CHAPTER 11

The use of non-destructive testing methods on glued laminated wood to obtain data

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ABSTRACT

Glued laminated wood is a mechanically processed wood product that requires strict quality control. Non-destructive evaluation can be employed on an industrial scale to improve the quality control process, allowing greater uniformity of raw materials and their by-products. The quality in the manufacture and the structural performance of elements in MLC can be guaranteed by the performance of tests, which have the function of characterizing the physical and mechanical properties of the parts. This work aims to present the main non-destructive methods used by glued laminated wood (MLC) to obtain data. The study presents the visual classification and non-destructive methods used for structural classification, including static flexion, machine stress rating (MSR), impulse excitation method, stress wave, and ultrasound. It is concluded that the choice of the method to be used in the mechanical characterization should be based on the knowledge of the advantages and disadvantages of each one, in line with the definition of the one that best suits the needs, the technique, and the cost of acquisition and maintenance.

Keywords: Quality control, Visual classification, Physical properties, Mechanical properties.

1 INTRODUCTION

Wood is a material with very variable properties that require the use of test methods for the knowledge of its characteristics allowing its best use. Among these methods, non-destructive evaluation tests have contributed significantly to obtaining data that guarantee a product with consistent and well-defined performance characteristics (ALVES et al., 2013).

Evaluation by non-destructive testing can be defined as the science of identifying the physical and mechanical properties of a material, without changing its usability (ROSS, 2015). The advantages of non-destructive testing are the use of portable equipment, which allows data to be obtained quickly. In addition, it is not necessary to remove specimens, avoiding the waste of material and the generation of waste (ROSA et al., 2014).

Non-destructive evaluation can be employed on an industrial scale to improve the quality control process, allowing greater uniformity of raw materials and their by-products (WANG et al., 2008). The use of this technology makes it possible to classify a variety of wood-based materials and products that are used in diverse applications.

Glued laminated wood is a mechanically processed wood product that requires strict quality control. MLC is a material produced from sawn wood lamellae glued together using specific structural adhesives in which the pieces must be arranged so that their fibers are parallel to each other (CEPELKA; MALO, 2017). The quality in the manufacture and the structural performance of elements in MLC can be guaranteed by the performance of tests, which have the function of characterizing the physical and mechanical properties of the parts (FARIA et al., 2019). Thus, higher-quality parts can be selected for critical use, while low-quality parts can be used in places where high strength and rigidity are not required.

In this context, this work aims to present the main non-destructive methods used in glued laminated wood (MLC) to obtain data.

2 NON-DESTRUCTIVE METHODS FOR MLC

The MLC has many advantages over sawn wood, among these the execution of large structural pieces in straight or curved format, which allows reaching large spans, including the possibility of architectural projects with unconventional geometry, ensuring beauty and sophistication (NATTERER, 1992; STARK, CAI, CARLL, 2010).

According to Mascia et al. (2018), the material has as a differential the use of sawn wood of lower resistance provided that these are used in laminations close to the neutral line of the piece. Thus, it is necessary to classify the pieces to ensure that those of greater resistance are glued to the external faces, where the bending effort is relatively greater.

For the structural classification of wooden pieces that will compose the element in MLC, non-destructive methods are used, which are visual and mechanical classification. Basically, in the visual classification, the inspector verifies each part and limits the type, location, and dimension of the defects that can contribute to the reduction of the structural strength (CARREIRA, 2003). The mechanical classification consists of determining the mechanical properties of the material, in particular the modulus of elasticity (MOE) (CHRISTOFORO et al., 2013). Among the non-destructive methods used for structural classification, we highlight static flexion, machine stress rating (MSR), impulse excitation method, stress wave, and ultrasound (CUNHA; MATOS, 2010).

2.1 VISUAL CLASSIFICATION

Because it is a material of natural origin, wood can present defects identifiable to the naked eye. Thus, visual inspection is the method to be performed for the identification of defects such as nodes and other natural faults own to s the structure of the trunk of trees and the stages of unfolding, drying, and storage of wood (ROSA et al., 2020). The visual classification added to the mechanical classification allows the manufacture of MLC beams with greater rigidity. Low-density woods may have minimal strengths for structural use, provided that the procedures for classifying these woods are applied.

The wood is separated according to specific rules and grouped into quality classes and distinct mechanical characteristics. There are some methods for the visual classification of woods recommended in standards, such as Southern Pine Inspection Bureau SPIB (2014), the American Standard Test Methods ASTM D-245 (2019), the European Standard - EN 14801 (2013), and the British Standard - BS 4978 (2007). Such regulations are based on pine species, commonly employed in their respective countries (SANTOS, 2019).

NBR 7190:2 (ABNT, 2022) defines the visual and mechanical classification criteria of structural wood parts and presents classification tables for Pinus *spp*, E. *urophylla, and E. grandis (urograndis) woods.*

The following are the main methods of visual classification according to the standards cited.

2.1.1 SPIB and ASTM D-245

The visual classification should be done on the four faces and at the ends (cross-sections) of the part. The location and nature of the nodes should be checked to the full extent. For the classification, ASTM D-245 presents criteria that allow the evaluation of any part in terms of a flexural strength ratio (CAREERS; DAYS, 2005). The resistance ratio is a hypothetical relationship between the strength of a piece of wood with visible growth characteristics and the strength of a defect-free specimen of that same wood.

The visual classification method established by SPIB defines 4 visual classes, SS, S1, S2, and S3, and their respective resistance ratios (Table 1). The part is classified as SS (*Select Structural*) when it has a low incidence and reduced dimensions of defects. As there is an increase in these defects the classification progressively follows. It should be noted that this classification was developed for use in common conifers in North America.

Table 1 – Visual quality class

Dimensions	Class	Flexural strength ratio (%)
Rafters and boards	Select Structural	67
	N°1	55

	N°2	45
	N°3	26
Posts	Select Structural	65
	N°1	55
	N°2	45
	N°3	26

Source: Adapted from Carreira e Dias (2005).

The classification using the mentioned rules was used to verify the effectiveness of the method in Brazilian species, P. *taeda* and *P. elliottii,* (CARREIRA, 2003). The visual classification of the wood by the North American method is made by comparing the limits established for the defects in each class with the measurement of the largest defects present in the pieces. Based on this, Table 2 presents criteria and dimensions for determining each of the visual classes. In practice, the verification should be done using a template.

Table 2 - Dimensions of defects for visual classification

Visual class	**We**		**The slope of the fibers**	**Ring cracks**		**Cracks**
	Narrow face	Broad face		Passing	Shallow	
SS	1/5	1/3	1:12	1 time width	Up to 600 mm	1 time width
S1	¼	7/16	1:10	1 time width	Up to 600 mm	1 time width
S2	1/3	½	1:8	1.5 times width	Up to 1/4 comp.	1.5 times width
S3	½	3/4	1:4	1/6 comp of piece	No limits	1/6 comp of piece

Source: Adapted from Career (2003).

The faces should be evaluated for the location and nature of the nodes, slope of fibers, warps and crevices, conferring a level of visual quality depending on the size of these defects. At the ends of the pieces, the number of growth rings per inch (approximately 25 mm) is evaluated, assigning to the piece of wood a density level according to Table 3.

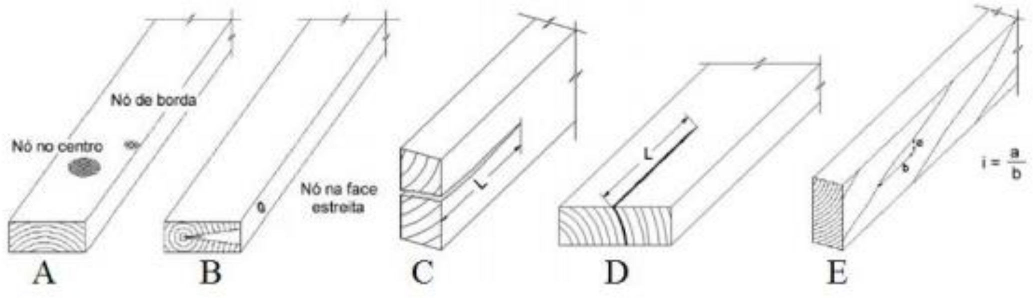
Table 3 – Visual classification attributed to density

Class	**Rings**	**Ring area**
Dense	≥ 6 and ≥ 4 and	>1/3 >1/2
Average	≥ 4 and	<1/2
Low	< 4 or	<1/2

Source: Santos (2019).

As for the nodes, for each piece, the three largest nodes positioned respectively in the center of the broad face, on the edge of the wide face and the narrow face are measured. The inclination of the fibers should be verified on the four faces, then the maximum observed inclination should be measured. Ring cracks and slits should be measured by their length parallel to the length of the piece.

Figure 1 Evaluation of defects in pine wood - A: Knot on the broad face; B:Knot on the narrow face; C: Cleft; D: Ring split; E: Slope of the fibers



Source: Santos (2019).

2.1.2 ABNT 7190:2 (2022)

The visual classification is made from the visual inspection of the two faces and the two edges of each piece about the existence of defects, disregarding those with exclusive occurrence in the tops. The following defects are considered in the standard design: the presence of medulla, knots, the excessive inclination of the fibers, passing and non-passing cracks, dimensional distortions (bending, bowing, canoeing, twisting, grinding), biological attacks, mechanical damage or resin pockets.

Depending on the defects present, a visual class is assigned to the sawn piece of wood from planted forests: Class 1, Class 2, or Class 3.   Table Table 4*Pinus* spp and Table 5

Table 5 *urophylla and E. grandis (urograndis).*

Table 4 – Requirements for visual classification of Pinus spp

Defect	**Class 1**	**Class 2**	**Class 3**
Marrow	It is not allowed		
We	1/5	1/3	1/2
Inclin. of the fibers (mm/mm)	1:9	1:6	1:3
Non-passing cracks (m)	The length of the cracks must not be greater than 1.0 m and not 1/4 the length of the piece		
Passing fissures (m)	Only passing cracks at the ends are allowed and the length should not be greater than the width of the piece		
Bowing/bowing (mm)	Less than 8 mm for every 1 m length		
Twisting (mm/m)	Less than 1 mm for every 25 mm length		
Canoeing(mm)	No restrictions		
Crushed (mm/mm)	Transversely less than 1/4of the thickness or width of the part No restrictions on the length		
Biological attacks	Areas attacked by fungi causing rot are not allowed Zones attacked by chromogenic fungi are allowed Holes caused by insects with a diameter of less than 2mm are admitted.		
Other	Mechanical damage, presence of resin bag and other defects are limited by analogy with some similar characteristic		

Table 5 - Requirements for visual classification of interspecific Hindu clone of E. urophylla and E. Grandis (Urograndis)

Defect	Class 1	Class 2	Class 3
Marrow	It is not allowed		
We	1/5	1/3	1/2
Inclin. of the fibers (mm. mm-1)	1:12	1:9	1:6
Non-passing cracks (m)	The length of the cracks must not be greater than 1.0 m and not 1/4 dthe length of the piece		
Passing fissures (m)	Only passing cracks at the ends are allowed and the length should not be greater than the width of the piece		
Bowing/bowing (mm)	Less than 8 mm for every 1 m length		
Twisting (mm/m)	Less than 1 mm for every 25 mm length		
Canoeing(mm)	No restrictions		
Crushed (mm/mm)	Transversely less than 1/4of the thickness or width of the part No restrictions on the length		
Biological attacks	Areas attacked by fungi causing rot are not allowed Zones attacked by chromogenic fungi are allowed Holes caused by insects with a diameter of less than 2mm are admitted.		
Other	Mechanical damage, presence of resin bag and other defects are limited by analogy with some similar characteristic		

2.2 MECHANICAL CLASSIFICATION

The mechanical characterization of wooden parts of structural dimensions can be obtained with the use of non-destructive tests. The following main non-destructive methods employed in the structural classification of wood parts and mechanically processed products, such as MLC, are static bending, *machine stress rating* (MSR), transverse vibration method, *stress wave method* and ultrasound.

2.2.1 Static bending

The static bending test can be considered a non-destructive method since the loading applied to the specimen causes a displacement of the piece and does not reach the rupture, that is, the modulus of elasticity is obtained in the elastic and linear region (ROSA et al., 20 20; SENA et al., 2019; BOURSCHEID et al., 2017; SEGUNDINHO et al., 2013).

The procedures of ASTM D 198 (2015) can be used to perform the non-destructive test of flexural strength at 3 points to obtain the modulus of elasticity of wooden parts. For the test the blades must be positioned in the direction of the least inertia, these must be bi-supported. The pieces must have structural dimensions, respecting the ratio L ≤ 21h, where L is the length of the span and the height of the piece. According to Christoforo et al. (2013), this relationship allows us to disregard the effects of shear in the calculation of the deflections of the pieces.

The loading should be applied at two points equidistant from the reactions. The two charging points must be at a distance from their reaction equal to one-third of the span (l/3) (loading of the third point). For the definition of the load, it is suggested to use the limit stipulated by NBR 7190:1 (2022) in which the maximum arrow is equal to L/200, where L is length between supports. This relationship ensures physical and geometric linearity for wooden beams (SEGUNDINHO et al., 2012;

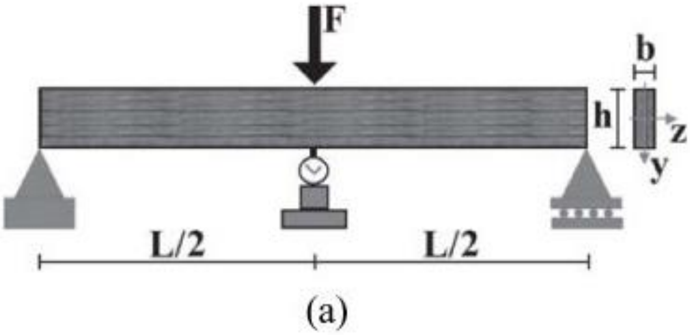
CHRISTOFORO et al, 2013). The reading of the displacement is done with the aid of a comparator clock.

The modulus of elasticity can be obtained by

$$E_M = \frac{P.L^3}{48.\delta.I}$$

Where E_M = modulus of elasticity at bending (MPa); P = force increment (N); L = distance between supports (mm); δ = vertical displacement due to the applied force (mm); I = moment of inertia of the cross-section (mm^4). Figure Figure *2* shows a diagram of the flexural strength test at 3 points.

Figure 2 – Scheme of the 3-point flexural strength test



Source: Christoforo et al., 2013.

In general, the modulus of elasticity obtained by the static bending method is used in comparison with the dynamic modulus of elasticity obtained by the non-destructive methods *of machine stress rating*, transverse vibration, longitudinal vibration, *stress wave*, and ultrasound.

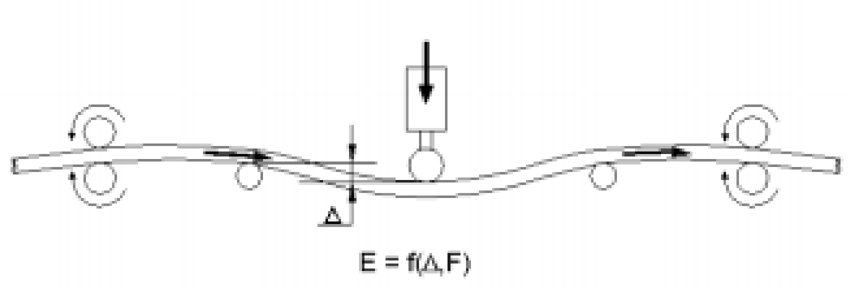
In the study for the classification of slides of *the species Cryptomeria japonica*, the MOE was obtained using static flexion assay (ROSA et al., 2020). In addition to the mechanical test, the MLC parts were assembled from the classification of the slides using the determination by visual classes. After the execution of the beams, the structural parts were tested by the static flexion test. It is concluded that solid wood of the studied species did not present minimum resistance to be classified as C-20 according to ABNT NBR 7190:1 (2022). However, the MLC beams obtained values within the minimum required for class C-20, according to ABNT NBR 7190:1 (2022).

The static bending test was used to verify the mechanical properties of reforestation wood parts, *Eucalyptus* sp. and *Pinus oocarpa*, which are commonly used in civil construction (SEGUNDINHO et al., 2012). The test was performed at three points on the pieces, according to ASTM D 198. The force was measured using a dynamometric ring of capacity equal to 4.7 kN and the displacement was measured with a comparator clock. The watch has a resolution equal to 0.01 mm and a stroke of 50 mm and has been positioned on the opposite face to the force application surface. The modulus of elasticities obtained were used for comparison with transverse vibration and longitudinal vibration tests. The methods studied showed good correlation (R2 values close to 1.0), which allowed us to conclude that the definition of the method can be done by practicality.

2.2.2 *Machine stress rating*

Mechanical stress rating uses the MSR (machine *stress rating*) machine in an automated process in which the wood passes through a series of rollers. During the execution of the test a load is applied perpendicular to the axis of least inertia of the cross-section of the part. Thus, the modulus of elasticity is measured for each part. Figure Figure *3* shows a scheme of operation of the machine. According to Carreira et al. (2003), MRS should be used for the mechanical classification of parts with thickness up to 38mm.

Figure 3 - Diagram of the operation of an MSR machine



Source: Carreira et al. (2003).

In practice, the part is positioned in the MRS in which the transducer reads possible pre-existing displacements and imperfections. The part is then directed into the machine by the feed cylinder. The part goes through the entire interior of the machine until it reaches the load cylinder. In this step, the pressure cylinder is triggered to apply a load while the part remains supported on steering and load cylinders. The loading causes the displacement and in this phase the transducer makes the reading (FREITAS, 2004).

Some machines have a device for measuring the MOE based on the displacement of the part and subsequent classification. The piece of wood classified by this method is called *MRS lumber*. Galligan and McDonald (2000) state that the machine's data output should be calibrated with statistical tests.

The machine has high productivity, which makes it possible to classify all parts in a large-scale manufacturing process. Therefore, the equipment becomes an excellent alternative for use in the wood industry and its mechanically processed products (GONG, 2019). The machine can reach an average of 300m/min. Despite these advantages, itshould be noted that the equipment requires periodic maintenance and that the acquisition implies in verifying the cost-benefit for the company.

The classification of 600 pieces of Pinus sp was made using an MRS equipment provided by a wood factory (CARREIRA et al., 2003). The machine used has a light beam that activates a photo sensor responsible for driving a piston that works on compressed air. The piston is responsible for flexing the part about the axis of least inertia. A device measures the displacement every 15 cm of the part. The machine feeds the computer with the displacement data and it calculates the dynamic MOE every 15 cm of section. Finally, the average modulus of elasticity of the part is obtained.

In the same study, the static flexion test was used to obtain the static EOM. Based on the results of the static flexion and MRS tests, the static and dynamic EOM were compared by linear regression. It was observed that the MSR machine tends to increase the error with increasing the magnitude of the MOE. The authors assume that compressed air leaks occurred and that because of this the machine could not maintain constant force for high MOE values.

The mechanical properties of the species *Larix gmelinii* were evaluated using the MRS assay and compared to the static flexion test (SHEN et al., 2011). From the results, it was observed that dynamic MOE is about 3.45% higher than static MOE. Linear regression analyses indicate that there is a relationship between static and dynamic elastic properties (at the significance level of 0.01), with a correlation coefficient of 0.9423 between the MRS test and the static flexion test. Thus, the authors concluded that the MRS assay can be used to estimate the MOE of sawn wood parts.

2.2.3 Impulse excitation technique

The impulse excitation technique is a methodology for the nondestructive characterization of wood elastic modules and their derivatives. The technique consists of determining the elastic modulus of a material from the natural vibration frequencies of a regular geometry specimen (bar, cylinder, disc, or ring).

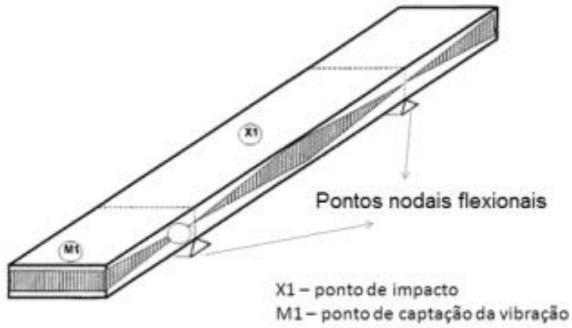
A short-duration mechanical impact is applied to the specimen, which allows the acoustic response to be captured by a sensor. To obtain the frequency spectrum, a mathematical treatment called Fast Fourier Transform is made (OTANI et al., 2017). Thus, the dynamic elastic modules are calculated utilizing equations provided in the norm.

For the excitation of the desired vibration modes, it is necessary to impose certain boundary conditions. These are responsible for determining which mode of vibration will be excited. The fundamental frequency of these modes is determined as a function of geometry, mass, dimensions and elastic moduli (CARRASCO et al., 2018).

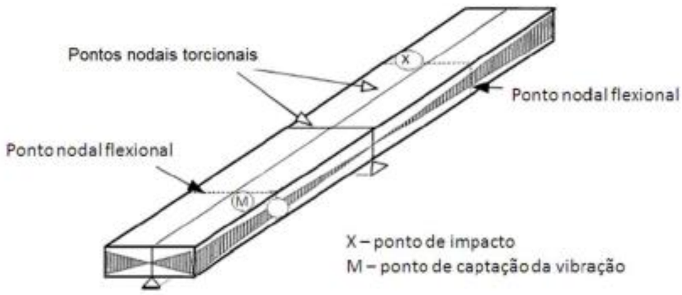
The vibration modes for prismatic bodies employed are longitudinal, flexional or transverse and torsional. The first two allow the calculation of Young's modulus and the last allows the determination of the shear modulus and the Poisson ratio. FigureFigure 4), (b) and (c) present the ideal boundary conditions for the main vibration modes of a bar. From the resonant frequencies of the sample (determined by the vibration mode) and using the equations described by ASTM E1876 (2015), the corresponding dynamic elastic modules are calculated.

Figure 4 – Vibration mode (a) flexional, (b) torsional and (c) longitudinal

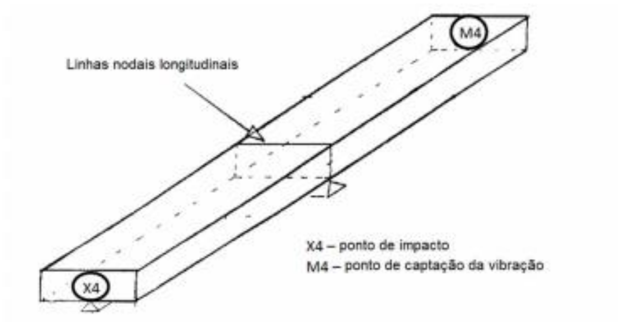
(a)



(b)



(c)

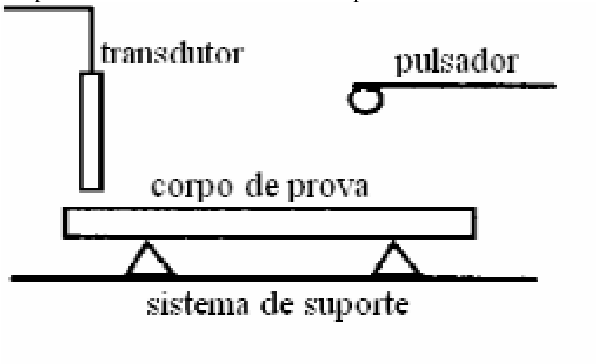


Source: Adapted from Otani et al. (2017).

To be used in the laboratory, the methodology can be separated into two parts: the first consists of excitation, detection and obtaining of resonance frequencies, and the second, in the use of mathematical relations and computational procedures, to obtain elastic modules from the resonance frequencies (COSSOLINO; PEREIRA, 2010).

Basically, in the impulse excitation method, the sample must be positioned to measure the resonance frequencies and then use a pulsator to give an impact the specimen to generate mechanical vibrations. The transducer's function is to capture the acoustic response and transform it into an electrical signal to obtain the resonance frequencies. Figure Figure 5 demonstrates a representative scheme of the impulse excitation method.

Figure 5 – Representative scheme of the impulse excitation method



Source: Cossolino and Pereira (2010).

According to Faria et al. (2018), the non-destructive method for determining the resistance properties of wood using longitudinal vibration is influenced by the speed of wave propagation along the tested piece and the density of the material. The higher the speed of wave propagation, the greater the modulus of elasticity of the part, provided that the other variables are maintained.

To perform the longitudinal vibration and transverse vibration tests there are some equipment and software available in the market. In the study developed by Segundinho et al. (2012), the longitudinal vibration test was performed according to the ASTM E1876 standard and used the *Sonelastic® Stand Alone* device. The system has a hammer used to excite the specimen and a directional microphone with a pedestal for capturing frequencies up to 20 kHz. The specimen can be placed on any surface, without the need for specific support or system calibrations.

The transverse vibration test was performed with a *Metriguard model 340 E-computer*. The unit responsible for capturing the signals receives the data provided by the load cell located on one of the supports and transmits them to the computer, where a program calculates and records the modulus of elasticity, density, and frequency of vibration. It should be noted that this system requires prior calibration. The results for the modulus of elasticity using the longitudinal and transverse vibration tests were compared to the static flexion test and it is concluded that the results presented good correlation. According to the authors, the use of the longitudinal vibration methodology was effective and can be used to determine the modulus of elasticity of structural pieces of wood.

The MOE values of MLC parts obtained through the free transverse vibration test and the static bending test were compared in a study in which the pieces were tested before and after treatment against the action of biological agents (SEGUNDINHO et al., 2013). The MLC parts were assembled without any type of condom treatment and then were submitted to static flexion and free transverse vibration tests.

Subsequently, the pieces by the Full Cell process, which uses water-soluble substances chromated copper arsenate (CCA) and chromated copper borate (CCB). After the drying period, the pieces went through the described tests again. For the transverse vibration test, Segundinho et al. (2013) used the free-free boundary condition. For this condition, the parts were suspended utilizing nylon lines and springs of small rigidity. The modulus of elasticity obtained by the transverse vibration test is 10 to 15% higher than those obtained by the static bending test. However, they showed a significant correlation both in the untreated and treated MLC specimens (0.85 and 0.99).

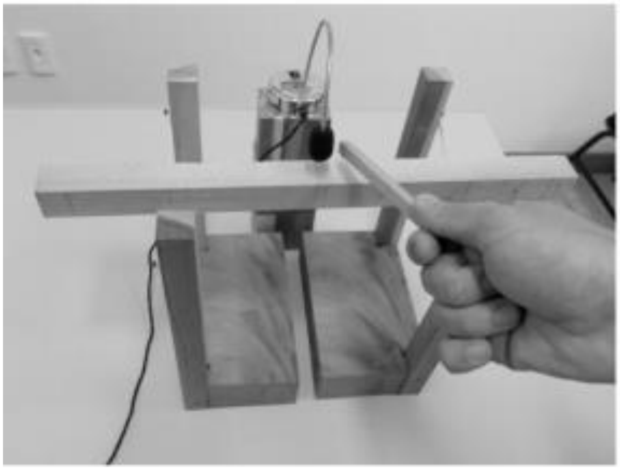
According to Carreira et al. (2012) it is the most reliable transverse vibration test arrangement for characterization of the mechanical properties of a beam under the free-free condition. The authors used longitudinal and transverse vibration tests for the mechanical characterization of reforestation woods of the species Teak (*Tectona grandis*) and tropical Guajará (*Micropholis venulosa*). The results obtained were compared to the static modulus of elasticity measured in the static flexion test and showed good correlation.

According to the studies of Yang et al. (2008), the transverse vibration test can be considered the most efficient non-destructive method of evaluation of sawn wood. The wood of *Douglas-fir* and Japanese cedar were subjected to visual classification and non-destructive tests, namely: ultrasound, *stress wave*, transverse vibration and static bending. From the determination of the dynamic MOE of the blades, the distribution of the parts for the assembly of the MLC beams was made. As reported by Zangiácomo (2003), MLC beams with non-random distribution of blades may present higher stiffness properties than d beams executed with random distribution of blades.

In the study by Segundinho et al. (2018), the longitudinal vibration test was considered the most appropriate method to obtain the dynamic longitudinal modulus of elasticity, considering that the cutting forces that occur due to shear stresses did not significantly influence the achievement of the EOM. For the research, static flexion, free transverse vibration and longitudinal vibration tests were performed.

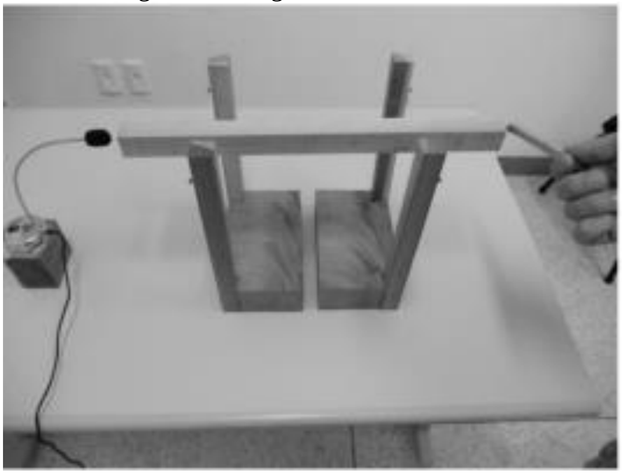
Figure 66). The specimen was placed on a stand and after impact, software was used to capture the natural frequency. The first resonance frequency was used to obtain the EOM. In the longitudinal vibration test, the direction of impact and sound capture occur in the longitudinal direction (Figure 7). However, an acoustic response composed of one or more natural frequencies of longitudinal vibration is obtained.

Figure 6 - Free transverse vibration test



Source: Segundinho et al. (2018).

Figure 7 - Longitudinal vibration test



Source: Source: Segundinho et al. (2018).

In general, the studies prove that the results obtained by the impulse excitation technique result in a dynamic modulus of elasticity up to 10% above the value of the static modulus of elasticity obtained by the static bending test. However, studies also prove that the values have good correlations. Calil and Miná (2003) obtained a correlation coefficient of 98% between the static and dynamic modulus of elasticity for pine parts.

2.2.4 *Stress wave*

Stress Wave is a dynamic method of emitting voltage (impact) waves. When employing this technique, the main parameters analyzed are the propagation velocity of an induced stress wave and its attenuation in the material (TARGA et al., 2005). This method can be applied to trees, trunks, lumber and processed wood materials such as MLC.

The passage of stress waves in wood is a dynamic phenomenon associated with the physical and mechanical properties of the material. Therefore, the speed of wave propagation can be influenced by several factors, such as the presence of nodes, grain, species, and temperature. The tension waves in the wood are propagated through the cell wall and their speed tends to reduce when encountering knots and spiraling grain (MADHOUSHI; DANESHVAR, 2016). The increase in temperature and humidity decreases the speed of propagation of the voltage wave (CHA, 1996). The age and diameter of the tree lead to an increase in the speed of propagation of the voltage wave (CUNHA; MATOS, 2010).

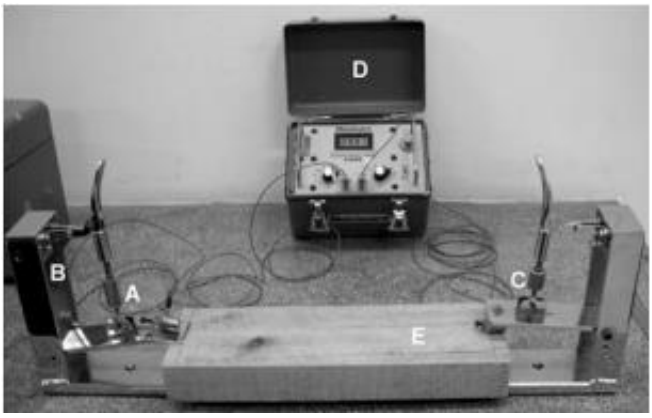
Thus, the measurements performed by the *Stress* wave method are based on the concept that the propagation of the stress wave is sensitive to the presence of deterioration of wooden limbs (ROSS, 2015). Tension waves pass through solid wood faster than deteriorated and lamellated wood. For the measurement of voltage wave time in MLC, access to the opposite sides of the limb is required to attach sensor probes (TEDER; WANG, 2013).

In practice, a voltage wave measuring equipment is used, such as the "Stress Wave Timer" (SWT), Model 239A, from Metriguard. This consists of two accelerometer transducers that must be arranged on the material to be measured and even has a clock recording the speed of the wave. The measurement process consists of the arrangement of the part between the two sensors; The recording clock must be zeroed and subsequently a metallic pendulum is released that clashes with the sensor that emits the wave on the transverse face of the part, causing the wave to cross the part longitudinally to the receiver. Thus, the speed of propagation of the wave is determined (CUNHA; MATOS, 2010; HODOUŠEK et al., 2017). To obtain the dynamic MOE of the lamellae, the equation is used:

$$MOE_d = \frac{V.ME_{12\%}}{A}$$

where: MOE_d = dynamic modulus of elasticity (MPa); V = wave propagation velocity (cm/s); $ME_{12}\%$ = specific mass at 12% humidity (g/cm^3); and A = acceleration of gravity (9.80 m/s^2). Figure Figure *8* shows details of the measuring device.

Figure 8 - Details of the measuring device: A: accelerometer transducers; B: pendulum ball hammer; C: stop clip; D: stress wave timer; and E: wood sample



Source: Adapted from Garcia et al. (2012).

The non-destructive *Stress wave* method was used by Cunha and Matos (2010) to obtain the modulus of elasticity of MLC beams produced with Pinus *taeda* and resorcina phenol formaldehyde adhesive. According to the authors, the different speed indices obtained in the beams are due to the presence of natural defects such as knots, the number of fittings used in the toothed seams and the adhesive used.

An arched MLC structure with 75 years of construction was evaluated with different destructive and non-destructive methods (TEDER; Wang, 2013). Among these, the stress wave was used to verify the conditions of one of the arcs. According to the results obtained, it is concluded that the arc presented a high degree of decomposition and delamination. The authors state that wave propagation time is a good indicator of verification of old decaying MLC structures.

The quality of blades produced with paricá wood (*Schizolobium amazonicum*) was evaluated by the *Stress wave* method (MELO et al, 2013). The results showed that there is a strong correlation between the speed of wave propagation with the dynamic modulus of elasticity, as well as the dynamic elasticity modulus and modulus of elasticity, obtained in a static bending test. Thus, itis included that the MOEd obtained by the Stress wave technique can be used with the classification of slides to be used in MLC.

The MOE was estimated for wood *Qualea brevipedicellata Stafleu* and *Erisma uncinatum Warm* using the *stress wave* method (RIBEIRO et al., 2016). The test was performed with the Stress Wave Timer model 239A. For each sample, three readings were taken and the result was obtained by the mean of the data. The results obtained by the *stress wave* method were compared with the static flexion test. For this purpose, the Person correlation was used. The analysis shows a strong correlation between the wave propagation velocity and the dynamic modulus of elasticity (MOEds), and between wave propagation velocity and the static modulus of elasticity (MOE). According to the authors, the variables are correlated with each other, and present significant values at 1 and 5% probability by the t-test.

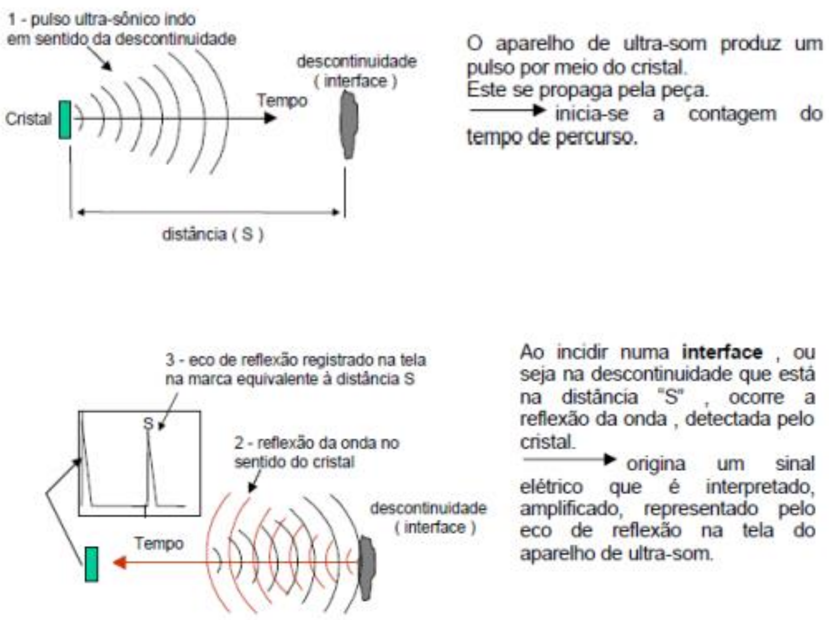
2.2.5 Ultrasound

Ultrasound is a non-destructive technique that consists of the analysis of the propagation of ultrasound waves and their relationship with the elastic constants of wood. Ultrasonic waves are acoustic waves that have a frequency higher than 20kHz (GONÇALEZ et al., 2001). In this method, an ultrasonic pulse is emitted by an electronic circuit. These pulses are conducted by coaxial cables and converted into elastic waves by a crystal, which is positioned in the transducers. Mechanical vibrations move through the material, which decreases the signal emitted by the generator. This signal is recovered by another crystal and then amplified and transformed into electrical pulses again to measure the propagation time. Thus, having the distance and the travel time of the wave, its velocity is obtained (CALEGARI et al., 2007; COSSOLINO; PEREIRA, 2010).

Like the *Stress wave,* the propagation of waves by the ultrasonic method in woods presents itself as a rather complex phenomenon. The evaluation of existing wooden structures using the ultrasound technique is characterized by a high variability in the results (OLIVEIRA et al., 2015). The constants of employees and the speed of propagation are influenced by anatomical properties, physical properties such as density, chemical composition, presence of defects such as knots and cracks, moisture content and geometry of the part (CARRASCO; OLIVEIRA JUNIOR, 2003).

In practice, ultrasound equipment produces a pulse through a crystal. When the pulse begins to propagate through the piece, the counting of time begins. When focusing on a discontinuity occurs the reflection of the wave, is identified by the crystal. From there, an electrical signal is interpreted and amplified by the equipment and represented by the reflection echo in the ultrasound apparatus. The position of the echo indicates the measured time of the return of the signal and the path taken by the sound to the discontinuity in the piece (COSSOLINO; PEREIRA, 2010; HASSAN; HORACEK; TIPPNER, 2013). Figure Figure 9 propagation of the ultrasonic pulse and the capture of the echo.

Figure 9 – (a) Ultrasonic pulse propagation scheme; (b) Echo catchment scheme



Source: Adapted from Cossolino and Pereira (2010).

The Brazilian standard NBR 15521 – Non-destructive tests – ultrasound – Mechanical classification of dicotyledon sawn wood (ABNT, 2007) presents ranges of characterization of the resistance of the wood using the ultrasound test according to the speed of propagation of the waves or the constant of stiffness of the pieces. It should be noted that the standard was designed for application in adult woods. The speed of propagation of the waves is determined by:

$$V = \frac{L}{t}$$

where, L is the length of the part, in meters, and t is the propagation time of the wave, in seconds.

From this we obtain the longitudinal stiffness constant (C_{LL}), in megapascals, as a function of the apparent density of the wood and the transport speed of ultrasonic waves, using the following equation:

$$C_{LL} = \rho_{12\%}.V^2.10^{-6}$$

where $\rho_{12\%}$ is the apparent density in the equilibrium humidity condition, in kg/m ^{3}, and V is the propagation velocity of ultrasonic waves in the same humidity condition, in m/s.

The Brazilian standard that deals with the ultrasound technique is based on adult wood. Sena et al. (2019) used young eucalyptus wood to verify whether the resistance classification ranges provided for by the standard can be obtained with ultrasound under these conditions. For the verification, the mechanical classification of the pieces was made by ultrasound and by the destructive tests of static flexion and compression parallel to the fibers.

The results showed a good relationship between the dynamic and static modulus of elasticity (R^2=0.7478). The study found that the modulus of elasticity obtained using ultrasound was 13% higher than that determined by destructive tests. The authors concluded that the ultrasonic wave propagation test is efficient in determining the mechanical properties of wood. However, it is suggested to apply a reduction coefficient in the dynamic modulus of elasticity.

To estimate the mechanical properties of *Peltophorum dubium* wood, the non-destructive ultrasound method was used (STANGERLIN et al., 2010). To perform the test, ultrasound equipment with dry spot transducers and a frequency of approximately 45 kHz was used. The transducers can provide the propagation time of the waves, in microseconds(s). For each body of evidence, two readings were made and after that the average was obtained. From there, the equations described in the norm were used to obtain the dynamic elastic modulus. The results were compared to the static flexion test.µ

Regression analysis was applied to analyze the results, in which the independent variable was the dynamic elastic constant obtained in the ultrasound test and the dependent variable the mechanical property of elasticity or rupture obtained in the static flexion test. There was great variability among the data studied. The dynamic elastic constant was about 1.37 times greater than the modulus of elasticity. According to Stangerlin et al. (2010), the static flexion test has a long duration compared to the ultrasound assay. Thus, the dynamic elastic constant obtained in an ultrasound test is, in general, greater than the modulus of elasticity at static flexion.

The performance of the ultrasum m technique was verified in the mechanical evaluation of sawn beams of the Brown species (*Castanea sativa Mill*.) that were removed from a building under renovation (OLIVEIRA; et al., 2015). To compare the effectiveness of the use of wave frequencies of 24 kHz and 54 kHz in the characterization of the modulus of elasticity and the flexural strength, different arrangements of the probes, coupling materials and test schemes were considered. 24 kHz transducers can better distinguish different types of nodes. In addition, they present smaller percentage errors when compared to the static flexion test.

The physical and mechanical properties of structural laminated panels produced with paricá wood (*Schizolobium amazonicum Huber ex. Ducke*) were investigated employing the ultrasound technique (MELO; MENEZZI, 2019). The results demonstrate that ultrasound is effective in determining the dynamic modulus of elasticity through the speed of wave propagation.

3 CONCLUSIONS

The characterization of mechanically processed wood parts and products can be carried out through non-destructive testing, which aims to determine the physical and mechanical properties of a structural element without changing its usability to use. Non-destructive tests avoid the extraction of specimens, enabling the study of structural integrity.

For MLC, the use of criteria for the classification and arrangement of the blades for the execution of the beam, ensures an increase in the strength and stiffness of the structural elements. In this way, the classification of the slides can be carried out, visually and mechanically, by non-destructive methods.

A visual classification is an important tool in the verification of defects that may occur due to the presence of growth characteristics, which can be observed and evaluated through templates. With the aid of classification rules, these growth characteristics are used to select the wood in quality classes. The visual classification should always be used in association with mechanical classification.

Non-destructive tests for mechanical characterization should be applied to parts with structural dimensions. Static bending can be considered a non-destructive method as long as the applied loading maintains the displacement of the part in the elastic regime. As for the dynamic methods, their choice is conditioned to the application and acquisition of equipment.

The impulse excitation technique presents a good correlation when comparing the dynamic modulus of elasticity to the static modulus of elasticity, obtained by the static bending test. According to the studies presented, the free transverse vibration and longitudinal vibration tests can be used for the mechanical characterization of wooden parts.

The characterization method that employs the MSR (machine *stress rating*) machine can be applied in companies because it is an automated process that presents good results. The so-called *stress wave* assay may suffer variation in its results due to factors such as the presence of anatomical features such as knots and grain. The ultrasound method presents relative simplicity in its application. However, it may present great variation in its results given the presence of defects in the wood that may interfere in the reading of the equipment.

Finally, the choice of the method to be used in the mechanical characterization should be based on the knowledge of the advantages and disadvantages of each one in line with the definition of the one that best suits the needs, the technique and the cost of acquisition and maintenance.

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