

Determination of the Elastic Modulus of Brazilian Tropical Wood at High Temperatures Using the Impulse Excitation Technique (IET)

Rejane Costa Alves

rejanealves.ufes@gmail.com

Universidade Federal do Espírito Santo

Gilson Mendonça Miranda Júnior

Universidade Federal do Espírito Santo

Edgar Vladimiro Mantilla Carrasco

Universidade Federal de Minas Gerais

Maria Teresa Gomes Barbosa

Universidade Federal de Juiz de Fora

White José dos Santos

Universidade Federal de Minas Gerais

Marco Antônio Penido Rezende

Universidade Federal de Minas Gerais

Eliene Pires Carvalho

Federal Center for Technological Education of Minas Gerais

Research Article

Keywords: Wood, temperatures, elasticity modulus, wave propagation

Posted Date: March 29th, 2024

DOI: <https://doi.org/10.21203/rs.3.rs-4165219/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

DETERMINATION OF THE ELASTIC MODULUS OF BRAZILIAN TROPICAL WOOD AT HIGH TEMPERATURES USING THE IMPULSE EXCITATION TECHNIQUE (IET)

**Rejane Costa Alves¹, Gilson Mendonça de Miranda Júnior², Edgar Vladimiro Mantilla Carrasco³,
Maria Teresa Gomes Barbosa⁴, White José dos Santos⁵, Marco Antônio Penido de Rezende⁶, Eliene
Pires Carvalho⁷**

ORCID: 0000-0003-4059-3974 Professor Adjunto no Departamento de Engenharia Florestal e Ciência da
Madeira/ Universidade Federal do Espírito Santo, rejanealves.ufes@gmail.com

ORCID: 0000-0002-9312-156X Estudante de Pós-Graduação em Engenharia Química/Universidade
Federal do Espírito Santo

ORCID: 0000-0001-7870-0283 Professor Emérito Aposentado (EE-UFGM), Professor Adjunto (EA-
UFGM) na Escola de Arquitetura/ Universidade Federal de Minas Gerais

ORCID: 0000-0002-3839-5728 Professor Titular na Faculdade de Engenharia/ Universidade Federal de
Juiz de Fora

ORCID: 0000-0002-7451-3365 Professor Associado na Escola de Engenharia/ Universidade Federal de
Minas Gerais

ORCID: 0000-0001-7896-8669 Professor Associado na Escola de Arquitetura/ Universidade Federal de
Minas Gerais

ABSTRACT

Wood, as a renewable and highly abundant material, has been receiving increasing attention for use in high-performance applications, such as a structural element subjected to high temperatures. For its successful implementation in the construction or timber industry sector, it is crucial to understand its behavior during and after exposure to high temperatures. In this study, the red angelim wood, *Dinizia excelsa*, is subjected to high temperatures, up to a temperature of 508 K, using the dynamic excitation wave propagation test. For the study, the samples tested in the furnace were dimensioned in six distinct directions: the three main ones (radial, tangential, and longitudinal) and three intermediate ones (longitudinal-radial, longitudinal-tangential, and radial-tangential). The static test used only the main directions of wood orientation. The values of elasticity modulus exhibited a reduction after the heat treatment, resulting in significant decreases of up to 45%. The results obtained demonstrated that the excitation wave propagation method was effective in estimating the elasticity modulus at room temperature up to 508 K. Therefore, this study contributed to the construction of a database that can be expanded by future research focused on Brazilian woods.

Keywords: Wood, temperatures, elasticity modulus, wave propagation.

1. Introduction

The use of wood in construction has a long history, so it is a widely used material in various structures due to its availability, strength, beauty, and ease of processing [Vilela and Mascia 2021; Ruthes et al. 2022; Eloy et al. 2023; Lima et al. 2024; Rodrigues et al. 2023]. In the Brazilian context, where vast expanses of tropical forests sustain a robust forestry industry, wood continues to play an essential role in architecture and civil engineering [Batista et al. 2023; Araújo et al. 2021]. However, the mechanical response of wood under extreme conditions, such as high temperatures, is an aspect that has received relatively limited attention compared to its widespread use [Calonego et al. 2020; Lengowski et al. 2020; Bandera et al. 2021; Oliveira et al. 2021].

Determining the modulus of elasticity, one of the fundamental mechanical properties of wood, is crucial for structural design and evaluation. This parameter quantifies the material's ability to withstand loads and deformations under the action of external forces. However, the variation of the modulus of elasticity under different environmental conditions, particularly at high temperatures, represents a critical aspect that directly influences the performance of structures built with wood [Juizo et al. 2019; Aydin (2020); Vieira et al. 2024]. These changes, in turn, have a direct impact on the mechanical characteristics of the material [Menezes et al. 2019; Barros and Politano (2019)]. However, most studies in this area focus on woods from European and North American regions, leaving a notable gap in understanding the behavior of Brazilian tropical wood under high temperatures.

Wave propagation in orthotropic materials subjected to high temperatures is a complex and ever-evolving topic. The reviewed studies emphasize the importance of considering temperature as a determining factor, while recent research indicates promising advancements in the use of non-destructive techniques to assess the behavior of these materials under extreme conditions [Bucur (1984), Reem and Samir 2024].

One aspect to be considered is the significant innovation that the application of the impulse excitation technique (IET) in high-temperature environments represents for the analysis of materials under extreme conditions [El Najar and Mustapha (2020); Bandera et al. 2021; Palma and Steiger 2020]. This technique, based on the generation of short-duration energetic pulses, allows for a dynamic assessment of the mechanical properties of materials even under unfavorable circumstances, such as high temperatures. Such an innovative approach plays an essential role in understanding the behavior of materials in situations of intense thermal exposure, contributing to the design and maintenance of structures subject to such challenging conditions.

In recent years, there has been a notable increase in interest in the application of IET, with recent research highlighting its effectiveness in obtaining precise data on the mechanical properties of materials in these

circumstances [Yassine and Mustapha (2023); Almeida et al. 2016; Ferreira et al. 2023]. This technique offers a unique opportunity for engineers and researchers to explore the behavior of structural materials under conditions of extreme thermal exposure, providing valuable insights for the development of safer and more efficient structures.

Despite notable progress, the application of IET at high temperatures in various materials still represents a relatively new research field, with vast possibilities to be explored. Therefore, this article aims to analyze the behavior of impulse wave propagation in high-density tropical wood under temperature variation of up to 508 [K] and evaluate its efficiency for estimating the modulus of elasticity.

2. Materials and methods

2.1. Materials

The study was conducted at the Advanced Research Laboratory for Wood and New Materials (CPAM) at the Federal University of Minas Gerais (UFMG). The Brazilian tropical wood species, *Dinizia excelsa*, known as angelim vermelho, was utilized. Seven replicates per orientation direction of the specimens (cps) were employed, oriented in six different directions: the three principal (radial, tangential, and longitudinal) and the three intermediate directions (longitudinal-radial, longitudinal-tangential, and radial-tangential). Dynamic tests using IET were then conducted. For the static test, samples were sized according to NBR 7190 (2023) and oriented in three principal directions (radial, tangential, and longitudinal) for the compression test.

2.2. Methodology

Thermogravimetry

Wood samples were transformed into sawdust using a Wiley-type laboratory mill, following TAPPI 257 om-85 standard (TAPPI 2001). The seven samples of the species were mixed into a single sample, resulting in composite sampling, and the fraction classified between sieves of 200 and 270 mesh was used.

For thermogravimetric characterization, the DTG-60H apparatus from Shimadzu was used. The analyses were conducted under a nitrogen gas atmosphere at a constant flow rate of 50 ml.min⁻¹, using approximately 2 mg in an open alumina capsule. Thermogravimetric curves were obtained from 323.15 K up to a maximum temperature of 673.15 K, with a heating rate of 283.15 K.min⁻¹. The thermogravimetric curve (TG) assesses mass loss as a function of temperature, and the first derivative thermogravimetric curve (DTG) evaluates the rate of mass loss.

Excitation Wave Propagation (IET)

Samples were subjected to characterization of flexural vibration modes. For this purpose, an adjustable support for bars, a pulser, a directional sensor, and specific software were used. Figure 1 illustrates the test methodology: in Fig. 1 (A), the sample positioning for the determination of longitudinal elastic modulus (E) can be observed, and in Fig. 1 (B), a zoom of the sample at the moment of the test.

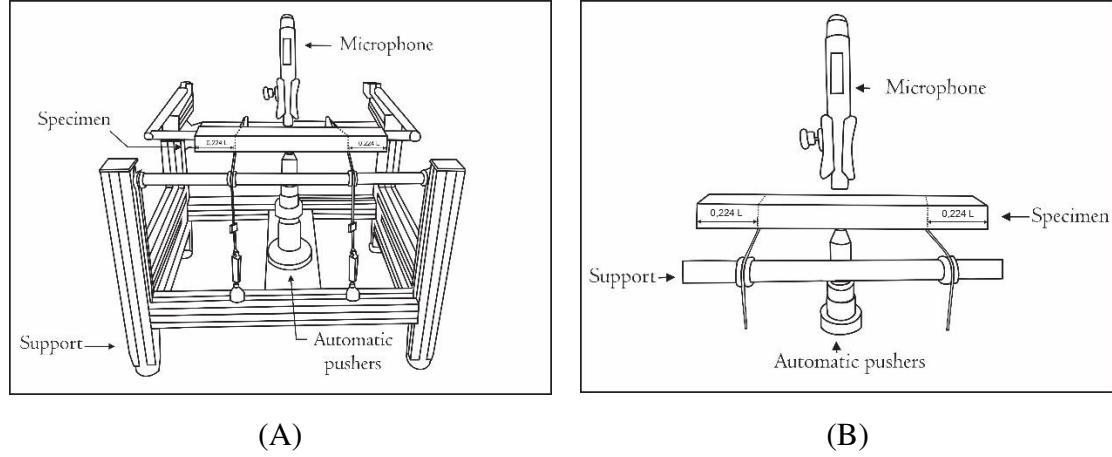
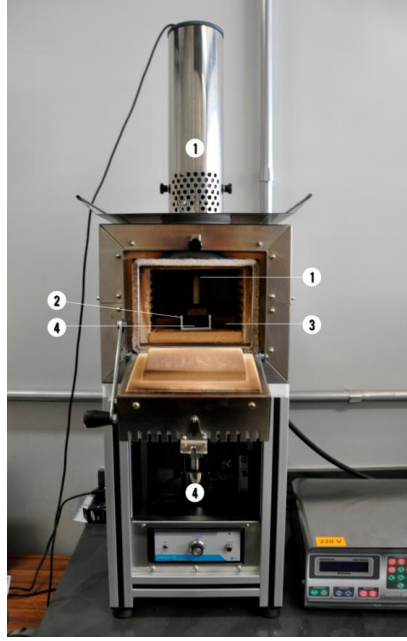


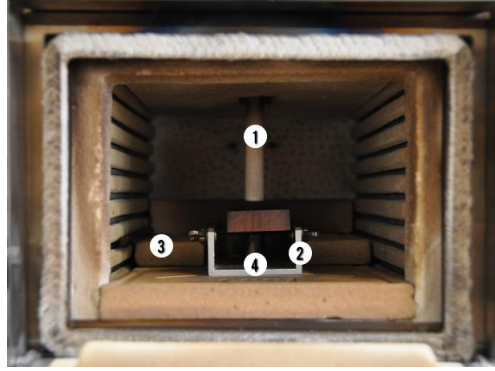
Fig. 1 (A) Sample positioning for the determination of longitudinal elastic modulus (E). (B) Zoom of the sample at the moment of the test

The impulse excitation technique (IET) is based on ASTM E1876 (2021) standard for its determinations. The Sonelastic testing instrument is employed to determine the elastic moduli from the natural vibration frequencies of the specimen (SP). The frequencies are excited by the striker, and the acoustic response is captured by a sensor. The signal undergoes mathematical treatment (Fourier transform) to obtain the corresponding frequency spectrum. Then, the dynamic elastic moduli are calculated, taking into account the SP's geometry, mass, dimensions, and the frequency obtained by the equipment used, Equation 1.

The samples have dimensions of 17 x 10 x 150 mm, with 42 SPs, equally distributed in the radial, tangential, and longitudinal directions, as well as in the intermediate directions (RT, LR, and LT). The SPs were marked with lines positioned 0.224 L away from each end (where L represents the length of the SP). These positions correspond to the nodal lines of the SP concerning the fundamental flexural vibration mode for rectangular bar geometries. The test was conducted under ambient conditions and at high temperatures since, along with the Sonelastic equipment, an HT1150 type oven was attached. The oven was specifically designed for calculating the elastic and damping moduli as a function of temperature, allowing continuous use up to 1,423.15 [K]. The oven features a proportional integral derivative (PID) controller and internal dimensions of 100 x 150 x 200 mm. Figure 2 presents the equipment version, where the dynamic modulus of elasticity response is given as a function of the internal temperature inside the oven.



(A)



(B)

Fig. 2 Equipment images. (A) Sonelastic HT1150 instrumented oven. (B) Zoom inside the Sonelastic HT1150 instrumented oven. Where 1 is Acoustic sensor; 2 - Metal profile for support of the test specimen; 3 - Ceramic mold for accommodating the test specimen support; 4 - Pulsator

The IET also uses ASTM E 1876 (2021) as the basis for its determinations. The methodology is similar to tests at room temperature; however, in this case, the value of dynamic modulus of elasticity was calculated up to a temperature of 508 [K].

Next, the formulas employed in determining the longitudinal modulus of elasticity (E) will be presented, in which the bending vibration frequency (ff) plays a crucial role in the calculation process, following the guidelines established by ASTM E1876 standard.

$$R = \left[\frac{1 + \left(\frac{b}{t}\right)^2}{4 - 2,521 \frac{t}{b} \left(1 - \frac{1,991}{e^{\frac{b}{t}} + 1}\right)} \right] \left[1 + \frac{0,00851 n^2 b^2}{L^2} \right] - 0,060 \left(\frac{nb}{L}\right)^{\frac{3}{2}} \left(\frac{b}{t} - 1\right)^2$$

$$T1 = 1 + 6,585 (1 + 0,0752\mu + 0,8109\mu^2) - \left(\frac{t}{L}\right)^2 - 0,868 \left(\frac{t}{L}\right)^4 - \left[\frac{8,34 (1 + 0,2023\mu + 2,173\mu^2) \left(\frac{t}{L}\right)^4}{1 + 6,338 (1 + 0,1408\mu + 1,536\mu^2) \left(\frac{t}{L}\right)^2} \right]$$

$$E = 0,9465 \left(\frac{m f_f^2}{w}\right) \left(\frac{l^3}{t^3}\right) T1 \quad (1)$$

Where:

E is the dynamic modulus of elasticity, in Pa (Pascals).

m is the mass of the CP, in g (grams).

b is the width of the CP, in mm (millimeters).

L is the length of the CP, in mm.

t is the thickness of the CP, in mm.

ff is the fundamental resonance frequency of the CP in bending, in Hz (Hertz).

ft is the fundamental resonance frequency of the torsion bar, in Hz.

T1 is the correction factor for the fundamental bending mode for finite thickness.

Compression

To assess the accuracy of the IET, specimens oriented in the three main directions of the wood (radial, tangential, and longitudinal) were subjected to compression testing to determine the static modulus of elasticity. Figure 3 shows the specimen to be tested under compression according to NBR 7190 (2023), using the EMIC universal testing machine, model DL 30,000, with a load capacity of 300 kN, on a cell with a capacity of 100 kN, previously calibrated.

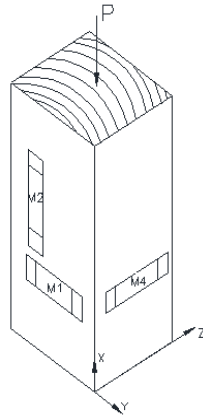


Fig. 3 Specimens tested under compression using the portable meter subjected to load P oriented in the longitudinal direction

2.3 Statistical Analysis

The data were subjected to Shapiro-Wilk normality and Bartlett's homoscedasticity tests. MiniTab 16 softwares was used for the aforementioned analyses.

3. Results and discussion

In Figure 4, the determined values for the modulus of elasticity in samples of red angelim oriented in the three main directions (tangential, radial, and longitudinal) are shown, along with the average values of apparent density at 12% moisture content.

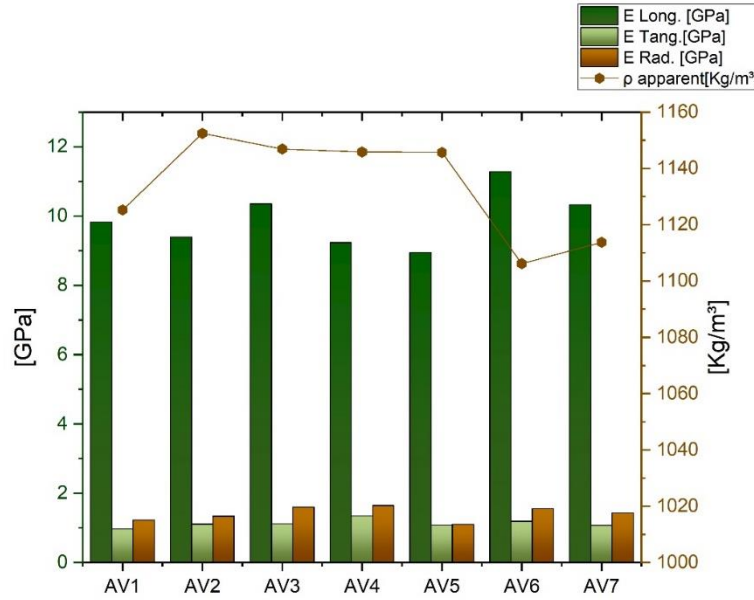


Fig. 4 Determined values of static modulus of elasticity in samples oriented in the three main directions of the wood, along with their respective apparent densities

The highest values of modulus of elasticity did not occur in samples with the highest apparent density, contrary to results found by Lai et al. (2020) and Ferreira et al. (2021). It can be observed that, as expected, the modulus of elasticity values are higher in the longitudinal direction of the fibers, followed by the radial and tangential directions. This is because the wood fibers are more strongly oriented in the longitudinal direction, providing greater stiffness and strength in this direction. The tangential and radial directions have a less organized structure, resulting in lower modulus of elasticity values. The longitudinal modulus of elasticity values range from 8.95 to 11.28 GPa, while the radial modulus of elasticity ranges from 1.1 to 1.64 GPa and the tangential modulus of elasticity ranges from 0.97 to 1.35 GPa. The proportions of the modulus EL/ET are: 8.79; EL/ER: 7.00; and ER/ET: 1.26.

The results obtained from the test using IET under high temperatures are shown in figure 5 (A-F). There is an evident inverse relationship between the modulus of elasticity and temperature, meaning that as the temperature increases, the values of dynamic modulus of elasticity decrease, with no increase compared to room temperature. This contradicts the findings of authors such as Bandera et al. (2021), who reported slight increases in modulus of elasticity at high temperatures, and Ferreira et al. (2019), who found no influence of high temperatures on modulus of elasticity values determined from static bending. For example, Aydin (2020) observed slight increases for the *Quercus petraea* Liebl species at moderate temperatures (up to 423.15K), but in subsequent treatments, all measured properties decreased significantly, including modulus of elasticity.

The main changes in wood subjected to high temperatures occur in the degradation of hemicellulose by deacetylation, depolymerization, and dehydration, as well as in structural changes and rearrangement of lignin (Dalla Costa et al. 2020). These chemical changes, primarily the degradation of hemicellulose, are considered responsible for the decrease in mechanical properties, as evidenced by reduced resistance to force application (Wentzel et al. 2019; Oliveira et al. 2022).

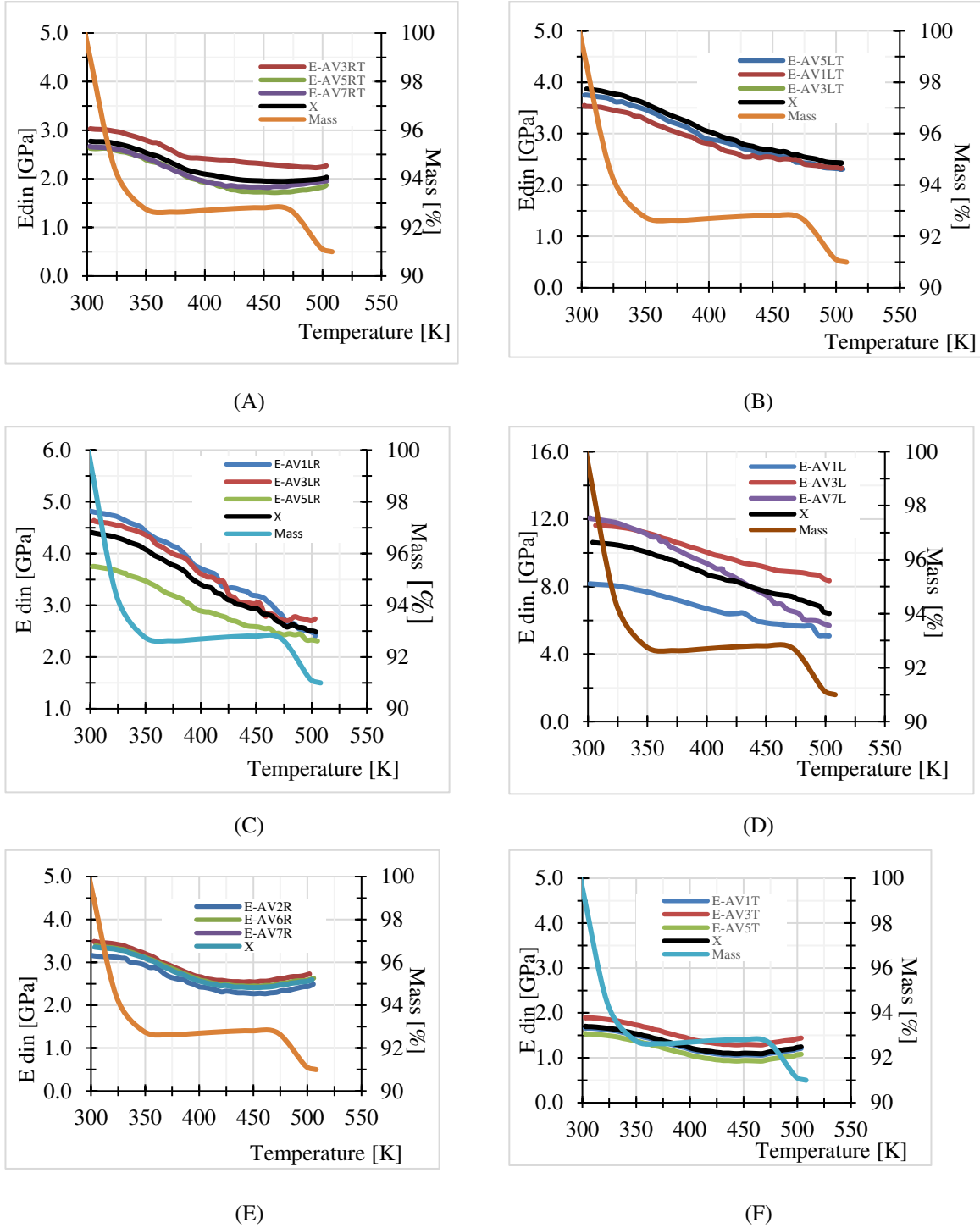


Fig. 5 (A-F) Variation of longitudinal modulus of elasticity and CP mass with increasing temperature. (A) Radial Tangential Direction; (B) Longitudinal Tangential Direction; (C) Longitudinal Radial Direction; (D) longitudinal to the fibers; (E) Radial Direction; and (F) Tangential Direction

The decreases in modulus of elasticity values occurred differently in relation to the orientation directions, with a milder decrease in the radial direction (22.85%), followed by the longitudinal (23.24%), radial-tangential (28.63%), tangential (33.86%), longitudinal-radial (40%), and longitudinal-tangential (45.62%) directions, as shown in Fig. 6. Corroborating this result, Oliveira et al. (2022) found reductions of up to 57% in the modulus of elasticity determined from axial compression in samples subjected to temperatures ranging from 428.15 to 458.15 K. In contrast, Danihelová et al. (2022) studied *Picea abies* (L.) Karst. and *Acer pseudoplatanus*, L. woods with thermal processes using the ThermoWood technique and treatments at 408.15, 433.15, and 458.15 K, reporting an increase in specific modulus of elasticity in all treatments, with the highest increases (6.8%) for Spruce wood treated at 433.15 K and 7.8% for Maple wood treated at temperatures of 433.15 K and 458.15 K.

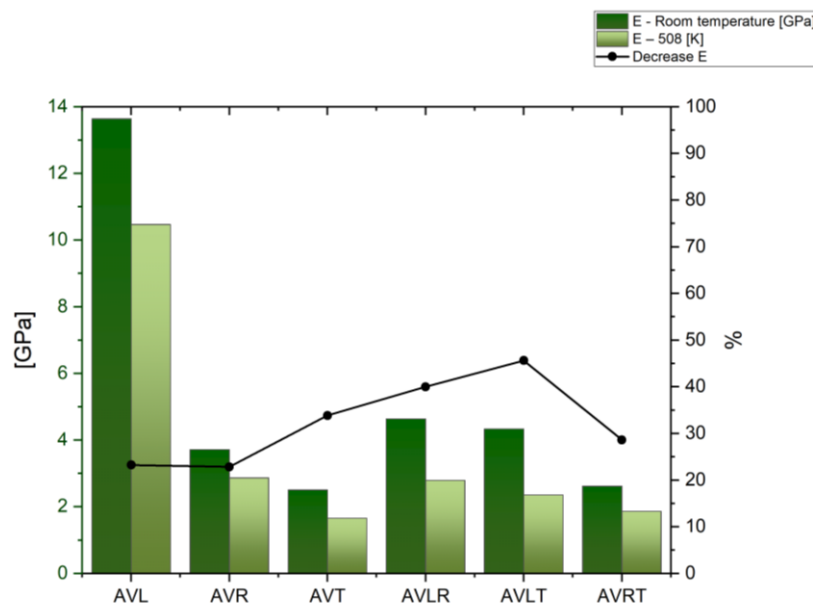


Fig. 6 Relationship of dynamic modulus of elasticity at room temperature and high temperature for the six main orientation directions

All samples in the study confirmed the trend of decreasing elastic modulus with increasing temperature, regardless of the orientation direction. This reduction can be justified by thermal expansion, which reduces the value of dF/dA (differential force over area, defining stress) and increases the separation distance between atoms, thereby reducing the binding energy between them and the effort needed to produce deformation, as well as the transformation of wood anatomical elements. Irvine (1984) mentions that the softening of constituents is accompanied by significant changes in the material's mechanical properties, with elastic modulus being the main one. Meanwhile, Hill et al. (2021) explain that there is a reduction in natural resonance frequency with temperature, which may be associated with the reduction in wood density as well as modifications associated with some chemical constituents of wood cell wall structure, such as degradation of hemicelluloses, free hydroxyl groups (-OH) in the amorphous region of cellulose, extractives, and lignin cross-linking.

Another important analysis is that even though the decrease occurred in samples oriented in the six wood directions, it occurred differently, showing that the anatomical arrangement alters the natural frequency response, and consequently the dynamic elastic modulus (E_{din}). Authors in their studies have reported that the elastic modulus can be influenced by anatomical characteristics and not just material density (Viala et al., 2023; Korkmaz and Büyüksarı, 2019; Ferreira et al., 2023). The decrease in E_{din} varied from 23 to 46% for longitudinal and longitudinal-tangential directions, while the mass loss determined from the thermogravimetric test was about 8%, as shown in Fig. 7.

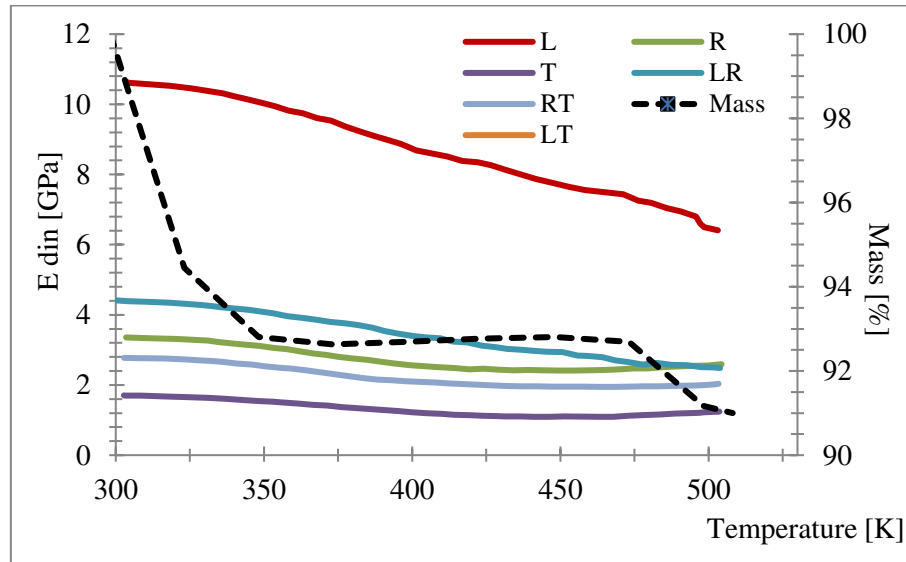


Fig.7 Variation of longitudinal elastic modulus and sample mass with increasing temperature, in the six sample orientation directions

4. Conclusion

This pioneering study reveals a clear trend of reduction in the elastic moduli of tropical wood *Dinizia excelsa* as the temperature increases, resulting in significant decreases of up to 45%. Although the degradation behavior of wood appears similar in the six directions analyzed under high temperatures, the loss of elasticity does not follow a uniform proportion, demonstrating the influence of anatomical arrangement. It is noteworthy that the most significant reductions were observed in the secondary directions, namely longitudinal tangential and longitudinal radial, indicating a differentiated sensitivity in these orientations. These innovative discoveries underscore the crucial importance of exploring Brazilian tropical woods and understanding the impact of temperature on the mechanical properties of these materials. This advancement contributes not only to the existing knowledge but also to the development of more efficient practices in the use of IET under challenging thermo-mechanical conditions.

References

Almeida, D. H., Ferro, F. S., Icimoto, F. H., Takeshita, S., Modes, K. S., Almeida, T. H., Christoforo, A. L. and Rocco Lahr, F. A. (2016). Determination of *Pinus elliottii* stiffness at different moisture levels by means of non-destructive mechanical tests. *Scientia Forestalis*, 44 (110), 303–309. doi:10.18671/scifor.v44n110.03.

AMERICAN SOCIETY FOR TESTING MATERIALS. Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration. ASTM designation E1876 – 09, 2006.

Araujo, V. A.; Vasconcelos, J. S.; Morales, E. A. M.; Lahr, F. A. R. Characterization of business poles of timber houses in Brazil. *Mercator*, Fortaleza, v.20, e20026, 2021. ISSN:1984-2201. <https://doi.org/10.4215/rm2021.e20026>

Aydin, T.Y. Ultrasonic evaluation of time and temperature-dependent orthotropic compression properties of oak wood. *Journal of materials research and technology*. 9(3): 6028–6036, 2020.

Bandara S, Rajeev P, Gad E (2023) Structural health assessment techniques for in-service timber poles. *Struct Infrastruct Eng* 19(4):439–459

Barreiros, R. M.; Lisboa, F. D.; Gouvea, C. F.; Reis, A. M. F.; Godinho, E. Z.; Dias, K. B. *Ciências Florestal*, Santa Maria, v. 33, n. 1, e67304, p. 1-18, 2023.

Barros, J. O. A.; Politano, R. Effects of Frequency, Temperature and Test Duration in the Viscoelasticity of Brazilian Hardwoods Used in Handmade Musical Instruments. *Materials Research*, v. 22, e20190190, 2019.

Batista. M.; Amorim, A.; Silva, D. A. L.; Aquino, V. B. M.; Lahr, F. A. R.; Christoforo, A. L. Representativeness of the fiber parallel elasticity modulus value referring to the Brazilian standard C40 strength class in the design of timber structures. *Ciência Rural*, Santa Maria, v.53:3, e20210289, 2023. <http://doi.org/10.1590/0103-8478cr20210289>

Bucur, V. *Acoustics of wood*. New York: CRC Press, 1995.

Bucur, V. Elastic constants for wood by an ultrasonic method. *Wood Sci. Technol.* v. 18, p. 255-265. 1984.

Bucur, V.; Bohnke, I. Factors affecting ultrasonic measurements in solid wood. *Ultrasonics*, v. 32, n. 5, p. 385-390, 1994.

Calonego, F.W.; Severo, E.T.D.; Sansígolo, C.A.; de Brito, A. F. Physical and chemical changes in juvenile and mature wood of *Shizolobium parahyba* caused by thermal modification. *Journal of Tropical Forest Science* 32(4): 333–340 (2020). <https://doi.org/10.26525/jtfs2020.32.4.333>

Carrasco, E. V. M.; Oliveira, A. L. C.; Mantilla, J. N. R. Influência da temperatura na resistência e no módulo de elasticidade em madeira de híbridos de eucaliptos. *Ciência Florestal*, Santa Maria, v.26, n.2, p-389-400, 2016.

Carvalho, D.E.; Juizo, C.G.F.; França, M.C.; Loiola, P.L.; Rocha, M.P. da. Effect of thermal modification in the natural resistance of *Eucalyptus grandis* and *Pinus taeda* woods. *Revista Brasileira de Ciências Agrárias*, v.14, n.1, e5606, 2019. <https://doi.org/10.5039/agraria.v14i1a5606>.

Cruz, N.; Bustos, C.; Aguayo, M. G.; Cloutier, A.; Castillo, R. Impacto of the chemical composition of *Pinus radiata* wood on its physical and mechanical properties following termo-hygromechanical densification. *Bioresources*, 13 (2), 2268- 2282, 2018.

Dalla Costa, H. W.; Coldebella, R.; Andrade, F. R.; Gentil, M.; Correa, R.; Gatto, D. A.; Missio, A. L. (2020) Brittleness increase in *Eucalyptus* wood after thermal treatment, *International Wood Products Journal*, 11:1, 38-42, DOI:10.1080/20426445.2020.1719298.

Danihelová, A.; Vidholdová, Z.; Gerge, T.; Lucia Spišiaková Kružlicová, L. S.; Pástor, M. Thermal modification of spruce and maple wood for special wood products, *Polymers*, v. 14, n. 14, pp. 2813, 2022. DOI: <http://dx.doi.org/10.3390/polym14142813>.

El Najjar J, Mustapha S (2020) Understanding the guided waves propagation behavior in timber utility poles. *J Civ Struct Heal Monit* 10:793–813

Esteves, B. M., Nunes, L., Domingos, I., and Pereira, H. (2013). “Comparison between heat treated sapwood and heartwood from *Pinus pinaster*,” *Euro. J. Wood Prod.* 72(1), 53-60. DOI: 10.1007/s00107-013-0751-y

Ferreira, M.S.; Melo, R.R.; Zaque, L.A.; Stangerlin, D.M. Propriedades físicas e mecânicas da madeira de angelim-pedra submetida a tratamento térmico. *Tecnologia em Metalurgia, Materiais e Mineração*, v.16, n.1, p.3-7, 2019. <https://doi.org/10.4322/2176-1523.20191297>.

Ferreira, P. S.; Ramalho, F. M. G.; Couto, A. M.; Protásio, T. P.; Monteiro, T. C.; Hein, P. R. G. (2023) Relationship among the stiffness, wave propagation speed, density and moisture content of *pinus elliottii* and *bertholletia excelsa* wood specimens, *Wood Material Science & Engineering*, 18:1, 151-160, DOI: 10.1080/17480272.2021.1996456.

Gaff, M.; Kacík, F.; Sandberg, D.; Babiak, M.; Turcani, M.; Niemz, P. The effect of chemical changes during thermalmodification of European oak and Norway spruce on elasticity properties. *Compos Struct*; 220:529–38, 2019.

Gerhards, C.C. Effect of moisture content and temperature on the mechanical properties of wood: an analysis of immediateeffects. *Wood Fiber*, 14(1), (1982):4–36.

Hidayat et al. (2015). Effect of Temperature and Clamping during Heat Treatment on Physical and Mechanical Properties of Okan (*Cylicodiscus gabunensis* [Taub.] Harms) Wood. *BioResources* 10(4), 6961-6974.

Hill, C., Altgen, M., Rautkari, L., Thermal modification of wood—a review: chemical changes and Hygroscopicity, *Journal of Materials Science*, v. 56, n. 11, pp. 6581–6614, 2021. doi: <http://dx.doi.org/10.1007/s10853-020-05722-z>.

Juizo, C. G. F.; Carvalho, D. E.; França, M. C.; Loiola, P. L.; Rocha, M. P. Ultrasound to determinate the modulus of elasticity of heat-treated woods subjected to field test. *Rev. Bras. Cienc. Agrar.*, Recife, v.14, n.3, e6309, 2019.

Korkmaz, O. and Büyüksari, Ü (2019) Effects of moisture content on mechanical properties of micro-size oak wood. *BioResources*, 14(4), 7655–7663.

Lengowski, E. C.; Júnior, E. A. B.; Silvana Nisgoski, S. Muñiz, G. I. B.; Klock, U. Properties of thermally modified teakwood. *Maderas. Ciencia y tecnología* 2021 (23):10, 1-16. DOI: 10.4067/s0718-221x2021000100410.

Lima, V. S.; Silva, M. G. S.; Menezes, G. C., et. al., revista *Matéria*, v.29, n.1, 2024. DOI: <https://doi.org/10.1590/1517-7076-RMAT-2023-0270>

Luikov, A.V. Systems of differential equations of heat and mass transfer in capillary-porous bodies, *Int. J. Heat Mass Transfer* 8 (1975) 1–14.

Menezes, W. M.; Souza, J. T.; Carvalho, D.E.; Talgatti, M.; Santini, E. J. Mechanical Properties of Thermally Modified *Corymbia Citriodora* and *Eucalyptus Saligna* Woods. *Floresta e Ambiente* 2019; 26(1): e20150114.

Oliveira, C. A. B. et al. Influence of commercial thermal treatment on *Eucalyptus grandis* Hill ex Maiden wood properties. *Revista Árvore*, v.45: e 4527, 2021.

Oliveira, C. A. B.; Oliveira, K. A.; Aquino, V. B. M.; Christoforo, A. L.; Molina, J. C. Characterization of *Acrocarpus fraxinifolius* wood submitted to heat treatment. *Maderas. Ciencia y tecnología* 2022 (24): 54, 1-12.

Otani, L. B.; Pereira, A. H. A. Guia de caracterização dos módulos elásticos e do amortecimento de madeiras e derivados utilizando as soluções Sonelastic. GC 02-ATCP, 2013.

Palma, P., Steiger, R. (2020) Structural health monitoring of timber structures—review of available methods and case studies. *Constr Build Mater* 248:118528

Paula, M. O.; Loiola, P. L.; Moreira, G. R.; Segundinho, P. G. A. Análise termomecânica da Madeira de *Corymbia citriodora* submetida a gradientes térmicos. *Floresta Ambiente*. 2014, vol.21, n.3, PP. 358-368. <https://doi.org/10.1590/2179-8087.032613>

Pereira, B. L. C.; Carneiro, A. C. O.; Carvalho, A. M. M. L.; Trugilho, P. F.; Melo, I. C. N. A.; Oliveira, A. C. Estudo da degradação térmica da madeira de *Eucalyptus* através de termogravimetria e calorimetria. *Revista Árvore*, Viçosa-MG, v.37, n.3, p.567-576, 2013.

Pinto, E. M.; Calil Jr, C. Estudo Teórico e experimental sobre a degradação térmica da madeira de *Eucalyptus* de uso estrutural exposta ao fogo. *Revista Minerva*, v. 3, p. 131-140, 2006.

Rodrigues, F. C. R.; De Araujo, V. A.; Arroyo, F. N.; Almeida, J. P. B.; Christoforo, A. L.; Lahr, F. A. R. Influência da posição dos anéis de crescimento da madeira na determinação de sua resistência ao cisalhamento paralelo às fibras. *Ambiente Construído*, Porto Alegre, v. 23, n. 2, p. 195-212, abr./jun. 2023. ISSN 1678-8621 Associação Nacional de Tecnologia do Ambiente Construído. <http://dx.doi.org/10.1590/s1678-86212023000200671>

Ruthes, H. C.; Mascarenhas, F. J. R.; Soares, L. S. Z. R.; Aquino, V. B. M.; Arroyo, F. N.; FragA, I. F.; Christoforo, A. L.; Lahr, F. A. R. Influence of moisture content on physical and mechanical properties of *vatairea sp.* wood. *Revista Árvore* 2022;46: e4606. <http://dx.doi.org/10.1590/1806-9088202200000006>

TECHNICAL ASSOCIATION OF THE PULP AND PAPER INDUSTRY - TAPPI -. TAPPI test methods T 257 cm-85: sampling and preparing wood for analysis. In: TAPPI Standard Method Atlanta: 2001.

Vega, A.; González, L.; Fernández, I.; González, P. 2019. Grading and mechanical characterization of small-diameter round chestnut (*Castanea sativa* Mill.) timber from thinning operations. *Wood Mater Sci Eng* 14(2): 81-87.

Viala, Romain, Cabaret, Jérémy, Sedighi-Gilani, Marjan, Placet, Vincent and Cogan, Scott. Effect of indented growth rings on spruce wood mechanical properties and subsequent violin dynamics. *Holzforschung*, 2024. <https://doi.org/10.1515/hf-2023-0090>

Vieira, T. A. S.; Trugilho, P. F.; Carabineiro, S. A. C.; Zanoncio, A. J. V.; Carvalho, A. G.; da Silva, L. F.; Vieira; M. B.; da Silva, C. M. S.; Carneiro, A. C. O. Production of high-quality forest wood biomass using artificial intelligence to control thermal modification. *Biomass Conversion and Biorefinery* (2024) 14:1731–1747. <https://doi.org/10.1007/s13399-022-02666-z>

Vilela, R.; Mascia, N. T. Avaliação de propriedades mecânicas da madeira de Pinus taeda provenientes de placas de cross laminated timber. Ambiente Construído, Porto Alegre, v. 21, n. 4, p. 89-110, out./dez. 2021. ISSN 1678-8621 Associação Nacional de Tecnologia do Ambiente Construído. <http://dx.doi.org/10.1590/s1678-86212021000400560>