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MECHANICAL PROPERTIES OF HIGH-PERFORMANCE LVL MADE FROM EUCALYPTUS GLOBULUS L.

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ABSTRACT: *Eucalyptus globulus* Labill. is a fast-growing hardwood with excellent mechanical properties and natural durability. Despite these qualities, the use of solid wood-based products from this species is constrained by challenges associated with sawing and drying processes, making it primarily intended for the paper and pulp industry. This study focuses on the experimental evaluation of laminated veneer lumber (LVL) made from *E. globulus* from Spain, a promising product that significantly reduces these processing hurdles. The main mechanical properties in bending, tension, compression and shear have been determined, taking into account the influence of different lay-ups. The results are quite encouraging, revealing a very high-performing structural timber product of great potential.

KEYWORDS: laminated veneer lumber, hardwood, bending, tension, compression, shear

1 – INTRODUCTION

Laminated Veneer Lumber (LVL) is one of the engineered wood products increasingly used in timber construction. Its thin veneer configuration eliminates or randomizes material defects, providing advantages over common solid wood based products, including more reliable mechanical properties and greater load-bearing capacity.

The commercial production of LVL in Europe began in the 1980s, primarily using softwood species like spruce and pine, under the Kerto® brand [1]. Numerous scientific studies have promoting the use of different species based on each region's natural resources [e.g. 2-4]. Research on hardwoods [e.g. 5-7] has driven further developments, with BauBuche [8] (made of beech) currently being the only hardwood LVL produced in Europe.

In an effort to broaden the raw material base for LVL production, *Eucalyptus globulus* Labill. stands out as a compelling resource. This fast-growing hardwood species is particularly significant in Australia, South America, South Africa and Europe, particularly in Portugal and Spain.

The Spanish visual grading standard UNE 56546:2024 [9] includes a single visual grade, MEF, for Spanish *Eucalyptus globulus* L., which has a characteristic bending strength of 46.4 N/mm^2. Based on this, it is classified as D40 strength class according to the European standard EN 1912:2024 [10]. This places it among the three species with the highest mechanical performance growing in Europe, along with beech and ash. In addition, *E. globulus* from the Galicia region (Spain) exhibits high natural durability against fungi [11].

The use of sawn timber from this species is limited due to difficulties experienced during the sawing and drying processes, demanding small cross-sections. These same issues also hinder the use of eucalyptus for glued laminated timber, requiring thin boards (typically around 20 mm thick) and radial cutting, which prevents the full utilisation of the log [12].

The delopment of a high value-added product such as LVL from this species emerges as a very interesting solution. It significantly reduces the obstacles faced in processing solid wood based products due to the thin veneers obtained from log peeling, thereby optimising resource utilisation in a high-performance product.

2 – PROJECT DESCRIPTION

This study aims to provide insight into the mechanical performance of LVL produced from *Eucalyptus globulus*

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Labill. grown in Spain, offering an experimental evaluation of its strength and stiffness properties. The findings could serve as a basis for the potential development of a commercial product.

Two types of LVL lay-ups were examined: LVL with all veneers oriented with the same grain direction (LVL-S) and LVL with the third veneer from the outer sides oriented crosswise (LVL-Q) (Fig. 1).

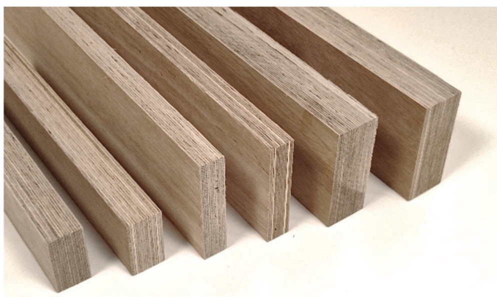

Figure 1. Some of the eucalyptus LVL lay-ups

For both LVL lay-ups, the following mechanical properties were determined:

- Edgewise bending strength.
- Flatwise bending strength.
- Tension strength parallel to the grain.
- Compression strength parallel to the grain.
- Compression strength perpendicular to the grain, both parallel and perpendicular to the glue lines.
- Shear strength related to edgewise bending.
- Shear strength related to flatwise bending.
- Modulus of elasticity parallel to the grain, determined in edgewise bending tests.

LVL boards were manufactured using a plywood press. For bending and tension tests, specimens were prepared from boards of 41 mm and 22 mm thickness, consisting of 22 and 12 veneers, respectively. Compression specimens were obtained from the 41 mm thick boards. Specimens for shear tests related to flatwise were prepared using the 22 mm thick boards, while those for shear tests related to edgewise were obtain from 30 mm thick boards with 16 veneers.

Table 1 shows the number of specimens and the type of LVL board (thickness t and S/Q lay-ups) used for each test group, leading to a total of 341 tests. For each test type and lay-up, three LVL boards were use to prepare the specimens to account for variability between boards.

Two different span lengths (L) were considered in the flatwise bending tests, as detailed in Subsection 3.1.

Prior to testing, the specimens were conditioned at 20ºC and 65% relative humidity until equilibrium moisture content was reached. The density of each specimen was measured according to EN 323:1993 [13], leading to a mean value of 869 kg/m^3.

3 – EXPERIMENTAL SETUP

The tests to determine the various LVL properties followed the specifications outlined in the European standard EN 14374:2004 [14].

All the tests were performed on a universal mechanical testing machine in displacement-controlled mode, with loading rates set to ensure specimen failure within 300±120 seconds.

3.1 BENDING TEST EDGEWISE AND FLATWISE

Four-point bending tests were conducted on LVL-S and LVL-Q in accordance with EN 408:2010+A1 [15], using the test setup shown in Fig. 2.

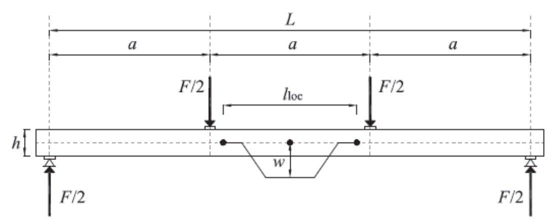

Figure 2. Four point bending test setup

The test span (L) was 18 times the height (h) of the specimens with 100×41 mm^2 cross-section, with the height being 100 mm for edgewise bending and 41 mm for flatwise bending. To analyse the influence of the board thickness, flatwise bending test were also performed on specimens with a 100×22 mm^2 cross-section. In addition, flatwise bending tests with spans of 30h were conducted for both the 22 mm and 41 mm depth specimens.

Edgewise and flatwise bending strength ($f_{m,0}$) were calculated for each specimen following Eq. (1),

$$f_{m,0} = \frac{3Fa}{bh^2} \tag{1}$$

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Table 1: Number of specimens tested for each type of test, based on different LVL board thicknesses and lay-ups

Type of test	t = 22 mm		t = 41 mm		t = 30 mm	
	LVL-S	LVL-Q	LVL-S	LVL-Q	LVL-S	LVL-Q
Edgewise bending (L=18h)	-	-	12	12	-	-
Flatwise bending (L=18h)	12	13	12	12	-	-
Flatwise bending (L=30h)	12	13	12	10	-	-
Tension parallel to the grain	12	12	8	6	-	-
Compression parallel to the grain	-	-	21	21	-	-
Compression perpendicular to the grain (edgewise)	-	-	26	18	-	-
Compression perpendicular to the grain (flatwise)	-	-	23	24	-	-
Shear related to edgewise bending	-	-	-	-	15	12
Shear related to flatwise bending	12	11	-	-	-	-

being F the maximum applied load, a (=L/3) the distance between loading position and the nearest support; b the width of the specimen, and h the height of the specimen.

According to EN 14374:2004 [14], the edgewise bending strength of LVL specimens with 100 mm height was adjusted to a reference height of 300 mm using the correction factor $k_{\mathrm{m,corr}}$, as defined in Eq. (2).

$$k_{\mathrm{m,corr}} = \left(\frac{h}{300}\right)^{s}; \quad s = 2 \cdot \nu - 0.05 \tag{2}$$

being s the size effect parameter and v the coefficient of variation.

Local deflections were measured using LVDTs at both sides of the specimens. The local MoE in edgewise bending was calculated between the two central loading heads, within the pure bending zone, according to Eq. (3),

$$E_{\mathrm{m,l}} = \frac{a l_{\mathrm{loc}}^{2}\left(F_2 - F_1\right)}{16 I\left(w_2 - w_1\right)} \tag{3}$$

being l_{loc} the base length of measurement (5h) and I the moment of inertia. A load increment (F_2-F_1) ranging between 10% and 40% of the maximum applied load was used, identifying the longest portion on the regression line giving a correlation coefficient of 0.99 or higher. The corresponding deflection increment, w_2-w_1, was obtained.

Characteristic values (5th percentiles) for strength were estimated using parametric methods in accordance with EN 14358:2016 [16].

3.2 TENSION TEST

Tension tests parallel to the grain were conducted following the test procedure specified in EN 408:2010+A1 [15]. LVL specimens of 70×41 mm^2 and 100×22 mm^2 cross-section for both S and Q lay-ups were tested. The specimen length between the testing machine grips was set to 1000 mm, meeting the requirement of at least nine times the larger cross-sectional dimension. The individual results were adjusted to a reference length of 3000 mm by applying the correction factor $k_{\mathrm{t,corr}}$ defined in Eq (4),

$$k_{\mathrm{t,corr}} = \left(\frac{l}{3000}\right)^{s/2}; \quad s = 2 \cdot \nu - 0.05 \tag{4}$$

where l represents the actual specimen length between the grips, and s is the size effect parameter.

3.3 COMPRESSION TEST

Compression tests, both parallel and perpendicular to the grain, were conducted on LVL-S and LVL-Q in accordance with the test method specified in EN 408:2010+A1 [15].

Specimens with 250 mm length and 41×70 mm^3 cross-section were tested for compression parallel to the grain. For the compression tests perpendicular to the grain, two types of specimens were used, either parallel or perpendicular to the glue lines, to account for the different loading on the product when used as a panel or beam. Specimenes of 41 mm length and 45×70 mm^2 cross-section were tested perpendicular to the glue lines, while those with a 70 mm length and 41×70 mm^2 cross-section were tested parallel to the glue lines.

3.4 SHEAR TEST

The shear tests related to edgewise bending were conducted following EN 408:2010+A1 [15]. Eucalyptus LVL-S and LVL-Q specimens, measuring 300 mm in length (l), 30 mm in width (b), and 55 mm in height, were

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glued to steel plates. The angle between the load direction and the longitudinal axis of the specimen was 14º. The corresponding shear strength was calculated using Eq. 5,

$$f_v = \frac{F_{max} \cos 14^{\circ}}{lb} \tag{5}$$

Shear tests related to flatwise bending were performed according to the planar shear test method given in EN 789:2004 [17]. LVL-S and LVL-Q specimens with dimensions of 225 in length (l), 100 mm in width (b), and 22 mm in thickness were bonded to 25 mm thick steel plates. The shear strength was determined following Eq. 6,

$$f_r = \frac{F_{max}}{lb} \tag{6}$$

4 – RESULTS

In general, eucalyptus LVL exhibited remarkably high mechanical properties for the different LVL lay-ups studied. The results obtained for bending, tension, compression ans shear are shown next.

4.1 BENDING STRENGTH AND STIFFNESS

Edgewise bending

The main mechanical properties obtained from edgewise bending tests for LVL beams in both S and Q lay-ups, are presented in Table 2, including the mean bending strength ($f_{m,0,edge,mean}$), characteristic bending strength ($f_{m,0,edge,k}$) and the mean local modulus of elasticity ($E_{m,0,edge,l}$).

Table 2: Edgewise bending strength and MoE of eucalyptus LVL-S and LVL-Q in edgewise with depth t=41 mm and 18h test span

t = 41 mm; 18h test span	**LVL-S**	**LVL-Q**
$f_{m,0,edge,mean}$ (N/mm^2)	87.2	81.6
$f_{m,0,edge,k}$ (N/mm^2)	78.4	73.3
$E_{m,0,edge,l}$ (N/mm^2)	25022	20676

Fig. 3 shows the characteristic bending strength values of some of the most significant engineered wood products available on the European market, including two common European strength classes of glued laminated softwood, GL24h and GL32h [18], glued laminated oak [19], glued laminated beech [20], softwood LVL-S [1], beech LVL-S [8], as well as *Eucalyptus globulus* solid timber [9] and the eucalyptus LVL-S studied here.

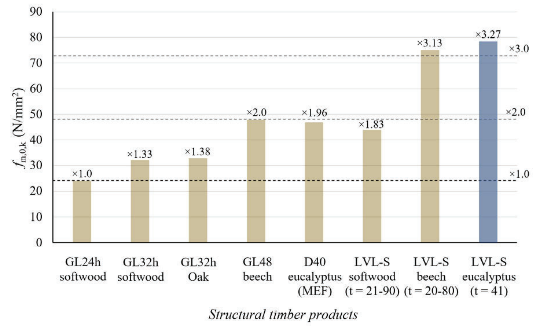

Figure 3. Characteristic bending strength of various timber products

As can be seen, the characteristic bending strength of the eucalyptus LVL-S is notably high, more than three times the strength of standard GL24h laminated timber, 78% higher than that of softwood LVL-S, and similar to that of beech LVL-S. Additionally, it represents a 69% improvement over the strength of *E. globulus* solid timber, due to the smaller defect size in LVL.

Fig. 4 compares the modulus of elasticity of the same products referenced in Fig. 3.

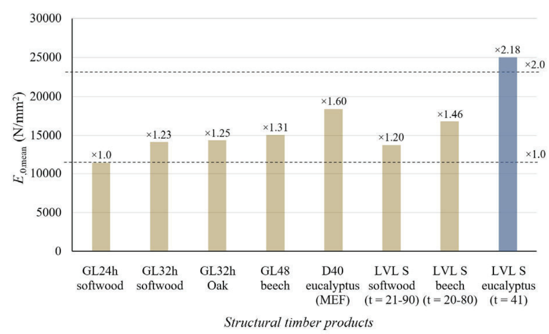

Figure 4. Modulus of elasticity of various timber products

As can be observed, the stiffness of eucalyptus LVL-S represents a significant improvement compared to other products, being more than double that of GL24h, 81% higher than softwood LVL-S, and 49% greater than beech LVL.

Furthermore, eucalyptus LVL-S offers a 35% increase over solid timber of the same species (18400 N/mm² [9]). This increase, which is greater than that achieved by other LVLs in relation to the solid wood of their respective species, may be due to the use of significantly thinner veneers in its production. While commercial LVLs typically use 3 mm thick veneers (after the pressing process) [1, 8], the eucalyptus LVL was made with 1.85 mm thick veneers, resulting in a substantial increase in

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the number of glue lines (approximately 60%) and, consequently, the proportional amount of adhesive used.

It should be noted that the high modulus of elasticity achieved enables a considerable reduction in the cross-sections of structural elements, which are often designed based on deflection limits.

Flatwise bending

The mean ($f_{m,0,flat,mean}$) and characteristic ($f_{m,0,flat,k}$) flatwise bending strength are presented in Tables 3 and 4 for specimens with 41 mm and 22 mm depths, and test spans of 18*h* and 30*h*.

Table 3: Flatwise bending strength of eucalyptus LVL-S and LVL-Q with depth t=41 mm and 18h and 30h test span

	Test spam	LVL-S	LVL-Q
$f_{m,0,flat,mean}$ (N/mm^2)	18*h*	97.0	78.3
$f_{m,0,flat,k}$ (N/mm^2)		73.3	56.2
$f_{m,0,flat,mean}$ (N/mm^2)	30*h*	122.0	98.2
$f_{m,0,flat,k}$ (N/mm^2)		98.9	73.5

Table 4: Flatwise bending strength of eucalyptus LVL-S and LVL-Q with depth t=22 mm and 18h and 30h test span

	Test spam	LVL-S	LVL-Q
$f_{m,0,flat,mean}$ (N/mm^2)	18*h*	111.3	77.3
$f_{m,0,flat,k}$ (N/mm^2)		89.9	66.6
$f_{m,0,flat,mean}$ (N/mm^2)	30*h*	130.9	91.5
$f_{m,0,flat,k}$ (N/mm^2)		109.3	77.9

The flatwise bending strength varied significantly depending on the different testing spans, with values for the 30*h* span always exceeding those of the 18*h* span. This is because, in the tests with an 18*h* span, shear failure was more prevalent among the specimens, while in the tests with a 30*h* span, the percentage of specimens that failed due to bending increased considerably.

Specifically, the mean flatwise bending strength for the LVL-S with a 30*h* test span reached high values of 130.9 N/mm^2 and 122 N/mm^2 for depths of 22 mm and 41 mm, respectively. These values were 17% and 26% higher than those from the corresponding tests with 18*h* test span. Very similar relative increases in mean bending strength were observed in the Q lay-up when the test span was increased from 18*h* to 30*h*. Specifically, an 18% increase was observed for the 22 mm depth and a 25% increase for the 41 mm depth.

Similarly, the characteristic flatwise bending strength were also high, giving 109.3 N/mm^2 and 98.9 N/mm^2 for the 22 mm and 41 mm depths with 30*h* span (LVL-S lay-up), wich represents and increase of 21.6% and 34.9% compared to the 18*h* span. These results suggest the convenience of increasing the test span established in the European LVL standard, at least for high-performance LVL where the predominant failure in bending tests with an 18*h* span is due to shear.

The LVL-Q consistently showed lower bending strengths than the LVL-S for the counterpart series of beam depth and test span, with the characteristic bending strength decreasing by 26% and 29% for the 22 mm depth, and by 23% and 26% for the 41 mm depth, for the 18*h* and 30*h* spans, respectively.

When comparing the characterisitic bending strength of the two studied depths, the 22 mm beams generally showed higher values than the 41 mm beams, indicating a clear influence of the size effect. However, the strength increase was more pronounced in the S lay-up than in the Q lay-up, with gains of 10.5% and 6%, respectively, for the 30*h* test span. This is because the strength increase due to the size effect when reducing the specimen depth is counteracted by the fact that the transverse veneers in the 22 mm thick board are relatively closer to the neutral axis than in the 41 mm thick board and, consequently, they are subjected to higher shear stresses.

4.2 TENSION STRENGTH

Table 5 shows the mean ($f_{t,0,mean}$) and characteristic ($f_{t,0,k}$) values for the tension strength parallel to the grain determined for eucalyptus LVL-S and LVL-Q and for the two cross-sections analysed.

Table 5: Tension strength of eucalyptus LVL-S and LVL-Q

	S (mm^2)	LVL-S	LVL-Q
$f_{t,0,mean}$ (N/mm^2)	70×41	77.9	72.1
$f_{t,0,k}$ (N/mm^2)		66.2	50.9
$f_{t,0,mean}$ (N/mm^2)	100×22	73.3	61.2
$f_{t,0,k}$ (N/mm^2)		56.7	53.6

Eucalyptus LVL exhibits very high mean tension strength in both the S and Q lay-ups, with higher values for the 41 mm thickness.

Assuming that the transverse veneers do not contribute to tension strength in the parallel direction, the tension strength for the Q lay-up could be estimated by multiplying the tension strength of the S lay-up by the specimen's η ratio (η = number of longitudinal veneers / total number of veneers), which takes values of 0.9 and 0.83 for thicknesses of 41 mm and 22 mm, respectively. Accordingly, the tension strength for LVL-Q with a 41 mm thickness would be 77.9×0.9=70.1 N/mm², while for the 22 mm thickness, it would be 73.3×0.83=60.8

N/mm², values that closely match experimental results. However, this relationship does not hold for characteristic values due to a high CoV in some lay-ups (12% for S-22 and 14% for Q-41), suggesting that a greater number of tests are needed to obtain more robust $f_{t,0,k}$ values. Despite this consideration, the values determined in this study provide a meaningful reference for comparison with other products.

Specifically, the 41 mm LVL-S has a characteristic tension strength of 66.2 N/mm², which is more than three times higher than that of GL24h, over 1.5 times greater than softwood LVL-S ($f_{t,0,k}$ = 35 N/mm²) [1], and more than 2.5 times higher than the D40 strength class of solid hardwood ($f_{t,0,k}$ = 24 N/mm²) [21].

When comparing these values to characteristic values of beech LVL [8], with a characteristic tension strength of 60 N/mm^2 for the S configuration, it is observed that eucalyptus LVL is in the same order of magnitude, or even shows a 10% improvement for the 41 mm thickness. For the Q lay-up, beech LVL shows characteristic tensile strengths of 46 and 49 N/mm^2 for different thicknesses, again slightly lower than those of eucalyptus LVL but still within the range.

4.3 COMPRESSION STREGTH

The results for the mean compression strength parallel to the grain ($f_{c,0,mean}$) and characteristic compression strength parallel to the grain ($f_{c,0,k}$), as well as the mean and characteristic strengths perpendicular to the grain, both edgewise ($f_{c,90,edge,mean}$, $f_{c,90,edge,k}$) and flatwise ($f_{c,90,flat,mean}$, $f_{c,90,flat,k}$) of LVL-S and LVL-Q are presented in Table 6.

Table 6: Compression strength of eucalyptus LVL-S and LVL-Q

	LVL-S	LVL-Q
$f_{c,0,mean}$ (N/mm^2)	80.0	66.1
$f_{c,0,k}$ (N/mm^2)	72.7	55.0
$f_{c,90,edge,mean}$ (N/mm^2)	7.3	10.2
$f_{c,90,edge,k}$ (N/mm^2)	6.5	6.8
$f_{c,90,flat,mean}$ (N/mm^2)	9.8	7.2
$f_{c,90,flat,k}$ (N/mm^2)	8.6	5.6

In the case of compression parallel to the grain, the LVL-S lay-up exhibited a very high mean strength of 80.0 N/mm², slightly higher than the value reported in previous studies by the authors for small clear specimens of solid eucalyptus wood (73.6 N/mm²) [21]. The LVL-Q lay-up also showed a high mean strength of 66.1 N/mm², although somewhat lower than expected, considering that transverse veneers have little influence on the compression strength parallel to the grain. Consequently, the compression strength parallel to the grain of the LVL-Q lay-up can be estimated as the product of the LVL-S compression strength parallel to the grain and the specimen's η ratio. The difference between the expected theoretical value (80.0×0.9=72 N/mm^2) and the experimental result may be attributed to a difference in quality between the specimens of both lay-ups, as the mean density of the LVL-Q (827.7 kg/m³) was 7.5% lower than that of LVL-S (894.5 kg/m³).

Eucalyptus LVL exhibits a characteristic compression strength parallel to the grain of 72.7 N/mm² and 55.0 N/mm² for the LVL-S and LVL-Q lay-ups, respectively. These values are 2.1 times those of softwood LVL, and are of the same order of magnitude as beech LVL-S (69 N/mm²) [8], although approximately 11% lower than beech LVL-Q.

In the case of compression perpendicular to the grain corresponding to the work as a panel (flatwise), the mean strength value obtained for the LVL-S lay-up was 9.8 N/mm², slightly lower than that of small clear eucalyptus wood in the radial direction (11.1 N/mm²) and very similar to the value reported for the tangential direction (10.2 N/mm²) [22]. The mean strength obtained for the LVL-Q lay-up was lower than that for LVL-S. This difference may be due to the lower density of the LVL-Q specimens.

The characteristic values for compression strength perpendicular to the grain in flatwise loading of eucalyptus LVL-S and LVL-Q were 3.6 and 2.5 times higher, respectively, than those of softwood LVL, but significantly lower than those of beech LVL-S (12 N/mm²) and LVL-Q (16 N/mm²) [8].

Regarding the compression strength perpendicular to the grain corresponding to the work as a beam (edgewise), the LVL-Q lay-up with transverse veneers parallel to the load direction provided higher values than the LVL-S lay-up. However, in contrast to other LVLs, the compression strength perpendicular to grain in edgewise loading was lower than that in flatwise loading. This is because several specimens from this lay-up failed at low load levels due to premature failures in the transverse veneers.

4.4 SHEAR STRENGTH

Table 7 shows the characteristic values for the shear strength related to edgewise bending ($f_{v,0,edge,k}$) and flatwise bending ($f_{v,0,flat,k}$), as well as the corresponding

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mean values ($f_{v,0,edge,mean}$ and $f_{v,0,flat,mean}$), for eucalyptus LVL-S and LVL-Q specimens.

Table 4: Shear strength of eucalyptus LVL-S and LVL-Q

	LVL-S	LVL-Q
$f_{v,0,edge,mean}$ (N/mm^2)	5.7	5.2
$f_{v,0,edge,k}$ (N/mm^2)	4.9	4.5
$f_{v,0,flat,mean}$ (N/mm^2)	6.2	3.1
$f_{v,0,flat,k}$ (N/mm^2)	4.4	2.3

The $f_{v,0,edge,k}$ values for eucalyptus LVL are relatively similar in both lay-ups, as observed with LVL made from other species. The obtained values are of the same order of magnitude as those of softwood LVL (4.2 N/mm² in S and 4.5 N/mm² in Q) [1], but significantly lower than those of beech LVL (8 N/mm² for S and 7.8 N/mm² for Q) [8].

The $f_{v,0,flat,k}$ values resulted in 4.4 N/mm² for eucalyptus LVL-S and 2.3 N/mm² for LVL-Q. These values are nearly double those of softwood LVL but lower than those of beech LVL (8 N/mm² for S and 3.8 N/mm² for Q). As can be observed, the $f_{v,0,flat,k}$ value for eucalyptus LVL-S is 1.9 times higher than the corresponding value for the Q lay-up. This significant difference is due to failure in the Q lay-up specimens caused by rolling shear. A similar ratio between the $f_{v,0,flat,k}$ values of the S and Q lay-ups can be found in both softwood LVL (1.77) and beech LVL (2.11).

5 – CONCLUSIONS

It is confirmed that LVL made from *Eucalyptus globulus* could be a very high performance product for use in load-bearing timber structures, with strength and stiffness values significantly higher than those of softwood LVL. In comparison to beech LVL, the parallel-to-grain strength values (for bending, tension, and compression) are of the same order of magnitude, while the values for compression perpendicular-to-grain and shear strengths are considerably lower. On the other hand, the local modulus of elasticity is significantly higher (1.49 times), offering a considerable advantage in the design of elements sized based on deflection.

However, to obtain definitive conclusions, further tests should be carried out on specimens obtained from boards manufactured on an industrial LVL production line.

This research not only contributes to increasing the value of this abundant hardwood species, but also offers a pathway towards sustainable and innovative solutions in timber product manufacturing.

6 – ACKNOWLEDGEMENTS

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