Bamboo: A Great Ally of the Civil Construction

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Abstract Sustainability adoption at the civil construction has been increasing over the years in a search for sustainable alternatives to reduce pollution and waste. One of those sustainable practices which has received great attention in the last few years is the application of bamboo as a raw material. In fact, bamboo has been employed in different areas, such as in the food industry, handicrafts, housewares, and furniture. Its main features are flexibility, durability, lightweight, strength, low cost and versatility, which enable its application at the construction industry. However, its use requires specific treatments, such as fungicide and insecticide, along with careful procedures for harvesting, curing and drying. Therefore, the aim of this research is to evaluate the potential use of bamboo as a building material for the construction industry by means of mechanical tests. Measurements were performed at the Materials Laboratory, School of Engineering from the Mackenzie Presbyterian University, Campus Higienópolis. The analysis was based on two bamboo species, which were chosen after interviewing experts in the field and searching the literature. For comparison purposes, two bamboo species were studied: *Dendrocalamus aesper* and *Phyllostachys pubescens*, which were chosen according to suggestions from experts in the field and by searching the literature, especially those contributions based on physico-chemical tests with other bamboo species. Based on the analyzed experimental data, the results evidenced the bamboo species studied herein could be applied to civil contruction. Both species chosen for this work provided suitable mechanical characteristics, since the average compressive strength for the *Dendrocalamus aesper* species was 83.14 MPa and for the *Phyllostachys pubescens* species was 97.67 MPa. The tensile strength for the *Dendrocalamus aesper* was 180.71 Mpa, whereas for *Phyllostachys pubescens* was 121.88 MPa. These results are in good agreement to the literature, which makes these bamboo species suitable as a sustainable alternative for the construction industry.

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1 Introduction

Bamboo comes from the family *Poaceae* (formerly called *Graminae*), which has over 1250 species. They are adaptable to tropical, sub-tropical and mild climates [1]. Bamboo may be found in diverse regions of the world, such as in the American, African and Asian continents [2].

Even though the biggest native bamboo forest is in the Brazilian territory, particularly at the State of Acre [3], there is some preconception about the use of bamboo. It was formerly employed as a building material by indigenous communities, followed by the slaves, which conceived the meaning of poverty and misery by the society. Moreover, bamboo may be associated to the lack of salubrity and subhuman living conditions. The image of social status, from the antiquity up to nowadays, is taken according to the type of housing. This type of construction was called wattle and daub (pau a pique, in Portuguese) [4].

On the other hand, bamboo has a broad range of applications in some countries from Asia, such as Japan and China, which comes from spiritual/religious reasons up to a myriad of others. Over 5000 uses for bamboo have been found all over the world [2]. Its versatility ranges from handicrafts, landscape design, paper fabrication, fabrics, musical instruments, reforestation of Riverside vegetation, recovery of eroded areas, control of steep slopes and a raw material for civil construction [5].

Some countries next to Brazil, such as Costa Rica, Ecuador and Colombia, have a higher acceptance to the use of bamboo as the raw material for construction, wherein it is employed for low-cost housing, as well as in large construction projects, such as bridges and pavilions. Therefore, it is well known that bamboo is not only a potential building material, but also a low-cost, eco-friendly and easy to handle alternative [6].

Even though the use of bamboo as a raw material in construction dates back to ancient times, it has become a sustainable alternative when the use of natural resources tend to decrease environmental pollution by giving priority to the natural environment, especially at the civil construction industry, since its residues are amongst the main sources of pollution to the environment. Moreover, bamboo has suitable physico-chemical properties, great durability, workability and versatility. It also serves as a tool for land restoration and erosion control [3].

Based on the suitable features cited above, the study of bamboo was proposed by considering its plantation, harvesting, drying, treatment and application in the housing industry, as well as the investigation of its mechanical properties.

A stable bamboo production takes about five to seven years, whereas its ripening takes place within three to four years. During this period culms and shoots are harvested to continue the cultivation and production. Bamboo irrigation is required, whereas no pesticide is needed. Manual harvesting may be carried out by using axes or jigsaw, which might help fortify the bamboo crop [7].

During bamboo growth, its fibers may become more resistant and harder. Its application in housing is recommended when it has the age of three to five years, since it acquires the maximum resistance [8]. Harvesting depends on the location: in tropical regions it is recommended to be carried out at the end of the dry season. In subtropical regions it should be performed during the winter season due to the smaller amount of water and starch in bamboo culms, since they store its reserves within the rhizome, which decreases the chances of fungi and insect attacks [9]. Moon phase and harvest time are also taken into account. Optimum harvest time would be on waning moon and before sunrise [7].

In order to increase durability and decrease the chance of fungi and insect attacks, harvested bamboo must undergo curing and treatment processes. Curing is highly recommended to be carried out inside the forest, since bamboo poles will still have its leaves and branches. They should be kept in a vertical position at the harvest site for four weeks over neighboring bamboo poles and rocks to avoid humidity. It should be done at the end of the dry season, but in the time, local pressure and humidity it was developed [7]. The treatment process occurs mostly by substituting starch by chemical substances. In Brazil, the most frequently used method is treating with boric acid and borax. The treatment occurs by dipping bamboo poles into a solution, which lowers starch concentration by trapping it into the tank water. Cleaning the tank from time to time helps avoid accumulation of reagents. Salts are absorbed and adhered to the bamboo walls, which hinders the growth of xylophagous organisms. The use of varnish and sealants is recommended for preserving bamboo [10].

Bamboo drying is an important step to provide suitable resistance and durability. If it were not done properly, bamboo pieces may suffer shrinkage, which will cause structural failure. It is highly recommended to dry bamboo inside greenhouses, since they are more efficient by harvesting sunlight during the day, without direct light illumination, and yet keeping it warm at night [7].

Storage should be done indoors, protected from the rain and sunlight, with the poles arranged in layers with some room for air ventilation. Bamboo poles should be kept 15 cm off the ground to avoid moisture. [9].

Bamboo has a high structural performance in terms of compression, torsion and bending. It is known to have good bending properties in light of its tubular volumetry and the longitudinally-oriented fibers, which create micro-tube bundles [10]. Nevertheless, the mechanical properties of bamboo are mainly influenced by its age, weather conditions, harvest time, species and moisture content [10].

Bamboo is a sustainable, low-cost, eco-friendly material with a large scale production. It provides less damage to the environment, both in its production and application in the housing industry, which decreases the amount of polluting residues generated there from. It is a environmentally friendly material with a myriad of applications in construction [11]. It is an efficient substitute for certain wood species in many construction types [12], besides being affordable to most social classes [13]. Therefore, the aim of this work is to show the mechanical properties of bamboo by carrying out tests for two bamboo species: *Dendrocalamus aesper* and *Phyllostachys pubescens*. Compressive and tensile strength were measured for both bamboo species and its technical viability studied for the housing industry.

2 Methodology

This research was carried out at the Materials Laboratory, School of Engineering from Mackenzie Presbyterian University—Campus Higienópolis, Brazil. The aim of this work was the study of mechanical and structural properties from bamboo culm from two species: *Dendrocalamus aesper* and *Phyllostachys pubescens*, which are native bamboo species from Atibaia, State of São Paulo, Brazil.

Due to the lack of specific standardization, the tests carried out in this work were based on the usually adopted standards and processes from the literature for the same analyses [14, 15].

2.1 Compressive Strength

According to suggestions from the literature, each sample was cut at a height of approximately two times its external diameter, as shown in Figs. 1 and 2. Those samples were polished from both sides in order to make them uniform, as well as to allow the uniform distribution of tension during compressive tests.

The height and inner diameter of each sample were measured by using a digital calliper with a resolution of 0.01 mm, which is similar to the universal calliper with the same resolution. Since throughout the bamboo sample the cross-sectional areas are not totally circular and there are changes in thickness, three measurements from the diameters were performed herein in different positions: top, center and bottom.

Tests were performed in a Universal Testing Machine, as shown in Fig. 3, with a maximum load of 60 tf and a loading rate of 10 mm/s.

The sample was placed in such a way that the movable cross head would match the cross-sectional area of the specimen. The compressive strength was calculated from

Fig. 1 Bamboo samples for compressive strength tests from the *Dendrocalamus aesper* species. *Source* Author's own figure

Fig. 2 Bamboo samples for compressive strength tests for *Phyllostachys pubescens* species. *Source* Author's own figure

Fig. 3 Universal Testing Machine for the compressive strength tests. *Source* Author's own figure

the relationship between the maximum supported load of each bamboo specimen and the external area (the average sample internal diameter was taken into account), as shown in Fig. 3.

The maximum compressive strength was achieved when bamboo failed. Figures 4 and 5 show two broken bamboo samples, just after tensile measurements. Twenty samples were measured: 10 from *Dendrocalamus aesper* and other 10 *Phyllostachys pubescens* species.

Fig. 4 Fractured bamboo samples from the *Dendrocalamus aesper* species. *Source* Author's own figure

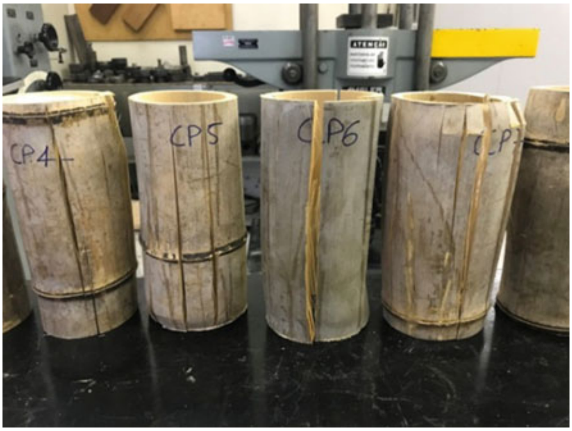

Fig. 5 Fractured bamboo samples from the *Phyllostachys pubescens* species. *Source* Author's own figure

2.2 Tensile Strength

Bamboo samples for the axial tensile strength tests were molded as shown in Figs. 6, 7 and 8. Strips were taken from culms with a height ranging from 20 to 29 cm and a thickness depending on the culm wall.

Bamboo strips were labeled sequentially from the edges (approximately 5 cm from the table length) in order to hold them tightly to the press. The central part of the specimen measured approximately 5 cm in length and 5 mm in width. Within the transition zone the width ranged from 5 up to 6 mm.

After the templates were ready and bamboo samples were properly labeled, the next step was to polish them to guarantee constant uniformity within the cross-sectional area to be fractured, making sure no error could happen. It is recommended,

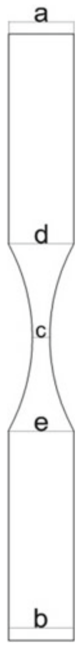

Fig. 6 Model for conducting the bamboo strip samples for tensile strength tests. *Source* Author's own figure

Fig. 7 Bamboo strip samples for tensile strength tests for the *Dendrocalamus aesper* species. *Source* Author's own figure

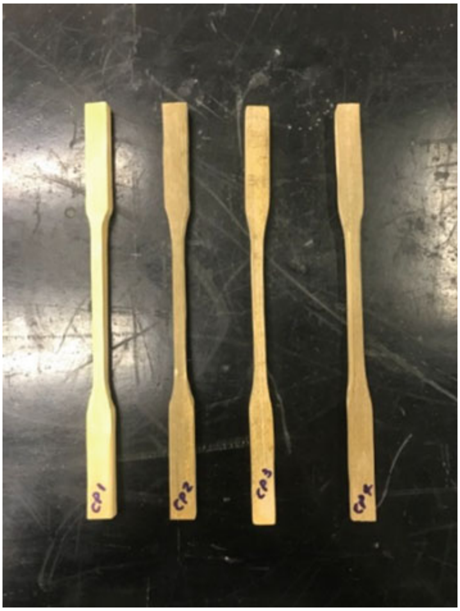

Fig. 8 Bamboo strip samples for the tensile strength tests for the *Phyllostachys pubescens*. *Source* Author's own figure

if fracture occurs away from the central region of the bamboo sample, that this result should not be analyzed. The reason for this fracture is usually shear stress.

In order to improve the adherence between the sample holder and the specimen a piece of sandpaper was inserted on each edge. This procedure aimed at minimizing sample slippage during tests, as shown in Fig. 9.

Width and thickness measurements were performed at the fracture zone of the specimen in order to determine the cross-sectional area before the tests were performed, exactly where it would occur.

The tensile strength tests were performed at a Universal Testing Machine with a load of 60 tf, as shown in Fig. 10. A total of 7 samples were analyzed: 3 from *Dendrocalamus aesper* and 4 from *Phyllostachys pubescens*. One sample from *Phyllostachys pubescens* species was used as an experimental run to specify test requirements for the other samples.

The tensile maximum load is found when there is a failure of the specimen. Figure 11 shows the failure for both bamboo species.

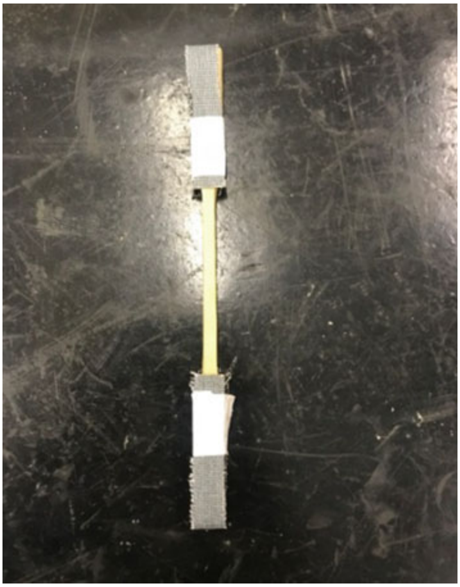

Fig. 9 Specimen for tensile strength tests. *Source* Author's own figure

Fig. 10 Universal Testing Machine used for tensile strength measurements. *Source* Author's own figure

Fig. 11 Samples from both bamboo species: *Dendrocalamus aesper* and *Phyllostachys pubescens*. *Source* Author's own figure

3 Results and Discussion

Measured data was analyzed by using a statistical software (*Statistical Package for Social Sciences*—SPSS, IBM, EUA). Both descriptive (especially those measured) and inferential analyses were performed at a significance level of 5%.

The first step was to check normality from the results by means of the Shapiro Wilk statistical test. Most of the results did not show normal distribution. Both non-normal, non-parametric analyses were associated in order to compare the results from the bamboo species, as recommended by the Mann-Whitney test.

The data from the statistical analyses for compressive and tensile strength are summarized in Tables 1 and 2.

Table 1 Statistical data from the variables of compressive stress (tf) and compressive strength (MPa) from two bamboo species, 2018

Statistics	Species	Compressive stress	Area	Compressive strength
Medium	*Dendrocalamus aesper*	24.56	29.10	83.14
	Phyllostachys pubescens	15.20	15.31	97.67
Minimum	*Dendrocalamus aesper*	19.80	24.72	59.95
	Phyllostachys pubescens	13.60	13.30	88.62
Maximum	*Dendrocalamus aesper*	31.40	36.09	98.24
	Phyllostachys pubescens	18.10	17.49	124.43

Table 2 Mann-Whitney test for comparison of species, variables: length (mm), external diameter (cm), weight (g), thickness (mm), internal diameter (cm) compressive stress (tf), area (cm^2) e compressive strength (MPa) de duas espécies de bambu, 2018

Variable	Specie	Median	p-valor
Length	*Dendrocalamus aesper*	304.65	0.0001*
	Phyllostachys pubescens	237.93	
Extern Diameter	*Dendrocalamus aesper*	14.19	0.0001
	Phyllostachys pubescens	10.69	
Weight	*Dendrocalamus aesper*	1145.60	1.0000**
	Phyllostachys pubescens	1145.60	
Thickness	*Dendrocalamus aesper*	13.24	0.0001
	Phyllostachys pubescens	9.84	
Internal Diameter	*Dendrocalamus aesper*	12.90	0.0001
	Phyllostachys pubescens	9.69	
Compressive Stress	*Dendrocalamus aesper*	23.70	0.0001
	Phyllostachys pubescens	14.73	
Area	*Dendrocalamus aesper*	28.21	0.0001
	Phyllostachys pubescens	15.16	
Compressive Strength	*Dendrocalamus aesper*	83.3750	0.0111***
	Phyllostachys pubescens	94.8445	

*Significant a 1%; **Equivalent; ***Significant a 5%

3.1 Compressive Strength Tests

Statistical data from Table 1 were achieved from compressive strength tests for 20 samples, 10 from each species. The average, maximum and minimum compressive strength supported by each sample in the test was determined from a general data analysis for each species.

Tensile data, as described earlier, was measured from sample failure. The area was calculated by subtracting two area values: the external and internal areas of bamboo samples. The outer and inner diameters were measured by using a digital caliper. A circular area was considered for bamboo. The corresponding areas were determined and the final area was calculated by subtracting the two values. Then the average, minimum and maximum data were determined for each species. Compressive strength was then determined from the relationship between tension and area.

According to Table 1, both bamboo species were within the reported parameter for the uniaxial compressive strength [16]. Samples from the *Dendrocalamus aesper* species provided a compressive strength of 83.14 MPa and those from *Phyllostachys pubescens* species 97.67 MPa.

Table 1 shows that the *Dendrocalamus aesper* species is able to withstand a higher load than *Phyllostachys pubescens*, since it has a higher cross-sectional area deriving from its structure and diameter. Nevertheless, when comparing both species by means of the average statistics, it is noticed that the *Phyllostachys pubescens* has a better compressive strength compared to *Dendrocalamus aesper*, which is ca. 17.48% higher, despite having a smaller structure, i.e., a smaller cross section to withstand the load.

The average, maximum and minimum data from each species described in Table 2, were achieved by a general analysis from 6 samples, 3 from each species, starting from tensile strength tests for each sample after their failure. Then the cross-sectional area was calculated from the failure location. Data were measured by using a caliper before failure. Tensile strength was derived from the relationship between tension and area.

Although most of the variables used in the Shapiro-Wilk test could be considered normal, nonparametric tests were chosen because of the small number of samples.

For Table 2, most of the variables were significant at 1%, except the mass, between the two species studied. However, when the medians such as length, internal and external diameter, thickness, compression stress, and area and between the species *Dendrocalamus aesper* and *Phyllostachys pubescens* are different, it is observed that the one of the first species cited is superior to of the second. Excluding the mass, which has a similar behavior between both species, and the exception appears in the variable resistance to compression, where the one of the species *Phyllostachys pubescens* is larger than the one of *Dendrocalamus aesper*. Therefore, it was concluded that in the majority of the measures evaluated the species *Dendrocalamus aesper* had higher values.

3.2 Tensile Strength

Table 3 shows data from tensile tests for parallel fibres from the bamboo sample. The tensile strength from the bamboo samples, in general, ranges from 40 to 215 MPa, with or without the presence of nodes [16]. Therefore, the average of tensile strength for both bamboo sample species was within the required parameter: 180.71 Mpa for *Dendrocalamus aesper* species and 121.88 MPa for the *Phyllostachys pubescens* species.

The analysis of Table 3 shows that the tensile strength for *Dendrocalamus aesper* species is higher than for *Phyllostachys pubescens*, i.e., 87.46% higher, which is able to withstand a higher load.

When comparing both species for their tensile strength, the *Dendrocalamus aesper* species had a better performance than *Phyllostachys pubescens*, since it provided a ca. two-fold increase for this parameter.

Both bamboo species chosen in this work provided suitable mechanical properties, which serve as a motivation for the use of bamboo as a substitute for steel [16], as well as a driving force for its use in association with other building materials such as concrete, in order to increase its mechanical resistance.

Compressive strength data was, on average, three times lower than tensile strength [14]. Then it was concluded that both *Dendrocalamus aesper* and *Phyllostachys pubescens* species have a higher tensile strength than compressive strength.

Here, also, non-parametric tests were chosen because of the small number of samples. although most of the variants used in the Shapiro-Wilk test can be considered normal. According to Table 4, although no test is significant at 5%, since a small sample has been used and non-parametric tests have been used, it can be considered that at 10% there is a significant difference between the medians for the measured variables c, height, tensile stress, area and tensile strength. Another important observation in Table 4 is that for all the significant measures the species *Dendrocalamus asper* has higher values than the species *Phyllostachys pubescens*.

Table 3 Statistical data from variables of tensile stress (tf) and tensile strength (MPa) from two bamboo species, 2018

Statistics	Species	Tensile stress	Area	Tensile strength
Medium	*Dendrocalamus aesper*	1256.67	0.68	180.71
	Phyllostachys pubescens	670.00	0.50	131.88
Minimum	*Dendrocalamus aesper*	990.00	0.64	151.22
	Phyllostachys pubescens	640.00	0.48	125.88
Maximum	*Dendrocalamus aesper*	1420.00	0.71	202.52
	Phyllostachys pubescens	720.00	0.52	136.44

Table 4 Mann-Whitney test for comparison of variable species: height (mm), mesure a (mm), mesure b (mm), mesure c (mm), tensile stress (tf), área (cm^2) e tensile strength (MPa) of two species of bamboo, 2018

Variable	Specie	Median	p-valor
Mesure a and b	*Dendrocalamus aesper*	11.47	0.2291
	Phyllostachys pubescens	11.87	
Mesure d and e	*Dendrocalamus aesper*	6.12	0.6291
	Phyllostachys pubescens	5.96	
Mesure c	*Dendrocalamus aesper*	5.73	0.0571*
	Phyllostachys pubescens	5.53	
Height	*Dendrocalamus aesper*	299.10	0.0571
	Phyllostachys pubescens	200.61	
Tensile Stress	*Dendrocalamus aesper*	1360.00	0.0571
	Phyllostachys pubescens	660.00	
Area	*Dendrocalamus aesper*	0.69	0.0571
	Phyllostachys pubescens	0.50	
Tensile Strength	*Dendrocalamus aesper*	188.38	0.0571
	Phyllostachys pubescens	132.60	

*Significant a 10%

4 Conclusion

The supply chain of the construction industry generates an enormous amount of pollutants to the environment. The main reason is associated to the chosen materials, which might be rather expensive in most cases. Therefore, thinking about sustainable and low-cost materials means to search for alternatives to comply with global environmental requirements, population growth and housing shortage.

Bamboo is a versatile material, which may be found in most of the Brazilian territory. However, there is some prejudice against its usage in Brazil since it is usually associated with poor houses, whereas in some other countries, especially in Asia, its use is encouraged since it is a highly resistant material.

The world has been changing and it is open to new cultures. In Brazil, the scenario is not different. Nevertheless, there is a lack of specific technical criteria for Engineers and Architects when they want to apply bamboo in their projects. The Brazilian standard for this material is yet under discussion and research studies could contribute for broadening its applications, corroborating its relatively high compressive and tensile strength, as well as in destroying the prejudice of “poor” housing. High complex structures endowed with strong aesthetics may be created by using this material.

The data from mechanical tests from *Dendrocalamus aesper* and *Phyllostachys pubescens* species showed that bamboo is a viable raw material for application in small and big construction projects.

According to the statistical studies carried out in the research, it was observed that the species *Dendrocalamus aesper* has characteristics superior to that of the species *Phyllostachys pubescens*. Suggesting that the geometry of *Dendrocalamus aesper* is best for use in construction.

Therefore, since bamboo is a sustainable material with large scale production, a low-cost and eco-friendly material, its use in housing projects can decrease the generation of polluting residues. Since it is a renewable resource, has a broad range of applications and is affordable to most social classes, it is considered a great material candidate for use in the housing industry.

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