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Basic Working Stress for Naturally Grown Bamboo *(Bambusa vulgaris)*

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Abstract: Classification of *Bambusa vulgaris* for structural application was carried out based on the maximum crushing strength perpendicular and parallel to the grain of the culm as well as bending moduli of rupture (MOR) and elasticity (MOE). The findings of the work showed that the MOR > 70 N/mm^2, MOE > 9000 N/mm^2 and compression strength > 35 N/mm^2. Following the standard classification of timber species for structural use in building, *B. vulgaris* is placed in group one as the strength properties surpassed the standard stress limit required for structural application. The basic density of *B. vulgaris* falls in the range of 755.22 to 877.23 kg/m^3 which is comparable to most bamboo as well as heavy tropical wood species used in construction. The overall specific strength properties of *B. vulgaris* were somewhat higher than and comparable to most timber species used in construction.

Keywords: *Bambusa vulgaris*, Crushing strength, Culm position, Density; Strength-to-weight ratio

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Introduction

Analysis of the mechanical properties is the investigation of the material's behaviour when subjected to loads. The specific strength of a material is the strength of the material divided by its density. It is also known as the strength-to-weight ratio. Similar to wood, bamboo is a heterogeneous and anisotropic material. The mechanical properties of bamboo are extremely unstable more than wood due to the uneven distribution of vascular bundles, density, shrinkage and strength at different position and ages of the culm (Chand *et al*., 2008). Several studies (Lee *et al*., 1994; Ahmad, 2000; Shupe *et al*., 2002) have been carried out to evaluate the strength properties of bamboo. The mechanical behaviour of round bamboo culms (Sattar *et al*., 1994; Espiloy *et al*., 1986; Anon, 1992) and small specimens (Lee *et al*., 1994; Abd Latif *et al*., 1990; Tewari, 1992) have been investigated. A sufficient knowledge of the mechanical behaviour of bamboo enables a safe design for the material's service life. For bamboo to be accepted as an alternative or supplemental structural material, its strength must be similar to the strength properties exhibited by wood. According to Janssen (2000), a comparison of the properties of bamboo with the properties of most wood shows that bamboo is stiffer and stronger. The bending stress at failure for air- dried bamboo is 0.14 times the density and the ultimate compressive stress of air-dried bamboo is 0.094 times the density.

The strength of bamboo depends on species, moisture content, density, age and height of the culm (Rangqui and Kuihong, 1987; Razak and Latif, 1995;

Chauhan 2000). Ageing of a bamboo culm influences the properties and consequently its processing and utilization (Lee *et al*., 1994; Ahmad, 2000; Shupe *et al*., 2002). The strength of bamboo increases as it becomes older due to the hardening of the culm walls, the culm wall thickness becomes hard resulting in maximum strength (Abd. Latif, 1987). With age increment, mature tissues start to develop and continue to influence density, strength properties etc. Generally, Bamboo matures and reaches its maximum strength in about three years (Liese, 1985). Most mechanical properties of bamboo are closely correlated with specific gravity (Janssen, 2000). The modulus of elasticity is correlated with the number of vascular bundles per mm^2, while the modulus of rupture relates to fibre length. Although, quite a number of studies have been carried out on the strength properties of different bamboos, however, little information exist on the strength-to-weight ratio of naturally-grown *Bambusa vulgaris* the most dominant bamboo species in Nigeria. Generally, Bamboos are being neglected to concentrate on timber species. In Nigeria, Bamboos are found in abundance but underutilized (RMRDC, 2004) and are usually subjected to annual burning as they are regarded as weed (RMRDC, 2004). Despite multi-purpose uses of bamboos, scaffolding and decking are the two major uses that bamboos are put to in Nigeria. Bamboos are usually restricted to construction in the rural areas owing to little information on the material properties. Therefore, the aim of this study was to evaluate the safe fibre stress of naturally-grown *Bambusa vulgaris* at different position and age of the culm with a view to promoting its utilization as supplemental structural material to wood in Nigeria. The strength properties evaluated were Compressive strength parallel and perpendicular to grain, bending moduli of elasticity and rupture (MOE and MOR).

Materials and Methods

Sample preparation

Culms of age 2, 3 and 4 years were harvested from naturally-growing *Bambusa vulgaris* groove on the campus of the Federal University of Technology, Akure. The culms were carefully marked and labelled for easy identification according to ages. The experimental specimens were sampled at 10%, 50% and 90% of the merchantable height to represent the base, middle and top position of the culm. All bamboo test samples were obtained from clear and uniform grained culms.

Determination of Culm Density and Strength Properties

The density and strength of *B. vulgaris* were tested following American Standard Method for Testing Small Clear Specimens of Timber. Culm density was determined following ASTM D 2395-93 (ASTM, 1993) but with slight modification in the dimension of the bamboo samples. Both the compression and bending test were performed following ASTM standard D1037-96a (ASTM, 1997) and ASTM D 3043-95 (ASTM, 1995) with slight modification owing to the varying nature of the bamboo thickness on a Testometric Universal Testing Machine with model No: 0050-01014 at a cross head speed of 1.00 mm/min. The machine has WinTest analysis as embedded software for the strength analysis. Five observations were recorded for each samples tested

The specific strength of the bamboo were determined as:

Specific Strength = Actual strength/culm density

Statistical Analysis

The effects of age and culm position on strength properties were evaluated by analysis of variance at the 0.05 level of significance. Duncan Multiple Range Test was used to determine most significance in means.

Results and Discussion

Variation in Culm Density of *B. vulgaris*

The density values of *B. vulgaris* were found to vary with age and along the height of the culm. The density varied from 709.63 kg/m^3 to 937.95 kg/m^3 and increased from the basal part of the culm to the top (Table 1). However, ANOVA result in Table 1 showed that there were no significant variation in culm density along the culm length as well as among the three age classes. DMRT result (Table 2) also showed that there were no significant variation in culm density along the culm length however, significant variations existed among the three age classes. Results from previous works (Liese, 1986 & 1998; Espiloy, 1987; Abd. Latif, 1993; Abd

Table 1. ANOVA for influence of age and culm position on density of *B. vulgaris*

Properties	Source of Variation	df	F-value
	Age	2	3.189 ns
	position	2	0.667 ns
Density (kg/m^3)	Age* position	4	0.473 ns

ns = not significant at ($p \leq 0.05$) probability level

Latif and Liese, 2002; Ahmad and Kamke, 2005; Malanit *et al*., 2008) supported the findings of this study. According to these authors, Bamboo density has a close relationship with vascular bundles and ground tissues percentages. The reason for higher basic density at the top position was attributed to the presence of higher proportion of fibrous tissue and higher frequency of vascular bundles at the top of the culm (Liese, 1998; Janssen, 1981; Espiloy, 1987 and Widjaja and Risyad, 1987; Razak *et al*., 2010) as well as maturation process that starts from the lower internodes to the upper internodes (Itoh, 1990). Variation in density showed an increase from age 2 to 3 with slight decrease at age 4. This may be due to the cell wall thickening during maturation of the culm from 1 to 3 years which leads to an increase in basic density of the culm material (Alvin and Murphy, 1988; Jamaludin *et al*., 1992; Abd. Latif 1993; Espiloy 1994; Sattar *et al*., 1994; Razak *et al*., 2007 & 2010). The increase in density is dramatic during the first two years but becomes more gradual during the third year and stabilized thereafter as reported by Abd Latif *et al*.,(1996) and Bath (2003) as well as starch deposition and lignification process that increases with age (Razak *et al*., 2010). Alvin and Murphy (1988) got similar findings for *Gigantochloa scortechinii* and *Sinobamboo tootsik*. The variation in the density of *B. vulgaris* is also similar to the findings of Espiloy (1987), Liese (1986) and Santhoshkumar and Bhat (2014). *B. vulgaris* from age 2 and 4 are very dense (641-800 kg/m^3) and are thus falls in group D30-D50 while age 3 are exceptionally strong (>800 kg/m^3) and are then placed within group D50-D60.

Compressive Strength of *B. vulgaris*

The maximum crushing strengths parallel and perpendicular to the grain of *B. vulgaris* are shown in Table 4. Generally, the compressive strength parallel to grain were higher than the compressive strength perpendicular to grains. Compression strength parallel to grain of *B. vulgaris* are not comparable to what were reported for some species of bamboo such as Madake (*P. bambusoides*) (92 N/mm^2) (Tada *et al*., 2010), 24 N/mm^2 for *B. blumeana*, 25.3 N/mm^2 for *B. vulgaris*, 31.5 N/mm^2 for *D. asper*, 27 N/mm^2 for *G. scortechinii*, 40 N/mm^2 for *G. levis*, 69 N/mm^2 for *Balanocarpus hemii*, 54.7 N/mm^2 for *Koompasia malaccensis* (Liese, 1985), 66.7 – 83.6 for *Thyrsostachys siamensis* and 64.7 – 69.7 for *D. membrances* (Maya *et al*., 2013) as well as 76.87-79.98 MPa for compressive strength of *Dendrocalmus strictus* reported by Bhonde *et al.,* (2014). There were significant variations in the compressive strength of *B. vulgaris* (Table 4). Only compressive strength parallel to grain showed no significant variation among the three age classes. Across the grain, the compressive

Table 2. Variations in the density of *B. vulgaris*

Source of Variation	Level	Density (kg/m^3)
Age	2	755.22c
	3	877.23a
	4	782.21ab
Position	Base	772.70a
	Middle	811.82a
	Top	830.11a

Means with the same letter vertically are not significantly different at ($p \leq 0.05$)

Table 3. ANOVA for influence of age and culm position on strength properties of *B. vulgaris*

Strength properties	Source of variation	df	F-value
Compression parallel to grain (N/mm^2)	Age	4	5.662 **
	Position	4	5.612 **
	Age*position	16	7.280 **
Compression perpendicular to grain (N/mm^2)	Age	4	2.690 ns
	Position	4	7.273 **
	Age*position	16	20.178 **
MOE (N/mm^2)	Age	4	14.846 **
	Position	4	10.006 **
	Age*position	16	8.013 **
MOR (N/mm^2)	Age	4	7.689 **
	Position	4	11.025 **
	Age*position	16	5.201 **

* = Significant at ($p \leq 0.05$) probability level; ns = not significant at ($p \leq 0.05$) probability level

strength was similar for age 2 and 3 but different for age 4 while the compressive strength along the grain was similar for all the age classes. Generally, age 4 had the highest compressive strength both along (2589.40 Nmm^{-2}) and across (1335.10 Nmm^{-2}) the grains of the bamboo.

Along the height of the culm, the compressive strength parallel to the grain increased from the base to the top (Table 4). The result of the compressive strength parallel to grain corroborated the findings of Widjaja (1985) who found that the compression strength as well as the percentage of sclerenchyma fiber increases from the bottom to the top in *Dendrocalmus giganteus* and *Gigantochloa robusta*. Espiloy (1987); Liese (1987); Sattar *et al*., (1990) and Kabir *et al*.,(1991) had similar findings. However, the result of compressive strength perpendicular to grain was in the reverse order where the values deceased from the base to the top of the culm. This was similar to the findings of Janssen (2000) and Sint and Myint (2008). They observed the strength properties of bamboo to decreased with the height of the culm. This statement does not hold true for all the strength properties for *B. vulgari*s under study. In this study, only compressive stress perpendicular to grain decreased with the height of the culm from base to the top (Table 4). This may be attributed to the individual characteristics of bamboo. Effect of age was not pronounced on the compressive strength parallel to grain (Table 3). Both age and position of the culm were seen influencing the compressive strength perpendicular to grain of *B. vulgaris*. Age 4 had the highest compressive strength (2589.40 N/mm^{-2}) along and (1335.10 N/mm^{-2}) across the grain of the bamboo. Interactions of the age and position of the *B. vulgaris* where samples were tested were also significant for all the strength properties (Table 3).

B. vulgaris showed to be very high in compression strength along the grain. Generally, bamboo is stronger than wood in bending, compression strength parallel to grain but similar in shear strength parallel to grain (Chaowana, 2013). When compared to wood species such as teak (32.48 N/mm^2 to 95.48 N/mm^2) (Izekor, 2010), *B. vulgaris* is stronger in compression strength. The compressive strength parallel to grain of bamboo is higher than the compressive strength perpendicular to grain. From the result, the compression strength parallel to grain decreases along the culm length from base to top with the top having the lowest. There were significant variations in the compression strength parallel to grain among the bamboo ages as well as along

Table 4. DMRT for Influence of age and culm position on strength properties of *B. vulgaris*

Source of Variation	Level	MCS (Perpendicular) (N/mm^2)	MSC (Parallel) (N/mm^2)	MOR (N/mm^2)	MOE (N/mm^2)
Age	2	1096.40a	2240.80a	176.22a	19016a
	3	901.45a	2251.90a	164.30a	19312a
	4	1335.10b	2589.40a	208.00b	21617b
Position	Base	1358.00b	2109.40a	186.21b	18272a
	Middle	1019.40a	2243.90b	162.84a	19991b
	Top	955.59a	2728.70a	199.47b	21617c

Means with the same letter vertically are not significantly different at ($p \leq 0.05$)

the culm length from base up. The reason for the very high compressive strength parallel to grain of *B. vulgaris* may be attributed to its higher cellulose content (Sadiku, 2016).

Bending Strength of *B. vulgaris*

The average values of modulus of elasticity and rupture of *B. vulgaris* are given in Table 4. The maximum bending modulus of elasticity (MOE) and rupture (MOR) of *B. vulgaris* was attained at age 4. The MOE values are extremely higher than those reported for *Bambusa arundinacea*, *Bambusa multiplex*, *Bambusa vulgaris*, *Bambusa vulgaris* var. striata and *Oxytenanthera abyssinica* wildly grown in Togo (Kokutse *et al*., 2013) and for cultivated *Oxytenanthera monostigama* in India (Maya *et al*., 2013). In the study of thirteen Malaysian bamboo species by Siam *et al*.,(2019), only *Schizostachyum brachycladum* reported higher value of 263 N/mm^2 more than the species in this present study. However, *G. ligulata* (180 N/mm^2), *G. wrayi* (201 N/mm^2), *G. thoii* (163 N/mm^2), *B. vulgaris* (172 N/mm^2) as well as *B. vulgaris* cv vittata (176 N/mm^2) had comparable MOR with the present study. All their bamboo species MOE were lower except *S. grande* (21,036 N/mm^2) and *S. brachycladum* (21,136) which have comparable MOE with the present study. The MOR values in this study were also comparable to that of Madake (192 N/mm^2) (*Tada et al*., 2010), *Thyrsostachy siamensis* (119 N/mm^2 to 129 N/mm^2) and *D. membrances* (97 N/mm^2 – 127 N/mm^2) (Maya *et al*., 2013) but extremely higher than that of *B. blumeana* (99.8 N/mm^2), *B. vulgaris* (62.3 N/mm^2), *D. asper* (85.7 N/mm^2), *G. scortechinii* (52.4 N/mm^2), *Balanocarpus hemii* (122.0 N/mm^2) and *Koompasia malaccensis* (100 N/mm^2) (Liese, 1985) and some economic timber species used in strength bearing applications such as Teak which varies from 76.86 N/mm^2 to 134.69 N/mm^2 for 15 to 25 years old (Izekor, 2010). The results showed that MOE do not differ between age 2 and 3 but those of age 2 and 3 were significantly lower than that of age 4. Along the culm length, the trend is the same with the top portion having the highest. The high MOE at the top of age 4 may be attributed to increase cellulose content and decreasing micro-fibril angle as well as higher content of vascular bundles

Table 5. Limits of Modulus of Rupture, Elasticity and Maximum crushing strength

Group	Maximum crushing strength (MCS) N/mm^2	Modulus of rupture (MOE) N/mm^2	Modulus of elasticity (MOR) N/mm^2
Group I	>70	>9000	>35
Group II	50-70	>6000	>30
Group III	30-50	>3000	>25

Source: Anon.(1993)

Table 6. Strength classes-characteristics values for hardwood species

Properties	D18	D24	D30	D35	D40	D50	D60	D70
Density kg/m^3	570	580	640	650	660	750	840	1080
Bending (N/mm^2)	18	24	30	35	40	50	60	70
MCS parallel (N/mm^2)	18	21	23	25	26	29	32	34
MCS perpendicular (N/mm^2)	7.5	7.8	8.0	8.0	8.3	9.3	10.5	13.5

Source: EN 338, (2000)

which account for the higher density of bamboo and hence increase modulus strength.

Generally, there were significant variations the in MOE along the culm length as well as among the bamboo ages. This result is in line with the report of Tommy *et al*., (2004), Rafidah *et al*., (2010) and Li (2004). The reason for the high MOE from base to top along the culm length may be attributed to the higher frequency of vascular bundles content as one progress from the base to the top (Tommy *et al*., 2004; Rafidah *et al*., 2010 and Li, 2004). According to Li (2004), the MOE also increases with increase in cellulose content and decreasing micro-fibril angle. The least MOE was recorded for age 2 while the least MOR was recorded at age 3. This shows that at age 4 *B. vulgaris* had the highest resistance to deformation compared to other ages. The MOE values were seen increasing with the height of the culm from base to the top. However, MOR decreased from the base to the middle but had the highest values at the top part for all the age classes. This was a bit different from the findings of Hamdan *et al*., (2009) where they found the MOR of *G. scortechinii* generally decreased in height from 129.2 N/mm^{-2} to 123.3 N/mm^{-2} and 155.8 N/mm^{-2} to 151.2 N/mm^{-2}. Generally, the highest MOE and MOR were observed at the top part of the culm. This corroborated the findings of Liese (1985), Espiloy (1985) and Sint and Myint (2008). There were significant variations in the bending properties among the three age classes and along the culm length (Table 3 and 4). Age and culm position seemed to influence these properties to a reasonable extent. MOE and MOR of age 2 and 3 were similar but significantly different from that of age 4. MOE were significantly different along the culm length from the base to the top. However, MOR at the base was similar to the top but different from the middle part.

Grouping of *B. vulgaris* Based on the Limit of MOR, MOE and Compressive Strength

The classification of timber species for structural use in building is done on the basis of modulus of rupture and modulus of elasticity. Similarly, bamboos can be classified on the basis of modulus of rupture (MOR), modulus of elasticity (MOE), and compressive strength (maximum crushing strength) (MCS). Therefore, *B. vulgaris* was classified based on the

Table 7. Limit of Modulus of Elasticity for different strength classes and grades of timber

Strength Class						
C14	C16	C18	C22	C24	C27	C30
Modulus of Elasticity (MOE)						
<7,000	7,000-8,000	8,000-9,000	9,000-10,000	10,000-11,000	11,000-12,000	>12,000
Strength grade (General Structural GS or Special Structural)						
GS				SS		

Source: LST EN,(2000)

Table 8. Guide to basic working-stress values for timber

Specific strength						
Strength group	**Strength rating**	**Density (kg/m^3)**	**MCS Perpendicular to grain (N/mm^2)**	**MCS Parallel to grain (N/mm^2)**	**MOE**	**MOR**
1	Weak	< 400	10.6	2.5	10	4
2	Fairly strong	401 - 500	1.2	10	15	6
3	Strong	501 - 640	2.0	13	20	7.5
4	Very strong	641 - 800	3.2	20	30	9.0
5	Exceptionally strong	> 800	5.0	29	50	10.5

MCS = Maximum crushing strength

Source: FAO, 2011

limits of these properties as outline by Anon (1993) (Table 5).

Based on the density of the culm, *B. vulgaris* from age 2 and 4 are very strong because the density fall within 641-800 kg/m^3 and are thus falls within group D30-D50 (Table 6) while age 3 are exceptionally strong (>800 kg/m^3). The basal part (772.70 kg/m^3) are very strong while the middle (811.82 kg/m^3) and top part (830.11 kg/m^3) are exceptionally strong and are then placed within group D50-D60. Likewise, on the basis of strength limits, *B. vulgaris* from all the three age classes are placed in group I as both compressive strength parallel and perpendicular to grain were >70 N/mm^2, MOE >9000 N/mm^2 and MOR >35 N/mm^2 (Table 5). Also, using the standard classification based on MOE as outlined in LST EN 338 (Table 7), *B. vulgaris* from all the three age classes are placed in group I as both compressive strength parallel and perpendicular to grain were >70 N/mm^2, MOE >9000 N/mm^2 and MOR >35 N/mm^2. Also, using the standard classification based on MOE as outlined in LST EN 338. *B. vulgaris* from all the three age classes from base to top along the culm height falls in classes 22 - 30 which are the classes belonging to timbers for Special Structural (SS) application (Table 7).

The specific strength of *B. vulgaris*

The strength to weight ratio of *B. vulgaris* were determined from the density and the values of the MOR, MOE and compressive strength to evaluate the basic working-stress for all the three age classes. The strength to weight ratio of *B. vulgaris* was also classified based on modulus of rupture, modulus of elasticity, maximum crushing strength for classifying timber species for structural application. The limits

Table 9. Strength-weight ratio of *B. vulgaris*

Source of Variation	**Level**	**Properties (N/mm^2)**			
		MCS Parallel to grain (N/mm^2)	**MCS Perpendicular to grain (N/mm^2)**	**MOR (N/mm^2)**	**MOE (N/mm^2)**
Age (years)	2	2.97	1.45	0.23	25.18
	3	2.57	1.03	0.19	22.02
	4	3.31	1.71	0.27	27.64
Position	Base	2.73	1.76	0.24	23.65
	Middle	2.76	1.26	0.20	24.63
	Top	3.29	1.15	0.24	26.04

MCS = Maximum crushing strength

of these properties is shown in Table 8 following the grouping as outlined by FAO (2011).

B. vulgaris is placed in group 4 and 5 (very strong and exceptionally strong) based on density. Considering the specific strength; all the bamboo from the three ages are placed in group 1 (weak) based on the specific compressive strength parallel to grain; group II (fairly strong) based on the specific compressive strength perpendicular grain; group 3 – 4 based on the specific MOE, while it may not be placed in any group considering the specific modulus of rupture as non of the values falls within the groupings as outlined by FAO (2011).

Conclusion and Recommendations

The density values of *B. vulgaris* were found to vary with age and along the height of the culm. There were no significant variation in culm density along the culm length however, significant variations existed among the three age classes. There were significant variations in the compressive and bending strength of *B. vulgaris*. Compressive strength parallel to grain were higher than the compressive strength perpendicular to grains. Along the height of the culm, the compressive strength parallel to the grain increased from the base to the top. The maximum bending moduli of elasticity (MOE) and rupture (MOR) of *B. vulgaris* were attained at age 4. *B. vulgaris* from all the three age classes from base to top along the culm height fell in class 30 which is the class belonging to timber for Special Structural (SS) application.

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