



Bending properties of LVL made by *Eucalyptus globulus* Labill. and its potential for hybrid glulam beams

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Received: 29 November 2024 / Accepted: 7 March 2025 / Published online: 17 April 2025
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Abstract

The growing demand for engineered wood products is mobilizing the industry and the scientific community to study alternatives to softwood species. Hardwood species have been studied within the last decades to assess their mechanical properties of sawn wood and engineered wood products. Despite that, in Europe there is a huge diversity of hardwood species, most of them considered as mid-density, being Southern blue gum (*Eucalyptus globulus* Labill.) considered as high-density with values of density of about 900 kg/m³. The present paper addresses an experimental campaign to assess the bending performance of Laminated Veneer Lumber (LVL) made with Southern blue gum (both edgewise and flatwise). An average modulus of elasticity of 22,015 MPa and bending strength of 85.6 MPa were obtained for edgewise direction, 30.5% higher than flatwise for modulus of elasticity and 5.5% lower than flatwise bending strength. The use of Southern blue gum LVL at both tension and compression external layers for glulam production in combination with Poplar (*Populus* spp.) was also considered as well as the use of LVL only at the tension layer. From the former (5 glulam beams) an average value of 19,713 MPa and 77.9 MPa was determined whereas from unsymmetric use of LVL (3 glulam beams) an average value of 13,634 MPa and 57.9 MPa were obtained for modulus of elasticity and bending strength, respectively. Non-destructive tests preceded static standard tests and correlations were drawn. Bonding performance assessment of both LVL and glulam beams followed EN 14734 and EN 14080, respectively.

1 Introduction

Engineered wood products (EWP's), specifically Glued Laminated Timber (glulam) and Cross Laminated Timber (CLT) have been mainly produced with softwoods due to the availability of raw material. However, climate change is influencing the way the European forests are being considered by the industry and end users. More severe and frequent events of droughts are increasing the frequency of bark beetle infestations, especially in spruce production (Jakoby et al. 2019). Also, the European Commission has been developing efforts to understand how climate change will modify the European forest distribution. Mauri et al. (2022) present “EU-Trees4F”, a new data set that shows the current and potential distribution of 67 species based on two emission scenarios (RCP 4.5 and RCP 8.5) and three-time steps (2035, 2065 and 2095). From the available data, it is

shown that the habitat suitability will significantly decrease in Central Europe for the most common softwood species used for engineered wood products (silver fir—*Abies alba* and Norway spruce—*Picea abies*). The effects of climate change were also reported by Langer and Busskamp (2023) for beech species especially caused by the exceptional drought since 2018 in several regions of Germany.

Since EWP's market is global and there is an increasing demand for renewable and sustainable solutions, the scientific community and industry have a key role in developing new alternatives based on process/production innovations or on the use of alternative species, namely underutilized hardwoods such as Southern blue gum (*Eucalyptus globulus* Labill.). Southern blue gum is considered a fast-growing species and occupies a large forest area in the Iberian Peninsula, with 845 kha in Portugal according to the 6th National Forest Inventory (data from 2015) (ICNF 2019) and 619.9 kha in Spain (data from 2019) (MITECO 2021). Southern blue gum has several applications being mainly considered for paper and pulp production, firewood, energy production and with small scale for plywood and furniture production. As Southern blue gum is a high-density species, it offers several constraints for its application for structural purposes, starting with the sawing and drying process of

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sawn wood (Franke and Marto 2014). The drying process of sawn wood boards usually requires longer periods compared to softwoods and the probability of cracks occurrence and/or cross-section collapse is higher (Hansmann et al. 2008; Downes et al. 2014). Touza and Saavedra (2002) developed a drying process proposal for Southern blue gum to obtain 12% moisture content in a period of 15–20 days starting with 30% moisture content.

The mechanical characterization of Southern blue gum sawn wood in bending was addressed by Martins (2015) on a 75 mm × 75 mm cross-section. Average values of 905 kg/m³ and 18,151 MPa were obtained for density and global modulus of elasticity while an average bending strength of 75 MPa was determined. Alvite et al. (2002) refer to Southern blue gum from Galicia (23 and 35 years old) with lower density values (760 kg/m³) and higher modulus of elasticity (20,580 MPa) and bending strength (130 MPa) for cross-sections below 60 mm × 200 mm. These results were considered the basis for the development of mean and characteristic values for the establishment of the “Eucalipto MEF” strength class at UNE 56546 (AENOR 2013). According to EN 1912 (CEN 2012a), Southern blue gum is considered as D40. Recently, Martins et al. (2023) developed a procedure for machine grading Southern blue gum in tension, considering sawn wood from five different provenances from Portugal and Spain. An average density value of 840 kg/m³ was obtained and 21,300 MPa and 77.8 MPa average values were determined for static modulus of elasticity and tensile strength parallel to grain.

The use of Southern blue gum for glulam was addressed by Martins et al. (2020) as a single species within the cross-section and also combined with poplar with a symmetric lay-up. The single species configuration (average density of 936 kg/m³) provided excellent mechanical performance with a global modulus of elasticity of 22,784 MPa similar to the value obtained by Alvite et al. (2002) and an average bending strength of 108.6 MPa, 13.3% lower than the value from Alvite et al. (2002) for glulam without finger joint. The same authors also presented results for glulam with finger joints with a bending strength of 103.4 MPa. Lara-Bocanegra (2017) assessed the influence of finger joint on bending strength, being observed a decrease of 19% compared to boards without finger joint. Despite the outstanding mechanical performance compared with other hardwoods, delamination tests showed a poor bonding performance.

Recent developments from the industry have introduced to the market glulam beams made with Laminated Veneer Lumber (LVL) from beech, being considered the strongest EWP's in the market assuming a GL75 strength class based on the ETA-14/0354 (Pollmeier 2024b). LVL consists of gluing several veneers with a maximum 6 mm thickness, being much easier the peeling process of veneers from logs and its drying process (steaming process) than sawn wood as shown by Çolak et al. (2007) for beech allowing also to keep intact the mechanical properties.

The present paper addresses the mechanical performance of LVL made with Southern blue gum veneers and its potential for hybrid glulam beams, namely through the assessment of the mechanical properties (modulus of elasticity and bending strength) as well as the bonding performance following the standard procedures established for softwoods.

2 LVL characterization

2.1 Raw material and production

For LVL (Laminated Veneer Lumber) production, Southern blue gum (*Eucalyptus globulus* Labill.) veneers of 2.2 mm thickness and about 2600 mm length by 650 mm width were supplied from industry and stored at SerQ laboratory facilities. Information about log dimensions, age, provenance, peeling and drying process was not available. Once at the laboratory, veneers of a final width of 120 mm were obtained and sanded at the edges to avoid wood splinters.

A total of 8 LVL specimens with average dimensions of 43 mm × 101 mm × 2500 mm (thickness × width × length) were produced. The production of LVL was carried out at SerQ facilities without industrial machinery being used. Accordingly, specifications of EN 14374 (CEN 2004a) were followed namely: the maximum thickness of each veneer; the minimum number of veneers and the dimensions (width and thickness) required for bending tests (both edgewise and flatwise). A total of 20 veneers (120 mm width) were assembled with a PRF adhesive (Aerodux 185 + HRP 150) that was manually applied, being the amount of adhesive controlled by weighing. This adhesive was used due to stock availability and the technical data sheet was followed as it was for hybrid glulam beam production. A ratio of 100/20 ppw (resin/hardener) was considered and a uniform distribution was aimed at each surface, being adopted 300 g/m². The assembly process was carried out at controlled conditions (20 ± 2 °C of temperature and 65 ± 5% of relative humidity), being adopted 0.8 MPa as the pressure level for 4 h with multiple hydraulic actuators.

2.2 Non-destructive and static tests on LVL

Before static bending tests on LVL specimens (edgewise), non-destructive characterization based on the longitudinal vibration method was considered to obtain the dynamic modulus of elasticity (E_{dyn}) that has been proven to be a good predictor of the mechanical properties of sawn wood. Machine Timber Grader device (MTG, Brookhuis®) was adopted and considered as input data apart from the cross-section dimensions measured at mid-length and both ends, the length, the weight and the moisture content measured at mid-length and from a distance of 60 cm from both ends according to EN 13183-2 (CEN 2002b). The test comprised

an impact with a sphere (incorporated at the MTG device) that induces a wave that travels through the specimen and returns to the same end (MTG has also a receiver). The wave signal response is transmitted via Bluetooth to the computer and a specific software provides both natural frequency and dynamic modulus of elasticity E_{dyn} through Eq. 1.

$$E_{dyn} = 4f^2 L^2 \rho \times 10^{-6} \quad (1)$$

where f is the natural frequency of vibration (Hz), L is the length of the specimen (mm), and ρ is the density (kg/m^3).

Static bending tests comprised the determination of modulus of elasticity (local, $E_{m,l}$ and global, $E_{m,g}$) and bending strength (f_m) for edgewise configuration. For flatwise bending strength tests on LVL, specimens were obtained from edgewise specimens if the required length for testing was available without signs of failure. Only the global modulus of elasticity and the bending strength were determined for flatwise configuration. The test layout, data recorded and loading procedure followed the EN 408:2010 + A1:2012 (CEN 2012b), namely a 4-point bending test was adopted with a span of 18 h and a distance between load application points of 6 h. For both $E_{m,l}$ and $E_{m,g}$ the applied load does not exceed a maximum of 40% of the estimated failure load and a constant rate of movement of 0.003 h mm/s was considered. A hydraulic actuator with 100 kN maximum capacity and linear transducers with 20 mm and 50 mm maximum capacity were considered for vertical displacement measurement (Fig. 1). Both data were recorded in intervals of 0.1 s. On the other hand, for bending strength only the applied load was recorded, and a constant rate of movement was adopted so that the maximum load was reached in (300 ± 120) s.

After each beam bending strength test (edgewise) one slice representative from the full cross-section of the specimen was obtained, located as close as possible to the failure zone and without defects. The slices were used for the determination of density and moisture content following the oven-dry method specified in EN 13183–1:2002 (CEN

2002a). The remaining parts without signs of failure resulted in a total of eleven specimens that were considered for flatwise tests. Only the global modulus of elasticity, $E_{m,g}$, and bending strength, f_m , were determined considering the acquisition of the applied load (hydraulic actuator with 100 kN maximum capacity) and deflection at mid-span through two linear transducers with 20 mm maximum capacity (Fig. 1).

2.3 Results and discussion on LVL mechanical tests

From the 8 LVL edgewise bending tests a ductile behaviour before failure was observed with a 10 to 30 mm of deflection close to the maximum load as shown in Fig. 2. The observed performance was also evident due to compression folds at the upper side of the specimens at the third central span before bending failure by tension as shown in Fig. 3. A single specimen presented shear failure at the collapse (Fig. 3). Concerning the 11 flatwise bending tests, the load vs deflection curves showed a performance closer to linear behaviour (Fig. 4). All specimens had a significant drop of load caused by shear failure (Fig. 4) followed by a horizontal plateau with an increase of deflection for a load level corresponding to half of the maximum load.

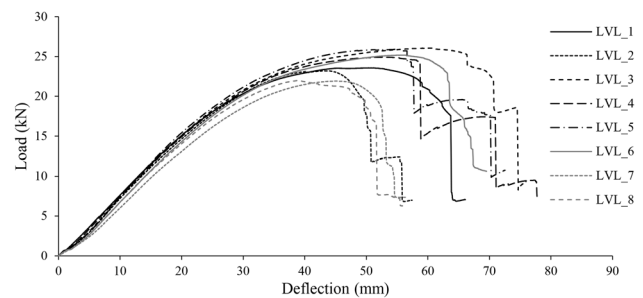


Fig. 2 Load vs deflection curves from edgewise bending tests on LVL specimens

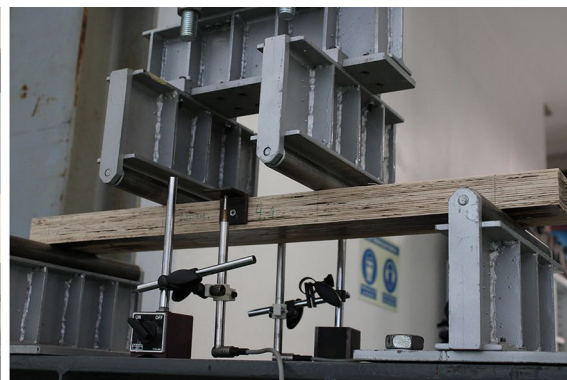
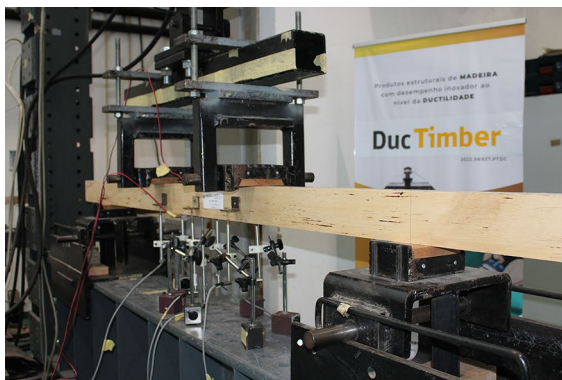


Fig. 1 Bending test layout adopted for LVL specimens (edgewise—left; flatwise—right)



Fig. 3 Failure modes observed from edgewise bending tests on LVL specimens: compression folds at the upper side combined with failure by tension (left); shear combined with tension failure (right)

A summary of LVL results from non-destructive tests (E_{dyn_LVL}) and static tests, both edgewise and flatwise (local modulus of elasticity, $E_{m,l}$, global modulus of elasticity, $E_{m,g}$ and bending strength, f_m) as well as moisture content (w) and density (ρ) is presented in Table 1. Based on recommendations from EN 384 (CEN 2022) for sawn wood, the correction of both $E_{m,l}$, $E_{m,g}$ and ρ to 12% moisture content was applied, presenting the adjusted values as average values according to EN 14358 (CEN 2016a). On the other hand, EN

14374 (CEN 2004a) presents the correction factor ($k_{m,corr}$) to be applied to individual bending strength edgewise to the reference value of 300 mm width. Characteristic values from density and bending strength followed the procedure from EN 14358 (CEN 2016a), considering parametric calculation.

The analysis of the LVL tests shows great potential in terms of mechanical properties, especially based on edge-wise tests, traditionally used for sawn wood mechanical characterization. Edgewise results provided a global modulus

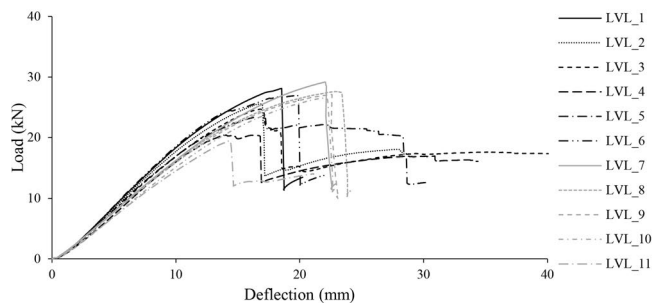


Fig. 4 Load vs deflection curves from flatwise bending tests (left) and shear failure mode observed (right)

Table 1 Summary of results of non-destructive and static bending tests—LVL (edgewise and flatwise)

		E_{dyn_LVL} (MPa)	$E_{m,l}$ (MPa)	$E_{m,g}$ (MPa)	f_m (MPa)	ρ (kg/m ³)	w (%)
Edgewise (8 tests)	Average	24,101	23,952	21,726	101.0	887.1	13.4
	Minimum	21,720	19,959	18,169	88.2	836.2	12.6
	Maximum	24,842	26,324	23,427	112.1	915.0	14.2
	COV (%)	4.4	9.9	7.5	7.6	2.9	4.6
	Adjusted value		24,267	22,015	85.6	881.1	—
Flatwise (11 tests)	Characteristic value		—	—	72.1	830.7	—
	Average	—	—	16,637	93.2	886.4	13.4
	Minimum	—	—	14,369	71.7	836.2	12.6
	Maximum	—	—	19,394	106.7	915.0	14.2
	COV (%)	—	—	10.3	12.2	3.4	5.1
Flatwise (11 tests)	Adjusted value		—	16,865	90.6	880.2	—
	Characteristic value		—	—	68.9	823.6	—

of elasticity 30.5% higher than flatwise and 8.4% higher if bending strength (without correction) is considered. As LVL is usually used as a surface material it was applied a correction for a 300 mm width reference and the difference between characteristic values of bending strength is only 4.7% (higher in edgewise tests). The use of non-destructive characterization (MTG) showed an overestimation of 10.9% compared to the static global modulus of elasticity (edgewise tests). However, a correlation analysis confirms the reliability of the prediction of both local and global modulus of elasticity with correlation coefficients of 0.85 and 0.91, respectively. For bending strength, the correlation coefficient was 0.65 which is slightly higher than 0.59, obtained from sawn wood bending tests conducted by Martins (2015) on a 75 mm × 75 mm cross-section. On the other hand, a higher correlation coefficient of 0.78 was obtained between the global modulus of elasticity and the bending strength, compared to 0.61 obtained by Martins (2015).

Figure 5 compares the results from the current study (BG-LVL-Edgewise/Flatwise) with the literature on Southern Blue gum on structural sawn wood (Alvite et al. 2002 and Lara-Bocanegra et al. 2017) and small clear wood samples (LNEC 1997), as well as results from LVL made with beech (*Fagus sylvatica* L.) (Pollmeier 2024a). A comparison with small clear wood results (LNEC 1997) showed that even with some veneers containing drying cracks or voids from knots, LVL results (edgewise) were significantly higher (25.8%) in terms of stiffness. The average densities were quite similar, being 3.7% higher for LVL. On the other hand, for bending strength, the absence of defects determined an average bending strength of small clear wood results 48.9% higher than LVL results. If compared with structural sawn wood, stiffness results from LVL (edgewise) were 7.0% and 22.6% higher if compared to Alvite et al. (2002) and Lara-Bocanegra et al. (2017), respectively. On the other hand, bending strength values from LVL were 34.1% and 20.0% lower compared to Alvite et al. (2002) and Lara-Bocanegra et al. (2017), respectively. Considering the lower presence of defects such as knots and their size in LVL veneers, such a significant difference in bending strength was not expected. However, the bonding performance of veneers might have had a negative effect, as well as possible fiber discontinuity.

Results from Alvite (2002) were considered as the basis for the development of characteristic values which are reported at UNE 56546 (AENOR 2013). Those values could be used to assign a strength class based on the mechanical properties of Southern blue gum from Spain, “Eucalipto MEF” (“MEF” means “Madera Estrutural de Frondosas—Structural Timber from Hardwoods”), considering specimens with maximum cross-section dimensions of 60 mm × 200 mm. Average and characteristic values of density of 797 kg/m³ and 672 kg/m³ are listed, as well as, 18,400 MPa and 13,500 MPa for modulus of elasticity while

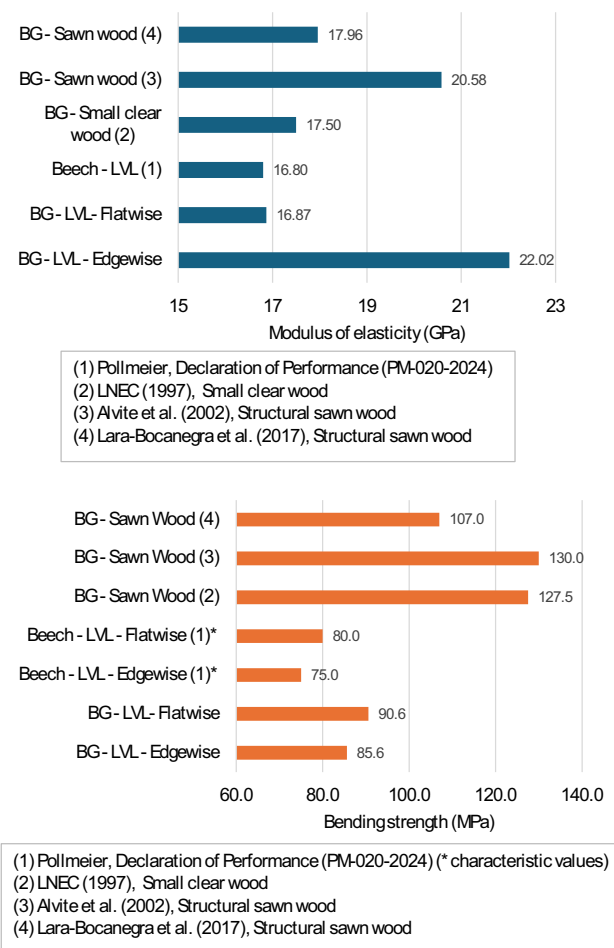


Fig. 5 Comparison of results from LVL with values from the literature: modulus of elasticity (left) and bending strength (right)

a bending strength characteristic value of 47 MPa is indicated. Results from LVL specimens clearly surpass these values, as well as edgewise results comply with the D70 strength class from EN 338 (CEN 2016b).

A comparison between the current results and LVL made with beech (Pollmeier 2024a) showed Southern blue gum LVL as a stiffer product (31.0%) for edgewise bending tests (Fig. 5). Despite the higher stiffness, bending strength characteristic values were 13.9% and 3.9% lower for flatwise and edgewise bending tests, respectively. The sample tested shall be increased to ensure the reliability of the current results.

2.4 LVL bonding performance assessment

Bonding performance from LVL specimens was assessed after edgewise bending tests. The procedure followed Annex B from EN 14374 (CEN 2004a), and a total of 5 specimens with 75 mm or more in width, 100 mm in length, and full thickness of the specimens were considered (one per LVL

specimen) without signs of failure or defects that might influence the performance. The specimens were immersed in boiling water for 4 h, followed by 16 h of drying in a ventilated oven at 60 °C. The immersion process in boiling water was repeated by an additional period of 4 h and then placed in water at room temperature (20 °C). The specimens were cleaved in two different positions using a chisel and a hammer and the apparent cohesive wood failure was determined following the method given in EN 314-1 (CEN 2004b). Figure 6 shows glue lines with apparent cohesive wood failure percentage above 70% whilst Fig. 7 shows glue lines from different specimens in which the required minimum of 70% of wood failure percentage was not achieved. Nevertheless, it should be noted that the production of LVL specimens was carried out in laboratory facilities without specific machinery for an adequate dispersion of the adhesive. There were also no evident signs of bending failure caused by poor glue line adhesion.

3 Hybrid glulam beams made of LVL and poplar sawn wood

3.1 Raw material, production and predictive methods

A total of 8 glulam beams with 92 mm × 120 mm × 2300 mm (width × depth × length) without finger joints were produced at SerQ laboratory facilities. Each beam comprised of 5 lamellae with 24 mm of final thickness. The glulam beams are considered hybrid (H) as they were produced by combining LVL and poplar sawn wood (BP) within the cross-section, divided by two configurations: HLVL-BP and HLVL-4BP. The HLVL-BP configuration considers a symmetric lay-up and comprises 3 central layers of sawn wood (poplar) and 2 external layers (1 in tension and 1 in compression) made with LVL (Southern blue gum). On the other hand, HLVL-4BP considers 1 single LVL layer at the tension side and the

remaining 4 layers of poplar promoting an asymmetric cross-section. Figure 8 shows the visual aspect of both configurations from hybrid glulam beams.

For the hybrid glulam beams production, 27 poplar boards with average dimensions of 36 mm × 121 mm × 3018 mm were selected from a broader sample. Concerning LVL, a total of 13 specimens (11 veneers each) with final average dimensions of 26 mm 120 mm × 2500 mm (thickness × width × length) were produced following the procedure described in subsect. 2.1. Both LVL and poplar boards (BP) were non-destructively characterized to obtain a dynamic modulus of elasticity based on the longitudinal vibration method as described previously for LVL characterization (subsect. 2.2). The non-destructive characterization was repeated before the bonding process, considering the final thickness of 24 mm and 100 mm width, obtaining the dynamic modulus of elasticity for each lamellae, E_{dyn_l} .

Regarding the 13 LVL lamellae an average value of E_{dyn_l} of 25,419 MPa with a coefficient of variation of 3.8% was obtained (values varied between 23,551 MPa and 27,076 MPa). About the 27 poplar lamellae, the values were significantly lower, 39.1% compared to LVL, with an average value of 9928 MPa and a coefficient of variation of 13.9% (a minimum of 7092 MPa and a maximum of 12,730 MPa). The differences of E_{dyn_l} are supported by the density values, being the average density of poplar 400 kg/m³ (with a coefficient of variation of 11.3%), 44.1% lower than the average density of LVL of 905 kg/m³ (with a coefficient of variation of 2.6%). LVL values for glulam beam production are slightly higher than the ones from Sect. 2, namely 5.5% and 2.0% for E_{dyn} and density, respectively. Figure 9 shows the distribution of dynamic modulus of elasticity values per lamellae, the respective average value ($E_{dyn_l_av}$), and the average density value for each hybrid glulam beam.

Previously to the bonding process and for both configurations of hybrid glulam beams, the Transformed Section Method (TSM) was adopted as a predictive method of the



Fig. 6 LVL bonding quality: wood fibre failure above 70%

Fig. 7 LVL bonding quality: wood fibre failure below or close to 70%



Fig. 8 Lay-up of HLVL-BP (left) and HLVL-4BP (right)

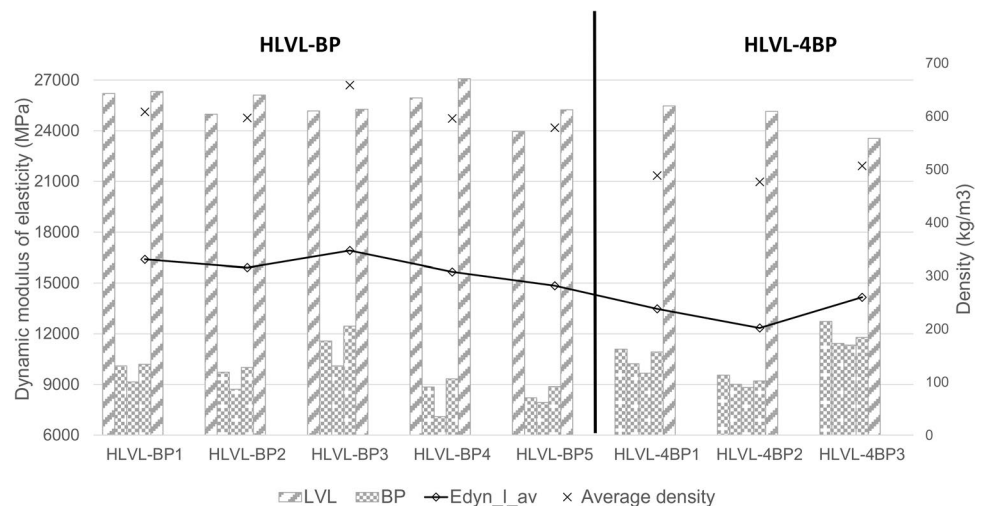
static modulus of elasticity following the equations presented in Annex A4 of ASTM D3737 (ASTM 2005). TSM converts a section with different mechanical properties (three stiffness zones symmetrically displayed) into a transformed section. A transformed section factor, T_i , obtained from Eq. 2, requires as input data the stiffness properties (E_1 , E_2 and E_3) from the raw material (E_{dyn_l} values) and the thickness from each layer. The factor is multiplied by the average stiffness of the outer zone and the estimated modulus of elasticity of the glulam beam is determined (E_{TSM}) according to Eq. 3.

$$T_i = \frac{E_1 d_1^3 - d_2^3 (E_1 - E_2) - d_3^3 (E_2 - E_3)}{E_1 d_1^3} \quad (2)$$

$$E_{TSM} = E_1 T_i \quad (3)$$

where T_i is the transformed section factor, E_1 is the average stiffness from the two outer layers, E_2 is the average stiffness of the two intermediate layers, E_3 is the stiffness of the central layer, d_1 is the distance between the surfaces of the two external layers, corresponding to the depth of the beam, d_2 is the distance between the outer part of the two

Fig. 9 Distribution of E_{dyn_l} and density from lamellae from HLVL_BP and HLVL_4BP glulam beams



intermediate layers and d_3 corresponds to the thickness of the central layer.

The bonding process considered for the assembly of the hybrid glulam beams was similar to LVL production, being considered the same adhesive (Aerodux 185 + HRP 150), as well as the same ratio resin/hardener (100/20). The adhesive was applied manually, and the amount (450 g/m^2) was controlled by weighing and a tooth spatula was used to ensure uniform distribution of the mixture. The assembly process was carried out at controlled conditions ($20 \pm 2^\circ\text{C}$ of temperature and $65 \pm 5\%$ of relative humidity), being adopted 0.8 MPa as the pressure level for 4 h with multiple hydraulic actuators.

3.2 Static bending tests and results

As described for LVL (see sub-sect. 2.2), the 8 hybrid glulam beams were non-destructively tested through the longitudinal vibration method, E_{dyn_glulam} after planning the final cross-section of $92 \text{ mm} \times 120 \text{ mm} \times 2300 \text{ mm}$. The cross-section dimensions were measured at midspan; the overall length and weight; and the average moisture content from measurements on constituent boards (electrical moisture meter) were considered as input data.

Static bending tests followed the principles from EN 408:2010 + A1:2012 (CEN 2012b) and both local and global modulus of elasticity, $E_{m,l}$ and $E_{m,g}$, respectively and bending strength (f_m) were determined. The layout, instrumentation for deflections and load measurements, as well as, load and acquisition protocols, were the same as for LVL tests (see sub-sect. 2.2.). Figure 10 shows a hybrid glulam beam to be tested for static modulus of elasticity.

After each beam bending strength test one slice representative from the full cross-section of the specimen was obtained, located as close as possible to the failure

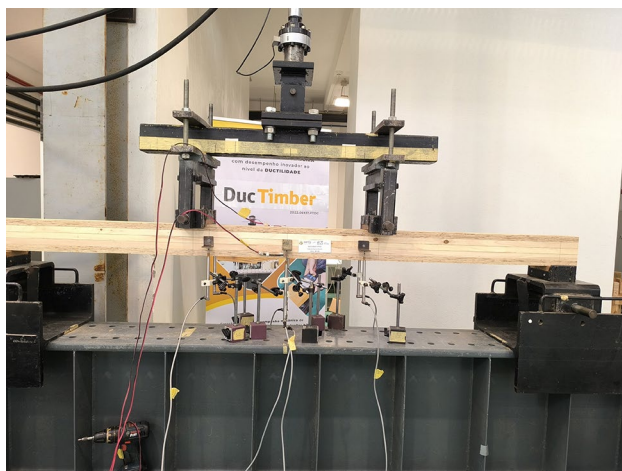


Fig. 10 Bending test layout adopted for testing hybrid glulam beams

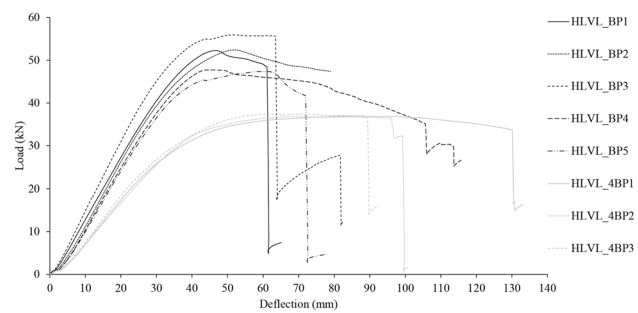


Fig. 11 Load vs deflection curves for both HLVL_BP and HLVL_4BP glulam beams

zone and without defects. The slices were used for the determination of density and moisture content following the oven-dry method specified in EN 13183–1:2002 (CEN 2002a).

During the loading protocol from bending strength tests, a significant increase of deflection before failure was observed, especially for HLVL-4BP glulam beams. Figure 11 shows the load vs deflection recorded from the hydraulic actuator during the loading of each glulam beam for bending strength test. It is observed that HLVL-BP achieves the maximum load-carrying capacity and an increase of about 20–30 mm occurs before failure by shear at the LVL from the tension side (Fig. 12). Similar performance was reported also by Martins et al. (2020) for hybrid glulam beams using Southern blue gum and poplar sawn wood. The ductile behaviour was even more remarkable for HLVL-4BP configuration where a horizontal plateau of deflection of about 50 mm was achieved before failure. The look-up after failure revealed the occurrence of compression folds at the central third span in both configurations as shown in Fig. 13.

From the non-destructive and bending tests, several properties were determined as shown in Tables 2 and 3 for HLVL-BP and HLVL-4BP, respectively. Concerning non-destructive tests, the longitudinal vibration method (E_{dyn_glulam}) and transformed section method (E_{TSM}) were obtained, while from static tests, local, and global modulus of elasticity ($E_{m,l}$ and $E_{m,g}$, respectively), and bending strength values were determined (f_m). Also, both the density (ρ) and the moisture content (w) were determined. The recommendation from EN 384 (CEN 2022) for moisture content adjustment was applied, as well as, the procedure for adjusted values from EN 14358 (CEN 2016a). On the other hand, EN 14080 (CEN 2013) presents the correction factors to be applied to bending strength due to the thickness of lamellae, factor k , and depth of the glulam beam, factor k_h . Characteristic values followed the procedure from EN 14358 (CEN 2016a), considering a parametric calculation.

The use of analytical (Transformed Section Method—TSM) and non-destructive methods (longitudinal vibration

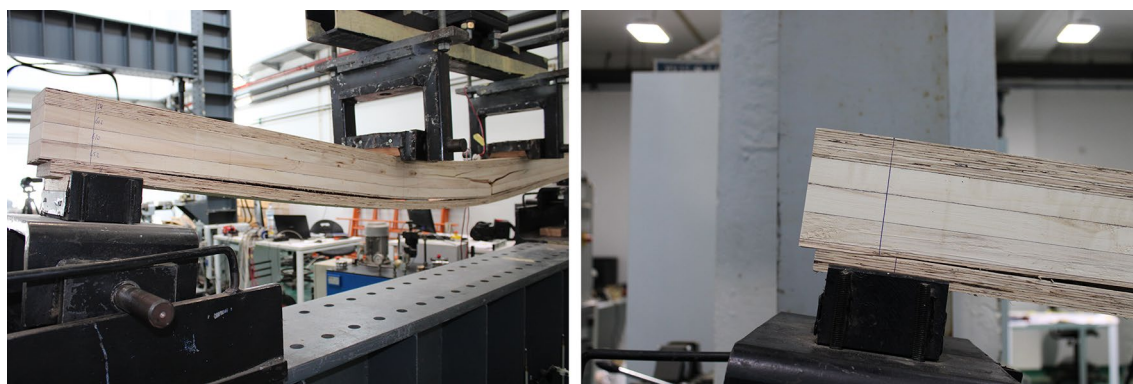


Fig. 12 HLVL-BP failure mode: shear at the bottom lamella (LVL)

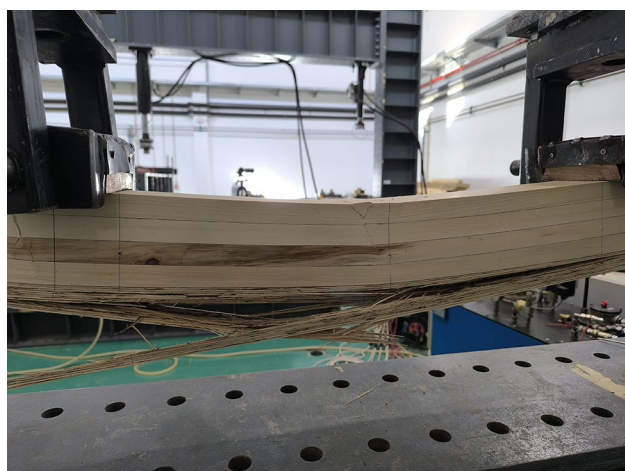


Fig. 13 HLVL-4BP failure mode: tension failure with compression folds at the upper lamellae

method—MTG) provided different predictions of the global modulus of elasticity. For HLVL-BP glulam beams, MTG underestimated by 17.1% the average value of modulus of elasticity while TSM presented an overestimation by 15.7%. Martins et al. (2020) showed similar prediction from the use of MTG with an underestimation of static global modulus of elasticity of 23.6% while TSM prediction was very accurate in terms of average value.

Concerning HLVL-4BP glulam beams, an average value from MTG is similar to the global modulus of elasticity while TSM overestimates the global modulus of elasticity by 22.2%. Despite the differences in average values and estimations, correlation coefficients are quite similar between both methods, being slightly higher for MTG, being 0.85 and 1.00 for HLVL-BP and HLVL-4BP, than TSM (0.83 and 0.84 for HLVL-BP and HLVL-4BP, respectively). It should be noted that the reduced number of tests may influence the correlations and an increased sample should be considered in the future to validate the results. For HLVL-BP a very high correlation coefficient (0.93) was determined between MTG and bending strength compared to the correlation coefficient from global modulus of elasticity (0.77) or TSM (0.58).

The analysis of the results from glulam beams made with LVL on both compression and tension layers (HLVL-BP) resulted in higher physical and mechanical properties compared to glulam beams with LVL only on the tension side (HLVL-4BP). HLVL-4BP presents an average density 19% lower than HLVL-BP which corresponds to an expected decrease in mechanical properties. For modulus of elasticity, it was registered a decrease of 37% and 31% for local and global, respectively while for bending strength a decrease of 26% was observed.

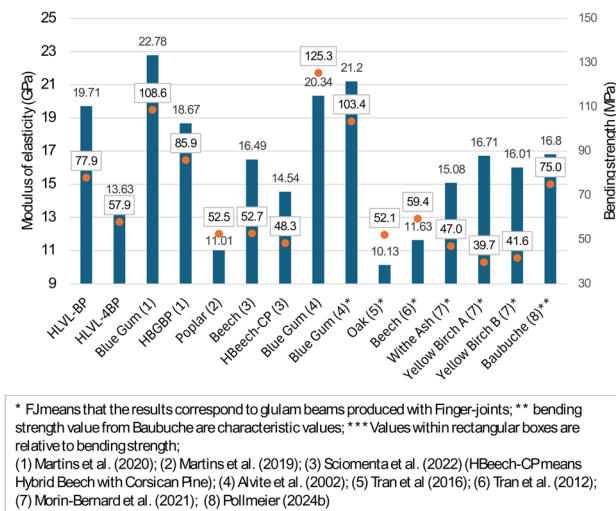
Figure 14 presents a summary of results (modulus of elasticity and bending strength) from glulam beams made

Table 2 Summary of results from non-destructive and static bending tests—HLVL-BP glulam beams (5 specimens)

	E_{dyn_glulam} (MPa)	E_{TSM} (MPa)	$E_{m,l}$ (MPa)	$E_{m,g}$ (MPa)	f_m (MPa)	ρ (kg/m ³)	w (%)
Average	15,929	22,233	22,314	19,218	82.5	616.5	14.6
Minimum	14,644	21,104	19,821	18,507	78.6	589.1	13.7
Maximum	16,978	22,743	25,416	19,662	85.6	673.4	16.6
COV (%)	5.8	3.0	10.0	2.3	3.9	5.6	1.2
Adjusted value			22,903	19,713	77.9	608.6	—
Characteristic value			—	—	71.0	522.7	—

Table 3 Summary of results from non-destructive and static bending tests—HLVL-4BP glulam beams (3 specimens)

	E_{dyn_glulam} (MPa)	E_{TSM} (MPa)	$E_{m,l}$ (MPa)	$E_{m,g}$ (MPa)	f_m (MPa)	ρ (kg/m ³)	w (%)
Average	13,304	16,290	14,052	13,334	61.3	497.0	14.2
Minimum	12,401	15,568	12,307	12,667	60.6	479.8	14.0
Maximum	14,102	16,703	15,038	13,937	62.2	514.2	14.4
COV (%)	6.4	3.9	10.8	4.8	1.4	3.5	1.6
Adjusted value			14,367	13,634	57.9	491.4	–
Characteristic value			–	–	55.4	437.9	–

**Fig. 14** Comparison of results from LVL with values from literature: modulus of elasticity (left) and bending strength (right)

with different hardwood species without or with finger joints (Martins et al. 2020; Martins et al. 2019; Sciomenta et al. 2022; Alvite et al. 2002; Tran et al. 2012; Tran et al. 2016; Morin-Bernard et al. 2021; and Pollmeier 2024b).

A comparison of the results from Fig. 14, namely the present study with HBGBP (hybrid glulam beams with two external layers of Southern blue gum sawn wood and 3 internal layers of Poplar) (Martins et al. 2020) shows small differences, being obtained in the present study a lower average density (4.5%; HBGBP = 637 kg/m³) but 5.6% higher modulus of elasticity. Regarding bending strength, the current study presented a lower average value (9.3%) compared

to HBGBP. Thus, the effect of using LVL layer did not significantly influence the mechanical properties compared to the adoption of sawn wood. However, the use of veneers can be a solution for the use of Southern blue gum for structural applications, as there are several studies that report the difficulties of sawing and drying Southern blue gum (Franke and Marto 2014; Hansmann et al. 2008) as well as the bonding performance (Lopez-Suevos and Richter 2009; Martins et al. 2020).

On the other hand, the HLVL-4BP configuration adopted for the present study can be considered a nature-based solution for the improvement/ reinforcement of Poplar glulam beams. The results from the 3 glulam beams HLVL-4BP compared with 18 glulam beams made by a full cross-section of poplar lamellae realized by Martins et al. (2019) shows higher values, being 14.8% higher in terms of density (428.1 kg/m³), 23.8% higher in terms of global modulus of elasticity and 10.4% higher in terms of bending strength. The differences are even more evident on bending strength if characteristic values are compared with 55.7% higher values for HLVL-4BP compared with 35.6 MPa for BP glulam beams. Despite the small number of glulam beams from HLVL-4BP the recorded CoV tends to be very small (1.4%).

Considering the full spectrum of results, values from HLVL-BP configuration were settled just below the configurations that include the full cross-section made of Southern blue gum sawn wood. HLVL-BP showed a 19.5% higher modulus of elasticity compared with glulam beams made with European beech (Sciomenta et al. 2022), and 17.3% if compared with Baubuche GL75, the strongest engineered wood product available in the market (Pollmeier 2024b). A comparison with hardwood species from Canada (Yellow

Table 4 Summary of specifications from delamination tests according to EN 14080

	Water Impregnation			Drying process		
		1st step (min)	2nd step (min)	Total time (min)	Temperature (°C)	Relative humidity (%)
Method A	Vacuum	5	5	130	60 to 70	< 15
	Pressure	60	60			
Method C	Vacuum	30	30	300	25 to 30	25 to 35
	Pressure	120	120			



Fig. 15 Specimens after delamination test: left—HBGBP (Martins et al. 2020); centre and right—HLVL-BP

birch and White ash) (Morin-Bernard et al. 2021) showed similar results with the difference varying between 18.0 and 30.7% for yellow birch and white ash, respectively. For bending strength, the comparison showed similar conclusions with HLVL-BP values highly above the results from other species and combinations, varying between 31.2 and 96.2%. Nevertheless, it should be noted that the current study does not include finger joints within the lamellae. Alvite et al. (2002) assessed the bending strength for Southern blue gum glulam beams with and without finger joints and a decrease of 17.5% was noticed as shown in Fig. 14. A similar conclusion was obtained by Lara-Bocanegra et al. (2020) for Southern blue gum sawn wood with and without finger joints where a decrease of 18.7% was recorded. Thus, considering the scenario of a 17.5% decrease in HLVL-BP bending strength due to the finger joint effect, an average bending strength of 64.3 MPa was calculated, which remains 6% above the results from beech (Tran et al. 2012) up to 61.9% for Yellow birch (Morin-Bernard et al. (2021).

3.3 Bonding process and performance assessment

The bonding performance was assessed after static bending tests through delamination tests, and for that purpose, Annex C from EN 14080 (CEN 2013) was followed as there are no available standards for this hybrid configuration and hardwoods. EN 14080 (CEN 2013) states that for service class 3, Method A or B shall be used for factory production control. For the present study, Method A was adopted and when double specimens were available from the same glulam beam Method C was also considered for

comparison. A total of 11 specimens of $92 \times 120 \times 75 \text{ mm}^3$ were cut after each bending strength test (without the presence of failure signs/marks). The delamination tests consist of introducing internal stresses on glue lines by immersion of the specimens into the water and applying a two process of vacuum–pressure, followed by a drying process in a specific drying duct with controlled temperature and relative humidity. The periods and specifications from each Method are summarized in Table 4. The delaminations were measured within 1 h after 2 cycles (Method A) or just 1 cycle (Method C). For Method A an additional test cycle can be performed if the total delamination exceeds 5%. According to EN14080, a limit of 10% of total delamination shall not be surpassed after the 3rd test cycle (Method A) or after the single test cycle (Method C).

The aim of the current study apart from the assessment of mechanical properties was also to assess the bonding performance of Southern blue gum veneers following Method A (7 specimens) but also Method C (4 specimens) obtained from 3 different glulam beams (all from HLVL_BP configuration). Average values and individual maximum total delamination from both methods were well below the maximum values from Method A (5% for 2nd cycle and 10% for 3rd cycle) and Method C (10%). From Method A average values of 0.8% and 1.2% were recorded for 2nd and 3rd test cycles, respectively, being 2.2% the maximum value. Concerning Method C 1.8% and 4.4% were the average and the maximum values recorded. Further tests are needed to improve the reliability of the results. These results surpass the performance observed by Martins et al. (2020) which obtained a poor bonding performance for glulam beams made by Southern blue gum sawn wood combined with poplar and

glued with PUR adhesive, following Method A from EN 14080 (CEN 2013). Figure 15 shows the difference between the delamination that occurred within a HBGBP specimen and two specimens from the current study (HLVL-BP). The bonding performance at the interface between Southern Blue gum and Poplar improved significantly.

4 Conclusion

The present paper aimed to assess the mechanical properties of LVL made of Southern blue gum veneers and its potential to be used as lamellae for glulam production. Southern blue gum veneer is traditionally considered for plywood production and can be combined with other species such as poplar. In the developed study LVL specimens were produced in the laboratory using a PRF adhesive and tested both on edgewise and flatwise (specimens obtained from edgewise tests). The use of non-destructive characterization was considered, and high correlation coefficients were obtained both for modulus of elasticity (above 0.85) and for bending strength (0.65). From edgewise tests values of 24,267 MPa and 22,015 MPa were obtained for local and global modulus of elasticity and a characteristic value of 72.1 MPa was determined for bending strength.

The use of LVL for glulam production was tested in two different configurations. A symmetric configuration allowed to optimize the use of underutilized raw material (poplar boards) to achieve a product with high mechanical properties compared to the most commonly used glulam strength class, GL24h. Both local and global modulus of elasticity values, 22,903 MPa and 19,713 MPa, respectively surpass the stiffness of the strongest product in the market with similar characteristic value of bending strength (71.0 MPa). On the other hand, the use of LVL in the tension side combined with 4 poplar layers provided a nature-based reinforcement of the mechanical properties for a low/mid-density product (491.7 kg/m³) with reasonable stiffness (14,367 MPa and 13,634 MPa for local and global modulus of elasticity, respectively) and an outstanding characteristic value for bending strength of 55.4 MPa. Besides the mechanical performance and the excellent bonding performance achieved between LVL and poplar, ductile behaviour was evident, being observed a minimum of 50 mm deflection at the maximum load level before failure. More tests are needed to confirm the data from the current study.

Acknowledgements This work was partially funded by FCT/MCTES through national funds (PIDDAC) under the R&D unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB/ 04029/2020, and under the Associate Laboratory Advanced Production and Intelligent Systems ARISE under the reference LA/P/0112/2020. It was also partially funded by the Portuguese Foundation for Science and Technology (FCT) through the project

DucTimber under reference 2022.06937.PTDC. The authors would like to acknowledge Laminar – Indústria de Madeira e Derivados for providing the Southern blue gum veneers.

Funding Open access funding provided by FCTIFCCN (b-on).

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest Disclosure of potential conflicts of interest.

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