LAMINATED WOOD AND MULTIMATERIAL WOOD – ADHESIVE MESHAS REPLACEMENTS OF SOLID WOOD IN RESTORATION OF HISTORICAL BUILDINGS

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ABSTRACT:

Wooden structure restorationwork in historical buildings requires substitution and/or reparation of structural elements. The aim of this investigation is to compare the density, wave velocity, dynamic module, and quality factor intest pieces of solid wood, laminated wood and a multimaterial of *P. pseudostrobus.* The work hypothesis proposes that dynamic modules of laminated wood and multimaterial laminated wood reinforced with stainless steel mesh are, at least, equal to solid wood. Small dimension test pieces made of solid wood, laminated wood, and multimaterial wood elaborated with the species *P. pseudostrobus* were prepared. Humidity content and apparent density of wood were determined. Ultrasound tests in radial, tangential, and longitudinal direction were doneand wave velocity, dynamic module, and quality factor were determined. Empiric evidence indicates that wave velocity, dynamic module, and quality factors are different with the three kinds of test pieces. Laminated wood and multimaterial wood characteristics are similar to *P. pseudostrobus* solid wood; so that the two compound material have good expectations to substitute some pieces that work as resistance elements in wooden structures.

1. INTRODUCTION

1.1 Problem

Wooden structure restoration work in buildings with historical and cultural value requires the reparation and/or, eventually, the substitution of structural elements such as beams, columns,girdersand the components of roof truss, walls, floors and stairways. (Van Roy et al., 2018) In order to respect the wooden historical structures preservation principles of the International Council on Monuments and Sites (ICOMOS, 1999), it is necessary to substitute some pieces of wood which are deteriorated by new elements of the same species and with technological quality equivalent to the wood in service (Cruz et al., 2015).
The person in charge of the restoration faces the problem of scarcity of wood pieces comparable in dimensions and similar to the structural elements in service. A practical solution to this problem is to elaborate reinforced and/or reconstructed laminated wood piecesthat satisfy the mechanical resistance criteria, in such a way that reliable structural criteria and the renovated structural service can be assured (Croatto y Turrini, 2014; Larsen y Marstein, 2016).

1.2 Reinforced Wood

Some elements made of wood, such as recycled beams used to support flexion charges, have been submitted for replacement or reinforcement with classical techniques which involve the use of common construction materialsuch as concrete or steel (Borriet al, 2005). However, literature reports new approaches and new technology in order to repair, restore and reinforce some pieces of wood present in buildings where wood plays an important role.

Recent research about the topic, reinforcement and reparation of structural wood elements, preferably studies beams of solid and laminated wood, that potentially or in-service structures exist for future edifications. For example, Jasiénko y Nowak (2014) reinforced beams with new and old wood with the purpose of evaluating different configurations of epoxy adhesive and flexion tested steel plaques; likewise, Frankeet al. (2015) reported different reinforcement techniques for beams depending on the kind or origin of the failure.

A favored strategy to reinforce pieces of wood is the use of carbon fiber reinforced polymer (CFRP). Schober et al (2015) recommend CFRP to repair and reinforce wood structures. In order to improve mechanical resistance in pieces of wood, Corradi et al (2015) add CFRP to pieces of solid wood of Castañee Sativa, while Nadir et al. (2016) did it with laminated wood of Hevea Brasiliensis. Reis et al (2018) recommend CFRP soaked bars to reinforce wood beams.

Particularly, working in historical buildings, Nowak et al (2013) added CFRP to reinforce *Pinus Sylvestris* beams in order to restore charge capacity in wooden beams. Chang (2015) reviews different techniques to reinforce and to repair wooden columns and walls, while Gubana (2015) did the same on wooden floors. Rescalvo et al (2017) and Rescalvo et al (2018) use different configurations of CFRP to reinforce *Pinus Sylvestris* old wood, and to analyze the increment in mechanical resistance.

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From another point of view, Zhou et al. (2011) report some results about the incorporation of galvanized steel mesh to reinforce wood. Marzi (2015) reviews the prospective of Nano-structured materials to protect and reinforce wooden structures. Byeon et al (2016) do some research on hybrid structural elements made of wood and other materials. Togay et al (2017) propose to reinforcestructural elements with aluminum mesh. Rangavar (2017) reports physical and mechanical properties found in cement-wood panels reinforced with steel mesh, while Kohl et al (2017) characterizemultimaterial based on wood dynamic conditionsand they suggest them as substitution to solid wood.

Synthetizing, the already mentioned authors' conclusions, contemporary tendency is to reinforce pieces of wood by incorporating synthetic and metallic material components in order to improve its technological properties. This way, substituting structural elements in restoration works in historical or damaged buildings would be done only because of exceptional events such as fire or earthquakes.

1.3 Ultrasound Characterization

Ultrasound technology applies in engineering analysis of historical wooden structures to measure the wave velocity (Íñiguez- González *et al.* 2015, Kloibe *ret al*. 2016, Branco *et al*. 2017, Riggio *et al.* 2018). Likewise, ultrasound is used in solid wood mechanical (Tipper *et al*.2016) and laminated (Sanabria *et al* 2011) characterization.

The necessary parameters to characterize dynamically the test pieces with different compounds of wood are the apparent density (Niklas and Spatz, 2010) and the wave velocity in three directions of anisotropy of wood (Dackermann *et al*, 2016).By combining wave density and velocity the dynamic module is determined (Gonçalves *et al*, 2014). Another parameter in the mechanical design is the quality factor, which is similarly usedto classify and to compare the quality of wood (Spycher *et al* 2008). A significant factor of quality suggests better resistance in relation with its density and good appreciation of wood as engineering material. (Ashby, 2011).

These characteristic have been reported for solid and laminated *Pinus pseudostrobus Lindl* wood done in the Laboratory of Wood Mechanics in the School of Wood Technology of the Universidad Michoacana de San Nicolas de Hidalgo, in Morelia, Mexico (Sotomayor *et al*, 2010, Sotomayor *et al*, 2015). However, information about multimaterial wood-adhesive-mesh characterized by ultrasound characterization was not found.

1.4 Hypothesis

Work hypothesis proposes that dynamic modules of laminated wood and multimaterial are, at least, equal to solid wood of *Pinus pseudostrobus*. This hypothesis can be verified if density and wave velocity are determined and dynamic modules are calculated.

1.5 Objective

The objective of this research is to compare the density, wave velocity, dynamic module and quality factor on three samples of test pieces of solid wood, laminated wood and multimaterial, all of which were taken from the specie *Pinus pseudostrobus*. As a corollary, laminated wood and multimaterial have been proposed as a substitute of solid material of pieces of wood in the restoration of historical buildings.

2. METHODOLOGY

2.1 Material

The experimental material consisted on three groups of 32 test pieces of sawed wood from *P. pseudostrobus* (Sáenz *et al*.2011) collected in the State of Michoacán, Mexico. The first group consisted of test pieces made of solid wood labeled as *solid wood* (Figure 1). The second group was formed by two sheets of wood joined together by an adhesive made of two components of polyurethane (50%-50%) labeled as laminated wood (Figure 2).

The third group, named multimaterial (figure 3) was made of two sheets of solid wood and between them a mesh of galvanized steel. (AISI 304 Stainless Steel Mesh). Wood pieces and the mesh were joined together with an adhesive made of two components of polyurethane. Both the laminated and the multimaterial test pieces were made-up under a pressure of 200 kg cm^{-2} and a temperature of 80°C during 30 minutes. The dimensions of the test pieces were 0,4 m x 0.05 m x 0,1 m in radial (R), tangential (T) and longitudinal (L) direction.

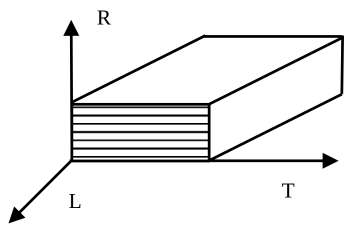


Figura 1. Solid Wood.

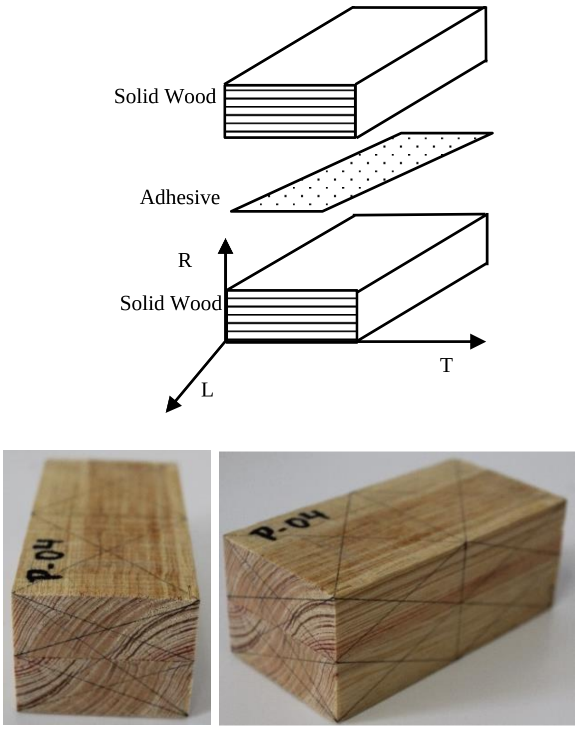


Figura 2. Laminated Wood.

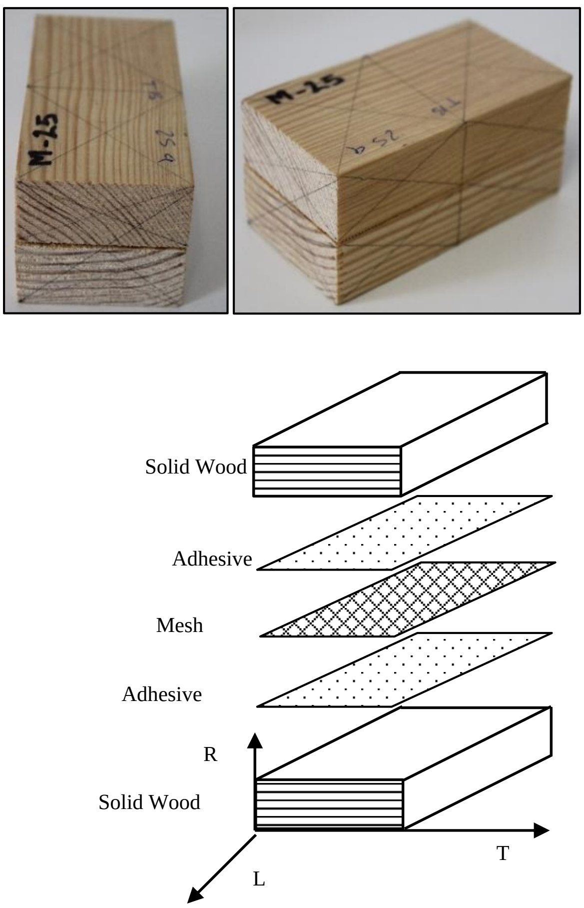
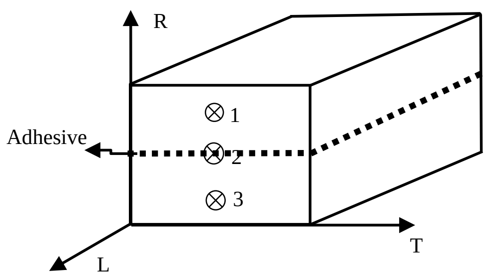


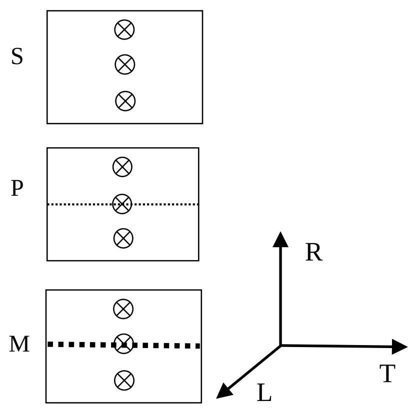
Figura 3. Multimaterial.

2.2 Test Program

Both the wood and the test pieces were stabilized before and after fabrication during 3 months in a conditioning chamber with a temperature of 20°C (±1° C) and an air relative humidity of 65% (± 2%), until they reached a constant weight. The apparent density of the test piece (ph) was determined taking into consideration the relation between weight and volume at the moment of the test, corresponding to the content of humidity in equilibrium (International Organization for Standardization ISO 13061-1:2014). With the objective of simplifying the text, from here on the term ‘apparent density’ will be named ‘density’. The content of humidity (H) of the wood was determined with the relation between the weight at the moment of the tests and the weight in an anhydrous state (International Organization for Standardization ISO 13061-1:2014).

The ultrasound tests consisted on measuring the wave transmission time with the apparatus *Sylva test*© (frequency 22 kHz) and dividing it by the distance between the ultrasound signal of emission and reception, located on the radial (R), tangential (T), and longitudinal (L) direction, normal to the corresponding contacting surfaces (RT, RL, and TL). Ultrasound velocity (Vus) was calculated in relation to transmission time/route distance. Three measures were done in each plane in positions 1, 2, 3 as indicated in Figures 4 and 5, so that the test pieces rotated 90° in order to get normal direction to the contact planes.





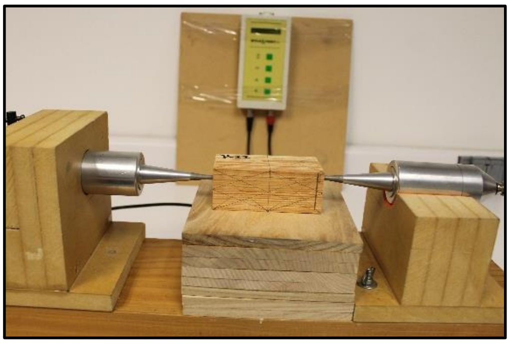
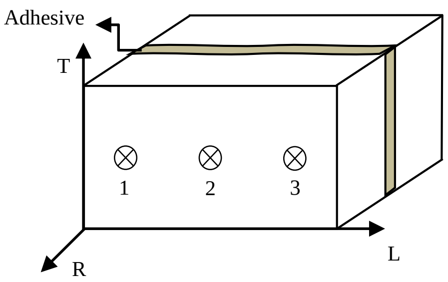
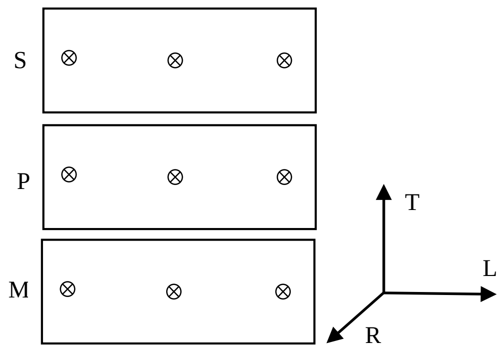


Figure 4. Ultrasound tests in the longitudinal direction.





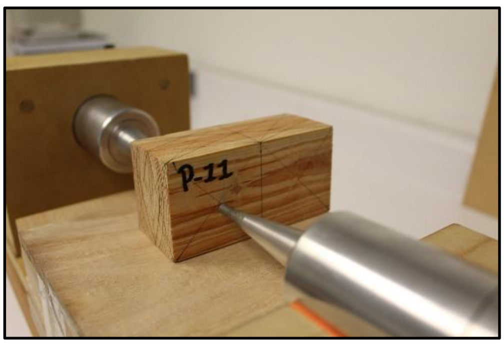


Figure 5. Ultrasound tests in the tangential direction

The dynamic module was calculated with the equation (1) (Dackermann et al. 2016):

$$E_{us}= \rho_H \times v_{us}^2 \qquad (1)$$

Where: Eus = Dynamic module (N m-²)
ρ_H= Density (kg m-³)
Vus= Wave velocity (m s -¹)

Quality factor was calculated with the equation (2) (Spycheret al. 2008):

$$F_{us}= v_{us} / \rho_H \qquad (2)$$

Where: F_{US} = Quality (N m-²)
ρ_H= Density (kg m-³)
Vus= Wave velocity (m s -¹).

2.3 Research Strategy

Experimental strategy consisted on determining medium values (Ẍ), standard deviation (Ϭ) and variation coefficient ((CV = Ϭ / Ẍ) of the three samples of test pieces: solid wood, laminated wood, and multimaterial.

In order to analyze the results two physical parameters were specified: humidity content (H) and density (ρ_H); and also three mechanical parameters: wave velocity (V_{us}), dynamic module (E_{us}) and quality factor (F_{US}). The sub index H means that density corresponds to the content of humidity of the specimen. The sub index (us) indicates that the parameters are derived from ultrasound tests. In the same context, three samples are defined: solid wood, laminated wood and multimaterial; three contact planes: TL, RL, and RT; and three directions of wave velocity: R, T, and L.

3. RESULTS AND ANALYSIS

Table 1 represents density (ρ_H), content of humidity (H), wave velocity (V_{us}), dynamic module (E_{us}), and quality factor (F_{US}) for solid wood, laminated wood and multimaterial.

Plane-Direction	TL-R	RL-T	RT-L
		Solid wood	
ρ_H (kg m^{-3})	589	589	589
H (%)	11.6	11.6	11.6
v_{us} (m s^{-1})	765	685	5040
E_{us} (MN m^{-2})	346	291	15062
F_{us} (m^4 kg^{-1} s^{-1})	1.30	1.16	8.55
		Laminated wood	
ρ_H (kg m^{-3})	583	583	583
H (%)	10.7	10.7	10.7
v_{us} (m s^{-1})	688	692	4110
E_{us} (MN m^{-2})	277	366	9873
F_{us} (m^4 kg^{-1} s^{-1})	1.18	1.19	7.05
		Multimaterial	
ρ_H (kg m^{-3})	586	586	586
H (%)	10.4	10.4	10.4
v_{us} (m s^{-1})	1291	493	4136

E_{us} (MN m^{-2})	976	143	10098
F_{us} (m^4 kg^{-1} s^{-1})	2.20	0.84	7.06

ρ_H = Density; H = Moisture content; v_{us} = Wave speed; E_{us} = Dynamic modulus; F_{us} = Quality factor.

Table 1 Density, humidity content, wave velocity, dynamic module, and quality factor.

3.1 Moisture Content

Humidity content of the three samples varies from the interval 10.4 to 11.6 (Table 1). The coefficient variation of humidity content in each sample interior varies from 5.1 to 9.8 %. Consequently, *P. pseudotrobus* wood is considered stabilized in dry state and it is proposed that the variation of the humidity content of the sample pieces does not intervene in a significant way in the results.

3.2 Density

Density magnitude for solid wood and laminated wood is similar to the ones reported by Sotomayor et al. (2010) for *P. pseudotrobus*wood and for laminated wood of *P. pseudotrobus*, Sotomayor et al (2015). However, no information to compare multimaterial densitycould be found. Laminated wood density decreases 1% and multimaterial density decreases 0.5% comparing both with solid wood density. (Table 1). These results suggest that laminated treatment and multimaterial fabrication do not modify in a significant way the density of specimens made only with solid wood.

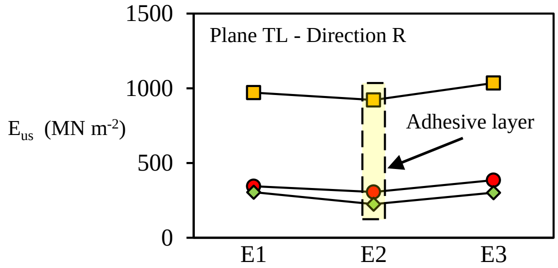
One of the criteria to substitute a piece of wood while restoring historical buildings is to use the same species, the same density and the same mechanical resistance (Cruz et al 2015) of *P. pseudotrobus*solid wood. It is wise to specifically study the variation in density when reconstituted wood is being fabricated using different species from the one studied in this research, in order for this proposal to be extended to other species.

3.3 Wave Speed and Dynamic Modulus

Figures 6, 7, and 8 detail the three dynamic modules (E1, E2, and E3) locally determined in the three positions of the specimens of the three samples according to the sampling strategy detailed in Figures 1 to 5.

The magnitudes of wave speed and dynamic module in *P. pseudotrobus* solid wood are similar to the ones reported by Sotomayor et al (2010) and Sotomayor et al (2015). However, the average values of Vu and Eusfor radial and tangential directions in this research (2019) are lower than the ones in the bibliography. This result is consistent with the later analysis of local measurements.

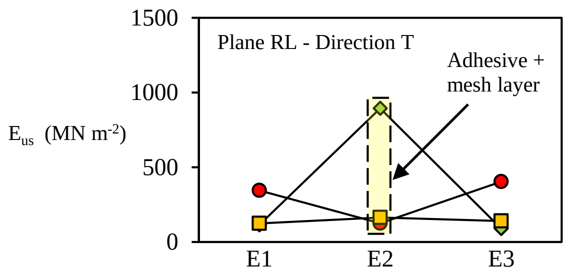
The three dynamic modules determined in radial direction in one specimen are similar among them (Figure 6). Nevertheless, there are variations among the three samples. The average dynamic modules of multimaterial (976 MN m-²) are as far as 2.8 times larger than the ones of solid wood (346 MN m-²) and even more, 3.5 times larger than the ones of laminated wood (277 MN m-²). This result indicates that in relation to solid wood and laminated wood of *P. pseudotrobus*, multimaterial increases the dynamic module in radial direction.



	E1	E2	E3
Solid wood	345	307	385
Laminated	305	225	302
Multimaterial	972	922	1035

Figure 6 Dynamic Modules in Radial Direction.

The three dynamic modules measured in tangential direction of the specimens for solid wood and multimaterial are similar (Figure 7). However, module E2 for laminated wood, corresponding to the layer where the adhesive is (plane RT parallel to the tangential direction) is larger 7.5 times in relation to solid wood, and 5.6 times larger in relation to laminated wood.



	E1	E2	E3
Solid wood	345	125	404
Laminated	115	894	90
Multimaterial	124	164	140

Figure 7 Dynamic Modules in Tangential Direction.

This way, specimens of laminated wood increase their dynamic module at local level because of the presence of adhesive. This phenomenon reflects the increment of the average dynamic module in the specimens of laminated wood in 20.5% with respect to solid wood and 60.1 % with regard to multimaterial. In the same context, a significant effect of the adhesive mesh plane has not been identified when measuring E1, E2, and E3 of the specimens of multimaterial.

As for the longitudinal direction, normal to the radial-tangential plane, dynamic modules of the specimen of laminated wood, combine withdynamic modules of the specimen of multimaterial (Figure 8). However, the dynamic modules of specimen of solid wood are larger in relation to laminated wood and multimaterial.

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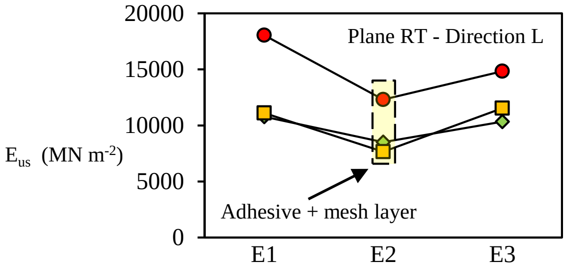


	E1	E2	E3
Solid wood	18050	12305	14831
Laminated	10781	8504	10334
Multimaterial	11104	7652	11539

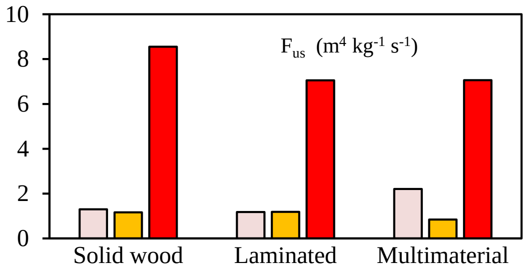
Figure 8 Dynamic Modules in Longitudinal Direction

Dynamic modules of solid wood are,as an average, 35.4% larger than laminated wood and 33% largerthan multimaterial. With regard to E2 values corresponding to measures through planes RT of adhesive in specimens of laminated wood and multimaterial aresmallercomparing them with dynamic modules of specimens of solid wood.

Dynamic module is calculated from density and wave velocity with equation (1). This way, when density increases, a lineal increment of the dynamic module is produced. On the other hand, when wave speed increases a second order intensification is provoked in the dynamic module.

3.4 Quality Factor

Taking into consideration the three samples studied, the average quality factor, which was calculated with average values of wave velocity and density, they are larger for longitudinal direction comparing it with quality factor corresponding to radial and tangential direction (Figure 9).



	Solid wood	Laminated	Multimaterial
TL-R	1.30	1.18	2.20
RL-T	1.16	1.19	0.84
RT-L	8.55	7.05	7.06

Figure 9 Quality Factor.

These magnitudes represent wave velocity measured in the three directions, radial (R), tangential (T) and longitudinal (L), corresponding to planes TL, RL, and RT, divided by average density of the 32 specimens of the three sample studied.

Particularly, the measurements of the corresponding points of velocity coincident to the adhesive planes (planes TL and RT of laminated wood) and the ones with adhesive and mesh (planes TL and RT of multimaterial) vary comparatively. However, to the purpose of the characterization, these data areintegrated in the values of quality factors.

The magnitudes of quality factor determined in this research (2019) were smaller than the ones reported by Sotomayor et al (2010) for solid wood of P. pseudostrobus

FUSR = 6.97, FUST = 1.96, and FUSL = 13.35, with ρH= 436 kg m-³ y H = 10.63%.

4. CONCLUSIONS

Density variation among the three samples did not vary significantly. This way it is possible to infer that anisotropy of wave velocity in wood is the parameter that characterizes the magnitude of the dynamic module in each one of the directions of the specimens. However, it is necessary to consider the effect at local level of the adhesive and the mesh that are the components of laminated wood and multimaterial.

Wave velocity, dynamic module and quality factor are different for the pieces of solid wood, laminated wood and multimaterial, which were fabricated with the species *P. pseudostrobus.* This conclusion is valid comparing different groupsof the studied specimens, but among the same directions of anisotropy observed.

Quality factor of laminated wood is similar to solid wood. This way, this compound may substitute solid wood in wooden structures. In the same context, the quality factorcorresponding to radial direction suggests that, in that direction, rigidity of multimaterial is larger than the ones in solid wood and laminated wood, comparatively.

Laminated wood and multimaterial characteristics are similar to the ones in solid wood of *P. pseudostrobus*. This way, the two compound materials have good prospects to substitute structural elements which work as resistance elements in wooden structures.

It is recommended to do intensive research with different species and configurations of test pieces as well as to use other kinds of non-intrusive and destructive tests in order to improve the characterization of laminated wood and multimaterial.

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