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ANALYSIS OF ELASTICITY IN WOODS SUBMITTED TO THE STATIC BENDING TEST USING THE PARTICLE IMAGE VELOCIMETRY (PIV) TECHNIQUE

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KEYWORDS

characterization, non-destructive testing, modulus of elasticity.

ABSTRACT

The most important parameter in terms of material mechanical behavior knowledge is the modulus of elasticity, being traditionally obtained through destructive tests. The objective of this study is the verification of the potential use of the particle image velocimetry technique (PIV) as a tool to obtain the modulus of elasticity in sawed wood samples (*Pinus oocarpa* and *Eucaliptus grandis*) and wood panels (Plywood, LVL and OSB). The PIV technique has as characteristics the low cost of equipment, fast results, no need for contact with the object tested, accuracy and possibility of application in the field. The application of the PIV technique occurred during the static bending tests where the deformations were also measured with a dial indicator (conventional method), thus obtaining comparative measurements. From the load values applied by a universal test machine and deformation values obtained by the dial indicator and PIV techniques, it was possible to calculate the modulus of elasticity through both methods. With the "*Student's t*" statistical test application with significance level of 1%, it was verified that the modulus of elasticity found by the PIV technique and the dial indicator were statistically equal. Average values for the modulus of elasticity found were respectively for the use of the conventional method and for the PIV method the values of: 13,077 and 13,027 MPA for *Eucalyptus grandis*; 6,171.6 and 6,418.8 MPa for *Pinus oocarpa*; 10,481.2 and 11,094.3 MPa for plywood; 8,687.4 and 10,261.0 MPa for the LVL; and 2,480.1 and 2,899 MPa for the OSB. It was concluded that the PIV technique is capable of measuring modulus of elasticity values with similar precision to the test techniques traditionally used for this purpose.

INTRODUCTION

The uses of different types of materials in civil construction demand the detailed knowledge of its characteristics and properties, mainly in loading situation.

The parameter most used when it comes to evaluation of the mechanical behavior is the modulus of elasticity (E). According to Matos (1997), this parameter provides information regarding the rigidity of the material and can be understood as the effort required doubling the size of a 1 cm² body. The higher the modulus of elasticity, the higher the resistance and the lower the deformity of the wood. Therefore, low values of this parameter will lead to poorer quality timber (Servolo Filho, 2013).

However, the conventional methodologies analysis traditionally employed nowaday are time-consuming and require specific equipment, besides a large number of samples (Mendes et al., 2012).

Non-destructive testing techniques are options for characterization of materials in comparison with conventional techniques, since this type of methodology does not detract the use of the objects after the analysis, it can be applied to structural parts in use, it has fast results and in general does not demand high-cost equipment.

One of the great advantages of the non-destructive test methods is the possibility of performing the *in loco* test, that is, without the need for laboratory procedures. This is of great value especially when it comes to materials that are already being used and need some sort of evaluation.

There are several non-destructive test techniques used to obtain the material modulus of elasticity. Among them highlight, the stress wave timer (Paula et al., 2016; Freitas et al., 2016), the ultrasound (Ribeiro et al., 2016, Melo & Menezzi, 2016), the vibrational techniques

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(Segundinho et al. 2012; Segundinho et al., 2013), among others.

In view of the increasing use of sawn wood and reconstituted panels of wood as structural parts in construction, it is necessary to search for new test methodologies capable of providing reliable and accurate results for a better application of these materials in the structures of buildings.

In this context, the particle image velocimetry (PIV) technique, which is an optical technique based on image analysis, appears as an option for the detailed evaluation of the mechanical behavior of the materials subjected to stress.

The objective of this research was the evaluation and validation of the PIV technique as a tool capable of characterizing lumber (*Eucalyptus grandis and Pinus oocarpa*) and reconstituted wood panels (Plywood, LVL and OSB) submitted to loading and providing their respective modules of elasticity.

MATERIAL AND METHODS

The research was carried out at the Federal University of Lavras, and the tests were carried out at the Materials Resistance and Structural Mechanics Laboratory at the Department of Engineering and the manufacture of all samples at the Experimental Unit in Wood Panels (UEPAM) at the Department of Forestry Sciences (DCF).

Five types of materials were used: sawn wood of the species *Pinus oocarpa* and *Eucalyptus grandis*, LVL wood panels, plywood and OSB. The number of test bodies for each type of material can be verified in Table 1.

TABLE 1. Number of samples of each material tested.

MATERIAL	NUMBER OF SAMPLES
Pinus oocarpa	23
Eucalyptus grandis	23
LVL Panels	30
Plywood Panels	30
OSB Panels	25

Source: The Author.

The sawed woods of *Pinus oocarpa* and *Eucalyptus grandis* were obtained from trees of experimental forest plantations on the campus of the Federal University of Lavras. The samples for the static bending tests on the sawn wood were made by means of a circular sawing cutter according to ASTM D143-94 (ASTM, 1994), dimensions 2.5 x 2.5 x 41 cm, and were then conditioned at 22 ± 2º C and relative air humidity of 65 ± 5%, as used by several authors (Avila Delucis et al., 2016; Cezaro et al., 2016).

For the preparation of the samples test of Plywood and LVL it was necessary to realize the production of the panels. For the elaboration of the panels of Plywood and LVL were used the *Pinus oocarpa* wood, with 25 years of age. The logs were sectioned using a chainsaw, becoming two logs, 60 centimeters long. They were peeled and heated in water at 66ºC for a period of 24 hours, as recommended by Iwakiri (2005). With the use of a lathe mill the logs were processed, obtaining sheets with a thickness of 2 mm. The sheets were guillotine at 55 x 55 cm and oven dried at 60 ° C until a moisture content of 5 to 6% was reached (Guimarães Júnior et al., 2015).

For the production of the panels the phenol-formaldehyde adhesive was used, with a solids content of 50.5%, at pH of 12.05, a timer gel of 5.30 minutes and a viscosity of 659cP. The adhesive formulation for the application was as follows (in parts by weight): adhesive FF = 100; wheat flour = 10 and water = 10. The sheets were glued with weights of 180 $g.m^{-2}$ (single line). The pressing cycle to obtain the plywood will occur with a temperature of 150 ° C, a time of 15 minutes and a pressing pressure of 11 $kgf.cm^{-2}$.

The plywoods were produced with seven sheets crossed among each other, while the LVL panels were produced with seven sheets positioned in the same direction.

The sheet quality classification (A, B, C and D) was performed with reference to NBR 9531 (ABNT, 1986), and it was possible to identify the classification B for the layers and the core of the panels.

The static bending test samples for the plywood and LVL panels were made using a circular saw, which was later air-conditioned at 22 ± 2ºC and 65 ± 5% relative humidity. The modulus of elasticity (E) was evaluated in a static bending test according to EN 310 (EN, 1993).

The Oriented Strand Board (OSB) panels were obtained through purchase in Lavras - Minas Gerais market. The OSB panels purchased are produced with phenol-formaldehyde adhesive, density of 0.65 $g.cm^{-3}$ and dimensions of 244 x 122 x 15 cm (length, width and thickness). The static bending test samples for the OSB panels were prepared and stored in accordance with ASTM D1037 (ASTM, 2006) and DIN 52362 (1982). The modulus of elasticity (E) was calculated according to ASTM D1037 (ASTM, 2006).

The samples were submitted to static bending in a Universal Testing Machine with load capacity of 30 tons-force, in which the PIV technique was applied to determine the Modulus of elasticity.

The Universal Testing Machine was instrumented with dial indicator (one in the center of the samples and two in the middle of the distance between the supports and the point of application of the load) to measure the displacement values of the beams. To capture the images, a professional digital camera (CANON EOS Rebel T3) was positioned perpendicular to the surface of the sample (25 cm away). The camera was equipped with a set of lenses to better adjust the focus to the surface of the samples. The capture of the images occurred with the use of a remote control to avoid any disturbance in the camera. The equipment used the configuration of the test, the test samples tested and the instrumentation of the universal test machine occurred according to Figure 1.

(a)

(b)

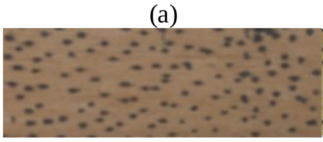
FIGURE 1. General View of the Universal Testing Machine and the instrumentation of the static bending test for the application of the PIV technique (a) and the samples used on the experiment (b).

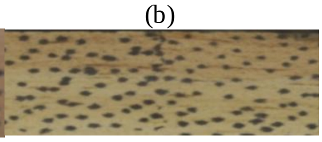
Subtitle: 1- Sawed wood *Pinnus oocarpa;* 2- Sawed wood *Eucalyptus grandis;* 3- LVL Panel; 4-Plywood Panel; 5- OSB Panel.

Source: The Author.

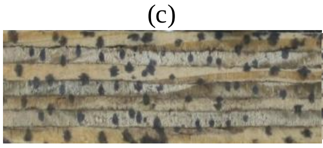
Prior to the capture of the images the surface of all the samples were marked with points made with a fine-tipped brush. The points were distributed throughout the surface of the samples with a density of points equal to 9.4 points.cm^{-2}. The mean diameter of the points was 1.5 mm, according to Figure 2.

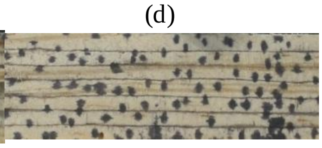
(a) (b)





(c) (d)





(e)

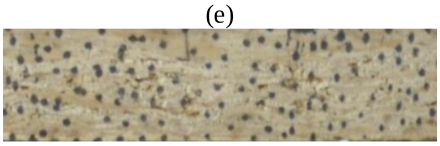


FIGURE 2. Markers insert on the surface of the materials tested.

Subtitle: Samples painted with markers and random pattern. (a) *Eucalyptus grandis*. (b) *Pinus oocarpa*. (c) Plywood Panel. (d) LVL Panel. (e) OSB Panel.

Source: The Author.

The images were captured during static bending tests at a regular interval of time. For the test samples of *Eucalyptus grandis* and *Pinus oocarpa* the interval between images was 30 seconds and for the LVL, Plywood and OSB Panels the interval between images was 5 seconds.

Considering that on average the static bending tests for *Eucalyptus grandis* and *Pinus oocarpa* samples had a duration of approximately 600 seconds (loading speed of 1.3 mm.min) and that the duration of the tests with the samples of The LVL, OSB and Plywood rotated around 90 seconds (loading speed of 5 mm.min), each samples obtained between 18 and 20 images, enough to verify the behavior of these materials in the loading situation through the PIV technique.

For the application of the PIV technique, the first image was captured before loading began (t = 0, d = 0) and the others were captured according to the preestablished time interval. Thus the first image (t = 0, d = 0) serves as a comparison parameter for subsequent images.

After the tests were finished, the captured images were manipulated in an image processing software (Image J) where the images were converted to the 8 bit format and the number of pixels of the images was reduced to 25% of the original with the intention of decrease its storage size. This procedure is important in order to make it possible to process them through the PIV algorithm in the GNU Octave free software. For the processing of the PIV technique, it was used the interrogation window of 32x32 pixel, step size of 1 pixel, search arm around the analysis region of 50 pixels and similarity threshold was used for correlation of the interrogation windows of 0.82.

After the images were processed in the PIV algorithm, the values of deformation were obtained for the places chosen for analysis. In this case, the chosen regions were those close to the three positioned dial indicator (left, center and right).

Based on ASTM D143-94 standard (ASTM, 1994) for sawn wood and in the EN 310 standards (EN, 1993) for Plywood and LVL panels and ASTM D1037 (ASTM, 2006) for OSB panels, it was used the values of deformation of the central part of the samples for calculating the respective modulus of elasticity (E).

For each test sample, two graphs "Load x Deformation" were made, one with the deformations obtained by the PIV technique and the other with the deformations from the dial indicator. The load values were provided by the Universal Testing Machine. In this way, the modulus of elasticity in each test sample of each material was calculated by means of the PIV technique and the conventional method (Dial indicator).

The statistical analysis of the data had the objective of comparing the modulus of elasticity calculated with the results of the PIV technique and with the values provided by the dial indicator.

The statistical procedure was delineated with the calculation of the modulus of elasticity in all the samples. Thus, it was possible at the end of the calculations to obtain two mean values of the modulus of elasticity (E_{PIV} and $E_{Dial\ indicator}$) for each material tested.

The statistical comparison between the values of the modulus of elasticity by the PIV (E_{PIV}) technique and the modulus of elasticity by the dial indicator ($E_{Dial\ indicator}$) was performed by comparing averages by applying the "Student's t" test.

For statistical verification of the equality between the module of elasticity by the PIV technique and by the dial indicator, the following hypothesis was formulated H_o: $\mu_{PIV} = \mu_{Dial\ indicator}$, that is, if the means of the modulus of elasticity by the two methods are equal.

With the application of the "Student's t" test with a confidence interval of 99%, the acceptance or rejection of the H_o hypothesis was determined, thus verifying the equality or statistical difference between the average modulus of elasticity found in each material by the two analysis methods.

RESULTS AND DISCUSSION

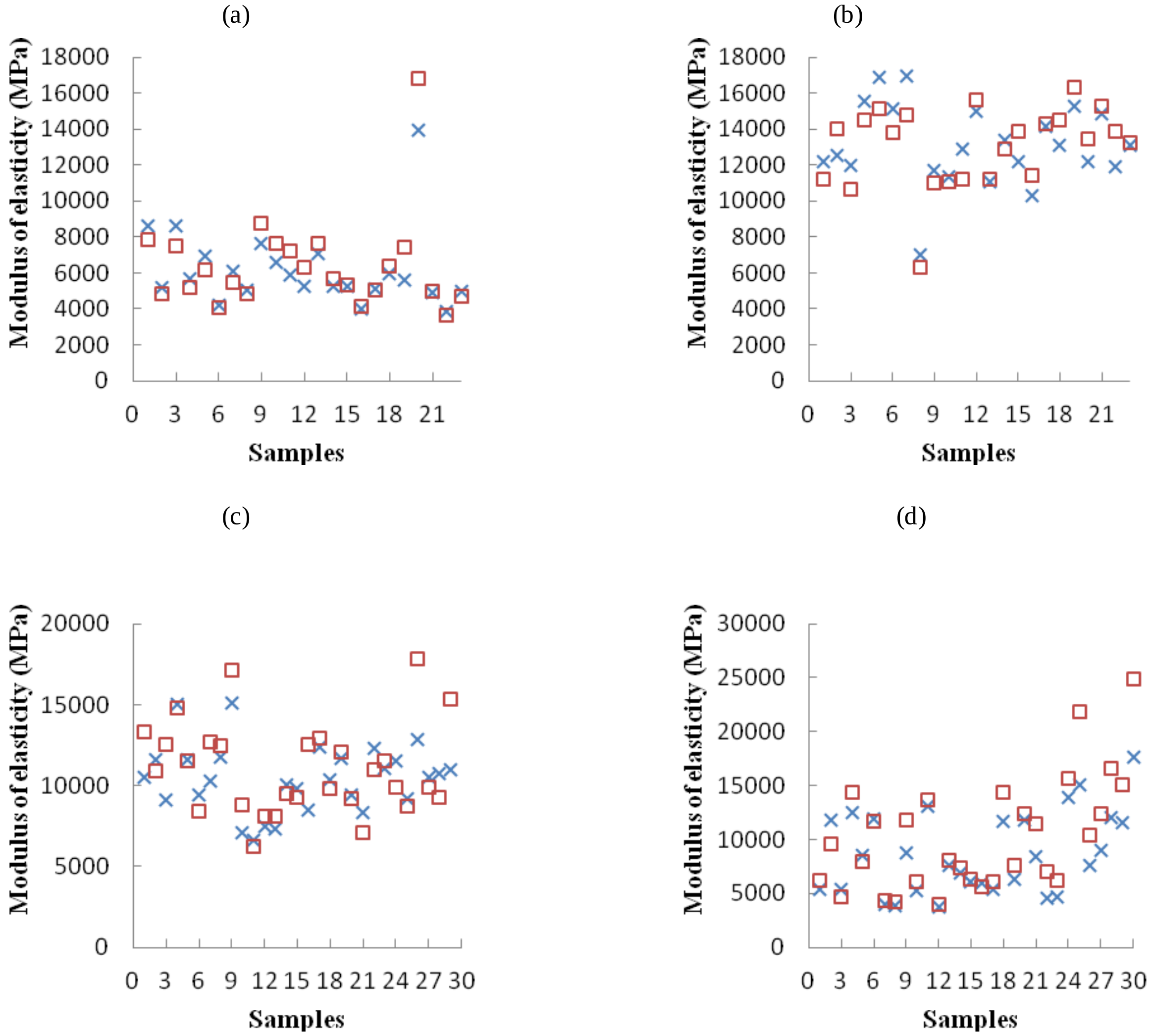
Modulus of elasticity Comparation

From the static bending tests the deformation values of the samples of the tested materials were obtained. Each test sample generated two sets of values containing the deformations during the test, one by the dial indicator and the other by the PIV technique.

Based on the specific standards for each type of material and from the "Strength x Deformation" graph of each test sample, the modulus of elasticity (E) was calculated by both methodologies. The comparison of these values is presented in Figure 3.

It can be seen from Figure 3 that in all tested materials the PIV technique presented values of modulus of elasticity (E) very close to those found by means of measurements with dial indicator.

In order to evaluate the variation between the values of modulus of elasticity (E) among samples of the same material, such as *Pinus oocarpa* lumber (FIGURE 3 (a)), it is observed that the PIV technique always accompanies the values of modulus of elasticity measured by means of the dial indicator, even in discrepant situations of the others, indicating that this technique works in different situations of loads and deformations.



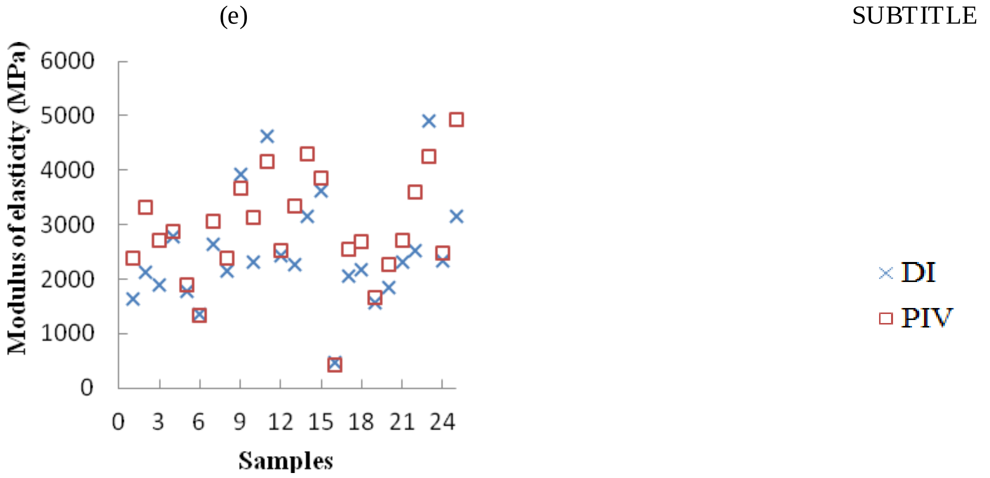


FIGURE 3. Comparation of modulus of elasticity obtained with the PIV technique and for the dial indicator.

Subtitle: Modulus of elasticity of samples of (a) *Pinus oocarpa*. (b) *Eucalyptus grandis*. (c) Plywood. (d) LVL. (e) OSB.

Statistical analysis

From the modulus of elasticity of each test sample, it was possible to calculate two mean values for each material, one for the values calculated with the dial indicator and the other with the PIV technique, comparing the two methodologies.

Statistical analysis was performed using a *"Student's t"* test for comparison of means. The data concerning the type of test, standard used, mean values of modulus of elasticity in each material and the statistical test are checked according to Table 2.

TABLE 2. Static comparation of the modulus of elasticity obtained by the conventional method and by the PIV technique.

Material	Test	Method	Average of Modulus of elasticity (MPa)	$t_{calc\ 0.005,n-1}$	$t_{ctab\ 0.005,n-1}$	H_0: $\mu_{PIV} = \mu_{DI}$
Eucalyptus grandis	Static Bending	DI	13,077.0	0.0730	-2.8187	Accepted
		PIV	13,027.0			
Pinus oocarpa	Static Bending	DI	6,171.6	-0.4338	-2.8187	Accepted
		PIV	6,418.8			
Plywood	Parallel Static Bending	DI	10,481.2	-0.9670	-2.7563	Accepted
		PIV	11,094.3			
LVL	Parallel Static Bending	DI	8,687.4	-1.3395	-2.7563	Accepted
		PIV	10,261.0			
OSB	Parallel Static Bending	DI	2,480.1	-1.7461	-2.7874	Accepted
		PIV	2,899.0			

Subtitle: DI= Dial indicator.

From the statistical comparison (Table 2), it was verified that in all materials tested, the mean modulus of elasticity calculated by the two methods was the same, according to the "Student's t" test with 1% confidence to means comparation. This result indicates the accuracy and reliability of the PIV technique versus a conventionally used method.

Other authors such as Ribeiro et al. (2016) and Melo & Menezzi (2016) studied the modulus of elasticity by means of non-destructive test techniques being, Stress wave timer and Ultrasound, respectively. They observed that these techniques were efficient in the inference of the Modulus of elasticity. However, techniques such as Stress wave timer and Ultrasound rely on physical principles such as density, humidity, fiber discontinuity and presence of imperfections inside the materials tested.

According to Stangerlin et al. (2011), this behavior is due to the fact that the voltage induced during the dynamic tests is small, that is, the dynamic measurements are based on the mechanical properties only at the elastic limit.

In this sense, the PIV technique has the advantage of evaluating only the surface of the tested material, not depending on the physical properties and characteristics of the interior of the material. Thus, it was able to follow the displacements of the samples from the beginning to the end of the test, even at the moment of rupture.

The values found in this study can be compared with values obtained by other authors. Trianoski et al. (2014) found a modulus of elasticity for *Pinus oocarpa* of 7,993.0 MPa. The values of modulus of elasticity found in this study, which were between 6,171.6 MPa (conventional method) and 6,418.8 MPa (PIV). This variation between the values can be caused by the environmental conditions where the forest individuals grew, as well as the place of removal of the samples from the trunk of the tree, near the base or the crown, or with a larger amount of heartwood or sapwood.

In relation to *Eucalyptus grandis*, several authors determined the mechanical properties of this material. Missio et al. (2013), for example, found mean modulus of elasticity values of 7,813.0 and 9,103.0 MPa for destructive testing and ultrasonic testing, respectively. These values of modulus of elasticity, when compared to the ones found in this research (13,077.0 MPa (conventional method) and 13,027.0 MPa (PIV)) show a certain variation, however similar values are still considered for this parameter.

Iwakiri et al. (2002) working with different adhesive phenol formaldehyde formulations on *Pinus oocarpa* plywood panels, found mean modulus values of 7,548.5 to 10,366.3 MPa. These values are consistent with those found in this research 10,481.2 MPa (conventional method) and 11,094.3 MPa (PIV).

Lima et al. (2013), studying the mechanical properties of LVL panels produced with different species and sheet configurations, found an average "E" value of 5,338.9 MPa in LVL panels of *Pinus oocarpa*. However, Müller et al. (2015) found an average modulus of elasticity (E) of 15,270.0 MPa in LVL panels of *Pinus taeda*. In this research the values of "E" found were 8,687.4 MPa using the conventional method and 10,261.0 MPa by the PIV technique, that is, intermediate values those found by the aforementioned authors. This can be explained by the number of sheets used to make the panels LVL, Lima et al. (2013) used 9 sheets, Müller et al. (2015) used 5 sheets and the panels of this study were made with 7 sheets.

Saldanha & Iwakiri (2009) found for OSB panels of *Pinus taeda* values of parallel modulus of elasticity (E) of 6,069.0 MPa. Mendes (2010) found a parallel (E) value of 8,222.0 MPa. These values are higher than those found in this study. It should be considered that the panels used in this research are commercial; however the values found through the conventional methodology were statistically the same as those found by the PIV technique, regardless of the value.

CONCLUSIONS

Based on the results of this research it was possible to conclude that:

By the statistical analyzes, the mean values of the modulus of elasticity found by the PIV technique did not present a statistically significant difference in comparison with the means of the modulus of elasticity obtained by the dial indicator in none of the materials.

The mean values of modulus of elasticity found with the conventional method and the PIV technique, respectively, were for *Eucalyptus grandis* of 13,077 and 13,027 MPA, for *Pinus oocarpa* of 6,171.6 and 6,418.8 MPa, for the plywood of 10,481.2 and 11,094.3 MPa, for the LVL of 8,687.4 and 10,261.0 MPa and for the OSB of 2480.1 and 2899 MPa.

The PIV technique was able to characterize all the materials tested in this study by means of their respective modules of elasticity with precision. In this way, the particle image velocimetry (PIV) technique can be used to characterize materials in loading situations, with the possibility of applying *in loco* in structural parts in use.

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