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MECHANICAL PROPERTIES OF LAMINATED VENEER LUMBER (LVL) MADE OF SECONDARY QUALITY OAK AND BEECH: THE EFFECT OF VENEER THICKNESS

Citra Yanto Ciki Purba [1,3], Guillaume Pot [2], Joffrey Viguier [2], Julien Ruelle [3], Louis Denaud [2], Meriem Fournier [1]

ABSTRACT: Finding an alternative use of secondary quality hardwood is essential. The valorization of this resource for the structural application requires an improvement of the mechanical properties and a better knowledge of the effect of the defects on the mechanical properties. The first objective of this work was to evaluate the mechanical properties of laminated veneer lumber (LVL) made of secondary quality beech and oak. The second objective was to study the influence of veneer thickness on LVL mechanical properties and to propose an adapted veneer thickness that provides the optimum mechanical properties. Forty-eight LVL boards were manufactured from three different veneer thickness and glued together using polyvinyl acetate (PVAc). Static and dynamic MOE, MOR, and shear modulus were measured using destructive and non-destructive methods. Different veneer thickness generated various mechanical properties on LVL made of secondary quality oak and beech. The LVL made of 3 mm thick veneer provided the optimum mechanical properties for both hardwood species. The shear modulus in edgewise direction was decreasing with the increase of veneer thickness. The stiffness of the LVL is comparable or even higher than the stiffness of LVL manufactured using other hardwood species.

KEYWORDS: Oak, Beech, LVL, Secondary wood quality

1 INTRODUCTION

Hardwood dominates both surface area and standing stock of French forests [1]. In contrast, wood harvested and timber produced are dominated by softwood [2]. Forests cannot produce wood with high-quality without also producing a large quantity of secondary quality. Besides, the new forest management systems based on intensive silviculture generally produce wood with lower quality. Young thinning, top wood and early harvested wood are secondary resources that have great potential for high-value applications.

The presence of various wood defects such as knots, grain deviation, juvenile wood, and reaction wood is restricting the utilization of secondary quality hardwood for structural application. The presence of knots and knotholes in timber induce zones with weaker strength where failure most likely started. Moreover, knot also creates a larger area surrounding the knot that has slopped grain. Young trees usually characterized by a high proportion of juvenile wood inside [3]. Juvenile wood is a zone close to the pith created at the beginning of the radial growth that can be characterized by lower mechanical properties [4]. Finding an alternative use of these abundant resources is essential. These resources have been insufficiently explored and commonly used only for firewood and wood composite (fiber & particle board). The valorization of this resource as structural material requires an improvement of the mechanical properties and a better knowledge of the effect of the defects on the mechanical properties.

Laminated Veneer Lumber (LVL) is a wood-engineered product produced from rotary peeled veneer glued together with the grain orientated mostly parallel to board length. LVL is usually used for the structural and nonstructural application such as flooring, furniture, and construction [5,6]. Compared to solid wood, LVL has fewer defects as it is dispersed through the production process, more stable in dimension, available in large dimension, and provide higher stiffness and strength compared to solid wood [7].

Generally, LVL mechanical strength increase with the number of veneers inside the LVL or with the thinner ones [8–10]. The thinner veneer will distribute the defect better than thicker veneer and improves the LVL strength. However, increasing the number of veneer inside the LVL demands much more glue for its production. Increasing veneer thickness helps to decrease the glue consumption. Moreover, other studies also reported that increased in veneer thickness decreased the shear strength and shear modulus of LVL especially in edgewise direction [7,11]. Rotary peeling creates lathe checks on veneer lose face surface. Under the same cutting condition, higher peeling thickness produces veneer with deeper lathe checks and a larger distance between two consecutive checks [12,13]. The decreasing of shear modulus with the increase of veneer

[1] Citra Yanto Ciki Purba, AgroParisTech, France, citra-yanto-ciki.purba@inra.fr
[2] Ecole Nationale Supérieure d'Arts et Métiers, France
[3] Université de Lorraine, AgroParisTech, Inra, Silva, F-54000 Nancy, France

thickness in edgewise is caused by the lathe checks, which are almost perpendicular to the veneer surface thus more penalizing in edgewise than flatwise [11]. More recent studies in LVL made of hardwood species reported that increasing veneer thickness gave low weakening on LVL strength and stiffness [11,14,15].

The first objective of this work was to evaluate the mechanical properties of the LVL made of secondary quality beech and oak. Most of the previous studies in hardwood LVL were performed using knot-free veneer. Another objective was to study the effect of veneer thickness on LVL mechanical properties and to propose an adapted veneer thickness that gives optimum mechanical properties. A compromise between the lathe checks properties generated from veneering and the knot proportion from secondary quality veneer was expected to occur.

2 MATERIALS AND METHODS

2.1 WOOD MATERIAL

Beech and oak were used for this experiment. These are two most important hardwood species in France particularly and Europe in general. The round wood of beech and oak were gathered during thinning of tree stands in a local forest in Lorraine, France. These round wood material comprised of 12 bolts of 150 cm long with diameters between 21 and 30 cm. Oak ages ranged between 61 and 90 years old while beech ages ranged between 57 and 84 years. Each bolt was extracted from the upper part of the tree and generally contained knots. This part of the tree is generally used as raw materials for energy & wood composite.

2.2 ROTARY PEELING

To minimize veneer lathe checks, all bolts were soaked in hot water at 60 °C for 24 hours before peeling. Afterward, bolts were cut into veneer using a rotary peeling machine (Figure 1). Three different veneer thickness (2.1 mm, 3 mm, 4.2 mm) were prepared using this method. The machine pressure bar maintained at 5% for all thickness (gap between knife and pressure bar is 5% lower than the expected veneer thickness). Each bolt was cut to produce one particular thickness. After peeling, the veneers were numbered and clipped in 0.6 x 0.5 m² sheets and dried using vacuum drying machine to reduce veneer moisture content (MC) to 18% and then air dried to about 10% MC.

Figure 1: *Peeling secondary quality oak*

2.3 LVL FABRICATION

The veneers were glued together with the grain orientated parallel to panel length using PVAc (Polyvinyl Acetate) as adhesives with glue spread of 180 g/m^2. Following this, glued veneers were then pressed under a pressure of 0.8 MPa for about 60 minutes in a cold press machine. For each combination of treatment (species, veneer thickness), 8 LVL panels were prepared. The LVL final thickness was 21 mm, the width of 250 mm, and length of 500 mm. After gluing and pressing, the LVL were stacked and stabilized for two weeks.

2.4 MEASUREMENT OF LVL MECHANICAL PROPERTIES

For the measurement of mechanical properties, nine specimens were prepared with a dimension of 500x21x21 mm^3 from each LVL panel (Figure 2). We measured the modulus of elasticity (MOE) in two directions i.e. flatwise and edgewise, using a non-destructive test called Bing [16,17]. LVL density was measured right before the Bing measurement performed. Bing measurement supplied the data of the LVL dynamic MOE and shear modulus.

Figure 2: *LVL specimen for the measurement of mechanical properties*

Following the non-destructive evaluation, we performed 4 points bending test to measure MOE and modulus of rupture (MOR) in both directions. The test arrangement was described in Figure 3. A half number of the specimens was dedicated for flatwise bending test and another half for edgewise. For the flatwise bending test, the load direction was perpendicular to the glue lines while in the edgewise test, the load direction was parallel to the glue line.

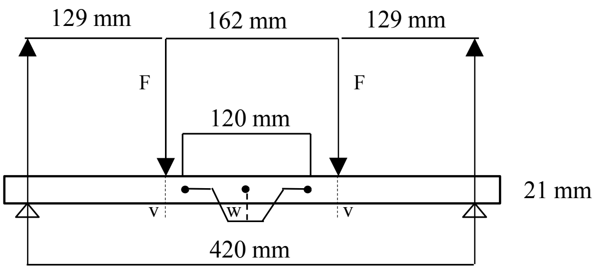

Figure 3: *Test arrangement for 4 points bending test for measuring local modulus of elasticity*

Local or pure MOE was calculated using this formula:

$$E_{m,l} = \frac{a l_1^2 (F_2 - F_1)}{16 I (w_2 - w_1)} \quad (1)$$

Where a = Distance between a loading position and the nearest support in a bending test (mm), l_1 = Gauge length for the determination of modulus of elasticity (mm), I = the Second moment of inertia (mm^4), F_2 - F_1 = The increment of load in Newton on the regression line with a correlation coefficient of 0.99 or better (Newton), w_2 - w_1 = The increment of deformation corresponding to F_2-F_1 (mm).

The global MOE was calculated from the very same test using the equation 2. Deflection was calculated based on the movement of the loading tools. We assume that the displacement between the two loading heads was the same when we do this calculation. We used the displacement of the loading tools testing machine as the measure of the global deflection.

$$E_{m,g} = -\frac{a^2 (F_2 - F_1)}{6I(V_2 - V_1)}(3l - 4a) \quad (2)$$

Where l = Length of test piece between the testing machine grips (mm), V_2-V_1 = The increment of displacement of the loading tools corresponding to F2-F1 (mm).

2.5 DATA ANALYSIS

The LVL density, local MOE, global MOE, local specific MOE (local SMOE), global specific MOE (global SMOE), Dynamic MOE, MOR, specific MOR (SMOR), and shear modulus were the measured parameters in this study. To evaluate the influence of different veneer thickness and testing direction on these parameters, multi-factor analysis of variance (ANOVA) and Tukey HSD (Honestly Significant Difference) multiple comparison tests were carried out. All of the statistical analysis was performed at a level of significance of 0.05 using the R-software. The results of the nondestructive evaluation and global MOE were used for predicting the LVL strength using simple linear regression model.

3 RESULTS AND DISCUSSION

3.1 LVL MECHANICAL PROPERTIES

3.1.1 MOE local

Table 1 presents the LVL density, local MOE, and local SMOE of oak and beech LVL. Specific modulus was calculated by dividing the measured modulus by the LVL density. The objective was to compare precisely the effect of veneer thickness on LVL stiffness without any distortion from the different value of wood density. For both hardwood species, there was no influence of testing direction on the local MOE value. In contrast, oak local SMOE in edgewise was higher than flatwise while beech showed the opposite. However, the statistical analysis showed that the difference was not statistically significant.

Oak lowest local MOE was found at the LVL made of the thinnest veneer (2.1 mm) tested in flatwise direction (10500.79 MPa), and the highest was at LVL made of 3 mm veneer (13610.15 MPa) tested in edgewise direction. Beech lowest local MOE was also found at the thinnest veneer (10097.33 MPa) tested on edgewise direction, and the highest at the thickest veneer (4.2 mm) tested on edgewise direction (13917.14 MPa).

For oak, 3 mm veneer produce the highest local SMOE (flatwise= 17.81 MNm/kg, edgewise= 18.12 MNm/kg). The difference with LVL made of other veneer thicknesses was statistically significant. Beech LVL made of the thickest veneer produced the highest local SMOE, but the difference with LVL made of 3 mm veneer was not statistically significant. On the other side, the standard deviation of local SMOE was increasing with the increase of veneer thickness in both species.

For both species, 3 mm thick veneers produced high local SMOE with relatively low standard deviation. For beech LVL, 4.2 mm veneer generated the highest local SMOE, but the standard deviation was more than two times higher than other veneer thicknesses.

Table 1: *Density, local MOE, & local SMOE of LVL beech and oak made of different veneer thickness*

Veneer thickness (mm)	LVL density (kg/m^3)		Local MOE (MPa)		Local SMOE (MNm/kg)	
	Flatwise	Edgewise	Flatwise	Edgewise	Flatwise	Edgewise
Oak LVL						
2.1	753.23	748.3	10500.79 ^{a}	10569.29 ^{a}	13.96^{a}	14.13^{a}
	(30.22)	(29.62)	(1826.86)	(1687.63)	(2.55)	(2.26)
3	752.51	754.39	13360.42^{bc}	13610.15 ^{c}	17.81^{bc}	18.12^{c}
	(36.86)	(37.18)	(1797.72)	(1771.08)	(2.64)	(2.81)
4.2	733.12	726.25	10581.74^{a}	11060.79 ^{ab}	13.88^{a}	15.36^{ab}
	(32.78)	(39.09)	(2479.82)	(2565.25)	(4.73)	(4.08)
Beech LVL						
2.1	736.48	732.72	10582.84 ^{a}	10097.33^{a}	14.35^{a}	13.75^{a}
	(31.57)	(35.58)	(1440.35)	(1527.69)	(1.75)	(1.81)
3	749.27	768.28	13161.43^{bc}	12841.64 ^{b}	17.69^{b}	16.41^{ab}
	(63.85)	(68.37)	(2317.26)	(1924.51)	(3.36)	(3.71)
4.2	707.79	700.14	13802.05 ^{cd}	13917.14 ^{d}	18.8^{b}	18.38^{b}
	(34.36)	(35.04)	(2573.22)	(1723.64)	(5.84)	(6.48)

Values followed by a different letter within a column are statistically different at P = 5 % (ANOVA and Tukey HSD test)
Values in parenthesis are standard deviations

Table 2: Summarized analysis of variance for the effect of species, testing direction, and veneer thickness on local SMOE

Species	SOV[1]	df[2]	p-value	
Oak	Wood species	1	6.01E-06	***
	Testing direction	1	0.679	
	Veneer thickness	2	5.30E-12	***
Beech	Testing direction	1	0.369	
	Veneer thickness	2	<2e-16	***

***** Denotes significance at alpha = 0.01.*
[1] *Source of variation*
[2] *Degrees of freedom*

Table 2 presents the ANOVA for the effect of wood species, testing direction, and veneer thickness on local SMOE of LVL. Apparently, different wood species and veneer thickness generated various values of the local SMOE. However, the testing direction provided relatively similar local stiffness on both hardwood species.

3.1.2 MOE Global

Table 3 presents the global MOE, global SMOE, MOR, and the dynamic MOE. The global SMOE were lower compared to the local SMOE presented previously. For oak, edgewise test showed higher global SMOE than flatwise. Beech demonstrated the opposite. However, the difference was not statistically significant. Analysis of global MOE and global SMOE demonstrated the same trends. For oak, both parameters showed the lowest value at the thickest veneer and the highest at 3 mm veneer. While for beech, the lowest value of both parameters was found at the thinnest veneer and the highest at 3 mm veneer. The standard deviation of global SMOE in oak was increasing with the increase of veneer thickness. This trend corresponded with the previous result in local SMOE. However, this was not the case with beech. The highest standard deviation of beech LVL global SMOE was at 3 mm veneer.

The optimum global SMOE in oak was found at LVL made of 3 mm veneer. While in beech, 4.2 mm veneer provided the optimum global SMOE. Veneer thickness providing optimum local and global SMOE was the same for oak. However, beech showed contrasting results between both measured parameters.

3.1.3 MOR

Table 3, also provides the MOR and SMOR value. Oak MOR from edgewise test was higher than flatwise, however, the difference was not statistically significant. For both hardwood species, the highest MOR and SMOR were found at LVL made of 3 mm thick veneer while the lowest was found at the LVL made of the thickest veneer. Nevertheless, for both species, the difference in SMOR among different veneer thickness was not statistically significant except for edgewise tested oak made of 3 mm thick veneer. The highest standard deviation of SMOR was always in 3 mm thick veneer for both species. These results were different compared with what was found before in local SMOE. However, for oak LVL, the global SMOE and SMOR demonstrated the similar trend. For both species, 3 mm veneer produced the optimum SMOR.

The increase of standard deviation of both local and global SMOE may be due to the effect of the distribution of defects. As the defects were distributed better in thinner veneer, the variation of SMOE was lower compared to thinner veneer. For thicker veneer, the defects were more concentrated thus provide a larger variation of SMOE. The increase of MOE variation with a rise in veneer thickness has been reported in the previous study in poplar [15].

3.1.4 Dynamic shear modulus

Figure 3 provides the shear modulus of LVL made of different veneer thickness. The value presented here was obtained from the non-destructive measurement. Here we can see that for oak, the highest shear modulus was at LVL made of the thinnest veneer and tested in edgewise (849.14 MPa) while the lowest was at veneer 3 mm evaluated in flatwise (597.01 MPa).

***Table 3:** Global MOE, global SMOE, MOR and SMOR of LVL beech and oak made of different veneer thickness*

Veneer thickness (mm)	Global MOE (MPa)		Global SMOE (MNm/kg)		MOR (MPa)		SMOR (MPa)	
	Flatwise	Edgewise	Flatwise	Edgewise	Flatwise	Edgewise	Flatwise	Edgewise
Oak LVL								
2.1	9218.07^{a}	9858.27^{ab}	12.27^{a}	13.18^{ac}	59.27^{ac}	61.87^{bc}	0.079^{ac}	0.083^{ac}
	(1537.45)	(1169.22)	(2.22)	(1.59)	(12.22)	(9.33)	(0.018)	(0.014)
3	10614.33^{bc}	11063.29^{c}	14.14^{bc}	14.7^{c}	63.41^{c}	68.18^{c}	0.084^{ac}	0.090^{c}
	(1822.3)	(1071.26)	(2.47)	(1.65)	(14.11)	(10.23)	(0.018)	(0.015)
4.2	8908.00^{a}	9347.75^{a}	11.65^{a}	12.91^{ac}	51.11^{a}	53.27^{ab}	0.070^{a}	0.074^{ab}
	(1453.9)	(1337.06)	(3.25)	(1.93)	(11.09)	(11.25)	(0.017)	(0.017)
Beech LVL								
2.1	9354.92^{a}	8863.23^{a}	12.71^{abc}	12.08^{a}	68.39^{ab}	62.87^{a}	0.093^{a}	0.086^{a}
	(837.96)	(965.68)	(1.19)	(1.15)	(9.19)	(8.36)	(0.013)	(0.011)
3	11039.36^{c}	10655.30^{bc}	14.82^{d}	13.62^{bd}	71.97^{ab}	72.18^{ab}	0.096^{a}	0.093^{a}
	(1604.72)	(1607.26)	(2.29)	(3.07)	(12.07)	(20.23)	(0.016)	(0.018)
4.2	9762.72^{ab}	9601.71^{a}	13.83^{bd}	13.73^{ad}	64.18^{ab}	64.96^{ab}	0.091^{a}	0.093^{a}
	(732.85)	(563.25)	(1.32)	(0.79)	(11.83)	(5.65)	(0.019)	(0.01)

Values followed by a different letter within a column are statistically different at P = 5 % (ANOVA and Tukey HSD test)
Values in parenthesis are standard deviations

In contrast, beech highest shear was at veneer 3 mm tested in flatwise (950.81 MPa) while the lowest was at the thickest veneer tested in edgewise (523.87 MPa). For both species, the shear modulus in edgewise direction was decreasing with the increase of veneer thickness. The thickest veneer generated the lowest shear modulus if tested in edgewise.

The decrease of shear modulus with thicker veneer in this study confirmed the previous report by Pot et al. [11] who studied the effect of veneer lathe checks on beech MOE using numerical analysis. Melo and Menezzi [18] also reported the decrease of shear strength by the increasing of veneer thickness in LVL made of Parica´ (Schizolobium amazonicum). Pot et al. [11] reported that lathe check is more penalizing in edgewise direction because lathe check is almost perpendicular to the veneer surface. Increase in veneer thickness provides lower check frequency and deeper lathe check.

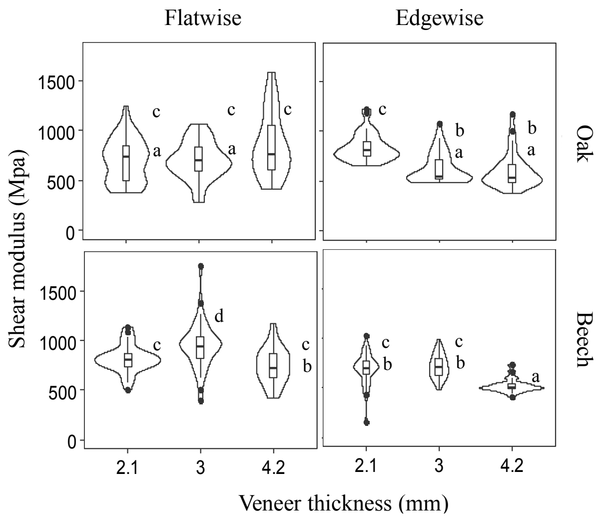

Figure 3: *Dynamic shear modulus of beech and oak LVL by different veneer thickness and testing direction*

From the literature review, we expected to get the best mechanical properties from LVL made from thinnest veneer since, in theory, the more veneer layer inside the better wood defects distributed thus, the higher mechanical properties. However, this is not the case in our research that demonstrated the contrasting results. Nevertheless, this contradiction can be explained by the different wood quality used in this research. In general, the previous study used knot free or much less defected veneer to fabricate LVL. The contrasting results with the research earlier were expected.

Similar to LVL made of knot-free veneer, LVL made of knotty veneer also generated different mechanical properties with different veneer thickness inside. Oak LVL made of 3 mm thick veneer produced the optimum local SMOE, global SMOE, and SMOR while beech LVL optimum local SMOE was at 3 mm veneer, global SMOE at 4.2 mm veneer and SMOR was at 3 mm veneer. For both species, the standard deviation of the measured local and global SMOE was increasing with the increase of veneer thickness. Moreover, the shear modulus was also decreasing with the rise in veneer thickness. By considering all the mechanical properties measured, i.e., stiffness, strength, and shear properties, and its standard deviation, we can conclude that 3 mm thick veneer provide the optimum mechanical strength on LVL made of secondary quality hardwood.

As expected, the stiffness and strength of beech LVL made of secondary quality beech in this study were much lower than the previous study using knot free LVL [14,19–21]. Burdurlu et al. [19] who studied the effect of ply organizations and loading direction on beech LVL strength and stiffness, reported that beech MOE in flatwise and edgewise were 12,679.6 MPa and 13,235.10 MPa while the MOR was 152.36 MPa and 148.30 MPa. Compared to knot-free beech LVL, our MOE was more than 25% lower while MOR was 50 % lower or more. This study was done using 3 mm sliced veneer. Daoui et al. [14] studied the influence of veneer quality on beech LVL mechanical properties. Compared to their results on 3 mm rotary peeled veneer pre-treated with log boiling in water in 70°c for 24h and peeled with pressure bar produced beech LVL, our MOE value was also more than 25% lower. However, the MOR value was only about 30% lower. Compared to beech LVL in the market (manufactured by Pollmeier), the MOE of secondary quality LVL was about 40% lower, but the MOR was comparable [22]. Nevertheless, the stiffness of LVL made of secondary quality oak and beech are equal or even higher than the stiffness of LVL made of other hardwood species such as eucalyptus, maple, aspen, and poplar [15,20,23].

Table 4: *Linear regression equations and correlation coefficients (y = global MOE, x = local MOE, r = correlation coefficient)*

Veneer thickness (mm)	Flatwise		Edgewise	
	linear equation	r^2	linear equation	r^2
Oak LVL				
2.1	y=2310+0.658x	0.61	y=3010+0.648x	0.87
3	y=-281+0.816x	0.65	y=4890+0.454x	0.56
4.2	y=4000+0.464x	0.63	y=5370+0.36x	0.48
Beech LVL				
2.1	y=5090+0.403x	0.48	y=2920+0.585x	0.84
3	y=4350+0.508x	0.54	y=2340+0.648x	0.6
4.2	y=6940+0.202x	0.5	y=9540-0.001	1.90E-05

Table 5: *Linear regression equations and correlation coefficients (y = global MOE, x = dynamic MOE, r = correlation coefficient)*

Veneer thickness (mm)	Flatwise		Edgewise	
	linear equation	r^2	linear equation	r^2
Oak LVL				
2.1	y=4480+0.364x	0.12	y=469+0.75x	0.9
3	y=668+0.70x	0.23	y=-4140+1.08x	0.82
4.2	y=498+0.72x	0.37	y=-1810+0.93x	0.85
Beech LVL				
2.1	y=2280+0.62x	0.56	y=85.6+0.79x	0.9
3	y=2410+0.648	0.82	y=890+0.74x	0.84
4.2	y=678+0.75x	0.67	y=2470+0.57x	0.66

3.2 CORRELATION AMONG MEASURED MECHANICAL PROPERTIES

3.2.1 The relationship between MOE global with MOE local and dynamic MOE

Table 4 presents the relationship between local and global MOE. For both species, the best correlation was found at LVL made of 2.1 mm thick veneer tested in edgewise while the lowest was in 4.2 mm veneer tested also edgewise. For flatwise test, the highest correlation was found at 3 mm veneer while in edgewise the highest was at 2.1 mm. In contrast with flatwise test, the correlation strength is decreasing with the increase of veneer thickness in edgewise. Especially for beech 4.2 mm measured in edgewise, no correlation was found between both parameters.

To understand whether the dynamic measurement can predict the static MOE in LVL made of knotty veneer or not, both parameters were correlated, and the correlation was presented in table 5. For both species, we can see that the correlation was much better in edgewise direction than flatwise. The best correlation was found at 2.1 mm measured in edgewise. In contrast, the lowest correlation was also found in 2.1 mm but evaluated in flatwise.

As mentioned previously, the veneer thickness influenced the shear modulus in edgewise. However, it was not the case in flatwise test. It explained why the correlation value of global and local MOE in edgewise was much more affected by veneer thickness than flatwise. For flatwise test, the quality of veneer on the outer layer most likely had a more critical influence on MOE than the veneer thickness.

The decrease of the correlation strength between local and global MOE with the increase of veneer thickness in edgewise test may be due to the higher heterogeneity on the thicker veneer. This higher variation not only caused by the higher concentration of defects in one area but also can be linked with the lathe checking.

Local MOE is calculated based on the measure of local deformation within the small zone between two loading positions while the global MOE is calculated using the measure of deformation in the mid-span relative to the position of the supports. The global MOE takes into account the contribution of shear thus the deformation in global MOE is not only caused by bending but also shear deformation.

The higher heterogeneity and the influence of shear modulus on global MOE with the increase of veneer thickness made the global MOE more dispersed. It explained why the correlation strength decreased over the rise of veneer thickness. This higher heterogeneity also produces more scattered results in dynamic MOE thus provides lower correlation strength with global MOE. Daoui et al. [14] also reported the decreasing correlation between dynamic MOE and global MOE in beech LVL in edgewise test.

3.2.2 Correlation of global MOE, dynamic MOE, and MOR

In Table 6, we correlated MOR and global MOE. In general, we can see good positive correlations between both parameters in both species except for LVL made of 4.2 mm veneer. Correlation in edgewise was better than flatwise. For both species, the highest correlation was found on edgewise tested LVL made of 3 mm thick veneer while the lowest correlation was found at the thickest veneer (4.2 mm).

Table 6: *Linear regression equations and correlation coefficients (y =MOR, x = global MOE, r = correlation coefficient)*

Veneer thickness (mm)	Flatwise		Edgewise	
	linear equation	r^2	linear equation	r^2
Oak LVL				
2.1	y=-6.53+0.007x	0.81	y=-2.89+0.006x	0.68
3	y=-7.13+0.006x	0.74	y=-30.9+0.008x	0.88
4.2	y=9.68+0.004	0.37	y=-15.9+0.007x	0.78
Beech LVL				
2.1	y=7.7+0.006	0.35	y=-3.22+0.007x	0.76
3	y=3.27+0.006	0.68	y=0.411+0.006x	0.8
4.2	y=-24.8+0.00911	0.33	y=27.6+0.003x	0.17

Table 7: Linear regression equations and correlation coefficients (y =MOR, x = dynamic MOE, r = correlation coefficient)

Species	Testing direction	Linear equation	r^2
Oak	Flatwise	y= 0.0038x + 8.61	0.22
	Edgewise	y= 0.0057 - 12.97	0.59
Beech	Flatwise	y=0.0039x + 20.27	0.38
	Edgewise	y=0.0040x + 17.23	0.80

Table 7 presents the correlation between MOR and dynamic MOE. The objective was to see if we can predict LVL MOR using the dynamic MOE measured using Vibration method. Here we can see a good correlation between both parameters, especially in edgewise direction. The highest correlation was found in beech evaluated on edgewise direction (r^2=0.80). The correlation was much lower in flatwise. Veneer in the outer layer receives the highest load in flatwise. The lower correlation between dynamic MOE and MOR in flatwise allegedly caused by higher dispersion of MOE due to the influence of high variation of veneer quality in the outer layer.

4 CONCLUSIONS

Different veneer thickness generated various mechanical properties on LVL made of secondary quality oak and beech. The LVL made of 3 mm thick veneer provided the optimum mechanical properties for both hardwood species. The shear modulus in edgewise direction was decreasing with the increase of veneer thickness. The stiffness of the LVL is comparable or even higher than the stiffness of LVL manufactured using other hardwood species.

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