

**PARTICLE IMAGE VELOCIMETRY TECHNIQUE AND ULTRASOUND METHOD
TO OBTAIN THE MODULUS OF ELASTICITY OF *Bertholletia excelsa* WOOD**

**Eduardo Hélio de Novais Miranda^{1a*}, Rayner Pathele Ferreira^{1b}, Rodrigo Allan Pereira³,
Taiane Oliveira Guedes^{4c}, Fernando Pujaico Rivera⁵, Diogo Antonio Correa Gomes^{6d}**

¹ <https://orcid.org/0000-0002-3156-658X>

² <https://orcid.org/0000-0002-5123-6246>

³ <https://orcid.org/0000-0002-1628-1172>

⁴ <https://orcid.org/0000-0003-2865-1406>

⁵ <https://orcid.org/0000-0002-4970-2818>

⁶ <https://orcid.org/0000-0003-3967-4574>

*** Corresponding author:** eduardohelio013@gmail.com

Received: June 14, 2021

Accepted: December 01, 2021

Posted online: December 02, 2021

ABSTRACT

Non-destructive techniques for characterizing materials in-service have been increasing in importance. Thus, it is relevant to assess the potential of non-destructive techniques for solid materials. This work aimed to determine the modulus of elasticity of *Bertholletia excelsa* wood using the particle image velocimetry technique and the ultrasound method to compare the results with the conventional methodology. For this purpose, samples of *Bertholletia excelsa* were made using a circular saw. The samples were evaluated for sound propagation to calculate the modulus of elasticity using ultrasound equipment. Subsequently, they were subjected to the compression parallel to grain test in a universal testing machine. The samples were marked and monitored during the loading session, with the repeated capture of images using a professional camera. The deformation values obtained were used to estimate the modulus of elasticity using the particle image velocimetry technique. The mean values of modulus of elasticity found were 17403 MPa for ultrasound, 15589 MPa for the particle image velocimetry technique, and 15333 MPa for the universal testing machine. The particle image velocimetry technique was considered to be statistically similar (Tukey $\alpha = 0,05$) to the other methods tested. The linear coefficient of determination (R^2) between the particle image velocimetry technique and the universal testing machine was 0,95, a high and satisfactory value. Thus, the particle image velocimetry technique and the ultrasound method are valid to estimate the modulus of elasticity of *Bertholletia excelsa* wood and possibly of woods with similar technological characteristics.

Keywords: Characterization of materials, conventional method, mechanical property, non-destructive techniques, particle image velocimetry.

^{1abc} Universidade Federal de Lavras, Departamento de Ciências Florestais, Lavras, Brasil.

² Universidade Federal de Lavras, Departamento de Engenharia, Lavras, Brasil.

³ Universidade Federal de Lavras, Departamento de Engenharia Agrícola, Lavras, Brasil.

INTRODUCTION

Conventional testing techniques used to analyze physical and mechanical properties of materials, such as the modulus of elasticity, usually require high processing time, specific equipment, a large number of samples and cause permanent damage to the material tested, making it unusable. Thus, non-destructive testing techniques become an option to determine the properties of materials in-service, usually requiring shorter application time and cost when compared to destructive tests (Pereira *et al.* 2019, Zahedi *et al.* 2020).

Among the non-destructive testing techniques, the Particular Image Velocimetry (PIV) technique and the ultrasound method stand out, as they are considered simple and fast tests. The Particle Image Velocimetry technique originated from the gaseous materials study field (Raffel *et al.* 2018). The technique was adapted to study the movement of solid materials through the analysis of images captured from samples marked with random points, at first using a laser (Braga-Júnior *et al.* 2015) and, more recently, using ink particles drawn on the sample surface (Pereira *et al.* 2019, Novosel *et al.* 2021). The time gap between photos is predefined and must contemplate the changes that occur in the material during the load application. These images are processed in a computational algorithm that calculates the displacement that occurred on the surface of the studied object (Pereira *et al.* 2019).

Guedes *et al.* (2019) determined the modulus of elasticity of *Cedrela* spp. and *Eucalyptus cloeziana* wood submitted to static flexion using the PIV technique. The authors found the technique results satisfactory when compared with the conventional method. Pereira *et al.* (2019) also evaluated the use of the PIV technique to measure the deformations of solid materials in wood panels of *Pinus oocarpa*, *Eucalyptus grandis*, plywood, laminated veneer lumber (LVL) and oriented strand board (OSB) subjected to static flexion. Obtained values were statistically equal to those of conventional methods. Therefore, even not allowing a three-

63 dimensional correlation of images resulting from the tests, as occurs in the Digital Image
64 Correlation (DIC) technique, the PIV technique has been showing satisfactory results in solid
65 materials (Peters *et al.* 1983).

66 Ultrasound is a technique that uses the propagation of sound created by high-frequency
67 waves to evaluate solid materials. Variations in the propagation speed of waves emitted by
68 ultrasound are captured by the equipment and generate information that makes it possible to
69 determine the modulus of elasticity of the material. Studies using different wood species aiming
70 to estimate physical and mechanical properties by the ultrasound technique have been carried
71 out, and satisfactory results have been found (Gonçalez *et al.* 2001, Ribeiro *et al.* 2013).

72 To work with a biological, heterogeneous, and anisotropic material such as wood which
73 is of great importance in civil construction requires many studies. Furthermore, Brazil,
74 according to the United Nations (UN) for the Agriculture and Food (FAO 2015), is the second
75 largest wood product of *Bertholletia excelsa* in the world, a complex wood species that needs
76 to be better characterized. Thus, innovative techniques such as the PIV technique for solids
77 and the ultrasound method must be tested in this and in different other wood species and
78 different types of materials.

79 In this context, studies are perceived as incipient, especially those that present a
80 combination of two non-destructive techniques for the characterization of solid materials, and
81 the research is justified by the attempt to consolidate two recent methodologies as simple, fast
82 and reliable tests in comparison with a conventionally used method.

83 This work aimed to determine the modulus of elasticity of the medium density wood
84 *Bertholletia excelsa* using the non-destructive techniques Particle Image Velocimetry and
85 ultrasound method as measurement tools.

86

87

MATERIAL AND METHODS

88

Material preparation

89

90

91

92

93

94

95

96

This study used timbers of *Bertholletia excelsa*, obtained from an experimental planting at the Federal University of Lavras (UFLA) from 20 years-old trees. The samples for the compression parallel to grain test and the ultrasound test were prepared according to the ABNT NBR 7190 (ABNT NBR 2010). A total of 30 specimens with dimensions of 100 mm by 25 mm by 25 were conditioned in climate at $22\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ and $65\% \pm 5\%$ relative humidity (RH) until they reach a moisture content of $12\% \pm 1\%$. Density value of beech specimen was measured as 587 kg/m^3 . The trees have an average diameter of 540 mm. The proportion of heartwood and sapwood was the same for the samples and all were taken from the same batch.

97

Ultrasound test

98

99

100

101

The speed of propagation of the sound wave through the specimen, in the longitudinal direction, was measured by the ultrasound equipment (Ultrasonic-Test BP-7) with 45 kHz transducers. Through this information, the modulus of elasticity was calculated (Equation 1) ABNT NBR 15521 (ABNT NBR 2007).

102

$$MOE = V^2 \cdot \rho \quad (1)$$

103

In which:

104

MOE = Modulus of elasticity (Pa);

105

V = propagation speed of the wave ($\text{m}\cdot\text{s}^{-1}$);

106

ρ = apparent density ($\text{kg}\cdot\text{cm}^{-3}$).

107

108

The equipment was calibrated with a standard acrylic sample before each test.

109 **Compression parallel to grain in the universal testing machine**

110 The samples went through the compression parallel to the grain test in a universal testing
111 machine (EMIC DL-30000), with the capacity of 30 tons-force and speed of 1 mm/min (adapted
112 from the ABNT NBR 7190 (ABNT NBR 2010) until the specimens reached the breaking point,
113 finishing the test.

114 **Estimation of the modulus of elasticity by the PIV technique**

115 The PIV technique was performed simultaneously with the compression parallel to the
116 grain test. For the PIV algorithm analysis, it was necessary to mark the samples with ink dots,
117 randomly distributed over their entire surface. Thus, consecutive images were captured during
118 the loading session. The professional camera (Sony alpha a330 10,4 megapixels) was
119 positioned perpendicularly to the sample surface, at approximately 25 cm distance (Figure 1).
120 The procedure started with the capture of the image at zero seconds. Subsequently, the capture
121 was performed every 30 seconds, from the activation of the Universal Testing Machine until
122 the rupture of the samples. The average time of each trial was 7 min.

123 With the strain values obtained by the PIV technique, the loads applied by the universal
124 testing machine and the geometric characteristics of the cross-section, it was possible to
125 calculate the modulus of elasticity of the samples tested. It should be noted that the standard
126 ABNT NBR 7190 (ABNT 2010) was used as a reference (Equation 2).

127
$$MOE = \frac{(\sigma_{50\%} - \sigma_{10\%})}{(\epsilon_{50\%} - \epsilon_{10\%})} \quad (2)$$

128 In which:

129 MOE = Modulus of elasticity (MPa);

130 σ = Stress (MPa);

131 ϵ = Specific deformation.

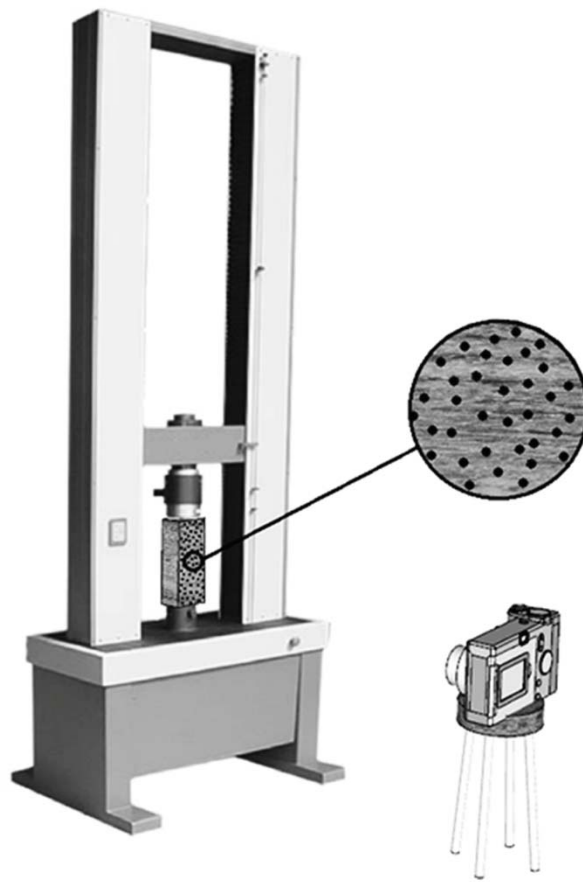


Figure 1: Setup of the PIV method and the compression test.

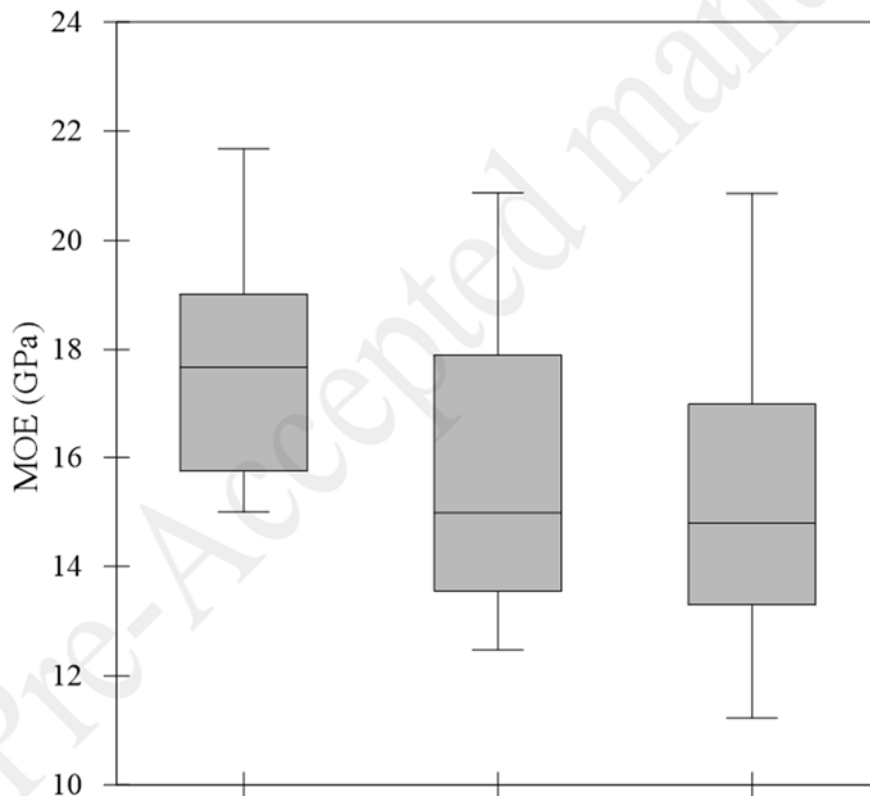
Data analysis

Descriptive statistics analysis and Tukey test ($\alpha = 0,05$) were used to compare the means of the modulus of elasticity obtained by the PIV technique, the conventional technique and the ultrasound method. In addition, regression analysis was also performed between the methods.

RESULTS AND DISCUSSIONS

The values of modulus of elasticity obtained by each test method can be seen in Figure 2. The mean values of sound wave propagation speed, measured by the ultrasound equipment, and apparent density of the specimens were 5038,79 m/s and 684,00 kg/m³, respectively. Visually,

144 the amplitude of the values for the techniques is similar. However, the absolute results by the
 145 ultrasound method were superior to those obtained by the other two techniques. According to
 146 Stangerlin *et al.* (2011), the induced stress in dynamic tests is reduced, that is, dynamic
 147 measurements are based on mechanical properties only in the elastic limit and therefore this
 148 method depends on physical characteristics of materials, such as density, moisture, and
 149 presence of imperfections inside the tested materials. The PIV technique has the advantage, in
 150 this sense, of evaluating only the surface of the tested material, not depending on the physical
 151 properties of the material. Thus, it was able to follow the displacements of the specimens from
 152 the beginning to the end of the test, including at the moment of rupture.

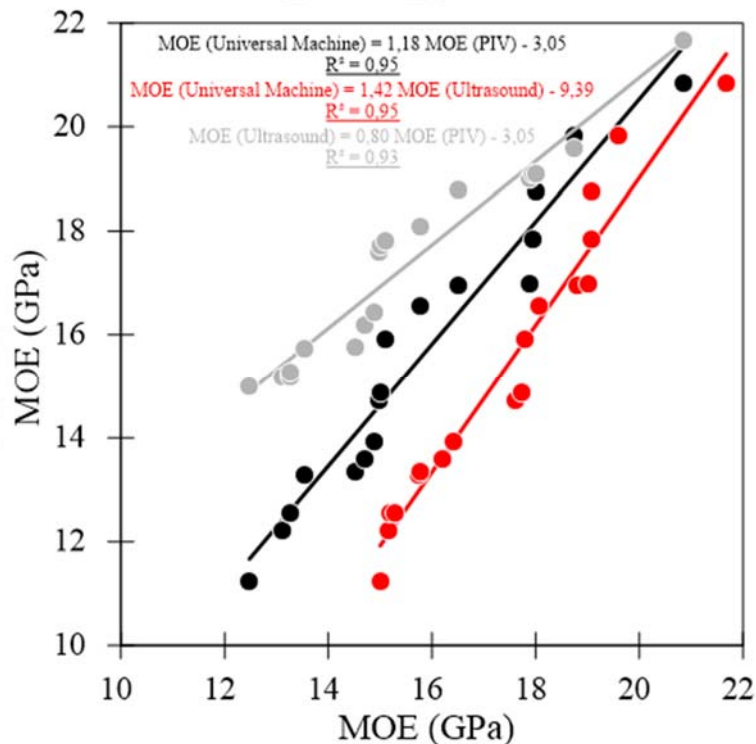


MOE (GPa)	Ultrasound	PIV	Universal Machine
	17,40 ^{(1,91)*} a**	15,60 ^(2,30) ab	15,33 ^(2,78) b
*Standard deviation of means. **Means followed by the same letter in the column do not differ at 5 % probability by the Tukey test.			

153 **Figure 2:** Range of values and descriptive statistics of *Bertholletia excelsa* modulus of
 154 elasticity (MOE) obtained by the Particle Image Velocimetry (PIV) technique, ultrasound
 155 method, and conventional method, using a universal testing machine.

156 The mean values for modulus of elasticity were 17403 MPa for the ultrasound method,
157 15589 MPa for the PIV technique, and 15333 MPa for the universal testing machine. The values
158 found corroborate with other researches with the species *Bertholletia excelsa*. Thus, for
159 example, Petrechen and Ambrósio (2016), Jesus *et al.* (2015) and Souza (2016) obtained values,
160 respectively, of 18220 MPa, 14881 MPa and 13474 MPa for the modulus of elasticity in the
161 compression parallel to the grain test, using the universal testing machine.

162 According to the Tukey test ($\alpha = 0,05$), there is no statistical difference between the PIV
163 technique results and those found with for the ultrasound method and those found with for the
164 conventional method. This result implies that the PIV technique is interesting to make
165 estimations. Its results are similar to those found with the method already used in the standard
166 (universal testing machine). As it is also similar to the ultrasound technique, another non-
167 destructive method, the results of this work are quite satisfactory. Figure 3 shows the linear
168 regression to verify the relationship between the methods.



169 **Figure 3:** Linear regression between the modulus of elasticity (MOE) values of *Bertholletia*
170 *excelsa* wood.

171 The coefficient of determination between the PIV technique and the universal testing
172 machine was 0,95. Thus, the PIV technique can estimate results for the modulus of elasticity
173 that will be very close to the values determined by the universal testing machine. Furthermore,
174 the coefficient of determination between the PIV technique and the ultrasound and between the
175 ultrasound and the universal testing machine were 0,93 and 0,95, respectively, equally high
176 values. These results validate the two recent non-destructive techniques as simple, fast and
177 reliable tests, in comparison with a conventionally used method, for the wood studied and
178 probably for woods with similar technological characteristics.

179 Other research has already proven the efficiency of the PIV technique and ultrasound
180 method, compared to conventional methodologies, to estimate physical or mechanical
181 parameters in wood (Pereira *et al.* 2019, Guedes *et al.* 2019, Gonalez *et al.* 2001, Ribeiro *et*
182 *al.* 2013).

183

184 CONCLUSIONS

185 The PIV technique was considered to be statistically similar (Tukey $\alpha = 0,05$) to the
186 ultrasound and standard method. The mean values of modulus of elasticity obtained by the three
187 techniques, ultrasound method, PIV technique and universal testing machine, were 17403 MPa,
188 15589 MPa and 15333 MPa, respectively. The linear coefficient of determination (R^2) between
189 the PIV technique and the universal testing machine was 0,95, a high and satisfactory value.
190 Thus, the PIV technique and the ultrasound method are valid to estimate the modulus of
191 elasticity of *Bertholletia excelsa* wood and possibly of woods with similar technological
192 characteristics.

193

194

REFERENCES

- 195
- 196 **Associação Brasileira de Normas Técnicas. 2010.** ABNT NBR 7190: *Projeto de*
197 *estruturas de madeira.* NBR. Rio de Janeiro, RJ, Brazil.
198 <https://www.abntcatalogo.com.br/norma.aspx?ID=3395>
- 199 **Associação Brasileira de Normas Técnicas. 2007.** ABNT NBR 15521: Ensaio não
200 destrutivo - Ultra-som - Classificação mecânica de madeira serrada de dicotiledôneas.
201 NBR. Rio de Janeiro, RJ, Brazil. <https://www.abntcatalogo.com.br/norma.aspx?ID=317>
- 202 **Braga Júnior, R.A.; Magalhães, R.R.; Melo, R.P.; Gomes, J.V. 2015.** Maps of
203 deformations in a cantilever beam using particle image velocimetry (PIV) and speckle
204 patterns. *Rev Esc Minas* 68(3): 273-278. [http://dx.doi.org/10.1590/0370-](http://dx.doi.org/10.1590/0370-44672013680016)
205 [44672013680016](http://dx.doi.org/10.1590/0370-44672013680016)
- 206 **Food and Agriculture Organization of the United Nations Statistics Division.**
207 **2015.** *Statistics* 2014. <http://www.fao.org/statistics/en/>
- 208 **Gonçalez, C.J.; Valle, D.A.; Costa, F.A. 2001.** Estimativas das constantes elásticas
209 da madeira por meio de ondas ultra-sonoras (ultra-som). *Cerne* 7(2): 81-92.
210 <http://www.redalyc.org/articulo.oa?id=74470208>
- 211 **Guedes, T.O.; Pereira, R.A.; Rivera, F.P.; Silva, J.R.M. 2019.** Particle image
212 velocimetry for obtaining the young's modulus in woods. *Cerne* 25(2): 240-245.
213 <http://www.cerne.ufla.br/site/index.php/CERNE/article/view/2115>
- 214 **Jesus, J.M.H.; Longsdon, N.B.; Finger, Z. 2015.** Classes de Resistência de Algumas
215 Madeiras de Mato Grosso. *J Eng Sci* 1(3): 35-42. <https://doi.org/10.18607/ES201531>
- 216 **Novosel, A.; Sedlar, T.; Čizmar, D.; Turkulin, H.; Živković, V. 2021.** Structural
217 reinforcement of bi-directional oak-wood lamination by carbon fibre implants. *Constr*
218 *Build Mater* 287(2021): 123073. <https://doi.org/10.1016/j.conbuildmat.2021.123073>

219 **Pereira, R.A.; Gomes, F.C.; Braga Jr, R.A.; Rivera, F.P. 2019.** Displacement
220 measurement in sawn wood and wood panels beams using the particle image
221 velocimetry. *Cerne* 25(1): 110-118. <https://doi.org/10.1590/01047760201925012619>

222 **Peters, W.H.; Ranson, W.F.; Sutton, M.A.; Chu, T.C.; Anderson, J. 1983.**
223 Application of digital correlation methods to rigid body mechanics. *Opt Eng* 22(6):
224 232-244. <https://doi.org/10.1117/12.7973231>

225 **Petrenchen, G.P.; Ambrósio, J.D. 2016.** Preparação e caracterização mecânica de
226 compósitos de polipropileno com resíduos lignocelulósicos da castanha do brasil
227 (*Bertholletia excelsa*). In *Congresso Brasileiro de Engenharia e Ciência dos*
228 *Materiais*, Natal, Brazil. <http://www.metallum.com.br/22cbecimat/anais/>

229 **Raffel, M.; Willert, C.E.; Scarano, F.; Kähler, C.J.; Wereley, S.T.; Kompenhans,**
230 **J. 2018.** *Particle image velocimetry*. Springer International Publishing AG, part of
231 Springer Nature. <https://doi.org/10.1007/978-3-319-68852-7>

232 **Ribeiro, G.P.; Gonçalez, C.J.; Gonçalves, R.; Teles, F.R.; Souza, F. 2013.**
233 Ultrasound waves for assessing the technological properties of *Pinus caribea* var
234 *hondurensis* and *Eucalyptus grandus* wood. *Maderas-Cienc Tecnol* 15(2): 195-204.
235 <http://dx.doi.org/10.4067/S0718-221X2013005000016>

236 **Souza, M.N. 2016.** Volumetria e qualidade da madeira de *Bertholletia excelsa* em
237 plantios na amazônia central. Master Thesis, Federal University of Amazonas,
238 Manaus, Brazil.
239 <https://www.alice.cnptia.embrapa.br/alice/bitstream/doc/1106937/1/Marrieth.pdf>

240 **Stangerlin, D.M.; Cademartori, P.H.G.; Gatto, D.A.; Melo, L.C.R.R.; Vivian,**
241 **M.A.; Modes, K.S. 2011** Propagação indireta e semidireta de ondas ultrassônicas na
242 estimativa de propriedades mecânicas da madeira. *Cienc Madeira* 2(2): 85-95.

243 <https://periodicos.ufpel.edu.br/ojs2/index.php/cienciadamadeira/article/view/4032/31>
244 [76](#)
245 **Zahedi, M.; Najafi, S.K.; Füssl, J.; Elyasi, M. 2020.** Characterization of Engineering
246 Elastic Parameters of Oriented Strand Board (OSB) Manufactured from Poplar
247 (*Populus deltoides*) Strands Using Ultrasonic Contact Pulse Transmission. *Drvna*
248 *industrija* 71(3): 227-234. <https://doi.org/10.5552/drvind.2020.1908>

Accepted manuscript