IC-NOCMAT 2007 Maceió

International Conference on Non-Conventional Materials and Technologies: Ecological Materials and Technologies for Sustainable Building

Maceió, Alagoas, Brazil, 14th-17th October 2007

In Honour of Professor R.N.Swamy

FLEXURAL BENDING STRENGTH OF STRUCTURAL BAMBOO USED IN SUSTAINABLE HOUSE CONSTRUCTION IN AMAZONIA

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Abstract: Thorough understandings of the physical, mechanical, and chemical properties are required to optimize bamboo utilization. When using bamboo as a building material, one needs to know its specific gravity and bending strength properties. This work investigated density and bending strength properties of four-year old *Bambusa vulgaris ‘Vittata’* grown in Manaus (03˚06’07” S, 60˚01’30” W, 93-m), used on the construction of a prototype ecological and sustainable village for Amazonia. Eight 9-m long culms were collected from two clumps for testing. Flexural bending strength samples were cut from each culm in three 3-m segments (base, middle, and top). The 3-m long culms were tested in third-point loading static bending with a clear span of 2.71 m. The average moisture content (MC) and density of the bamboo culms tested were 12.95% and 646 kg/m^3, respectively. The average ultimate load, modulus of rupture (MOR) and modulus of elasticity (MOE) were 7885 N, 88 MPa and 9646 MPa, respectively. Analysis of the results showed that culm density can be used to determine its strength and stiffness.

Keywords: *Bamboo bending strength, density, Bambusa vulgaris ‘Vittata’, Amazonia.*

INTRODUCTION

Bamboo has a long tradition as a building material in the world's tropical (with Brazil being an exception) and sub-tropical regions, as cited by Sá Ribeiro et al. [1]. It is widely used for many forms of construction, particularly housing in rural areas. It is a renewable resource with high strength and low weight, and is easily worked using simple tools. Bamboo constructions are easy to build, resilient to wind and even earthquake forces when given the correct detailing. Associated products, such as bamboo based panels and bamboo reinforced concrete, also find applications in the construction process.

The density of bamboo is found to vary from 500-800 kg/m^3, depending on the anatomical structure such as the quantity and distribution of fibers around the vascular bundles [2]. Density increases from the center to the periphery of the culm [3, 4] and also from the base to the top of the culm. The maximum density is attained in about three-year-old culms [5, 6, 7, 8].

Bamboo has excellent strength properties, especially tensile strength. Most of the properties depend on the species, and the climatic conditions under which they grow [9, 10]. Strength varies along the culm height [11]. Compressive strength increases with height, while bending strength decreases with height [3, 5, 6, 7, 12, 13, 14]. An increase in strength is reported to occur at 3-4 years, and thereafter it decreases [5, 6, 7, 8]. Therefore, the maturity period of bamboo may be considered as 3-4 years with respect to density and strength. Maturity of culm is a prerequisite for the optimum utilization of bamboo in construction and other structural uses.

The determination of the critical load on bamboo culms is difficult because of the variation along the culm axis of the MOE, thickness and diameter, and by the presence of nodes and the variations of the said factors in the nodal region. Lastly, the inherent crookedness of the culm induces early P-delta effects that must be taken into account. This P-delta effect has a very random nature, since it is mobilized not only by the lateral deformations of the structure under lateral loads, but also governed by the initial deformations of the culm [15].

It is important that results of clear specimens are not directly transferred as those of full culms because, among other reasons, there will be a tendency of the culm to fail in the region of the nodes, the weakest link, and to develop high tensile parallel stresses, both factors being very much random in nature. Initial deformations of the culms would also lead to low rigidity at the beginning of the force - deformation path [15].

Bambusa vulgaris is the most common cultivated bamboo species in Manaus (03˚06'07" S, 60˚01'30" W, 93-m). In spite of its plentiful, the properties of *B. vulgaris* grown in this region are yet to be researched in detail. Vetter et al. [16] investigated the seasoning, density and shrinkage characteristics of *Bambusa vulgaris 'Vittata'* grown in Manaus. This work aimed to attain data on density and bending strength properties of full culm *B. vulgaris 'Vittata'* and how these properties are related.

EXPERIMENTAL PROCEDURES

Sampling and Conditioning

Eight 9-m culms from two clumps were collected from a plantation at the Brazilian National Institute for Amazonian Research (INPA) in Manaus (latitude -3˚06'07", longitude -60˚01'30", altitude 93 m), Amazonas (Figure 1). The culms were approximately four years old with 87-mm average diameter.

FIGURE 1 – COLLECTING CULMS FROM CLUMP AT INPA.

Each culm was cut into three segments (base, middle, and top) of 3-m long, labeled, measured, and conditioned according to the standard ISO N315 DTR-2001 [17]. These culms were conditioned for the flexural bending test. Some specimens were discarded due to cracks along the length of the culm, and were not substituted due to time constrains. Samples for MC determination and density were taken from each culm immediately after the completion of the bending test.

Testing the Culms

Determination of moisture content, density (mass by volume) and bending strength properties of the bamboo culms were done according to the standard ISO N314 DTR-2001 [18]. Flexural bending test of full bamboo culms was done using a Universal Testing Machine with a 500-kN load cell capacity at a speed of 30 mm/min up to rupture. Test specimens were loaded with a third point loading and simply supported over a 2.71-m clear span, as illustrated in Figure 2. Deflections were measured at mid-span using a potentiometer. The potentiometer was Celesco position transducer with a measuring range of 254 mm and a position sensitivity of 94 mV/V/inch. The testing procedure was the following:

1. Connect the potentiometer to the test specimen.
2. Apply third point loading at a load rate of 30 mm/min up to rupture, using a Universal Testing Machine. Measure and record displacements and loads.
3. Check system recovery after rupture.

A small piece was cut from each specimen near the point of failure for MC and density determination. MC was determined by oven-dry method and volume by water-displacement method.

FIGURE 2 – THIRD-POINT LOADING BENDING STRENGTH TEST FOR BAMBOO CULM.

ANALYSIS AND RESULTS

Physical and mechanical characteristics of the bamboo culms are given in Table 1.

TABLE 1 – PHYSICAL AND MECHANICAL PROPERTIES OF THE BAMBOO CULMS TESTED.

SAMPLE CULM	D (mm)	t (mm)	MC (%)	ρ (kg/m^3)	P_{PL} (N)	Δ_{PL} (mm)	P_{max} (N)	I (mm^4)	σ_{bmax} (MPa)	E (MPa)	Δ_{max} (mm)	σ_{bPL} (MPa)
A1B	87,99	12,84	12,61	719	8826	130	12259	2,2E+06	111	10890	226	80
A1M	88,86	7,57						1,6E+06				Outlier
A1T	66,57	6,11						5,4E+05				Outlier
A2M	87,64	6,98	10,94	717	5688	120	8238	1,4E+06	113	11560	186	78
A2T	71,88	6,12	10,43	708	3727	134	5590	6,9E+05	132	14255	270	88
A3B	98,19	11,64	18,23	655	10788	130	12161	3,0E+06	89	9712	180	79
A3M	96,31	7,34	14,15	771	9219	140	10592	2,0E+06	113	11374	200	98
A3T	76,39	5,98	10,48	799	3727	126	5080	8,3E+05	106	12652	186	78
A4B	103,98	11,74	15,31	630	14318	140	16770	3,7E+06	107	9828	184	91
A4M	102,95	7,71						2,6E+06				Outlier
B1B	89,13	11,14	15,24	613	4413	120	5100	2,1E+06	48	6136	155	42
B1M	82,34	5,46	10,31	554	1961	98	3089	9,8E+05	59	7217	176	37
B2B	87,63	10,63	11,35	604	5982	136	7041	1,9E+06	72	8004	188	61
B2M	81,36	6,16	10,76	533	2746	122	3531	1,0E+06	63	7673	180	49
B3B	94,60	13,09	15,72	578	8238	140	9219	2,9E+06	69	7279	170	62
B3M	89,38	6,93	10,81	587	4707	138	5639	1,5E+06	74	7849	178	62
B4B	82,71	10,41	15,01	579	5688	120	6080	1,6E+06	72	10614	145	67
MEAN	87,52	8,70	12,95	646			7885	1,8E+06	88	9646		
STD. DEV.	10,17	2,68	2,59	83			3897	8,8E+05	26	2371		
COV (%)	11,62	30,79	20,03	12,90			49,43	48,84	29,12	24,58		

The average moisture content (MC) and density of the bamboo culms of *B. vulgaris* tested were 12.95% and 646 kg/m^3, respectively. The average ultimate load, modulus of rupture

(MOR) and modulus of elasticity (MOE) of full culms tested in third-point loading bending were 7885 N, 88 MPa and 9646 MPa, respectively. Other findings attained from several researchers are summarized in Table 2. While the average density of *B. vulgaris* from different places in the world shows similar values, bending strength properties (MOR and MOE) vary widely. The researchers certainly used the same well known standard procedure to determine the density of the bamboo. If this is true, *B. vulgaris* average density may not vary significantly with the location. On the other hand, the determination of the bending strength properties was attained by the researchers using different standard procedures including dissimilar test specimens and MC. Therefore, it is not possible to make a straight comparison on the bending strength property values acquired by the researchers. Cumbersome adjustments would be necessary, and are beyond the scope of this present work.

TABLE 2 – PHYSICAL AND BENDING STRENGTH PROPERTIES OF *BAMBUSA VULGARIS* FULL SIZE CULMS.

RESEARCHERS	LOCATION	PHYSICAL PROPERTIES				BENDING STRENGTH PROPERTIES	
		D (mm)	t (mm)	MC (%)	DENSITY (kg/m^3)	MOR (MPa)	MOE (MPa)
Sattar et al.1992 [19]	Bangladesh			12,50	680	75	14318
Prawirohatmodjo 1990 [20]	Indonesia			17,00		84	
Palisoc and Bello 1996 [21]	Philippines			104,30	630	39	7080
Ghavami 1988 [22]*	Rio de Janeiro	69,50	7,50	16,05	650	78	5900
Sá Ribeiro et al. 2007	Manaus	87,52	8,70	12,95	646	88	9646
MEAN		78,51	8,10	32,56	652	73	9236
STD. DEV.		12,74	0,85	40,15	21	19	3731
COV (%)		16,23	10,48	123,31	3,20	26,73	40,40

*small test specimens

A plot for the load-displacement of the bamboo culm – bases, middles, and tops tested on third-point loading flexural bending is illustrated in Figure 3. As expected, the base-culms carried more load than the middle-culms, and the latter carried more load than the top-culms.

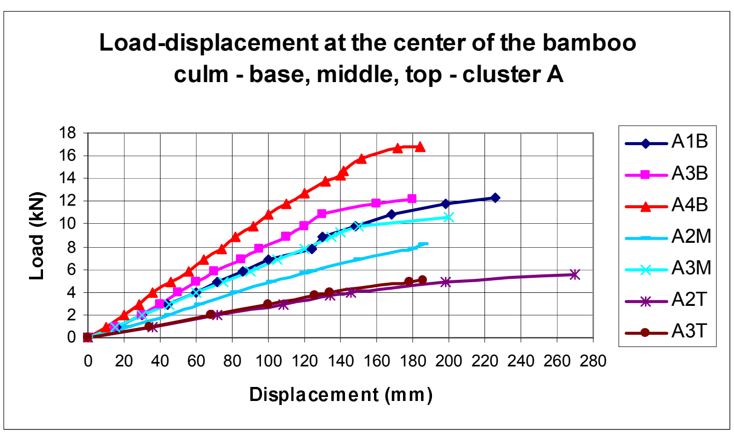

FIGURE 3 – LOAD-DISPLACEMENT DIAGRAMS FOR BAMBOO CULMS – BASE-MIDDLE-TOP.

A plot for the load-displacement of the bamboo culm - bases tested on third-point loading flexural bending is depicted in Figure 4. The bamboo culms from cluster A carried a bit more load than those from cluster B. This behavior is mainly due to higher density of the bamboo culms from cluster A.

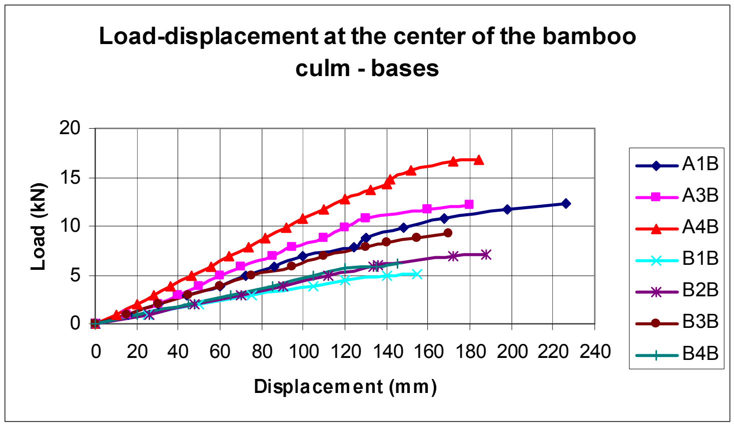

FIGURE 4 – LOAD-DISPLACEMENT DIAGRAMS FOR BAMBOO CULMS.

This work emphasizes the use of statistical relationships between variables for the determination of bending strength properties of bamboo culms. MOR, MOE, and apparent density were analyzed statistically. Correlations between mechanical and physical properties were determined. Linear regressions were run to see which factors would predict MOR and MOE efficiently.

The linear regression analysis between MOR and MOE presented a significant coefficient of determination (r^2) of 0.83. The regression equation for MOR versus MOE, plotted in Figure 5, proved to be a good predictor, and the coefficient was considered a good estimator with 95% confidence. Thus, this model can explain 83% of the variation in MOR.

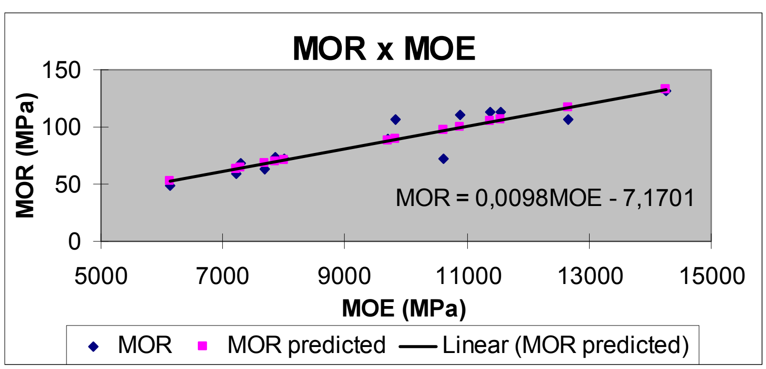

FIGURE 5 – MOR VERSUS MOE RELATIONSHIP FOR BAMBOO CULMS.

The linear regression analysis between MOR and apparent density (ρ) showed an r^2 of 0.66. The regression equation for MOR versus ρ, plotted in Figure 6, proved to be a good predictor, and the coefficient was considered a good estimator with 95% confidence. Therefore, this model can explain 66% of the variation in MOR.

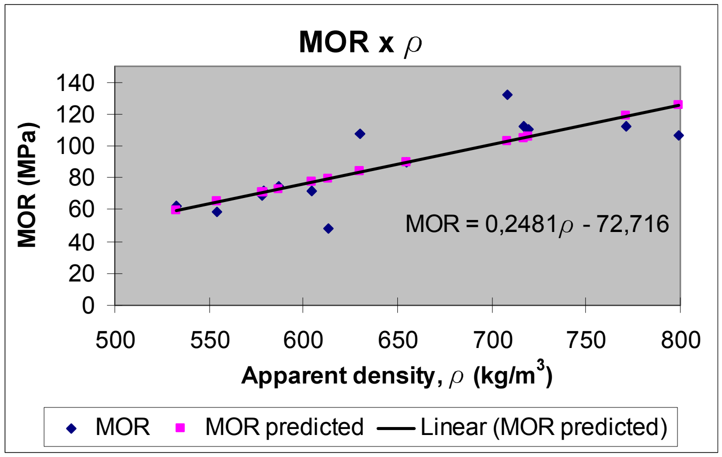

FIGURE 6 – MOR VERSUS DENSITY RELATIONSHIP FOR BAMBOO CULMS.

The linear regression analysis between MOE and ρ showed an r^2 of 0.62. The regression equation for MOR versus ρ, plotted in Figure 7, proved to be a good predictor, and the coefficient was considered a good estimator with 95% confidence. Therefore, this model can explain 62% of the variation in MOE.

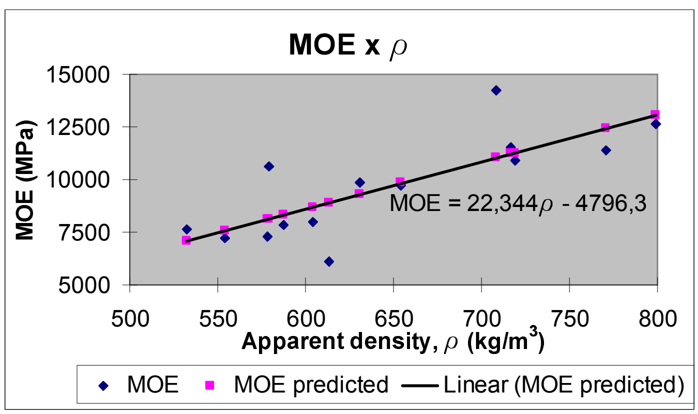

FIGURE 7 – MOE VERSUS DENSITY RELATIONSHIP FOR BAMBOO CULMS.

CONCLUSIONS

In order to simplify the use of bamboo culm strength properties this work suggests applying the average values among base, middle, and top parts. The MOR values of the tested bamboo culms varied from 48 to 132 MPa and MOE, from 6136 to 14255 MPa (Table 1).

Preliminary analysis of the literature available on physical properties of *B. vulgaris* suggests that the average density may not vary significantly with location. Average density values varied from 630 to 680 kg/m^3 (Table 2) with a low coefficient of variation of 3.20%. The average apparent density of 646 kg/m^3 for *B. vulgaris 'Vittata'* from Manaus at 12.95% MC is very close to the average value of 652 kg/m^3 for *B. vulgaris* from different locations.

Bamboo culm density can be used to determine its MOR and MOE with reasonable confidence (r^2 of 0.66 and 0.62, respectively). Also, full size bamboo culm MOE can be used to predict its MOR with high confidence (r^2 of 0.83). The predicted values from the models are good for 3-m culms of *B. vulgaris* grown in Manaus. Gnanaharan et al. [23] reported that density an outer diameter of *Guadua* bamboo culm can be used to predict MOR and MOE with high confidence (r^2 of 0.994 and 0.989, respectively).

The importance of testing bamboo in full size is emphasized by the standard ISO N314 DTR-2001 [18]. The predictability of MOR and MOE of full size bamboo culms using density shall be verified and confirmed by further testing of different bamboo species of large, medium and small diameter.

ACKNOWLEDGEMENTS

This work represents part of *Projeto CasaEco*, financed by FINEP/HABITARE - *Linha 2 - Tecnologias para a Construção Habitacional mais Sustentável*.

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