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Original Article

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# *Schizolobium Parahyba* var. Amazonicum Glulam Classified by Non-destructive Tests

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## ABSTRACT

The objectives of this study were to evaluate the relationship between the density and the $E_W$ (modulus of elasticity) values obtained by two non-destructive methods: the accuracy of an expeditious method using a graduated ruler; and the homogenization of elasticity between the methods for glulam elements. In the analysis, displacements were measured with a graduated ruler and an automatic data acquisition system of 136 glulam pieces with corresponding structural size was used. The methods were evaluated by correlations, and the homogenization of elasticity was evaluated by the Tukey test. We found that density does not influence the $E_W$ values obtained by the studied methods, and it is concluded that an expeditious method using a graduated ruler can be used to determine $E_W$ by applying a corrected equation.

**Keywords:** planted forest timber, paricá, modulus of elasticity, glulam.

## 1. INTRODUCTION

Glued laminated timber (Glulam) is an engineered product that demands precision at all stages of the production process, given its use in construction for long periods of time, and must be resistant to stresses with the least possible deformation (Segundinho et al., 2013). Therefore, glulam requires quality control during its production to ensure that its physical and mechanical properties are adequate to the requirements of projects and standards.

For the best use and quality of glulam material it is necessary to know the physical and mechanical properties of the laminated wood pieces that will compose the glulam. However, in the manufacturing process it is often not possible to obtain material of the same origin, and there may be a lot of wood pieces with different densities and/or ages among the glulam timber. In heterogeneous batches, it is necessary to make the separation by density, creating new lots with more homogeneous properties. It is possible to estimate the mechanical properties of a new batch of wood based on the direct relation between its density and the mechanical characteristics of the same species (Armstrong et al., 1984; Bodig & Jayne, 1993; Dias & Lahr, 2004; Lobão et al., 2004).

According to the American ASTM D3737 standard (ASTM, 2012) for batches of the same species, classification criteria are also implemented for the best positioning of the laminated pieces in producing glulam beams. Classification can be performed visually or mechanically, enhancing the performance of the glulam element. However, since visual classification of laminated wood pieces does not take into account resistance parameters, the longitudinal elastic modulus ($E_W$) obtained by non-destructive tests in producing glulam elements is also implemented (Terezo & Szücs, 2010; Cunha & Matos, 2011; Segundinho et al., 2013; Iwakiri et al., 2014). This procedure assists in rationally using wood, making it possible to have higher quality and more resistant laminated pieces in place at the sites of greater axial tension (traction and compression) and lower quality wood in areas near the neutral line (Bodig & Jayne, 1993; Carreira et al., 2012). $E_W$ values can be obtained for each laminated piece through non-destructive tests.

The Brazilian Standard for Wood Structures NBR 7190 (ABNT, 1997) recommends destructive tests to evaluate the mechanical properties of wood, and although they are widely used (Vivian et al., 2012), time consuming costs for preparing test specimens and testing machinery becomes expensive for glulam companies. On the other hand, the use of non-destructive methods enables evaluating the wood properties without altering its capacity for end use, and also obtaining more extensive and accurate information due to the possibility of testing a large number of samples given the low cost and time to perform the tests (Stangerlin et al., 2008; Sales et al., 2011; Ross, 2015).

There is different equipment used in non-destructive tests, and among them the main ones for estimating $E_W$ are described below: transverse vibration (Carreira et al., 2012), stress wave (Dong & Hai, 2011; Liu et al., 2014; Ribeiro et al., 2016), ultrasound (Missio et al., 2013; Cademartori et al., 2014; Oliveira et al., 2015; Melo & Del Menezzi, 2016), and the resistograph (Carrasco et al., 2013). According to the authors, these devices effectively determine the $E_W$, however these methodologies become difficult to be applied by small glulam companies due to their high cost.

$E_W$ determination can be performed according to the American Society for Testing Materials – ASTM D4761 (ASTM, 2013) norm specifications in structural parts without their rupture, and can be performed in a non-laboratory environment. The test consists in measuring the displacement caused by applying a known force in the direction of the lowest inertia and in the center of a predetermined gap in a laminated wood piece supported by two points.

Also according to this same norm, the displacement determination must be made using precision equipment (capable of obtaining readings of 25 mm up to 0.0025 mm), such as displacement transducers. In conditions where there is no precision equipment, a method is required that can measure displacement as effectively and at low cost, such as the fast use of a graduated ruler.

No studies demonstrating the use of a graduated ruler as an effective method for determining the displacement of laminated wood pieces in relation to electronic equipment according to ASTM D4761 (ASTM, 2013) are found in the literature. Thus, the objective of this study was to evaluate if the apparent density is related to the $E_W$ values in both the fast ruler method and in the method with automatic displacement transducers, as well as to identify if the fast method with a ruler can be used to obtain the $E_W$ values of laminated paricá wood pieces, and further to evaluate the analytical model to obtain the $E_W$ value in making it compatible with glulam elements.

## 2. MATERIAL AND METHODS

### *2.1. Sampling*

The paricá wood used in the present study came from planted forests in the northeastern region of Pará state. Trees at ages of 6 and 10 years were planted in the Municipality of Aurora do Pará (2°10'27.5" S latitude and 47°32'42.0" W longitude), and plantations with trees of 19 and 28 years of age in the Municipality of Tomé-Açu (2°23'42.7" S latitude and 48°08'43.4" W longitude).

The logs were sawn in the tangential direction and converted into boards of 250 cm × 20 cm × 5 cm, dried in a greenhouse at 12% moisture, in the city of Belém, Pará state, and then transported to the Laboratory of Wood Technology in the municipality of Lages, Santa Catarina state, where they remained stored and protected from bad weather until reaching equilibrium moisture of 13.87%. The boards were then sawn into 136 laminated wood pieces of 241 cm × 5 cm × 2 cm using a circular saw.

Due to the heterogeneity of the batch caused by the different ages and supply, the laminated pieces were distributed by apparent density (at equilibrium moisture of 13.87%), determined by the ratio between the individual mass obtained by a digital scale, and the volume measured with a digital caliper and measuring tape, according to Annex B of NBR 7190 (ABNT, 1997).

In order to randomize the distribution of density classes, the frequency distribution procedures were implemented according to the Sturges rule (Correa, 2003), resulting in 8 classes with the following ranges: Class 1 (C1) = 270 to 300 kg.m$^{-3}$; Class 2 (C2) = 300.1 to 330 kg.m$^{-3}$; Class 3 (C3) = 330.1 to 360 kg.m$^{-3}$; Class 4 (C4) = 360.1 to 390 kg.m$^{-3}$; Class 5 (C5) = 390.1 to 420 kg.m$^{-3}$; Class 6 (C6) = 420.1 to 450 kg.m$^{-3}$; Class 7 (C7) = 450.1 to 480 kg.m$^{-3}$; Class 8 (C8) = 480.1 to 510 kg.m$^{-3}$.

The laminated pieces were tested by two non-destructive methods using a ruler and transducer, totaling 16 treatments: Ruler C1 (C1-E); Ruler C2 (C2-E); Ruler C3 (C3-E); Ruler C4 (C4-E); Ruler C5 (C5-E); Ruler C6 (C6-E); Ruler C7 (C7-E); Ruler C8 (C8-E); Transducer C1 (C1-T); Transducer C2 (C2-T); Transducer C3 (C3-T); Transducer C4 (C4-T); Transducer C5 (C5-T); Transducer C6 (C6-T); Transducer C7 (C7-T); and Transducer C8 (C8-T); the repetitions varied according to the density frequency determined by the Sturges rule.

### *2.2. Non-destructive testing*

All laminated wood pieces were identified and the assay procedure was based on ASTM D4761 (ASTM, 2013). Preliminary flexural tests were performed on five laminates using the automatic displacement transducer to define the maximum load of 30 N. In doing so, it was guaranteed that the displacement to be measured in the other pieces was always in the elastic limits. The constant interspace of the test was 220 cm, as shown in Figure 1.

In the expedited method using a ruler, two displacement measurements were made at the central point of the interspace: the first without load and the second with load using a graduated ruler. In the transducer method, the displacement was determined

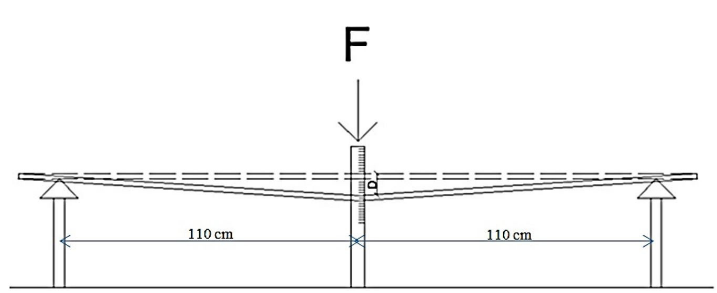


**Figure 1.** Application scheme of 30 N (F) load and displacement measure (D) to determine the stiffness of laminated wood pieces using a measuring ruler and an inductive transducer.

using an inductive transducer (WA® 50 mm) coupled to a data acquisition system (Quantum-X®) and a software program (Catman Easy®) from HBM®. Two displacement measurements were performed for each piece; the same procedure was repeated for the back of the laminated piece at the end of the first measurement, obtaining a second measurement. $E_W$ was then calculated with the mean displacement according to Equation 1. Thus, after finishing all measurements each method resulted in 136 mean $E_W$ values.

$$MOE = F.L348.Dx.I\ E_w = \frac{F\,L^3}{48\,D_x\,I} \quad (1)$$

where: $E_w$ = Modulus of Elasticity in N.mm$^{-2}$; $F$ = Applied force on the center of the interspace in N; $L$ = interspace between supports in mm; $D_x$ = Mean piece displacement in mm; $I$ = Inertia moment of the piece in mm$^4$.

## 2.3. Data analysis

The following tests were performed to evaluate if the apparent density has influence on the $E_W$ obtained by both methods: (1) spurious values (Grubbs) per treatment/class, 8 laminated pieces discarded in total, 128 laminated pieces remaining; (2) normality (Kolmogorov-Smirnov); and (3) variance (Bartlett). The design was completely randomized, arranged in a factorial scheme with two factors, measurement method and classes of apparent density. The means were compared by the Scott Knott test. All statistical tests were done at 5% significance.

In order to estimate the $E_W$ of the transducer method in relation to the $E_W$ in the fast ruler method, a correlation analysis was performed between the paired variables. Non-significance of the correlation coefficient was obtained with $p > 0.05$ by the t distribution. Using the mathematical expression of the correlation, the $E_W$ of the expedited method with a ruler was corrected and the relative error (Equation 2) was evaluated between the methods.

$$\frac{\textit{ruler value - transducer value}}{\textit{transducer value}} * 100 \quad (2)$$

Then, tests of normality, variance (requiring the data transformation by Johnson), and Tukey's mean test (not significant $p > 0.05$) were performed to observe if implementing the mathematical expression corrected by the relative error would present statistical differences between the $E_W$ of the methods.

## 2.4. Classification of laminated pieces and analytical composition of glulam specimens

The 128 laminated wood pieces were separated by 50% for the upper class and 50% for the lower class based on their respective $E_W$ values. Next, the highest $E_W$ pieces were positioned in the outer zone of maximum tension, a second piece with the highest $E_W$ was positioned in the zone of maximum compression, and the lower $E_W$ pieces were positioned in the central part of the glulam sample piece (SP), according to Figure 2. This form of systematic distribution of 4 laminated pieces for each SP aimed to provide similar $E_W$ values between all the final samples (Bodig & Jayne, 1993). A total of 32 SPs were used for non-destructive analytical evaluation. Thus, elasticity was homogenized by an arrangement of the laminated wood pieces.

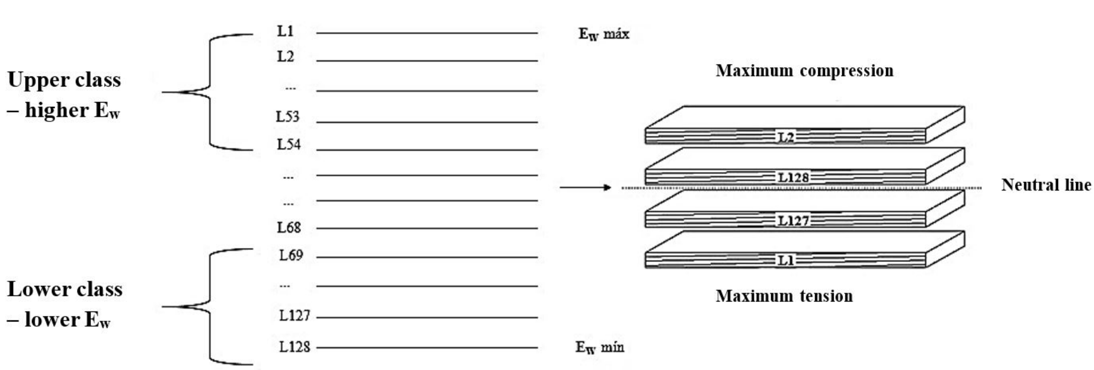


**Figure 2.** Distribution of laminated pieces for glulam sample composition.

### *2.5. Homogenization of elasticity in glulam sample pieces*

The individual $E_W$ of each SP was calculated according to the standard revision project of NBR 7190 (ABNT, 2010). The glulam SP was composed of the combination of laminated pieces with higher $E_W$ values, used in the quarters furthest from the neutral line. Laminated pieces with lower $E_W$ values were employed in the central half of the cross section (Figure 3). The flexural stiffness of the SPs was calculated by considering the transformed section, as suggested by Equation 3:

$$EI = [2 * Em,s * I(1/4) + Em,i * I(1/2) \quad (3)$$

where: EI = flexural stiffness of the structural element; $E_{m,s}$ = mean elasticity modulus value of the upper class batch; $E_{m,i}$ = mean elasticity modulus value of the lower class batch; $I_{(1/4)}$ = inertia moment of the fourth part farthest from the barycentric axis (x); $I_{(1/2)}$ = inertia moment of the central half of the cross section, relative to the barycentric axis (x).

### *2.6. Data analysis of glulam sample pieces*

In order to compare the $E_W$ of SPs between treatments, the standard error of the sample was calculated by Equation 2, and the data were evaluated by the normality tests (Kolmogorov-Smirnov) and homogeneity (Bartlett), followed by analysis of variance (ANOVA) and a comparison of means by Tukey's test, and all statistical tests were performed at 5% significance.

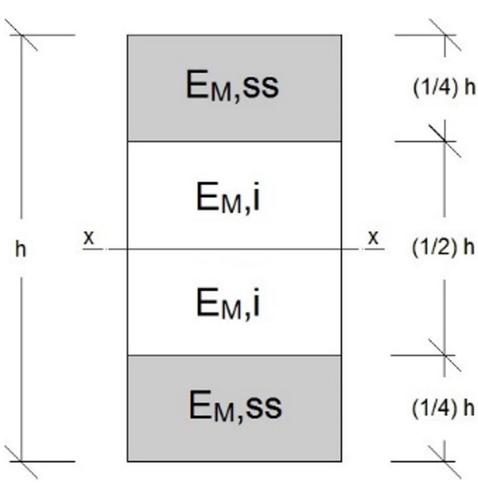


**Figure 3.** Transversal section of glulam samples with 4 laminated pieces ordered by its $E_W$ classification.

## 3. RESULTS AND DISCUSSION

Figure 4 shows the frequency of laminated pieces within the 8 apparent density classes with values ranging from 270 to 510 kg.m$^{-3}$. It was verified that the largest amounts of pieces were classified within classes 3 and 4 with apparent density ranging from 330 to 390 kg.m$^{-3}$. There was great variation in values due to the age and/or origin of the trees, and batch homogenization in classes by density could facilitate the evaluation between the methods. Therefore, the mechanical properties became compatible with each density class, as verified by Lobão et al. (2004), who evaluated *Eucalyptus* sp. by destructive tests.

Table 1 shows that the factors vary independently of each other, since there was no interaction between the factors of apparent density classes and the determination methods of $E_W$ (p-value = 0.6977). However, Cademartori et al. (2014) verified the influence of *Eucalyptus grandis* wood densities on the wave propagation velocity, thus promoting an $E_W$ classification by ultrasound. For Abruzzi et al. (2012) and Dias & Lahr (2004), the direct influence of the density is observed when it presents a positive linear relation with the $E_W$, but this behavior is not observed in the batch when maintaining the homogeneity of the density variable.

No significant statistical differences were observed between the methods for estimating $E_W$ in C1, C5, C6, and C8 density classes. Equality between methods in C1 class may have occurred due to low sampling and a high coefficient of variation (C.V.)

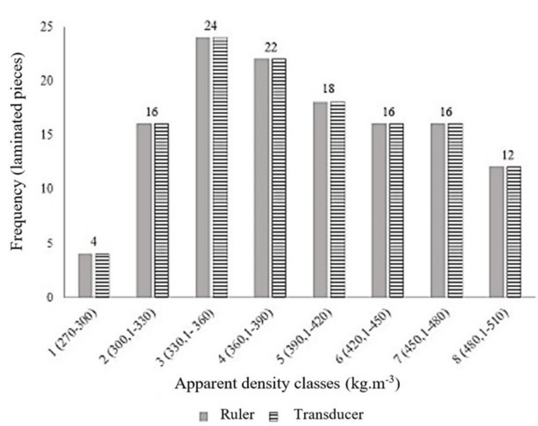


**Figure 4.** Distribution of laminated wood pieces into 8 apparent density classes.

**Table 1.** Mean values of $E_W$ (MPa) for different density classes and measurement methods of $E_W$ (MPa).

| Apparent density classes | Measurement methods: Ruler $E_w$ (MPa) | Measurement methods: Transducer $E_w$ (MPa) | P-value |
|---|---|---|---|
| **C1** (270-300 $kg.m^{-3}$) C.V.(%) | 7,042.62 a *44.05* | 5,140.06 a *35.01* | 0.3295 |
| **C2** (330.1-330 $kg.m^{-3}$) C.V.(%) | 7,899.01 a *19.55* | 5,927.06 b *32.44* | 0.0033 |
| **C3** (330.1-360 $kg.m^{-3}$) C.V.(%) | 8,095.00 a *14.48* | 6,983.30 b *48.81* | 0.0147 |
| **C4** (360.1-390 $kg.m^{-3}$) C.V.(%) | 8,291.54 a *22.34* | 6,904.86 b *29.47* | 0.0228 |
| **C5** (390.1-420 $kg.m^{-3}$) C.V.(%) | 8,538.66 a *24.74* | 8,036.64 a *30.44* | 0.5144 |
| **C6** (420.1-450 $kg.m^{-3}$) C.V.(%) | 8,941.32 a *19.58* | 8,080.84 a *35.51* | 0.3141 |
| **C7** (450.1-480 $kg.m^{-3}$) C.V.(%) | 9,645.94 a *24.95* | 7,296.46 b *34.61* | 0.0114 |
| **C8** (480.1-510 $kg.m^{-3}$) C.V.(%) | 11,451.31 a *18.91* | 9.375.84 a *43.96* | 0.1406 |
| **Overall mean** | **8.738 a** | **7.218 b** | **0.0000** |

Means followed by the same letter in the row do not differ statistically by the Scott-Knott test with 5% significance. C.V. = coefficient of variation.

value, with 4 laminated pieces (repetitions) in the class. Despite a higher number of samples, the high C.V. values may have also influenced the equality between the methods in the C5, C6 and C8 density classes. Even through a density classification, the different sources of the trees and an influence of juvenile and adult wood may have influenced the high data variability, since the mechanical behavior between young and adult woods are different (Vidaurre et al., 2011).

The statistical differences between the methods were verified in the C2, C3, C4, and C7 density classes, as well as for the overall mean. It can be said that the smallest $E_W$ values occurred due to the high precision of the automatic transducer displacement reading. Even with the high value of C.V., whose $E_W$ differences may be due to a tree's internal heterogeneity (Ballarin & Palma, 2003), the data presented similar results to those of the authors who carried out destructive and non-destructive tests for the same paricá species (Almeida et al., 2013; Terezo et al., 2015).

According to the t-distribution (p-value 0.0038), Figure 5 shows that there is a significant linear correlation between the methods, indicating an increasing trend in the difference between the results for the ruler and transducer methods as the $E_W$ value increases.

Studies comparing destructive methods using the displacement transducer method were not found until the time of performing this work, however there are those that use the displacement transducer method to determine the mechanical properties to evaluate several materials, indicating good precision for this equipment (Lu et al., 2015; Wei et al., 2015; Fossetti et al., 2015; Song et al., 2017; Hong et al., 2018; Cepelka & Malo, 2018).

$E_W$ differences obtained through different destructive and non-destructive techniques were also observed in other studies (Targa et al., 2005; Stangerlin et al., 2008; Teles et al., 2011; Cademartori et al., 2014). The main justification for this difference may be due to the great variability of the mechanical properties present in juvenile wood (Stangerlin et al., 2010; Vidaurre et al., 2011).

The correlation equation of Figure 5 showed an average relative error of 13.5% between the ruler method and the transducer method. Thus, a correction of this equation was suggested for greater precision in the $E_W$ estimation, which resulted in the Equation 4:

$$E_W transducer = 0.2790\, E_W ruler + 3898.99 \tag{4}$$

In Figure 6, it can be seen that when estimating the transducer $E_W$ values again by the Equation, the correlation behavior becomes strongly positive with $R^2$ of 0.9844 and with high significance for the t-distribution (p-value 0.0000), thus validating Equation 4.

In applying Equation 4, it can be seen that the $E_W$ values of the corrected fast method with rulers do not present significant differences in relation to the $E_W$ values obtained by the transducer method (p-value = 0.3998). It is emphasized that the mathematical expression refers to the specific batch of studied paricá in this work, thus it is important to evaluate the equation for each new age and origin.

Table 2 shows that even with a difference of 260 MPa between the $E_W$ results, the mean test indicated statistical

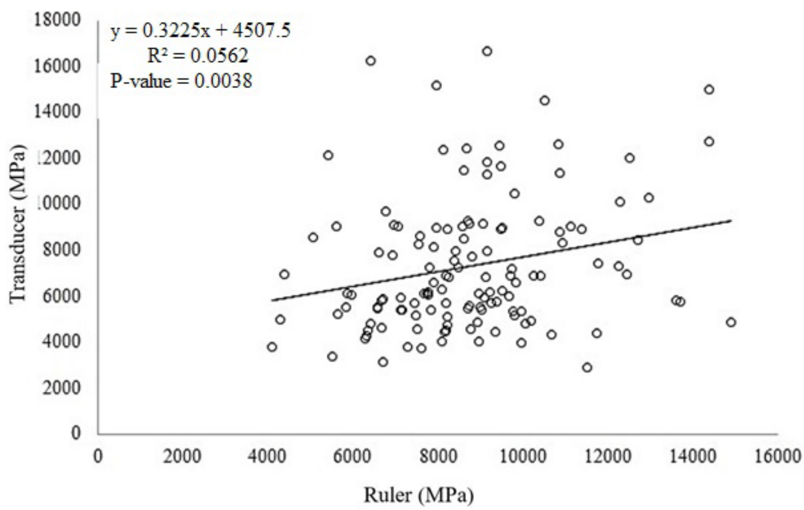


**Figure 5.** Correlation of transducer $E_W$ in relation to the $E_W$ using the fast ruler method.

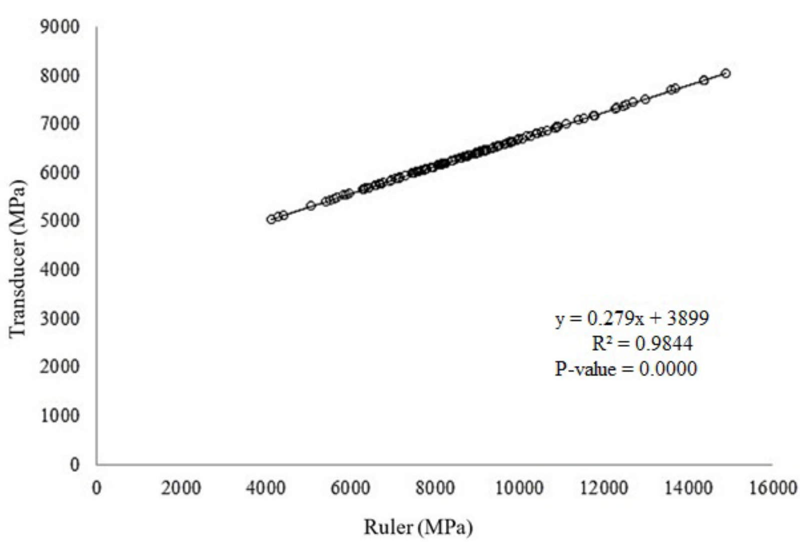


**Figure 6.** Correlation of transducer $E_W$ in relation to the fast ruler $E_W$ method.

**Table 2.** Mean $E_W$ of the glulam samples (SPs) with laminated pieces classified by expeditious ruler and transducer displacement methods.

| SPs | $E_W$ (MPa) | | R.E. (%) | SPs | $E_W$ (MPa) | | R.E. (%) |
|---|---|---|---|---|---|---|---|
| | Ruler | Transducer | | | Ruler | Transducer | |
| **V1** | 9,351 | 10,003 | -6.52 | **V17** | 9,535 | 9,213 | 3.49 |
| **V2** | 9,349 | 8,785 | 6.43 | **V18** | 9,532 | 9,291 | 2.60 |
| **V3** | 9,367 | 8,887 | 5.41 | **V19** | 9,520 | 9,221 | 3.25 |
| **V4** | 9,451 | 8,939 | 5.73 | **V20** | 9,527 | 9,239 | 3.12 |
| **V5** | 9,493 | 8,966 | 5.88 | **V21** | 9,526 | 9,314 | 2.28 |
| **V6** | 9,476 | 8,930 | 6.12 | **V22** | 9,517 | 9,354 | 1.75 |
| **V7** | 9,479 | 8,797 | 7.76 | **V23** | 9,510 | 9,322 | 2.01 |
| **V8** | 9,456 | 8,839 | 6.97 | **V24** | 9,536 | 9,377 | 1.70 |
| **V9** | 9,483 | 8,837 | 7.32 | **V25** | 9,536 | 9,477 | 0.63 |
| **V10** | 9,483 | 8,818 | 6.34 | **V26** | 9,554 | 9,522 | 0.35 |
| **V11** | 9,550 | 8,998 | 6.13 | **V27** | 9,557 | 9,537 | 0.21 |
| **V12** | 9,538 | 9,119 | 4.60 | **V28** | 9,545 | 9,580 | -0.37 |
| **V13** | 9,539 | 9,147 | 4.29 | **V29** | 9,533 | 9,623 | -0.94 |
| **V14** | 9,547 | 9,154 | 4.30 | **V30** | 9,553 | 9,629 | -0.79 |
| **V15** | 9,534 | 9,159 | 4.09 | **V31** | 9,574 | 9,757 | -1.87 |
| **V16** | 9,551 | 9,212 | 3.67 | **V32** | 9,570 | 9,816 | -2.51 |
| **Mean Ruler** | | **9,509 a** | **Mean Transducer** | | **9,249 b** | **p-value** | 0.0002 |
| **C.V.(%) Ruler = 0.62** | | | | **C.V.(%) Transducer = 3.46** | | | |

Means followed by the same letter do not differ statistically between rows by the Scott-Knott test with 5% significance. R.E. = relative error; C.V. = coefficient of variation.

differences (p-value = 0.0002) between glulam SPs in each of the non-destructive tests. Thus, even with the $E_W$ correction in the fast method with a ruler using Equation 4, the compatibilized $E_W$ was larger than the SPs with the laminated pieces classified by the transducer method. The difference between the means may have occurred (as previously discussed) by the variation in the material origin and high reading accuracy of the displacement transducer. The compatibilized $E_W$ values are similar to studies with paricá wood by Almeida et al. (2013) and Terezo et al. (2015).

## 4. CONCLUSIONS

The apparent density was not related to the $E_W$ values of the laminated paricá pieces obtained from both the ruler and transducer methods.

It is suggested the use of a corrected equation in order to use the expedited method with a ruler in determining $E_W$ ($E_W$ = 0.2790x + 3,898.99), and thus obtain values closer to those determined by the transducer method. It should be noted that such an expression must be measured for ages and sites with different soil and climatic characteristics. Therefore, the use of the expedited method with a ruler can be applied in yards of a company producing artisanal paricá glulam, thereby increasing the production quality of glulam.

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