Doctoral School on Engineering Sciences
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Extended summary

Bamboo structures: Italian culms as likely resource for green buildings

Curriculum: Architettura, Costruzioni, Strutture

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Abstract. In this thesis the results of compression, tensile and bending tests on Italian bamboo culms are discussed. The analyzed bamboo are of two species, namely *Phyllostachys Edulis* (MOSO) and *Phyllostachys Viridiglaucescens*. These tests are carried out following the rules of ISO 22156 and ISO 22157. The characteristics values of the compressive and flexural strength of Italian bamboo culms are determined. A new and versatile connector for bamboo structures is developed and tested to evaluate its effectiveness. This connector is realized by wood parts and screws and it is appropriate for constructing trusses and space frames. The use of the screws to connect wood and bamboo is due to two main aspects. First, the screws are easy to use and no particular skill is needed. Second, no splitting arises along the culm since a preliminary drilling is needed to introduce the screw.

In the second part of the thesis, the linear buckling problem of non-uniform columns is treated. Firstly, a brief overview of the history of the linear buckling is described. Since bamboo culms present non-uniform flexural stiffness along the length, an approach to evaluate the approximate analytical solution of the governing equation is presented. This method can calculate the critical load in a simple way, directly accessible to the designers. The proposed method gives a closed-form estimate of the bamboo column deflection, subjected to an eccentric axial load and initial curvature (crookedness).

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Keywords. Mechanical strength of bamboo, Green buildings, Connector (joint) for bamboo structures, Critical load of non-uniform columns, Initial imperfections.

1 Introduction

The classical building materials such as concrete and steel are always more frequently substituted by timber and other natural materials that are defined *green materials*. In this scenario, new materials characterize the actual research, with particular reference to the materials that are sustainable and have good mechanical properties. Among all natural materials, the plant of bamboo seems to be one of the best candidate.

Many researches have dealt with suitable applications of this plant in the civil engineering due to its fast growing, significant mechanical properties and economical characteristics. Cambridge University plotted the performance of many materials versus their density and Young's modulus, in order to provide a method to select advantageous building materials [1]. From their results (shown in Figure 1), we can see that the performance of bamboo is better than other materials. Other researchers dealt with the strength of this plant by experimental tests, as reported in [2-7], obtaining high values of tensile, compressive and flexural strength. For its high strength, bamboo is called the *vegetable steel*: its tensile strength can reach about 300 MPa.

The scope of our work is to investigate the mechanical properties of the Italian growing bamboo in order to recognize whether it can be comparable to the classical construction materials that are used in our country. The investigated species of bamboo are *Phyllostachys Viridiglaucescens* and *Phyllostachys Edulis* (MOSO). The first specie has been harvested from bamboo forests situated near Viareggio (N 43° 56' 5", E 10° 16' 1") and Paliano (N 41° 46' 9", E 13° 0' 57"), the latter near Genova (N 44° 20' 53", E 9° 21' 1"). For this purpose, we use ISO 22156, ISO 22157-1 and ISO 22157-2 that are the international standards for structural bamboo. The tests are carried out in the laboratory of Dipartimento di Ingegneria Civile ed Architettura of Università Politecnica delle Marche. These tests are useful to estimate the compressive strength, tensile strength, bending strength and the respective Young's modulus.

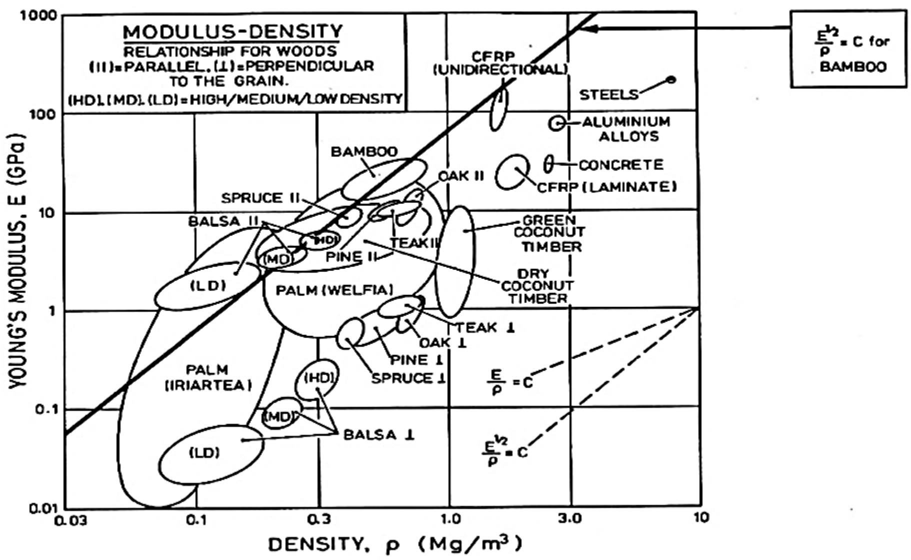


Figure 1. Performance of bamboo and other materials in relation to their E (Young's modulus) and ρ (density). The picture is taken from [1].

Figure 2. *BAMwood.*

Since the bamboo culm (the term of *culm* is referred to the stem of any plant) can be considered as a tubular rod, it is appropriate to realize trusses and lightweight space frames. Nevertheless, the bamboo culm is weak in shear since the fibers are all parallel to the length and the transversal strength is very low, thus the transversal forces to the culm should be avoided. Furthermore, the culm can be cracked when nails are put into the culm reducing the strength of the connection. A possible solution is shown by Albermani et al. [8], which tested a special joint for bamboo structures using PVC connector glued to bamboo culm skin by an epoxy resin. Other solutions proposed by several authors are reported in [9] such as filling the culm by concrete mortar and inserting the steel connector inside. This kind of joint was designed by Markus Heinsdorff and it was used to build the Pavilions for the "German Esplanade" in China during a cultural initiative in 2007.

Our proposal is to avoid the use of the epoxy resin, in order to improve the green aspect of construction, and the concrete mortar to make lighter the joint. This connector, called *BAMwood* (Figure 2), is made of a wooden cylinder that is introduced into the culm and it is fixed to the bamboo by using screws. The use of the screws to connect wood and bamboo is due to two main aspects. First, the screws are easy to use and no particular skill is needed. Second, no splitting arises along the culm since a preliminary drilling is needed to introduce the screw. Its mechanical behavior is investigated by means of the tensile and compression tests.

Important care is required for the bamboo structure design against the buckling of culms being organic material and not perfectly straight. Elastic stability of the bamboo culms is studied and an approximate formula for the estimate of the critical behavior is proposed.

2 Experimental tests

The goal of the tests is to define the main physical and mechanical properties of two species of Italian bamboo. The aim of this work is firstly to know the characteristics of this material, and then is to extend the number of the experimental results in accordance with international standards [10-12].

The part of the culm for structural purposes is between 1.0 m and 7.0 m from the ground root. Since the percentage of sclerenchyma tissue (fibers) increases from bottom to top of the culm, the specimens for mechanical tests need to be taken from various parts of the culm. Generally, bamboo culms are classified in three parts: B (bottom), M (middle) and T (top). Every part is 2.0 m long. The specimens for our mechanical tests are taken manly from B and M parts. The bamboo culms at our disposal are stored in a place without sunlight for three months before tests. The temperature is between 19 °C and 23 °C. The relative humidity (R.H.) is between 80% and 95%. This high value of R.H. would provide very safety values of the strength to design with bamboo. Other characteristics of tested culms are reported in Table 1.

In our work, the physical properties of the culms consist of geometrical properties (length, diameter, wall-thickness, rate of the taper of the culms), density (ρ) and moisture content (MC). The mechanical properties of the culms consist of compressive strength, tensile strength, flexural strength, and respective Young's moduli.

The connector (*BAMwood*) is tested under compressive and tensile loads in order to recognize its mechanical behavior. The shape of the tested samples are shown in Figure 3.

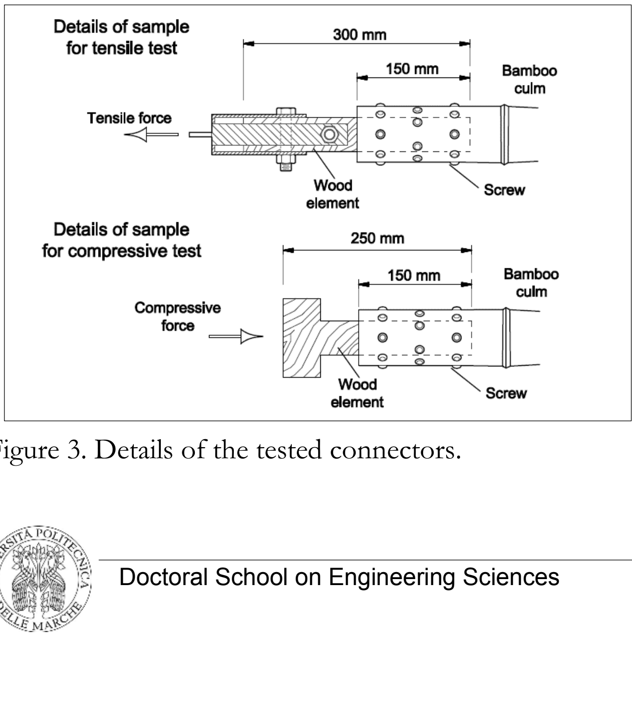
3 Results of mechanical tests

Our results show that Italian bamboo can be a suitable material for building structures. The analyzed culms are medium size (*Phy. Viridiglaucescens*, VV and VP) and medium-giant size (*Phy. Edulis*, EG). Both the external diameter and the wall-thickness decrease from bottom to the top of the culm: the external diameter increases up to 8-9% per meter along the height. The density of EG is about 756 kg/m^3, whereas the density of VP is about 805 kg/m^3. No considerations about the density of the VV specimens since they have been treated by boric acid.

Table 1. General characteristics of the culms for mechanical tests

Species	Phy. Edulis (EG)	Phy. Viridiglaucescens (VV)	Phy. Viridiglaucescens (VP)
Origin	Carasco (GE)	Viareggio (LU)	Paliano (RM)
Years of culms at harvesting	3-5	4-5	unknown
Storage place and period*	outdoor 3 months	outdoor 2 years	outdoor 1 month
Treatments	none	boric acid	none

* The period before the storage at University.



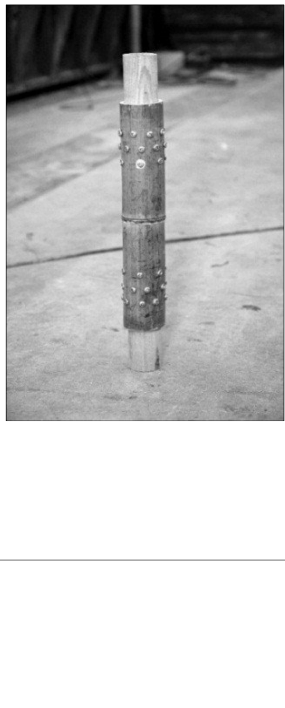


Figure 3. Details of the tested connectors.

The moisture content of the specimens is rather high (25%-44%) and it greatly affects the mechanical properties. The strength of bamboo is comparable to the other classical building materials such as concrete and timber. The compressive strength is about 55 MPa for EG, 56 MPa for VV and 69 MPa for VP. No considerable difference of the compressive strength is obtained between node and internode samples. These results are obtained without intermediate layer between the specimens and the universal machine steel plates and therefore they are not conservative: the actual values should be reduced by 10-15%. The average Young's modulus under compression loads is about 2900 MPa for EG, 3100 MPa for VV and 3400 MPa for VP.

The tensile strength of bamboo is very high, namely 2-3 times its compressive strength: 127 MPa for EG and 159 MPa for VP (averaged values). This fact should be taken into account in the design of the bamboo structures. The Young's modulus under tensile loads varies from 12000 MPa (EG) to 22500 MPa (VV), but these values are not sufficiently reliable owing to the high standard deviation associated to these data. Additional tests are required.

The flexural strength of bamboo is comparable to tensile strength and it is about 1.5-2 times the compressive strength: about 97 MPa. The tests are carried out only on EG since the culms of other species at our disposal are too short for the bending tests. The Young's modulus in bending varies along the height of the culm from about 12600 MPa (bottom part) to 13800 MPa (middle part). The Young's modulus in bending increases from bottom to the middle part of culm by 9-10%.

The proposed connector shows good mechanical properties and it may be considered suitable for bamboo trusses and space frames by using connection systems currently used in the steel space structures. The obtained compressive strength, about 27 MPa (referring to the cross-sectional area of the bamboo culm), is equal to the tensile strength and it is about half of the bamboo compressive strength.

4 The linear buckling problem of non-uniform columns: the case of bamboo culms

The bamboo culms are tubular tapered columns with variable Young's modulus along the length. In literature it is very difficult to find exact closed-form solutions of critical buckling load of columns with variable geometrical and mechanical properties. The reason of this lack is the complexity of solving in exact way the governing equation and only few cases with specific non-uniformities of columns subjected to a concentrated force can be solved in terms of specific functions [13]. In our work, a method for evaluating approximate critical buckling load is proposed. Another characteristic of bamboo columns are the marked imperfections that hugely reduces its compressive buckling strength. The approximate transversal deflection of bamboo columns subjected to an eccentric axial load and initial curvature (crookedness) is also determined.

Using the dimensionless variable length ξ in place of x and in according to Euler-Bernoulli beam theory, the differential equation that governs the buckling problem is

$$D(\xi)v''(\xi) + \omega v(\xi) = 0 \tag{1}$$

where $D(\xi)$ describes the variable flexural stiffness of column and ω is the dimensionless critical buckling load. The boundary conditions for hinged-hinged columns are

$$v(0) = v(1) = 0 \tag{2}$$

The proposed method, directly accessible to the designers, is based on replacing the effective flexural stiffness in Eq.1 with a new function such that the governing differential equation of the buckling can be solved in closed-form. The new function is a linear function with the following form: $\widetilde{D}(\xi) = a + b\xi$. The two values a and b should be evaluated so that $\widetilde{D}(\xi)$ fits very well the exact flexural stiffness $D(\xi)$. To achieve this goal, the continuous summation of all the squared residual

$$\int_0^1 \left[D(\xi) - \widetilde{D}(\xi)\right]^2 d\xi \qquad (3)$$

has to be minimized. The solutions of differential equation in Eq.1 with $\widetilde{D}(\xi)$ are in terms of Bessel's functions of order one [14].

5 Results

In order to analyse the effectiveness of the proposed method, we consider typical geometric and mechanical properties of Italian bamboo culms belonging to *Phy. Edulis* species. The critical buckling loads with the exact flexural stiffness are obtained by using the eigenvalue routine provided by *Mathematica* software and they are compared with those obtained by the proposed method.

Defining k as wall-thickness to diameter ratio, the percentage errors of the approximate loads are plotted as function of $m_{er}\ L/r_0$ and shown in Figure 5 (the main geometrical and mechanical characteristics of the bamboo columns are defined in Figure 4). It can be seen that the results obtained by using the proposed method are in good agreement with those obtained by using the specific software. In fact, the percentage error is not higher than 3% for the analyzed cases. The error amplifies with increasing $m_{er}\ L/r_0$ value and it can be neglected for $m_{er}\ L/r_0 \leq 0.1$ for each case.

Considering an initial deflection of the bamboo column (δ), the analytical expression of the approximate transversal deflection of the column subjected by an axial load with eccentricity (e_c) can be obtained by using the proposed method. The solution with the exact flexural stiffness is obtained by using *Mathematica* software (numerical solution) and it is compared with the analytical solution provided by the suggested method (proposed solution). We find that the proposed solutions are in good agreement with the numerical solutions (Figure 6).

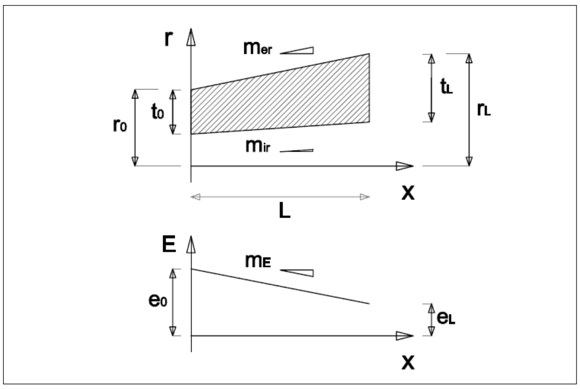


Figure 4. The main geometrical and mechanical characteristics of the bamboo culm.

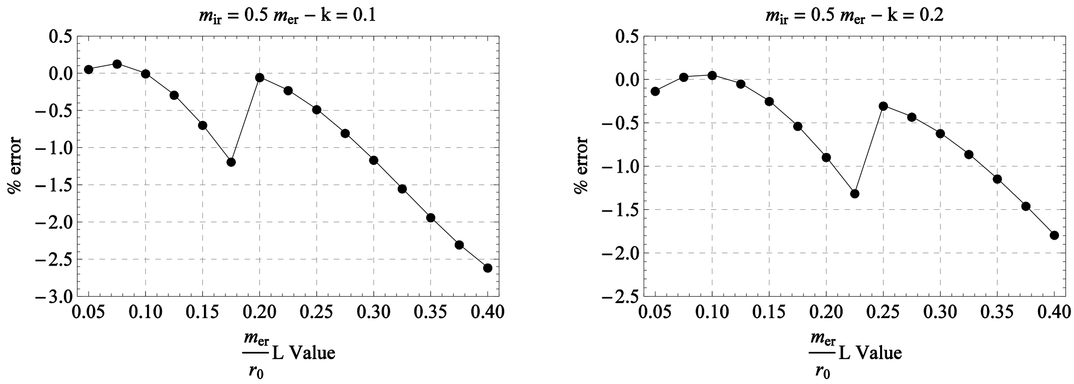


Figure 5. The percentage errors in the buckling load versus $\frac{m_{er}}{r_0}L$ values.

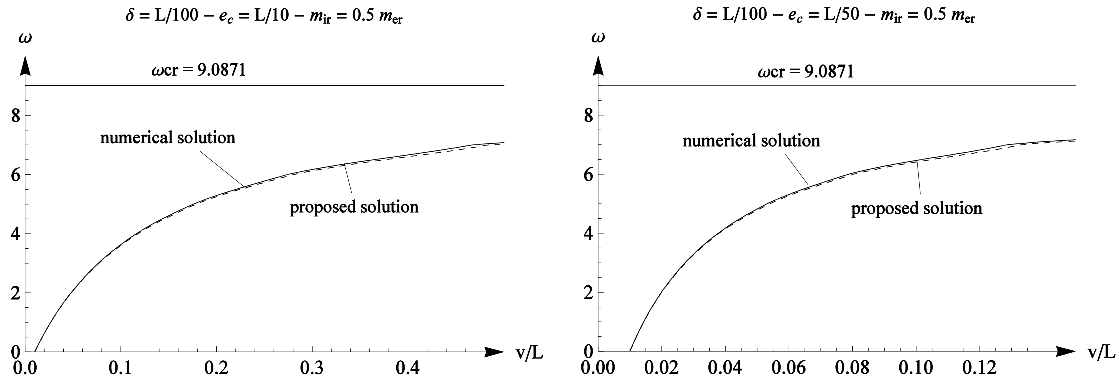


Figure 6. The numerical solutions obtained by *Mathematica* in comparison to the solutions obtained by the proposed approximate method ($\frac{m_{er}}{r_0}L = 0.2$).

6 Conclusions

The purpose of our work is the experimental characterization of the mechanical properties of two species of Italian bamboo and encourage the researchers to study the properties and the possible applications of this plant. The compressive and flexural strength of bamboo obtained in our tests are excellent results when compared to the strength of other natural materials, and the average tensile strength is better than the tensile strength of other natural materials such as wood. The proposed connector (*BAMwood*) exhibits a good strength under tensile and compressive loads and, thus, it could be a good solution to build trusses and space frames with bamboo.

The linear buckling problem for bamboo columns is studied and a method is proposed to calculate the analytical solution of the governing differential equation. The method provides approximate solutions that are in good agreement with the solutions obtained by using any numerical analysis software.

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