standards)	3-point test
NTC 5525	0.5 mm/s	30 x D; whole culm	whole culm; node & internode	4-point test
ISO 22157	0.5 mm/s	30 x D; whole culm	whole culm; node & internode	4-point test

explained by the different sizes of bamboo samples used (whole culm vs. split sections) as well as the use of 3-point vs. 4-point bending tests. The ideal full culm 4-point bending test is also the most cumbersome to perform in a traditional material testing laboratory and has been seen to produce lower MOR values than the split test specimen values (Gnanaharan et al. 1994). This explains why the ISO 22157 average MOR values (Figure 9) result in much lower values than the N/A tests, which use no specific standard (a split section is generally used for simplicity). The primary and secondary labels in ASTM 143 refer to the use of a larger, primary sample if available, but if not available, the use of a smaller, secondary sample is acceptable. In wood standards, such as ASTM 143, there are types of failure shown to help understand and classify the material, but these are not included in bamboo standards.

Tensile testing details comparing the different most common testing standards used are presented in Table 6. The tensile test in the ISO 22157 and NTC 5525 standards require a dog-bone shape of a node cut from split bamboo; bamboo is not easy to shape into a dog-bone which explains why few of these tests have been conducted. The node section is required for testing as it results in a significant weakening of the bamboo, only 30% of the internode value (Arce 1993). For the ASTM 143 standard, the dog-bone shape has a thinner 'neck' and there is no

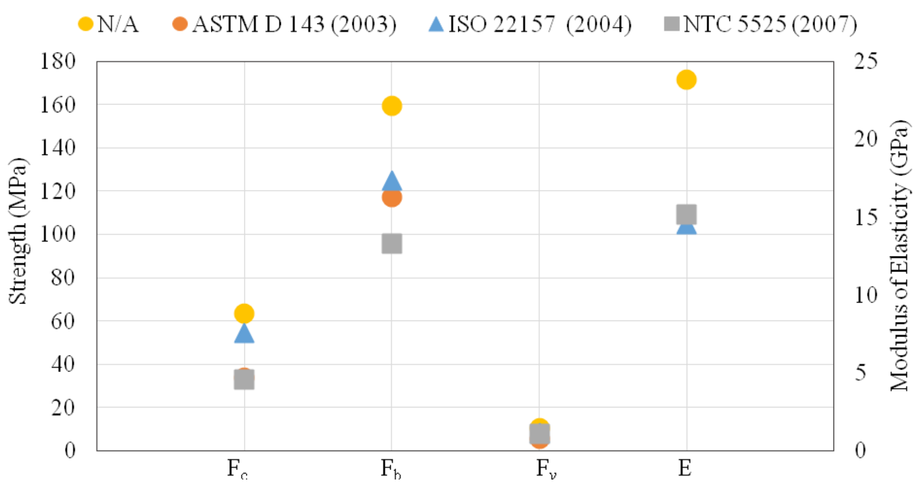

Figure 9. Common bamboo testing standards results for mechanical properties: compressive strength (F_c), modulus of rupture (F_b), shear strength (F_v), and combined modulus of elasticity (E). Sample size: F_c (47), F_b (36), F_v (15), E (39).

specification about node or internode (as it is an adapted wood standard). Some of the other less commonly used standards (N/A) test the bamboo using just a split section which is much easier to cut. There were insufficient data to compare tensile strength in Figure 9.

Shear testing information comparing the different most common testing standards used is presented in Table 7. The ASTM 143 timber standard specifies the use of a 2x2x2.5-inch specimen cut in a way that is not feasible for bamboo, therefore there must have been variation in the method used to apply this test when adapted for bamboo by the researchers reporting its use.

The combined MOE values (Figure 9) were measured using 3 different types of tests: compression, bending, and tension, so perhaps the variation caused in this way is so great that no clear trend could be found. Additionally, the NTC 5525 standard is only used for the bamboo species *Guadua angustifolia*, which therefore confounds the additional variable of bamboo species.

From this comparison it was found that the testing standard greatly influenced the bamboo mechanical property values. This is logical as the test setup can vary greatly for the different standards, such as using split sections of bamboo versus entire sections of culm. The bamboo mechanical property value data used in this analysis was obtained using these different testing standards or no standard test method at all. This was shown to cause the data to vary in many cases as the testing standard is a highly weighted variable. Because the testing standard is such an important variable it may confound other factors such as density and moisture content, so that they show less correlation with the mechanical property values reported.

Combining an extensive amount of data from the literature, obtained by different researchers using different testing methods and calculation methods for the specific mechanical property values, will inevitably lead to a broad range of results. Nevertheless, this compilation of data allows readers to see the full range and average values of bamboo mechanical property values that one might expect in the field. In addition, regardless of the many differences caused by the diversity of variables compared, the average values and ranges of the mechanical properties obtained in this meta-analysis were consistent with values for bamboo reported in the literature.

Table 6. Tensile test data.

	Loading Rate	Length	Node vs. Internode	Misc.
ASTM 143	0.016 mm/s	'dog-bone' shape (Primary: 925mm Secondary: 476mm thin section)	N/A (wood standards)	'special grips' used
NTC 5525	0.01 mm/s	'dog-bone' shape (10-20mm thin section)	node	N/A
ISO 22157	0.01 mm/s	'dog-bone' shape (10-20mm thin section)	node	Clamped at grips, no friction layer

Table 7. Shear test data. Length is reported as L, diameter as D.

	Loading Rate	Length	Node vs. Internode	Misc.
ASTM 143	0.01 mm/s	50 x 50 x 63 mm	N/A (wood standards)	'notched' in a way not easily possible for bamboo
NTC 5525	0.01mm/s	L = D	50% node; 50% internode	'bow tie'
ISO 22157	0.01mm/s	L = D	50% node; 50% internode	'bow tie'

CONCLUSIONS

Numerous studies have attempted to quantify the mechanical properties of bamboo and to correlate them with a wide range of variables. From the comparative analysis of 43 selected peer reviewed publications, it was found that three variables do influence bamboo mechanical property values to some extent: the test standard, moisture content and, to a lesser degree, bamboo species. However, the correlation is not strong or consistent, and in our meta-analysis we produced a single value for each mechanical property, which can be applied for all bamboos regardless of these variables, but with an understood variability (Table 8).

We recommend that variability should be addressed conservatively in the use of bamboo as a building material by applying appropriate, substantial safety factors. This was underlined by often contradictory findings in the literature regarding the mechanical properties of bamboo, which clearly show that substantial additional research and development in the structural use and testing of bamboo is still necessary.

In order to truly establish bamboo as a conventional building material, it must have established mechanical property values and ranges for designers to incorporate into practice. Once established these values will make designing with bamboo similar to designing with conventional materials, in that more predictable factors of safety, or strength reduction factors can be applied.

Neither the effect of the changing diameter of bamboo along the culm length, or tapering, nor how to design despite this irregularity has been addressed satisfactorily by the literature. Because of this, bamboo cannot be treated as a uniformly shaped material in design and analysis. This natural variability renders bamboo a non-uniform material, thereby making it more difficult to design with. Calculating stress in bending of tapered sections by conventional methodologies is also reported to be inaccurate as discussed by Nugroho and Bahtiar (2012; 2013).

Research into options for post-harvest treatment of bamboo are still in the early stages. Although many possibilities are available, none have been formally established as best practice. The mechanical property values that have been cited for bamboo are nearly all obtained from untreated green or dry bamboo. Thorough research on how treatment of bamboo affects its mechanical properties has yet to be undertaken. Additionally, experiments to test the effect of bamboo post-harvest treatments are all analyzed under laboratory conditions. More efforts should be made to test these treatments after real world outdoor exposure.

Although the connection joints used in timber construction are well understood (Parker 1979), the rules do not hold true for bamboo. Anecdotally, bamboo should never be drilled but should instead be tied in order to achieve the best performance. Although some efforts have been made to study fiber and metal connection joints for bamboo (Awaludin & Andriani 2014; Trujillo & Wang 2015), connections using traditional tying methods should also be studied.

Table 8. Average bamboo mechanical property values. N is the number of studies from which the data were collected. Mid 50% values is the range of values for the middle 50% of values

Mechanical Property	Symbol	Average Value (N)	Mid 50% Values
Shear Strength Parallel to Grain	F_v	9 MPa (18)	6.8–11.7 MPa
Compressive Strength	F_c	52 MPa (59)	40.7–61.9 MPa
Modulus of Rupture, Bending Strength (MOR)	F_b	120 MPa (52)	79.6–149 MPa
Tensile Strength	F_t	159 MPa (21)	89.5–206 MPa
Compressive Modulus of Elasticity (MOE)	E_c	16 GPa (19)	9–20.7 GPa
Bending Modulus of Elasticity (MOE)	E_b	17 GPa (34)	14.3–20 GPa
Tensile Modulus of Elasticity (MOE)	E_t	14 GPa (10)	9.5–18 GPa
Combined Modulus of Elasticity (MOE)	E	16 GPa (63)	11.8–19.7 GPa

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Appendix 1

The 43 peer-reviewed publications from which the data for Figures 1-9 were obtained, with the mechanical properties used.

Citation	F_v	F_c	F_b	F_t	E_t	E_c	E_b
Aladin et al. 2014.						×	×
Amatosa & Loretero 2016		×					
Askarinejad et al. 2015	×						
Bahari & Ahmad 2009	×						
Berndsen et al. 2013		×	×			×	
Chung & Yu 2001		×	×			×	
Colla et al. 2011			×				×
Correal & Albeláez 2010	×	×	×			×	×
Cruz 2002	×			×			
Erakhrumen & Ogunsanwo 2010			×				×
Espiloy et al. 1986		×			×		
Fabiani 2015		×		×			×
Ghavami & Marinho 2005	×	×			×	×	
González, E.G. et al. 2002			×				×
González, H.A.B. et al. 2006				×	×		
González, H.A.B. et al. 2008		×				×	
Gupta et al. 2015		×					
Gyansah et al. 2010		×					
Jiang et al. 2012a	×	×					×
Kamruzzaman et al. 2008			×				×
Lakkad & Patel 1981	×	×			×		
Lee et al. 1994		×		×			
Luna et al. 2014		×				×	×
Manalo & Acda 2009			×				×
Matsuoka & Beraldo 2013			×				×
Mota et al. 2017			×				
Nordahlia et al. 2011			×				×
Nurmadina et al. 2017							×
Okhio et al. 2011		×					
Omobowale & Ogedengbe 2008				×			
Ramírez et al. 2018		×					
Sánchez-Echeverri 2014			×				
Sattar et al. 1990		×	×				×
Takeuchi et al. 2013		×					
Tomak et al. 2012		×	×				
Valero et al. 2005		×	×				
Wahab et al. 2006		×	×				
Wahab et al. 2007	×	×	×				×
Wakchaure & Kute 2012		×		×			
Xu et al. 2014	×					×	
Yu et al. 2008				×	×		
Zaragoza-Hernandez et al 2015		×	×		×	×	×