



COB-2021-0392

DYNAMIC CHARACTERIZATION OF YOUNG AND SHEAR MODULUS OF THE BAMBOO

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Abstract. *In recent years, it has been increasing the use of bamboo in various engineering applications. For the projects of these applications may be carried out in a precise and reliable way, it is essential to know the dynamic behavior of their materials. For this, it is essential to know the mechanical properties of bamboo. This work presents a methodology for characterizing the mechanical properties of bamboo, where dynamic flexion and torsion tests were performed to determine the elasticity and shear modulus of bamboo. The bending tests were performed with cantilever beams made from bamboo samples with different sizes. The natural frequencies of the beams were measured and, using the Euler-Bernoulli equations, the Young modulus of the samples could be determined. The shear modulus was determined in a similar way, however, by performing torsion tests of samples with a disk at the tip. To validate the characterized properties, a four-floor portico was built and the first natural frequencies were measured. Through a numerical modal analysis of this portico, modeled using the finite element method and using the characterized properties, it was found that the experimental and numerical natural frequencies converged. Furthermore, the results obtained in this work are in good agreement with results presented in the literature.*

Keywords: *bamboo, dynamic behavior, boundary conditions, natural frequency.*

1. INTRODUCTION

Bamboo culms are materials that can be produced inexpensively, efficiently, sustainably and with low negative environmental impact. These vegetable tubes can be used as structural elements in civil construction.

Bamboo wood is a natural composite with a functional gradient of cellulose fibers dispersed in a lignin matrix. In today's world, the use of this type of biomaterial is increasingly necessary and appropriate. Bamboo is a light, resistant, stable structural material that has been used to build housing and everyday products for thousands of years, especially in the tropical world and in countries such as China and Japan.

Non-renewable raw material sources are running out, and energy is also a scarce resource. According to Ghavami (1992), bamboo is a material that requires 50 times less energy to be produced than the same mass of steel. In addition to being a material with adequate mechanical resistance to be used as a structural element, bamboo is a very energy efficient plant. Bamboo has several other applications in engineering, as reported in their works (Ghavami *et al.*, 2017) and (Ostapiv and Salamon, 2020).

Also according to Salamon and Ostapiv (2017) There are several problems to be overcome so that bamboo culms and the wood from these can be used in housing structures or in other industrialized products. Bamboo culms present several imperfections in the circularity of the cross sections, as shown in Fig.1, in conicity, in wall thickness variation, in axiality deviations, in the presence of knots, etc. In addition to the fact that the material changes its mechanical characteristics over time. Hence the difficulty in processing and standardizing this material. Some species such as *Phyllostachys pubescens* have a reasonably linear longitudinal axis, while other species, such as *Bambusa vulgaris*, have a significant undulation along the central line of the culm.

The determination of the mechanical properties of different materials can be obtained through standardized guidelines. However, the literature lacks standardized methods to determine these properties for bamboos.

This work presents a proposal for the characterization of the mechanical properties of bamboo, through experiments with samples in the free-mounted condition. To validate the determined properties, a four-floor portico was built with bamboo and its natural frequencies were determined and measured.



Figure 1. Cross section of culms of *Bambusa vulgaris*: on the right, distortion in the vicinity of the node (Ghavami *et al.*, 2017).

2. MATERIALS AND METHODS

2.1 Samples Selection

The bamboo bars of the species *Phyllostachys pubescens* used in this work were purchased in the market as bamboo sticks or skewers for culinary use. The samples used in the work were selected so that they presented better surface finishes, absence of cracks and were free of nodal regions of the bamboo, as shown in Fig.2.

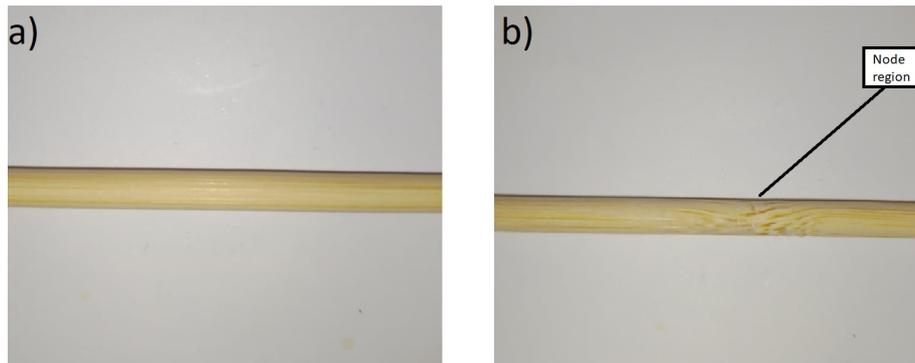


Figure 2. Illustration of two samples: (a) unknotted (valid sample), (b) knotted (discarded sample).

After selected, the density [ρ] of some samples was determined. For this, a caliper was used to measure the diameter and length of each sample, to calculate the volume [v], and, using a precision scale, the mass [m] was measured. With this, the density of the samples were determined through:

$$\rho = \frac{m}{v}, \quad (1)$$

and their values are shown in Tab. 1.

Table 1. Bamboo Samples Density.

Sample	Volume (mm ³)	Mass (g)	Density (kg/m ³)
1	3.54	2.7	762.10
2	1.37	0.9	653.82
3	2.14	1.6	605.47
4	3.48	2.3	659.92
Avarege Density			670.33

2.2 Determination of the Young's Modulus

The determination of the Young's modulus of the samples was carried out through tests of vibration of the samples in the cantilever beam condition. For this, a steel block and an accelerometer from the Endeveco brand, model 256-100, were added at the tip of the sample, which together totaled a mass of 24 g, as shown in Fig. 3.

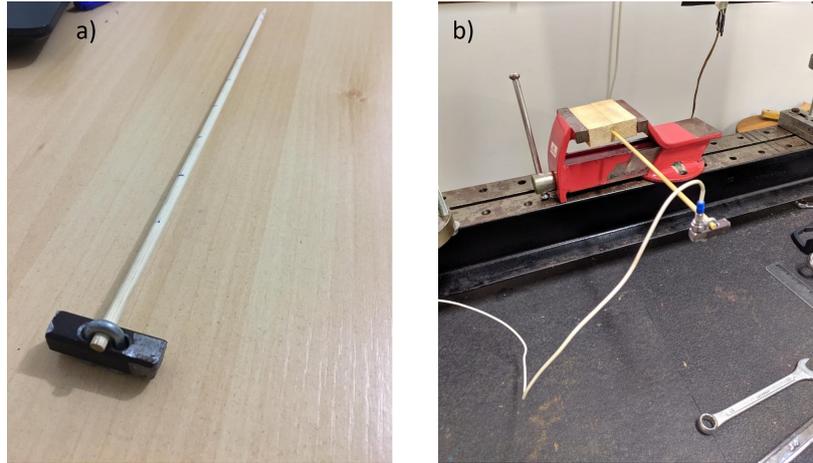


Figure 3. a) Illustration of samples used in bending tests, b) Sample crimping system..

Thus, impacts were given at the beam tip and the first natural bending frequency was measured for each sample, and for different lengths. Each sample was tested in the following lengths: 200 mm, 170 mm, 140 mm, 110 mm, 80 mm e 50 mm.

To better perform the setting of the samples, a split system with a hole in the middle was developed in soft wood, with the same diameter as the samples, as shown in Fig. 3. With this, each sample could be set firmly without its geometry being damaged.

To determine the Young's modulus of the tested samples, the concept of equivalent stiffness of cantilever beams was used. As shown by (Meirovitch, 2001), the equivalent stiffness of a uniform beam of length $[L]$ can be determined by using the transversal displacement at the tip, $\omega(L)$, due to a punctual and unitary force F applied also at tip, as:

$$K_{eq} = \frac{F}{\omega(L)} = \left\{ \int_0^L \left[\int_0^\zeta \frac{l-\xi}{EI(\xi)} d\xi \right] d\zeta \right\}^{-1}, \quad (2)$$

where $[E]$ is the Young's modulus of the sample and $[I]$ the moment of inertia of the cross section of the sample. Considering that $[E]$ is constant, Eq. 2 can be rewritten as:

$$K_{eq} = \left\{ EI \int_0^L \left[\int_0^\zeta (L-\xi) d\xi \right] d\zeta \right\}^{-1} = \left[EI \int_0^L \left(l\zeta - \frac{1}{2}\zeta^2 \right) d\zeta \right]^{-1} = \frac{3EI}{L^3}. \quad (3)$$

Then using the concept of equivalent stiffness and disregarding the beam mass (bamboo sample), the natural frequency $[\omega_n]$ of the system is associated with the end mass $[m]$ and with the equivalent stiffness $[K_{eq}]$ of the sample by the following equation:

$$\omega_n = \sqrt{\frac{K_{eq}}{m}}, \quad (4)$$

or yet,

$$\omega_n = \sqrt{\frac{3EI}{mL^3}}. \quad (5)$$

Therefore, through the natural frequencies measured for each sample, the modulus of elasticity were determined through:

$$E = \frac{\omega_n^2 L^3}{3Im}, \quad (6)$$

The moment of inertia of the samples was calculated using:

$$I = \frac{\pi d^4}{64}, \quad (7)$$

where $[d]$ refers to the beam diameter.

2.3 Determination of shear modulus

To determine the bamboo's shear modulus, a procedure similar to the one presented in Section 2.2 was used. As can be seen in Fig. 4, a metal disk of 91 mm diameter, for samples 1 and 3, and 146 mm for samples 2 and 4, was attached to the tip of each sample. An Ethylene-vinyl acetate (EVA) block was added to this disc for accelerometer fixation. The samples were fixed in the same previous hook system. To perform the excitation of the samples, in different lengths, a slight initial rotation to the disk was imposed with the hands, causing an initial torque, and then released, causing the system to vibrate naturally at its first natural frequency.

Each sample was tested in the following lengths: 200 mm, 170 mm, 140 mm, 110 mm, 80 mm e 50 mm.

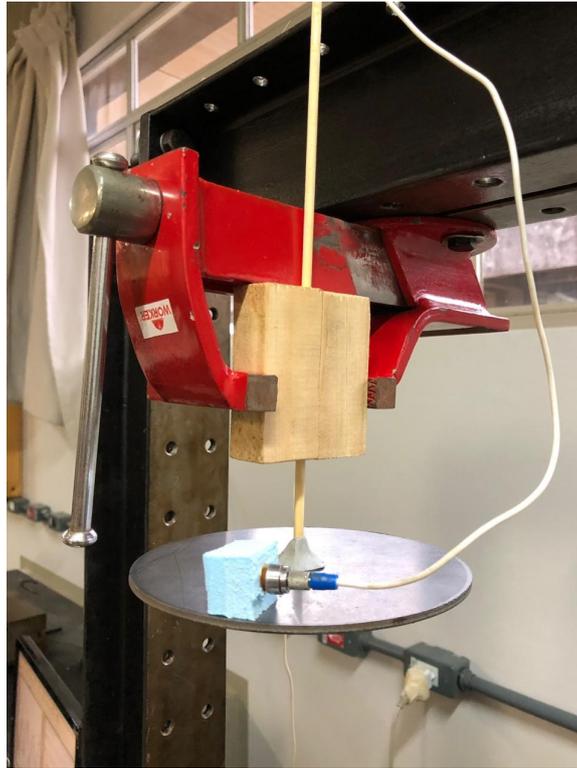


Figure 4. Torsion System.

To determine the shear modulus $[G]$, the concept of equivalent stiffness was used again, which, for a shaft with a disk at the tip, is given by (Meirovitch, 2001)

$$K_{eq} = \frac{GJ_p}{L}, \quad (8)$$

where $[J_p]$ is the polar moment of inertia of the cross section of the sample, and $[L]$ is the evaluated length.

Thus, using the concept of equivalent stiffness $[K_{eq}]$ and disregarding the polar moment of inertia of the sample mass $[J]$, the natural frequency of the system $[\omega_n]$ can be expressed as:

$$\omega_n = \sqrt{\frac{K_{eq}}{J}}, \quad (9)$$

where $[J]$ is the polar moment of inertia of the disk's mass. We can still rewrite Eq.9 as:

$$\omega_n^2 = \frac{GJ_p}{LJ} \quad (10)$$

Therefore, through the first measured natural frequency, the shear modulus could be determined for each sample by the following equation (Inman, 2013):

$$G = \frac{\omega_n^2 J L}{J_p}, \quad (11)$$

where there is two different polar moments of inertia, $[J_p]$ being the moment of inertia of the sample and $[J]$ the disk's.

2.4 Property Validation

To verify the validity of the determined properties, a four-floor portico was built and the natural bending frequencies were measured. Additionally, a numerical modal analysis was performed on a finite element model of this same portico and the experimental and numerical natural frequencies were compared.

Each floor of this portico is built in wood with a dimension $199 \times 150 \times 20$ mm. Columns constructed with bamboo rods were fixed at the vertices of the floors, with the same diameter as the samples tested. To fix the rods to the floors, the boards were drilled with drills of the same diameter as the rods. Thus, cascorez type glue was added to the holes and the rods were inserted into the holes. A 200 mm spacing between floors was considered.



Figure 5. Portico assemble.

As can be seen in Fig. 6, the portico was fixed by the base by means of a thick plate fixed to an inertial base. Thus, using the same accelerometer mentioned above, the first 4 natural bending frequencies could be measured through impacts performed in the center of the pavements.

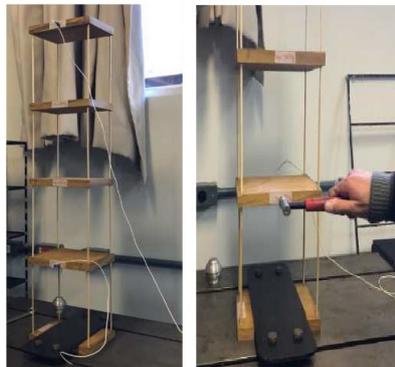


Figure 6. Left, positioning of accelerometers. Right impactation for bending test.

Using the dimensions of the constructed portico and the properties characterized for the bamboo, a finite element model was built in the ANSYS computer program, as illustrated in Fig. 7.

To carry out the coupling between the columns and the floors, the "bonded" contact element was considered. Furthermore, it was also considered that the materials are isotropic and homogeneous, such as the mesh that has been defined as the different meshes, one for the bamboo sticks and other for the boards.

With this, a numerical modal analysis of this model was performed and the first 4 natural bending frequencies were simulated and compared with the experimental ones, whose results are presented below..

3. RESULTS AND DISCUSSIONS

The first bending and torsional natural frequencies were measured in the dynamic tests in several samples lengths and their results are shown in tables 2 and 3. Using these results at the equations 6 and 11, the elastic and shear modulus of each sample were determined and are shown in the figures 8 and 9, respectively.

In the bending test it can be seen that the results were obtained for results obtained in a much wider frequency range. Being the leftmost points between 0 Hz and 10 Hz refer to the results obtained for the samples with longer lengths and the rightmost point between 40 Hz and 60 Hz the samples with the smaller lengths.



Figure 7. Portico Model.

Table 2. First natural bending frequency of samples.

Length (mm)	Sample 1 (Hz)	Sample 2 (Hz)	Sample 3 (Hz)	Sample 4 (Hz)
200	8,75	7	7,75	6,5
170	11,25	8,5	9,75	8
140	15	11,25	12,75	10,5
110	21	15,25	18,25	14
80	32,75	25	29,25	22
50	58,5	46,75	56,25	45

Table 3. First natural torsion frequency of samples.

Length (mm)	Sample 1 (Hz)	Sample 2 (Hz)	Sample 3 (Hz)	Sample 4 (Hz)
200	10,75	3,25	10,25	3
170	11,5	3,5	11,25	3,5
140	12,5	4	11,75	3,75
110	13,75	4,5	13	4
80	16	4,75	15	4,5
50	18,5	5,75	17	5,25

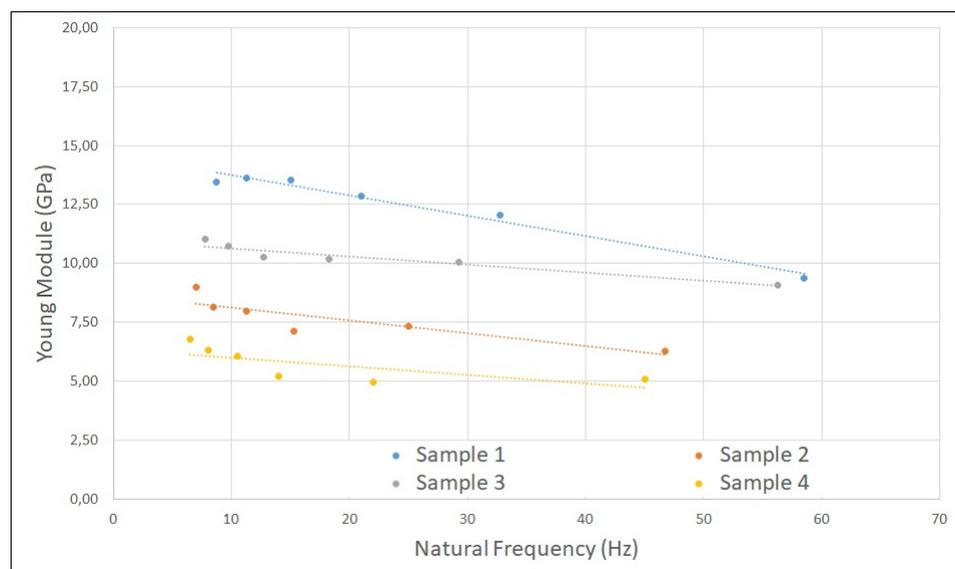


Figure 8. Young Modulus.

As for the torsion tests, it is observed that the results for the shear modulus had closer values, and the frequency range was smaller than in the bending test. However, there was more dispersion of these results compared to those.

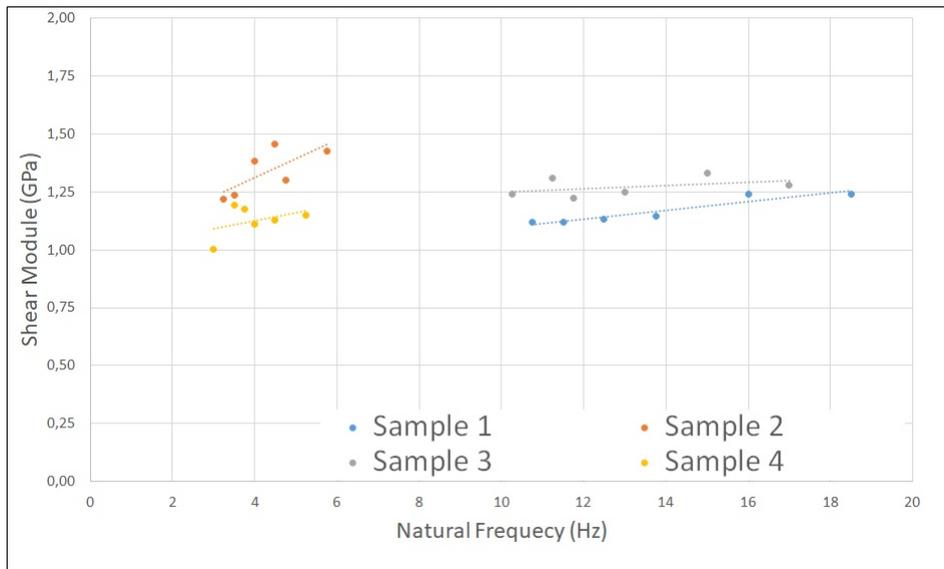


Figure 9. Shear Modulus.

Similar dispersion was also verified by Tamayo (2009), which attributed to the fact that the samples had different fibrous density, as they may have been collected from different places on the bamboo culm. However, this analysis was not performed in this work.

For the future use of the modulus, it was necessary to calculate their average, as shown in Tab. 4

Table 4. Mechanical Proprieties Of Bamboo.

	Maximum (GPa)	Minimum (GPa)	Average (GPa)	Standard Deviation (GPa)
Young's modulus	13.64	4.96	9.02	2.74
Shear modulus	1.38	1.00	1.23	0.11

Kubojima *et al.* (2009) carried out the characterization of other bamboo species, using different methods, and obtained results close to those presented in Tab.4.

To validate the elasticity and shear modulus of bamboo, an analysis was carried out with a four-story frame. Through numerical modal analysis of this finite element frame, the first four natural bending frequencies could be simulated. The modal forms of this analysis are shown in Fig. 10.

Through the bending tests of this same frame, it was also possible to measure the first four natural bending frequencies. The comparison of the natural frequencies of numerical and experimental bending are presented in Tab.5

Table 5. Comparison between Numerical and Experimental Natural Frequencies.

	Experimental (Hz)	Numerical (Hz)	Error (%)
ω_{n1}	2.34	2.43	3.70
ω_{n2}	6.54	7.03	7.49
ω_{n3}	10.45	10.82	3.54
ω_{n4}	12.40	13.29	7.18

As can be seen in Tab. 5, the numerical natural frequencies presented values very close to the experimental ones. It appears that the greatest deviation occurred in the second natural frequency, which presented a percentage error of 7.49 %. These results indicate that the properties used in the numerical model could well represent the experimental dynamic behavior of the evaluated frame.

4. ACKNOWLEDGMENTS

To the advisors, professors Giovanni Bratti and Fabiano Ostapiv for their dedication, support and knowledge to this study dedicated .

To my parents, for giving me the opportunity to study, for teaching me about dedication and persistence, and for always supporting my dreams.

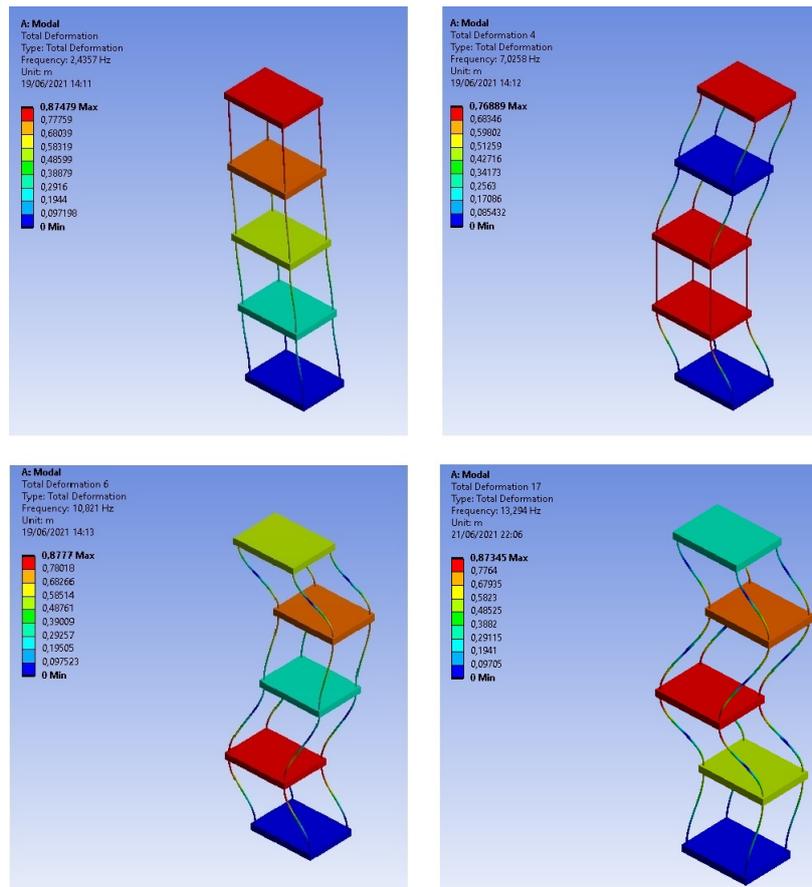


Figure 10. Four first Mode Shape of the structure.

The vibrations discipline groups due to information and time shared.

The Federal Technological University of Parana, for providing laboratories and equipment, and above all knowledge, which made this study possible.

5. REFERENCES

- Ghavami, K., 1992. "Bambu: um material alternativo na engenharia". *Revista do Instituto de Engenharia, São Paulo*, Vol. 492, pp. 2–7.
- Ghavami, K., BARBOSA, N.P. and MOREIRA, L.E., 2017. "Bambu como material de engenharia". In *Avaliação de Desempenho de Tecnologias Construtivas Inovadoras: Conforto Ambiental, Durabilidade e Pós-Ocupação*, Editora Scienza, pp. 305–348. doi:10.26626/978-85-5953-029-2.2017c0012.p.305-348.
- Inman, D.J., 2013. *Engineering Vibrations, International Edition*. Pearson Education Limited. ISBN 0273768441.
- Kubojima, Y., Ionokuchi, Y., Suzukl, Y. and Tonosaki, M., 2009. "Shear modulus of several kinds of japanese bamboo obtained by flexural vibration test". *Journal of Wood Science*, Vol. 56, No. 1, pp. 64–70. doi:10.1007/s10086-009-1047-z.
- Meirovitch, L., 2001. *Fundamentals of vibrations*. McGraw-Hill, Boston. ISBN 0070413452.
- Ostapiv, F. and Salamon, C., 2020. "O bambu como material para engenharia – produtos, ensaios e modelamento." *A Engenharia Mecânica na UTFPR. Editora Casalettras, Porto Alegre*, Vol. 2, pp. 61–64.
- Salamon, C. and Ostapiv, F., 2017. "Planificação de colmos de bambu para produção de painéis." *Mix Sustentável - Ed. 05, Florianópolis, SC*, Vol. 3, No. 1.
- Tamayo, P.L., 2009. "Estudo teórico experimental daspropriedades dinâmicas do bambu". *Dissertação (Mestrado em Engenharia Civil)–Pontifícia Universidade Católica do Rio de Janeiro*.

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