BENDING, SHEARING, AND COMPRESSION PROPERTIES OF FAST GROWING FRENCH DOUGLAS FIR LVL

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ABSTRACT: The French resource of large diameter Douglas fir is currently keeping growing, while these large diameter trees are complicated to process efficiently by the sawmilling industry. The rotary peeling process appeared to be particularly adapted as an alternative to the usual sawing. This primary processing method produces veneers used to make a wood engineering product material called Laminated Veneer Lumber (LVL). The manufacturing process of LVL enables the distribution of the resource defects, allowing for increased mechanical behaviour compared to the solid wood from which it comes from. The main objective of this study is to present the principal Douglas-fir heartwood LVL mechanical properties such as longitudinal and shear moduli of elasticity, bending, shear and compressive strengths. Up to now, there were no study on LVL derived from this resource. This study focuses on heartwood because of its very interesting natural durability properties for constructive outdoor applications. Moreover, a comparison with structural timber properties was also achieved to place the material in terms of mechanical performance among the market. Globally, this LVL material showed high compressive and shear properties. Nevertheless, even though the bending properties were significantly lower than data from Douglas-fir LVL literature, they are still quite acceptable for structural applications.

KEYWORDS: Laminated Veneer Lumber, Douglas fir, heartwood, mechanical properties

1 INTRODUCTION

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is a softwood species that originated from the Pacific coast of North America. After two reforestation impulses in the middle of the 19th century and the second half of the 20th century, France currently has the largest Douglas forest surface in Europe, with about 420,000 ha. In 2018, the harvest volume was around 3 million m^3. Moreover, Douglas-fir forest resource is increasing significantly [1], since it is estimated that this volume could exceed 6 million m^3 by 2030 [2]. This forecasted increase in volume is essentially due to the increase of diameter of the trees. There were already significant quantities of Douglas-fir trees with a diameter of more than 47.5 cm in 2012 [3], and they continue to grow since.
Douglas fir heartwood have a mechanical support role in the tree, and important chemical transformations impact its cell structure conferring its high resistance to insect and fungal attacks, and thus, high durability [4]. Because of these specificities, the potential to exploit heartwood in outdoor construction without recourse to any treatment is high. Douglas-fir generally has a high proportion of heartwood [5]. This fact combined with the large diameters of the resource lead to an interesting potential of volume of heartwood available to product engineering wood products (EWP) for construction purposes.
However, the absence of thinning for some of these trees leads to the presence of various wood defects such as knots, grain deviation, juvenile wood, and reaction wood which could degrade the mechanical performance of the material [3], and thus restrict the use of large Douglas-fir for structural applications. In addition, large diameters logs cannot be transformed in regular industrial sawmills with canter lines, thus band saw are used, but they present lower yields. Finding an alternative to sawmills and sawn products for this abundant resource, which is reaching its maturity, would participate significantly to optimize its potential.
Laminated veneer lumber (LVL) represents a solution that can deal with these drawbacks. LVL is an EWP, usually used for structural applications such as flooring and

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construction. It is made of a stack of veneers glued together with their grain oriented mainly in the same longitudinal direction [6,7]. These veneers are the result of a primary wood processing operation called rotary peeling, which can easily deal with large diameter logs. The LVL allows for the homogenization of wood defects, such as the knots, in the mass, by a distribution of them inside the entire timber volume. This homogenization of the product avoids the localization of mechanical weakness, and thus allows for increased mechanical performance if compared to glulam or solid wood for instance [8-10]. Besides, rotary peeling is also an interesting process to separate heartwood from sapwood efficiently and thus obtaining an EWP made of pure heartwood.

This study is based on French Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco). This species is still not used in the manufacture of LVL in Europe, where spruce and pine are preferred. No study was found dealing with LVL made from this resource. Moreover, even if literature dealing with Douglas fir grown in other areas of the world exists [7][11-13], no scientific work focusing on heartwood LVL can be found, whereas there are evidences of variation of mechanical properties according to the distance to the pith of the tree [14]. The purpose of this paper is therefore to present the first large-scale test campaign for the mechanical characterization of an LVL composed from a French Douglas-fir resource. The objective of this research study is to evaluate the main mechanical properties (bending parallel to the grain; shear and compression parallel and perpendicular to the grain) of LVL made of heartwood large Douglas-fir tree. A comparison with structural timber grades is performed to have reference values to compare with.

2 MATERIALS AND METHODS

2.1 DOUGLAS FIR PROVENANCE AND PEELING

Three different parcels from Corrèze, a French region in the western part of Massif Central, make up the Douglas-fir resource used to compose the LVL panels. This location is one of the main reserve of this species in France. These 3 forest plots vary in terms of silviculture (location, altitude, thinning), log cutting ages (65, 60 and 44 years old), to get as much resource representativeness as possible. However, the log diameter distribution among the 3 parcels is relatively homogeneous with a minimum diameter of 50 cm and a maximum of 68 cm.

All logs were soaked by water aspersion for 48 hours to get a temperature of 50 +/- 2 °C before peeling, intending to ease the rotary peeling by increasing the material deformability [15]. Afterward, logs were cut into veneers using a rotary peeling lathe equipped with an automatic centering device, a cylindrical rotating pressure bar adapted to softwood, and a pin drive device. The rotary peeling speed is automatically controlled by the machine. The veneers obtained presented visually a high knottiness. The thickness of each veneer was set to 3.1 mm to reach 3 mm after drying. The dimensions of each veneer at green state were 2,600 mm × 1,300 mm. A resistive moisture content (MC) measurement of each veneer was performed by contact with electrodes directly on the rotary peeling line. This MC assessment allows the selection among the veneers to separate heartwood from sapwood [16]. A veneer with less than 30% MC was automatically identified as heartwood. A second control was involved for veneers with a moisture content value between 30 and 100% MC. In Douglas fir, the colour of heartwood (salmon pink) is highly differentiated from sapwood [17]; correspondingly, heartwood veneer were retrieved visually thanks to their colour. Then, the veneers were dried using an industrial air drier to reduce the veneer moisture content to 6% MC. Quality control considering the veneer surface appearance according to EN 635-3 [17] was performed on all veneers.

2.2 PANELS MANUFACTURING

The heartwood Douglas-fir veneers were glued together with the grain orientated parallel to panel length. The glue used is a phenolic glue spread at 190 g/m²; then, the glued veneers were pressed together between 1 and 1.1 MPa for about 30 minutes in a stage press at 200 °C to compose the panel. The final dimensions of the Douglas fir LVL panels were 2,500 mm × 1250 mm × 45 mm. There were 9 purely heartwood panels. After gluing and pressing, the LVL were stacked and stabilized for three days before being sawn into beams. A preliminary study required the sawing of these panels in 2,500 mm × 120 mm × 45 mm elements, thereby conditioning the size of the test specimens in the present study. It is important to note that the heartwood Douglas-fir LVL panels were manufactured without any research to homogenize the repartition of defects in the material. As a result, it may have favoured the overlapping of knots through the stacking of veneers.

2.3 SAMPLES PREPARATION

In order to measure the bending properties, 63 Douglas-fir beams (data presented in Table 1) were prepared from the panels with nominal dimensions of 850 mm × 45 mm × 45 mm. Once tested by non-destructive method and destructive bending testing (explained in the next subsection), both ends of each beam were preserved and sawn to be reused as new specimens for compression and shear tests purpose.

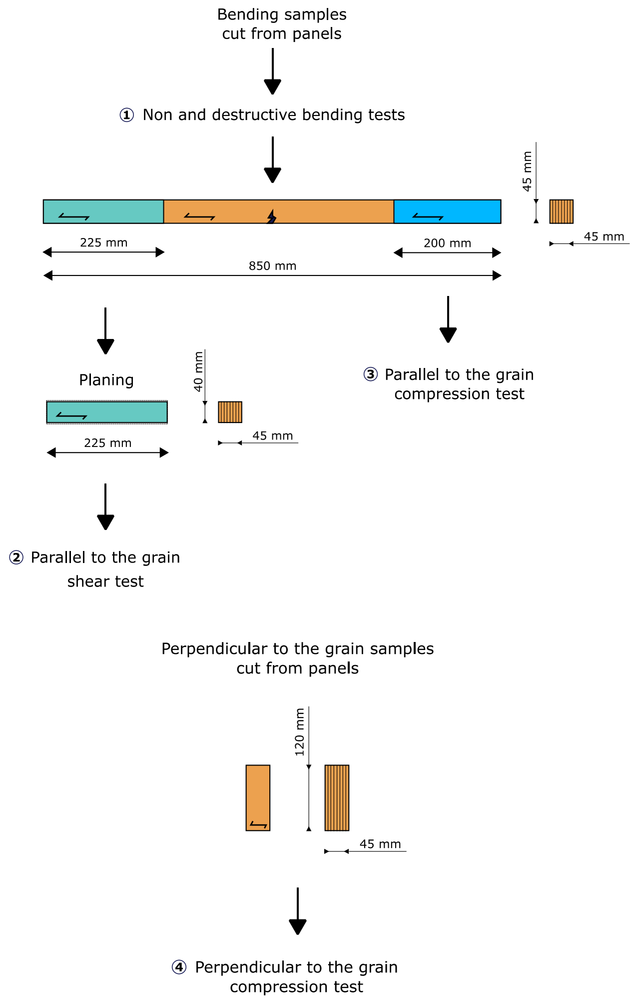


Figure 1: *Cutting samples scheme*

Figure 1 explains the samples extraction from the bending specimen, after rupture in 4 points bending, for the subsequent compression and shearing tests. Particular attention has been paid to visually check that no cracks, consequent to the central failure of the beams, have propagated to the reused ends, so it did not affect the mechanical integrity of the material to be tested once again. This is partly why the number of compression and shear samples is lower than the bending ones: it happens that failure spreads to the ends.

The specimens taken from the right end of the bending specimens were designed for the longitudinal compression assessment, measuring 200 mm × 45 mm × 45 mm, cross section dimensions are in accordance with the minimum section prescribed in EN 14374 standard [6]. The left specimens, measuring 225 mm × 45 mm × 40 mm were used to make parallel to the grain EW shear specimens adapted from EN 789 standard [18]. The 40 mm dimension is due to a 0.1 mm precision planing performed on 2 sides of the specimen to maximize the effectiveness of the loading plates gluing (detailed in section 2.5.2). Four perpendicular to the grain compression samples were taken from each panel. They were 120 mm × 45 mm × 45 mm, cross section dimensions are in accordance with the minimum section prescribed in EN 14374 standard [6].

Table 1 summarizes the number of specimens for each test.

Table 1: *Samples count summary table*

	French Douglas fir heartwood LVL
EW bending samples	63
Parallel to the grain compression samples	34
Perpendicular to the grain compression samples	40
Parallel to the grain EW shear samples	17

A MC measurement was performed on random samples by resistive pin-type wood moisture meter before non-destructive test, allowing the wood MC to be estimated to be between 6 and 8 %.

2.4 NON-DESTRUCTIVE DYNAMIC MEASUREMENT

[19] showed that the Timoshenko's bending theory can be applied to determine the dynamic longitudinal modulus of elasticity (MoE) and the shear modulus (G) from the flexural vibration frequencies in free-free boundary condition. Indeed, they gave the following solution of the equation of motion of a vibrating beam at the first order:

$$\frac{MoE_{dyn-XW}}{\rho} - \frac{MoE_{dyn-XW}}{KG_{XW}} x_n = y_n \quad (1)$$

where

- $MoE_{dyn\text{-}XW}$ is the longitudinal dynamic MoE when bending is performed edgewise or flatwise, "XW" being replaced by "FW" or "EW", respectively (Pa)
- ρ is the density (kg/m^3)
- K is the shear factor (K = 5/6 for a rectangular cross-section)
- G_{XW} is the dynamic shear modulus when bending is in edgewise or flatwise direction, "XW" being replaced by "FW" or "EW", respectively (Pa)
- x_n and y_n are parameters depending on the vibrational mode frequency (see (19) for details) (unit).

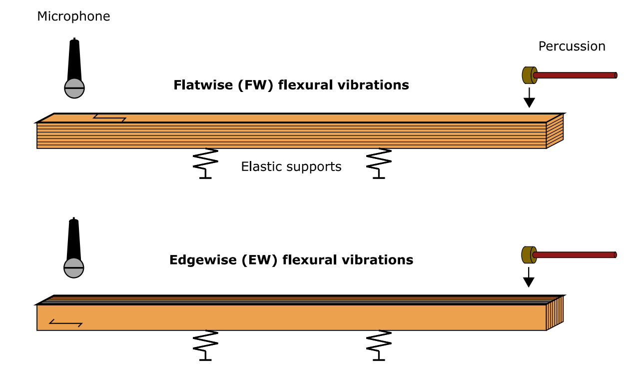


Figure 2: *Beam Bing method testing configurations*

By plotting y_n against x_n for different vibration modes, a linear regression allows to identify both the dynamic MoE and the shear modulus. The deviation of this equation is generally less than 1% if the length-to-depth ratio is between 10 and 20 from [19] (about 18 in the present work). Based on this theory, the BING device (Beam Identification by Non Destructive Grading [20]) was used to test all the samples in flatwise (FW) and edgewise (EW) flexural vibrations, and thus obtain $MoE_{dyn\text{-}EW}$, G_{EW}, $MoE_{dyn\text{-}FW}$, and G_{FW} as shown in Figure 2. This paper focuses on the corresponding mean values of this parameters computed from the 63 beams, denoted: $MoE_{dyn\text{-}EW,mean}$, $G_{EW,mean}$, $MoE_{dyn\text{-}FW,mean}$ and $G_{FW,mean}$. The density, required for Equation 1, was obtained by dividing the mass of each beam by its volume. Concerning the volume calculation for each beam, height and width dimensions are the means of a 3 different location measuring points with a calliper, at both extremes and at the centre of the beam. The accuracy of these two dimensions is +/- 1 mm. The width value was very broadly sensitive to the variability of the thickness of the veneers. The length was measured with a measuring tape, with a precision of +/- 0.5 mm. Mass were measured with a numerical balance with a precision of 0.1 g. Since the density ρ of each beam was measured, ρ_{mean}, mean value of all the ρ of the population was computed.

2.5 DESTRUCTIVE TEST

2.5.1 Bending test set-up

After non-destructive testing, a four points bending test has been performed on every specimen based on the EN 14374 standard [6]. A distance equal to 810 mm, as 18 times the specimen height between the lower supports, was set, as shown in Figure 3. The distance between the loading head and the nearest support (*a*) was set to 285 mm, which is 6.33 times the height, in order to prevent possible shear failures. All the specimens were tested in EW direction only. This choice was made to guaranty a sufficient number of successful bending tests in this direction which is the one used for LVL as slender flexural product. Besides, this test configuration presents two advantages for a fair comparison of the material properties: all the plies are subjected substantially to the same mechanical loading, and the glue joints between plies are much less subjected to stresses than in FW bending.

The 4-points bending tests were made with a dedicated testing machine composed of an electric actuator, equipped with a 100 kN load sensor, and a global deflection rotary potentiometer sensor. The upper and lower supports were made by 4 cm wide metal plates, fixed on pivot allowing the rotation of the beam supports.

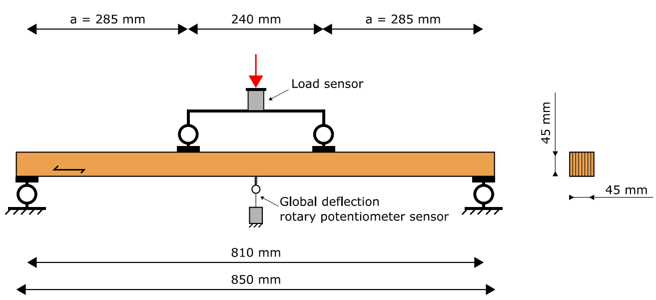


Figure 3: *4-points bending test arrangement*

The 5th percentile values were calculated according to the method given in EN 14358 standard [21], as recommended in EN 14374 standard [6]. The hypothesis of logarithmic normal or normal distribution has been validated also regarding in EN 14358 standard [21]. Finally, the following parameters were computed: $f_{m,mean}$, mean value of all the f_m values of the population, and $f_{m,k}$ the 5th percentile value.

In this study, the global MoE is used to quantify rigidity. Although the EN 384 [22] provides a formula for adjusting the global modulus of elasticity MoE to the modulus of elasticity parallel to the grain E_0, this applies to solid wood, and not for LVL. The global MoE was calculated according to EN 408+A1 standard [23]. Finally, $MoE_{g\text{-}EW,mean}$, mean value of all the $MoE_{g\text{-}EW}$ values of the population was computed.

2.5.2 Shear and compression test set up

Shear tests were made with a universal testing machine, which loads the samples by uniaxial compression. The whole shearing test set-up is described in Figure 4. It is composed of a frame and a crosshead, which provide a maximal load capacity of 250 kN. For parallel to the grain EW shear tests, the set up used was taken from the EN 789 standard [18]. Two 250 mm × 45 mm × 45 mm beech elements have been prepared to replace the steel plates advised in the standard (but not mandatory). This species was chosen by its excellent stiffness in the RL plan and superior to the intended strength range for the species tested. The glue used to fix the beech elements to the specimen is a white vinyl glue. The surfaces of beech elements were planed down and double-gluing technique was operated to maximize the quality and strength of the collage. In accordance with the manufacturer's requirements, a pressure of 1 MPa was applied by a mechanical press during a minimum of 6 hours, and a curing time of at least 48 h was performed for each specimen.

Originally designed for planar shear properties testing, the work-holding device and test specimen principle were here used for shear testing in EW plane. The major disadvantage of the asymmetric specimen shape is the eccentricity of the applied load generated. To minimize the slight parasitic bending moment in the proof body, a work-holding device is therefore necessary. It is made up of 2 orthogonal metallic plane elements, providing plane support for the 2 elements made up by beech. The specimen is stopped in translation in a plane perpendicular to the loading direction by an adjustable stop held in place by clamp screws, tightened upon contact with the test body. PTFE plates were in use to reduce the friction between the work-holding device and the specimen during the loading. Two 250 mm × 45 mm × 45 mm beech elements have been prepared to replace the steel plates advised in the standard (but not mandatory). This species was chosen by its excellent stiffness in the RL plan and superior to the intended strength range for the species tested. The glue used to fix the beech elements to the specimen is a white vinyl glue. The surfaces of beech elements were planed down and double-gluing technique was operated to maximize the quality and strength of the collage. In accordance with the manufacturer's requirements, a pressure of 1 MPa was applied by a mechanical press during a minimum of 6 hours, and a curing time of at least 48 h was performed for each specimen.

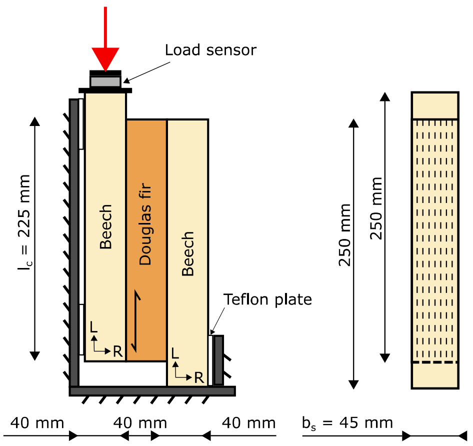


Figure 4: *Scheme of shear test arrangement*

Maximum parallel to the grain EW shear stress was calculated. Finally, the following parameters were computed: $f_{v,0,mean}$, mean value of all the $f_{v,0}$ values of the population, and $f_{v,0,k}$ the 5th percentile value.
Compression tests were made with the same universal testing machine than shear test. To perform parallel and perpendicular to the grain compression test, 2 parallel-plane bearing plates were used. The maximum perpendicular and parallel to the grain compressive stresses were calculated. Finally, the following parameters were computed: $f_{c,0,mean}$, mean value of all the $f_{c,0}$ values of the population, and $f_{c,0,k}$, the 5th percentile value, $f_{c,90,mean}$ mean value of all the $f_{c,90}$ values of the population, and $f_{c,90,k}$ the 5th percentile value.

3 RESULTS AND DISCUSSION

Table 2 presents results of destructive tests performed in this study, compared when it is possible with C24 mechanical properties. This choice of class is justified by its wide use for structural applications.

Table 2: Density, stiffness and strength results

	Loading	Property	Douglas-fir heartwood LVL	C24
		ρ_{mean} (kg/m^3)	544 (4)	420
Stiffness (GPa)	Parallel to the grain shear	$G_{FW,mean}$	0.789 (18)	0.690
		$G_{EW,mean}$	0.907 (17)	
	Parallel to the grain bending	$MoE_{dyn-FW,mean}$	13.7 (11.8) A	11.0
		$MoE_{dyn-EW,mean}$	13.2 (10.3) A	
		$MoE_{g-EW,mean}$	12.3 (11.1)	/
Strength (MPa)	EW parallel to the grain bending	$f_{m,mean}$	49.7 (21.9)	/
		$f_{m,k}$	32.9	Non-comparable
	EW parallel to the grain shear	$f_{v,0,mean}$ (CoV)	5.33 (16.5)	/
		$f_{v,0,k}$	3.62	4.0
	Parallel to the grain compression	$f_{c,0,mean}$ (CoV)	46.9 (15.2)	/
		$f_{c,0,k}$	33.3	21
	Perpendicular to the grain compression	$f_{c,90,mean}$ (CoV)	7.2 (15.9)	
		$f_{c,90,k}$	5.1	2.5

Values followed by capital letters are results of ANOVA and Tukey DHS test at p-value = 5 %.

3.1 ELASTIC BENDING PROPERTIES

Table 2 shows the results of the vibratory and destructive tests (tests n°1 in Figure 1) in terms of dynamic MoE performed in EW and FW bending and global MoE in EW for each beam.

According to a Tukey's HSD test, there was no significant difference between $MoE_{dyn-FW,mean}$ and $MoE_{dyn-EW,mean}$ at 5% level: the stiffnesses were the same in both bending directions in average as expected for a random repartition of the defects. The same trend was noted for CoV. As a longitudinal property, the MoE is expected to be the same on a homogeneous material whatever the bending direction. For LVL, a difference could appear if for example stiffer veneers were located on the outer plies of the lamination, which would result in higher MoEs in FW bending than in EW bending. The present results can be interpreted as a proof of a certain homogeneity in the LVL layouts.

Table 3: *Literature Douglas-fir LVL global MOE mean values*

	Raw material quality	EW (GPa)	FW (GPa)
Jung (1982)	Low to High	15.5-19.2	15.4-19.3
	Random	17.6	16.6
Kunesh (1978)	C and D	15.9	16.1
Kretschmann and others (1993)	/	9.0-12.8	9.0-13.7

When comparing destructive and non-destructive MoEs, it is noted that $MoE_{g\text{-}EW,mean}$ mean values are systematically lower than $MoE_{dyn\text{-}EW,mean}$. This could be explained because no correction in the global *MoE* formula has been applied as it is done for sawn timber according to EN 384 standard [22]. The observed systematic difference is not particularly surprising, since the measurement of MoE is actually a complex subject for a heterogenous material as wood the interested reader can refer to [24] for more details on the subject.

In terms of density, a mean value $\bar{\rho}$ of 544 kg/m^3 has been found for heartwood. For Douglas-fir, it is completely consistent with data from literature, both for solid wood (540 kg/m3) [4] and for LVL (520 kg/m3) [25]. However, a variation in pith-to-bark density was observed on Douglas-fir from New-Zealand in the work of [26]. A differentiated mature wood/juvenile wood effect could be a very likely cause. As a result, a lower average for heartwood was expected.

The obtained MoE_{dyn} were high for knotty heartwood, corresponding, on the basis of structural timber grades of EN 338 [27], to the stiffness of classes C35 ($E_{m,0,mean}$ of 13.0 GPa) and higher than a C24 class ($E_{m,0,mean}$ of 11.0 GPa). This being equal to the highest timber grades currently used in structural applications. According to Table 3, the mean stiffness values determined in the destructive test of this study are low but consistent with what already exists in the literature. As a result, the obtained MoE for LVL made of large French Douglas-fir heartwood are interesting, because they are comparable to the values needed for structural design.

3.2 BENDING STRENGTH

Table 2 shows results of destructive bending tests (tests n°1 in Figure 1). It should be noticed that, given the low height of the beams tested (45 mm) and the known existence of size effects, this study does not allow for a formal conclusion on the results of strengths to be used in structural design, but it draws trends in terms of maximum stresses. The calculated 5th percentile value of maximum stress of Douglas-fir Heartwood LVL is slightly lower to the resistance of timber of C24 class, and actually comparable to a C22 class, by recalculating its resistance (32.18 MPa) for a height of 45 mm and taking into account the test configuration via the 2 adjustment factors given by EN 384 [22]. As a result, the bending strength of Douglas-fir heartwood LVL would seem sufficient for structural purpose. The obtained strength is interesting, especially considering the quality of the wood, in use, because if the same wood material has been sawn, it would likely not had fulfilled the strength grading requirements for structural use (because of knots localized in the same region inducing high stress concentrations).

However, the bending strength was expected to be higher if we refer to the high stiffness obtained and to usually very high strength of LVL products [28].This relatively low 5th percentile value of bending strength can be explained by an important knottiness which increases the probability of a weakening knot in a volume of beam that could prematurely initiate the failure phenomenon. A collateral effect to greater knottiness in a material would be a larger CoV in strength results. Indeed, this increases the probability of interlayer overlapping of knots favouring low-stress failure, but some specimen can still also present higher-stress failure. This effect of knots overlay in Douglas-fir materials due to the lack of optimization of defect distribution in the multi-layers induces low $f_{m,mean}$ and large CoV, which highly impacts the 5th percentile value.

3.3 SHEAR PROPERTIES

3.3.1 Shear moduli

Table 2 shows the results of the vibratory test (tests n°1 in Figure 1) in terms of dynamic G performed in EW and FW bending for each beam. $\bar{G}$ is higher in EW than in FW position (+ 15.0%). The hierarchy between G_{RL} and G_{TL} shear moduli for Douglas-fir clear wood is unclear according to sources [29,30]. [31] had pointed out that deep lathe checks are much more penalizing shear moduli in EW than in FW direction. it would have been expected lathe checks initiated during the rotary peeling, the drying and the pressing operations would have induced lower shear moduli on EW. This potentially depends on lathe checks characteristics (frequency and depth), proportion and size of knots, and the effect of growth rings, which limits the interpretation of these results. It is also important to remind that in the present study, wood with important defects was in use, thus it also influences a lot the shear properties. Finally, there are to many influencing parameters to be able to conclude why a greater $G_{EW,mean}$ than $G_{EW,mean}$ is observed.

However, it is clear that the Douglas-fir heartwood presents very good shear stiffness properties, comparable at least to a EN338 C30 class [27] (G_{mean} of 0.75 GPa) and higher than a C24 class (G_{mean} of 0.69 GPa) when loaded in FW as in EW direction.

3.3.2 Parallel to the grain EW shear strength

Parallel to the grain EW shear test is described as test n°2 in Figure 1. Only specimen results showing 100 % cohesive failure in the LVL material were retained as shown in Figure 5, which is a typical shear failure example.

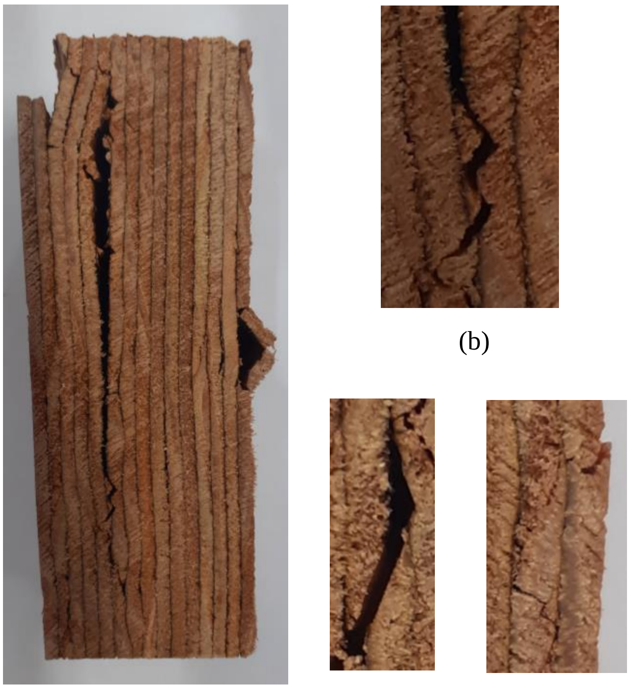
Figure 5: *Parallel to the grain edgewise shear specimen failure*

Table 2 shows results of parallel to the grain edgewise shear tests. Based on the results of these tests, Douglas-fir heartwood is lower than a C24 class ($f_{v.0.k}$ of 4.0 MPa), but comparable to a C20 class ($f_{v.0.k}$ of 3.6 MPa) and which is quite remarkable.. It is lower than the shear characteristic resistance of C24 class, but if it appears to be an issue, this could be managed by the use of cross layers which increase EW shear strength as in some existing industrial products [32].

3.4 COMPRESSION STRENGTH

3.4.1 EW perpendicular to the grain compression strength

Perpendicular to the grain compression test is described as test n°4 in Figure 1 1.
Figure 6 shows a typical failure specimen profile. by observing the failure profiles of the specimens, some factors that enable the propagation of failure can be described. Most of the time, a buckling of the laminations is observed, which result in a delamination in the glue joints (Figure 6(a)). The morphological characteristics of the veneers influence crack propagation: the sawtooth profile visible in Figure 6(b) shows the role of lathe checks in the propagation of failure. The growth ring limits, which mark the transition zone between earlywood and latewood, are areas of weakness in the veneer, which also favour crack propagation (Figure 6(d)).



(b)

(a) (c) (d)

Figure 6: *(a) Edgewise perpendicular to the grain compression specimen failure, (b) sawtooth propagation, (c) inter-plies growth ring limit propagation (c),inter-plies lathe check propagation (d)*

Table 2 shows results of perpendicular to the grain EW compression tests. One hypothesis to explain the good results of the Douglas-fir could be its great thickness of latewood [33]. This characteristic thus implies a great proportion of tracheids of smaller diameter and greater thickness than in earlywood, which is particularly beneficial to the performance in compression. Morever, the EW perpendicular to the grain loading stress the wood of LVL material only in its tangential direction, unlike solid wood. The performance of Douglas-fir heartwood is well above all the classes presented in EN 338 [27] (C50 to $f_{c.90,k}$ of 3.2 MPa), which leads to a very good ranking of the Douglas-fir LVL's EW compression behaviour when compared to the structural requirements.

3.4.2 Parallel to the grain compression strength

Parallel to the grain compression test is described as test n°3 in Figure 1. In the same way as perpendicular to the grain compression, delamination initiated by buckling can be observed on a very large number of specimens in the glue plane, as shown in Figure 7.
Table 2 shows results of parallel to the grain compression tests. The high CoV could again be explained by the high knottiness. However, the compression strength values found for Douglas-fir are very promising since they are over all classes presented in EN 338 [27] (the C50 characteristic value $f_{c.0.k}$ is 30 MPa).

***Figure 7**: Parallel to the grain compression specimen failure*

4 CONCLUSIONS

This study is the first to deal with the valorization of large French Douglas-fir heartwood into an LVL material and the comparison of its mechanical characteristics with solid timber.

The LVL material produced from heartwood of these Douglas fir trees showed high shear and compressive properties. However, the bending properties were significantly lower than in the literature, but are still quite acceptable for structural applications. Indeed, these bending properties are compatible with structural purposes (32.9 MPa of 5th percentile bending strength for a 45 mm thick beam, which would correspond to C22 class for solid timber). This result is especially interesting considering the fact that the strength grading of Douglas-fir sawn timber generally leads to low yields, thus the valorisation of this resource for structural purposes should be greater with LVL products than sawn products from the same resource. It is also worth reminding that this product would exhibit natural durability allowing its usage in specific applications for which there would be no other LVL product competitor on the market.

Considering that the Douglas-fir veneers were not sorted for the LVL manufacturing, these results are very promising for the possible use of LVL as a constructive element. From the point of view of CoV for strength values, high dispersions are observed. This was expected in a material where the probability of interlayer knot overlap is increased for a wood with more knots per unit volume. This dispersion could be reduced by a proper sorting of the veneer, which can be imagined on a peeling line equipped of non-destructive measurement devices.

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REFERENCES

[1] IGN. La forêt plantée en France: état des lieux. [En ligne] Mai 2017. https://inventaire-forestier.ign.fr/IMG/pdf/if40_plantations.pdf

[2] France-Douglas. 1. Origins ; 2. Ressource. [En ligne] 2020. https://www.france-douglas.com/le-douglas/ressource.html

[3] ProSilva. Importance et rôles des gros bois et très gros bois en France. [En ligne] 2012. https://www.prosilva.fr/brochures/brochure_Etude_Gros_Bois_2011_V27.pdf

[4] Cirad. Fiche de l'essence DOUGLAS. Tropix. [En ligne] 22 03 2012. https://tropix.cirad.fr/FichiersComplementaires/FR/Temperees/DOUGLAS.pdf.

[5] France-Douglas. Le Douglas, un choix naturel pour la construction. france-douglas.com. [En ligne] September 2012. https://www.france-douglas.com/assets/components/francedouglas/images/mediatheque/catalogues/construction.pdf.

[6] NF EN 14374. Timber structures - Structural laminated veneer lumber - Requirements. s.l. : Classification index: P 21-401, March 2005.

[7] LVL Handbook Europe. Helsinki : Federation of the Finnish Woodworking Industries, 2020. p. 225. ISBN 978-952-94-2347-7.

[8] Buchanan, A. Timber design guide. Wellington : 3rd edn. New Zealand Timber Industry Federation, 2007.

[9] Strength properties of laminated veneer lumber in compression perpendicular to its grain. Ido, H., et al. 5, 01 10 2020, Journal of Wood Science, Vol. 66, pp. 422-428.

[10] Comparative properties of Douglas-fir boards made from parallel-laminated veneers vs. solid wood. Echols, R. M. et Currier, R. A. 2, &çè", Forest Prod. J., Vol. 23, pp. 45-47.

[11] Parallel-laminated veneer: processing and performance research review. Laufenberg, Theodore L. s.l. : Forest Prod. J. 33(9):21-28, 1983.

[12] Shear Strength of Douglas-Fir Laminated-Veneer Lumber. Bohlen, J. C. 2, s.l. : Forest Products Journal, February 1975, Vol. 25.

[13] Mechanical properties of laminated veneer lumber made from interior Douglas-fir and lodgepole pine. Hesterman, N. D. et Gorman, T. M. 11/12, November/December 1992, Forest Products Journal, Vol. 42.

[14] Pot G, Collet R, Olsson A, Viguier J, Oscarsson J. Structural properties of douglas fir sawn timber – significance of distance to pith for yield in strength classes, 2020. Santiago, Chili WCTE.

[15] Peeled Veneer from Douglas-Fir: Soaking Temperature Influence on the Surface Roughness.

Frayssinhes, R., et al. Corvallis, OR, USA : s.n., 2019. Proceedings of the 24th International Wood Machining Seminar. p. 10.
[16] Heart dryness of Douglas fir and ability to rotary cutting: Research of alternative boiling processes. I. Moisture content distribution inside green wood and water impregnation with an autoclave. . Mothe, F., R., Marchal et W., Tilmant Tatischeffc. 57, 2000, Ann. For. Sci., pp. 219–228.
[17] NF EN 635-3. Plywood - Classification by surface appearance - Part 3 : Softwood. s.l. : Classification index: B 54-170-3, July 1995.
[18] NF EN 789. Timber structures - Test methods - Determination of mechanical properties of wood based panels. s.l. : Classification index: P 21-304, April 2005.
[19] Natural vibration analysis of clear wooden beams: a theoretical review. Brancheriau, L. et Bailleres, H. 36, 2002, Wood Sci Technol, pp. 347-365.
[20] CIRAD. Non-destructive testing of wood. [En ligne] 2020. https://www.picotech.com/library/application-note/non-destructive-testing-of-wood.
[21] NF EN 14358. Timber structures — Calculation and verification of characteristic values. s.l.: Classification index : P 21-399, December 2016.
[22] NF EN 384. Structural timber - Determination of characteristic values of mechanical properties and density. s.l.: Classification index: P 21-358, November 2018.
[23] NF EN 408+A1. Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties. s.l. : Classification index: P 21-302, September 2012.
[24] Using the right modulus of elasticity to get the best grades out of softwood timber species in Great Britain. Gil-Moreno, D., Ridley-Ellis, D. et Mclean, P. [éd.] WCTE 2016. 2016.
[25] Engineered bamboo for structural applications. Scharma, B., et al. 2015, Construction and Building Materials, Vol. 81, pp. 66-73.
[26] Modelling the variation in wood density of New Zealand-grown Douglas fir. Kimberley, M. O., et al. 2017, New Zealand Journal of Forestry Science, p. 15.
[27] NF EN 338. Structural timber - Strength classes. s.l. : Classification index: P 21-353, 2016.
[28] Metsawood. Kerto(R) S LVL - S-beam. [En ligne] 2018. https://www.metsawood.com/global/tools/materialarchive/materialarchive/metsawood-kerto-s-french.pdf.
[29] Guitard, D. Mécanique du matériau bois et composites. Toulouse : C. E. P. A. D. U. E. S. Editions, 1987. p. 220 pages.
[30] Ross, Robert J. Wood handbook: wood as an engineering material. s.l.: USDA Forest Service, Forest Products Laboratory, General Technical Report FPL-GTR-190, 2010: 509 p. 1 v., 2010. Vol. 190.
[31] Numerical study of the influence of veneer lathe checks on the elastic mechanical properties of laminated veneer lumber (LVL) made of beech. Pot, G., Denaud, L. et Collet, R. 3, 2015, Vol. 69, pp. 247-316.
[32] Metsawood. Kerto(R) Q LVL - Q-beam. [En ligne] 2018. https://www.metsawood.com/global/Tools/MaterialArchive/MaterialArchive/MW-KertoLVL-Qpanel-datasheet-FR.pdf
[33] Nepveu G., Blachon J.L., Largeur de cerne et aptitude à l'usage en structure de quelques conifères : Douglas, pin sylvestre, pin maritime, épicéa de Sitka, épicéa commun, sapin pectiné, Rev. For. Fr. 41 (1989) 497-506.