Key Mechanical Properties of Cross-banded Laminated Veneer Lumbers Manufactured from Blending Spotted Gum and Hoop Pine Veneers

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The main objective of this study was to investigate the key mechanical properties of cross-banded laminated veneer lumbers (LVL-C) manufactured from blending veneers recovered from sub-optimal native forest spotted gum and plantation hoop pine logs. The recovered veneers were separated into three grades based on their dynamic modulus of elasticity (MOE). Additionally, the spotted gum veneers were visually graded to evaluate whether a relationship exists between the MOE-based and visual grades. In total, six 12-ply reference LVL and six mixed-species 12-ply LVL-C panels were manufactured and analyzed for (i) flatwise and edgewise bending performance; (ii) bearing and tension strength perpendicular to the grain; and (iii) longitudinal-tangential shear strength. Little correlation was found between MOE-based and visual grades for the spotted gum veneers. The LVL- C showed flatwise and edgewise MOE up to 24% and 13% lower, respectively, than the reference mixed-species LVL. The flatwise and edgewise modulus of rupture were up to 39% and 19% lower, respectively. On average, the tensile and bearing strengths of the LVL-C were considerably higher than the hoop pine LVL and mixed-species LVL, with the former being approximately three times higher. The manufactured LVL-C showed markedly higher bending properties and tensile strengths than commercial LVL-C products.

Keywords: Cross-banded laminated veneer lumber; Mixing species; Sub-optimal native forest logs

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INTRODUCTION

Small-diameter (less than 30 cm in diameter at breast height) spotted gum (SPG; *Corymbia citriodora*) hardwood logs are potentially available from sustainably managed native Australian forests. However, this resource is currently considered sub-optimal in quality due to incompatibility with traditional converting techniques, and therefore contributes minimal or no value. Thus, the resource has not been fully utilised (McGavin and Leggate 2019). This species of SPG is known for its high mechanical properties and durability (Bootle 2005), and therefore it could be used for various structural applications. To process such small diameter logs, relatively new spindle-less rotary veneer technology has been demonstrated to be efficient, recovering up to 70% of the log into veneers that have properties well suited to structural veneer-based products (VBP) (McGavin *et al.* 2014a; McGavin and Leggate 2019).

While the volume of the above SPG logs is limited, a large volume of hoop pine (HP; *Araucaria cunninghamii*) softwood plantation logs are available, with HP being one of the well-established commercial plantation trees in Queensland. A potential commercialization opportunity for the small quantity of rotary-peeled veneers from small-diameter native SPG logs is currently being investigated through a strategy of blending SPG and HP veneers to produce laminated veneer lumbers (LVL) and cross-banded laminated veneer lumbers (LVL-C) (McGavin and Leggate 2019; Nguyen *et al.* 2019). Mixing these two species into LVL and LVL-C results in veneer lumbers with structural characteristics that are comparable or superior to currently commercialized VBP (McGavin *et al.* 2019; Nguyen *et al.* 2019). However, the number and grade of SPG and HP logs used to manufacture the veneer products in these studies were chosen so as to provide benchmark performance data using generic product construction strategies and identified opportunities for further optimization. To further pursue this opportunity, Nguyen *et al.* (2019) developed a tool to optimize the use of given resources while targeting final grades of products, but the optimum LVL-C products resulted from this optimization tool were not fully tested. Although in Nguyen *et al.* (2019), dynamic modulus of elasticity (MOE)-based veneer grading was adopted to optimize the products, visual grading is still widely accepted for VBP in Australia (McGavin *et al.* 2014b; McGavin and Leggate 2019) and research is still needed to understand the relationship between MOE-based veneer grading for the SPG veneers and the visual grading method.

Consequently, the key objectives of this work are to: (i) evaluate the difference between visual-grading and MOE-grading methods when applied to rotary peeled SPG veneers from small-diameter logs; (ii) to examine the mechanical properties (edgewise and flatwise bending static MOE and modulus of rupture (MOR), tension and bearing strength perpendicular to the grain, and longitudinal-tangential shear strength) of optimised LVL-C products manufactured by blending SPG and HP veneers; and (iii) to compare the measured properties to LVL manufactured from SPG and HP veneers or commercially available LVL-C.

Unlike plywood products, which have alternate cross-laminated veneers (Walker 2006), LVL-C that is usually manufactured with one-fifth of veneers glued crosswise was proposed to overcome the low mechanical properties perpendicular to the grain typically encountered in LVL, resulting in the possibility of premature splitting failure in structural connections (Kobel *et al.* 2014). Especially, relevant to this study, low tension perpendicular to the grain capacity (about 1.0 to1.5 MPa) were reported for VBP manufactured from small-diameter plantation-grown SPG logs (Gilbert *et al.* 2018a).

This paper is part of various Australian projects aiming at developing a market for forest resources with inadequate size and qualities to be efficiently considered (McGavin *et al.* 2013; Gilbert *et al.* 2014, 2018b; McGavin *et al.* 2019).

METHODOLOGY

Timber Used

As part of a collaborative project between the timber industry and the Queensland government, aiming at transforming lower-cost logs into high-performance engineered wood products, small diameter native forest SPG and commercial plantation HP logs were rotary peeled using a spindle-less rotary veneer lathes into nominal 3.0 mm thick veneers. About 60 SPG logs were peeled and thus produced the feedstock for the LVL manufacturing. A sub-set of 163 SPG veneer sheets of dimension 1.5 m × 2.6 m were taken from the recovered veneers, whereas 246 HP veneer sheets of 1.5 m × 2.6 m were selected from the production line of a commercial veneer manufacturer. The details (age of the trees, breast height diameter, number of trees, *etc*.) of the SPG resource and processing information has been previously reported by McGavin and Leggate (2019). Resource information was not available for the HP as the veneers were collected from within a commercial process. After peeling, the veneer sheets were dried to a target moisture content of 8%.

Veneer Grading

The dried SPG veneers were visually graded first, and their dynamic MOE was then measured. For the HP veneers, only their dynamic MOE was measured.

Visual grading of each 1.5 m × 2.6 m SPG veneers was undertaken in accordance with Australian and New Zealand standard AS/NZS 2269.0 (2012). This standard separated veneers into the following grades: A (high-quality appearance), B, C, D, and reject F-grade, based on the presence and severity of defects. This grading process is well accepted by the Australian veneer industry, and similar systems also exist internationally (Wang and Dai 2013; Leggate *et al.* 2017; McGavin and Leggate 2019).

To measure the dynamic MOE parallel to the grain ($E_{\text{L-Veneer}}$) of the SPG and HP veneers, a 200 mm (tangential direction) x 1,200 mm (longitudinal direction) strip was cut from each veneer sheet. An acoustic natural-vibration method (Brancheriau and Baillères 2002; CIRAD 2018) was used to measure the dynamic MOE of each strip, following the procedure detailed in McGavin *et al.* (2019). The longitudinal natural frequency of the strip were recorded and analysed using the software Beam Identification by non-destructive grading (CIRAD 2018). For each species, three grades, referred to as low, medium, and high, were identified and equally divided the veneers into three bins. The MOE cut-off values between the grades were the 33rd and 66th percentile values of the cumulative distributive function of each species. The MOE cut-off values and the grade notations for the two species followed the methodology reported by Nguyen *et al.* (2019), and is shown in Table 1.

To understand whether visual grading could be an appropriate approach to guide the manufacture of VBP of targeted MOE from the native forest SPG, the correlation between MOE-based grades and visual grading is determined through the established distribution of MOE-based grades (*i.e.*, “Low”, “Medium”, and “High”) in each visual grade (*i.e.*, A, B, C, D, and F).

Table 1. Veneer MOE Grading

Species	Grade	MOE threshold (GPa)
Spotted Gum	SPG_L	MOE < 20.3
	SPG_M	20.3 ≤ MOE<23.7
	SPG_H	MOE ≥ 23.7
Hoop Pine	HP_L	MOE < 11.3
	HP_M	11.3 ≤ MOE <13.1
	HP_H	MOE ≥ 13.1

Construction Strategies and LVL Manufacturing

Two different construction strategies for both the reference 12-ply LVL and optimized 12-ply LVL-C were investigated and are shown in

Fig. Fig. 1. They consist of one single-species reference HP LVL, one mixed-species reference LVL, and two mixed-species LVL-C. Note that SPG veneers are placed as face veneer in mixed-species LVL and LVL-C products to improve the flatwise bending properties but also appearance of the investigated products. The construction strategies are detailed as follows:

- Strategy LVL_1 consisted of a reference LVL manufactured from HP veneers only. All veneers have a dynamic MOE greater than 13.1 GPa (High grade).
- Strategy LVL_2 consisted of a reference LVL with eight HP veneers of various grades in core [(6 × low grade; MOE < 11.3 GPa); and (2 × high grade; MOE > 13.1 GPa)]. Two SPG veneers (one high grade (MOE ≥ 23.7 GPa) and one low grade (MOE < 20.3 GPa)) on each face. In the optimization process (Nguyen *et al.* 2019), this strategy aimed at targeting a final product with an edgewise bending MOE greater than 14 GPa while maximizing the use of low-grade HP veneers and minimizing the use of high-grade SPG veneers.
- Strategy LVL-C1 consisted of mixed-species LVL-C with eight HP veneers of different grades (6 × low grade and 2 × medium grade (11.3 GPa ≤ MOE < 13.1 GPa) in core and two high-grade SPG (MOE > 23.7 GPa) veneers on each face. Two out of the six low-grade HP veneers were rotated at 90^o (cross-banded veneers). The LVL-C1 aimed at minimizing the use of high-grade SPG veneers while targeting average edge bending dynamic MOE greater than 14 GPa (Nguyen *et al.* 2019).
- Strategy LVL-C2 consisted of mixed-species LVL-C that were manufactured from the exact same veneer sheets used in the manufacture of LVL_2, but with two HP veneers rotated at 90^o. This allows a direct comparison between the two products.

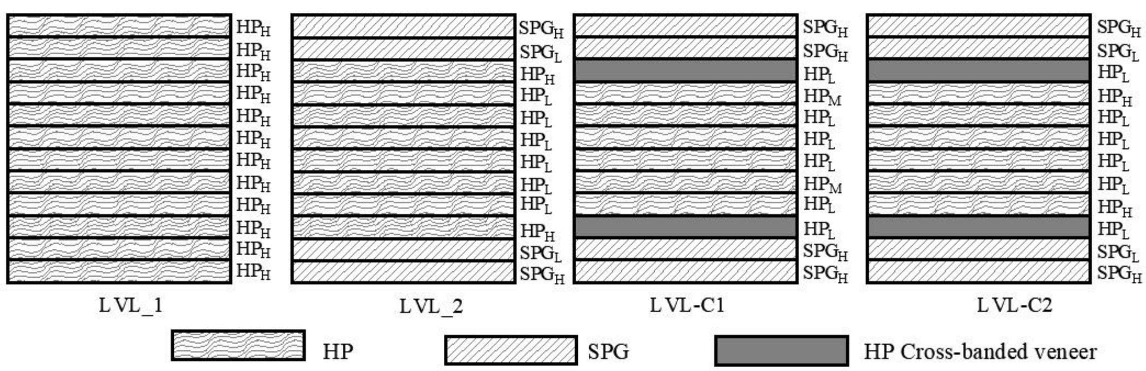


Fig. 1. Construction strategies of LVL and LVL-C

Panel Manufacturing

Three panels per construction strategy, *i.e.*, a total of 12 panels with a targeted thickness of 36 mm, were manufactured. The veneers were glued using a commercial melamine urea formaldehyde (MUF) adhesive with a glue spread level of 400 g/m^2 per glue line. This adhesive was selected to achieve a B-bond glue line that is suitable for application involving up to two years exposure to the weather or damp condition as outlined in Australian Standard AS/NZS 2754.1 (2016). The panels were pre-pressed with an open assembly time of 22 min (measured from adhesive application to the first veneer to when pressure was applied in the press) and hot-pressed at 1.1 MPa and at a temperature of 135 °C during 26 min. After hot-pressing, the panels were stacked for two weeks for post curing.

Two panels (one for strategy LVL-C1 and one for strategy LVL-C2) experienced gluing problems during the manufacturing process and were discarded.

Test Samples and Test Set-up for Mechanical Properties

After LVL manufacturing, the samples were cut from each panel using the cutting patterns reported by McGavin *et al.* (2019). These samples were then experimentally evaluated for the following properties: Static edgewise bending MOE (E_{b_e}); static flatwise bending MOE (E_{b_f}); edgewise bending MOR (f_{b_e}); flatwise bending MOR (f_{b_f}); tension perpendicular to grain strength ($f_{t\_\perp}$); bearing perpendicular to grain strength ($f_{c\_\perp}$); and longitudinal-tangential shear strength (f_s).

The samples were conditioned at 20 °C and 65% relative humidity before being tested, following the recommendations in the Australian standard AS/NZS 4357.2 (2006). Bearing and tension samples tested perpendicular to the grain were weighed immediately after being tested to calculate the moisture content of the timber at the time of testing, following the over-dry methodology in the Australian and New Zealand standard AS/NZS 1080.1 (2012). Similarly, for bending samples, a 25 mm long piece was cut from each sample and weighed immediately after testing to determine the moisture content of the samples.

For all LVL and LVL-C samples, the thickness (t_{LVL}) of each panel was measured by averaging the thicknesses of all the test samples cut from the same panel. The same calculation was applied for density and moisture content (MC) determinations.

Note that due to the nature of rotary peel veneers the perpendicular direction to the grain corresponds to the tangential direction of the wooden material. The testing methodology for each test are described in the following subsections.

Edgewise and flatwise bending strengths and static MOE

The static bending tests were conducted in accordance with the Australian standard AS/NZS 4357.2 (2006) using a four-point bending test set-up. From each panel, two 60 mm (height) × 1,200 mm (long) samples were tested in the edgewise bending and two 100 mm (wide) × 800 mm (long) samples were tested in flatwise bending using a Shimadzu universal testing machine (AG-100X, Brisbane, Queensland, Australia) at a stroke rate of 5 mm/min to reach failure between 3 min and 5 min. The apparent static MOE was determined from the measurement of the mid-span vertical displacement, measured with a digital camera (Fig. 2a-2c), of the samples as,

$$MOE = \frac{23 \times L^3}{108 \times b \times d^3} K_{elas} \quad (1)$$

where L (mm) is the total span, d and b (mm) are the measured depth and width of the samples, respectively, and K_{elas} (mm) is the elastic stiffness of the load-displacement curve, calculated herein by performing a linear regression on the linear part of the curve.

The MOR of the samples is calculated as,

$$MOR = \frac{F_{ult} \times L}{b \times d^2} \quad (2)$$

where F_{ult} (mm) is the ultimate load.

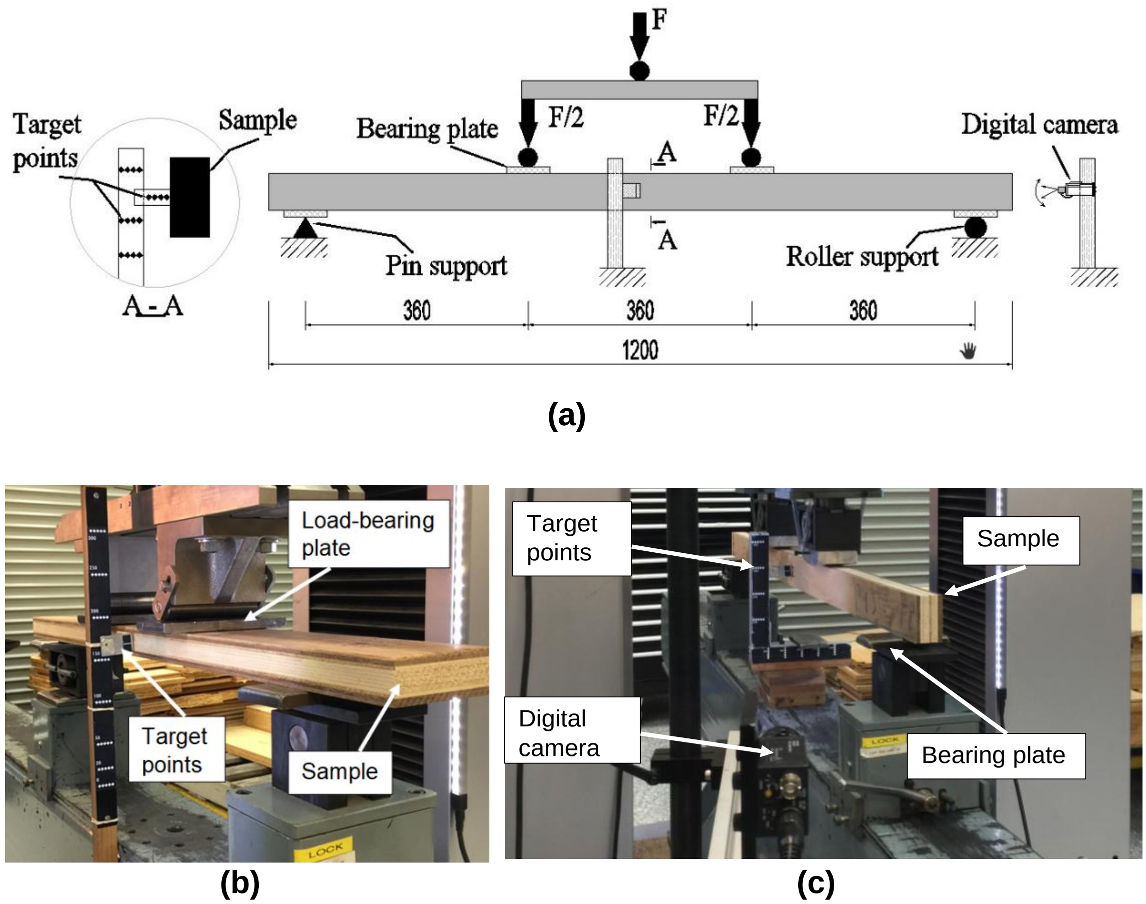


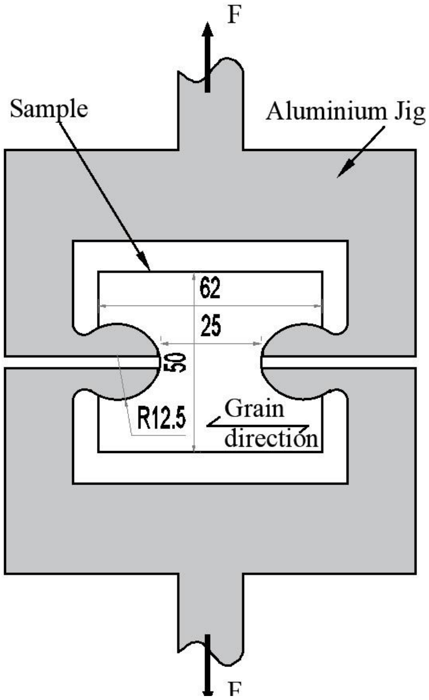
Fig. 2. Static bending test set-up, (a) schematic and (b-c) photos

Tensile strength perpendicular to the grain

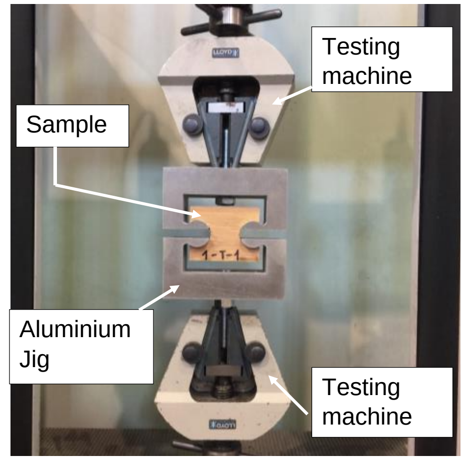
The tensile strength perpendicular to the grain was determined following the configuration in the ASTM D143-14 (2014) that was developed for solid timber specimens. The procedure was successfully adopted in the literature to LVL samples (Ardalany *et al.* 2011; Gilbert *et al.* 2018a). Three samples were cut per panel to the dimensions given in Fig. 3a. The samples were then inserted into an aluminium jig as shown in Fig. 3b. The jig was gripped in the jaw of a 30 kN capacity Lloyd universal testing machine (LR30K, Goldcoast, Queensland, Australia), which was driven in displacement control, at a stroke rate of 2.5 mm/min, to reach failure between 1.0 min and 3.0 min. The tensile strength perpendicular to grain $f_{t\_\perp}$ of the samples is calculated as,

$$f_{t\_\perp} = \frac{F_{ult}}{w \times t} \tag{3}$$

where F_{ult} is the ultimate applied force, and w and t (mm) are measured width and thickness of the sample, respectively. The width w is measured at the minimum cross-sectional width as shown in Fig. 3, with nominal w equal to 25 mm.



(a)

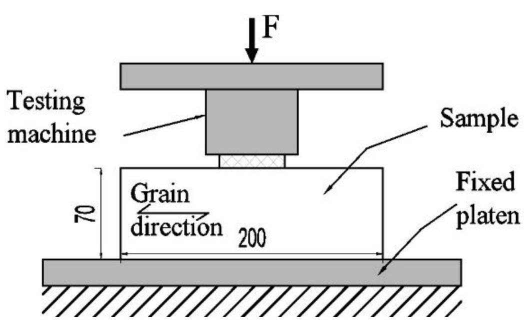


(b)

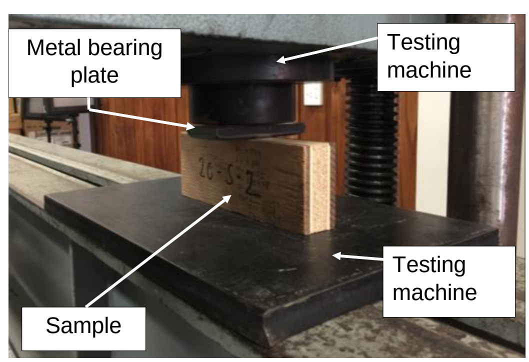
Fig. 3. Tension perpendicular to grain test set-up, (a) schematic and (b) photo

Bearing strength perpendicular to the grain

Bearing strength perpendicular to the grain was determined using the bearing strength test method from Australian standard AS/NZS 4063.1:2010 (2010). Two 70 mm (height) × 200 mm (long) test samples were cut from each panel. The tests were conducted in a Shimadzu universal testing machine and the load was applied at a speed rate of 1.0 mm/min to reach failure between 2 min and 5 min. The load was transferred to the samples through a metal bearing plate of 50 mm in width placed across the upper surface of the samples at equal distances from the ends of the sample (Fig. 4).



(a)



(b)

Fig. 4. Bearing perpendicular to grain test set-up, (a) schematic and (b) photo

The bearing strength perpendicular to the grain $f_{c\_\perp}$ was calculated from the following equation,

$$f_{c\_\perp} = \frac{F_p}{50 \times b} \tag{4}$$

where F_p (mm) is the value of applied load corresponding to a 2.0 mm deformation, b (mm) is the breadth of the test piece. Note that the displacement of the stroke of the testing machine was taken as the deformation of the testing sample.

Longitudinal-tangential shear strength

Longitudinal-tangential shear strength testing was conducted in accordance with Australian standard AS/NZS 4063.1 (2010). Two 70 mm (height) x 570 mm (long) samples were cut per panel and tested using a three-point bending test set-up, as shown in Fig. 5. The shear strength f_s of a sample is calculated from the following equation,

$$f_s = \frac{0.75 \times F_{ult}}{b \times d} \tag{5}$$

where F_{ult} (mm) is the ultimate value of the applied load, b and d (mm) are the measured width and depth of the cross-section, respectively.

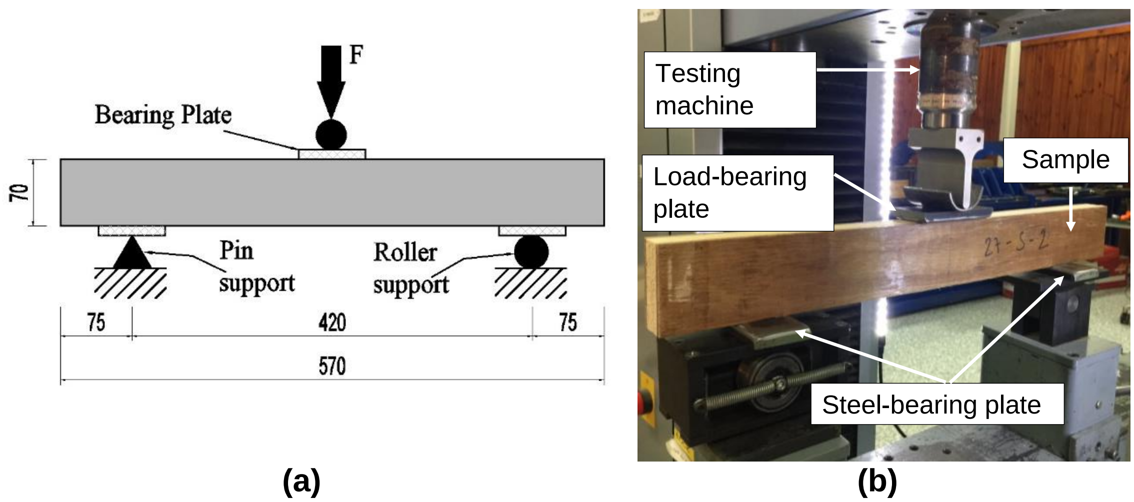


Fig. 5. Longitudinal-tangential shear test set-up, (a) schematic and (b) photo

Commercial LVL-C Used for Comparison

The mechanical properties of the manufactured LVL-C are compared in this paper to product literature for commercially available 11-ply LVL-C products, namely Kerto-Q and STEICO LVL-*X* manufactured from Metsä wood company (Metsä Wood company 2019), and STEICO company (STEICO group 2019), respectively. These LVL-C products included two cross-banded veneers and were manufactured from spruce (*Picea abies*) or pine (*Pinus sylvestris*) veneers of nominal thickness 3 mm.

RESULTS AND DISCUSSION

Veneer Grading

Figure 6 presents the visual-grading distribution of SPG veneers with 3%, 6%, and 70% of veneer sheets being classified into B-grade, C-grade, and D-grade, respectively. The remaining veneers were classified as F-reject. No veneers were graded into A-grade.

Figure 7**Fig.** plots the distribution of MOE-based grades for each visual grade and indicates that there was limited correlation between visual-grading and the MOE-based grading, especially for C-grade and below. Veneers visually graded as B-grade were all graded as having high MOE, while C-grade, D-grade, and F-reject had a relatively uniform distribution of low, medium, and high dynamic MOE graded veneers. This suggests there is limited opportunity for a commercial product manufacturer to utilize a visual grading system to target veneers with specific veneer stiffness properties.

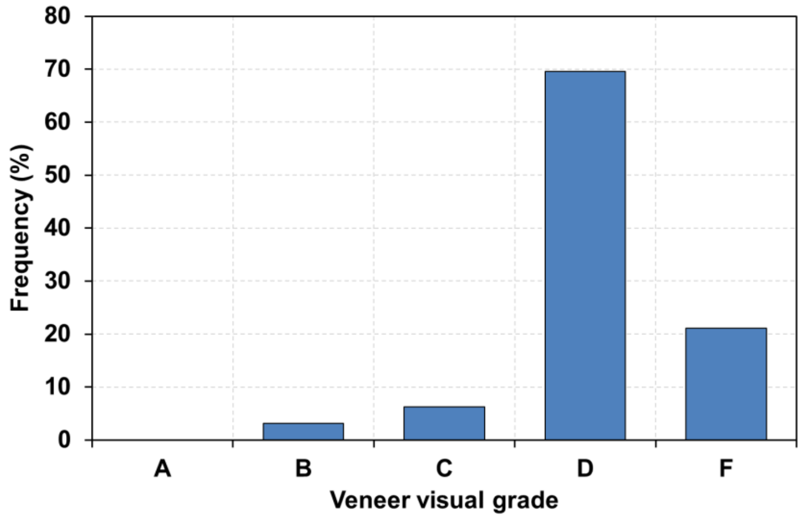


Fig. 6. SPG veneer visual grade distribution

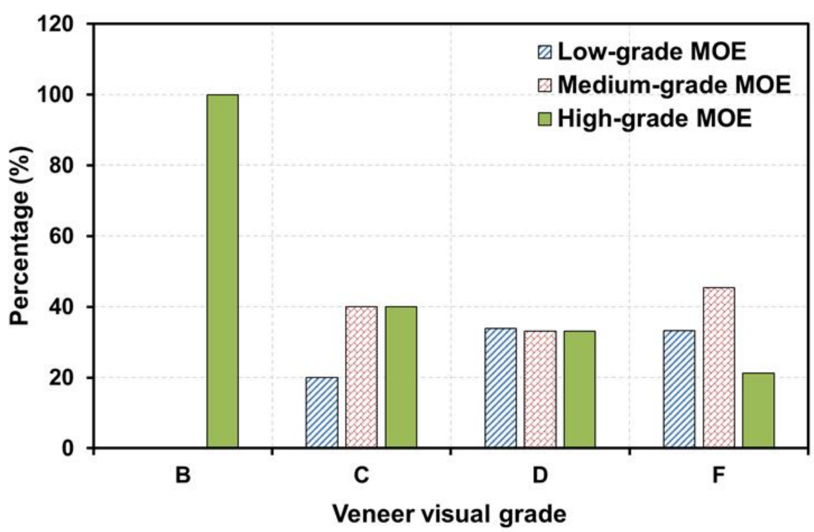


Fig. 7. The distribution of MOE-based grades for each visual grade of SPG veneers

Panel Thickness and Moisture Content

The average thickness, density, and moisture content at the time of testing for all panels are summarised in Table 2. The mean oven-dry moisture content at the time of testing for all investigated products ranged from 11.5% to 13.6%.

Table 2. Physical Properties of LVL-C and LVL

Types	Panel	Thickness t_{LVL}		Moisture Content		Density	
		Average (mm)	CoV (%)	Average (%)	CoV (%)	Average (kg/m^3)	CoV (%)
LVL_1	1	33.2	3.05	12.7	2.26	629	1.55
	2	33.7	2.47	13.1	2.30	658	1.40
	3	33.0	1.69	13.6	5.27	637	2.60
	Ave.	**33.4**		**13.1**		**648**	
LVL_2	1	34.8	2.24	11.8	2.23	779	2.32
	2	34.5	1.15	12.5	2.88	805	2.10
	3	34.4	0.67	12.2	2.26	780	2.09
	Ave.	**34.5**		**12.2**		**788**	
LVL-C1	1	35.0	3.60	12.3	1.31	766	2.85
	2	34.9	1.44	11.8	4.20	793	1.40
	Ave.	**35.0**		**12**		**780**	
LVL-C2	1	34.4	3.80	12.1	2.07	746	2.80
	2	33.8	0.88	11.5	1.97	756	2.30
	Ave.	**34.1**		**11.8**		**751**	
CoV (%) represents the coefficient of variation							

Edgewise and Flatwise Bending Test Results

TableTable 3 shows the calculated static MOE and MOR for both flatwise and edgewise bending for all investigated products. Due to LVL_2, LVL-C1, and LVL-C2 construction strategies that use high MOE veneers as face veneers, their static flatwise bending MOE E_{b_f} was found to be 20% higher on average than the corresponding static edgewise bending MOE E_{b_e}. The average flatwise and edgewise bending MOE value of the single-species HP LVL_1 was up to 29% and 12% lower, respectively, than the mixed-species LVL and LVL-C. Despite sharing the same veneers in the manufacture, LVL_2 had an edgewise and flatwise bending MOE 13% and 24% higher, respectively, than LVL-C2. This indicated that a relatively large contribution of the two cross-banded low MOE HP veneers on the stiffness of the products. Due to the two high-grade MOE SPG veneers against one high-grade and one low-grade veneers on each side, LVL-C1 showed higher MOE values than LVL-C2.

On average, the MOR of the investigated products was significantly higher for flatwise bending than edgewise bending, as shown in Table 3**Table**. Due to the strategic positioning of higher MOE veneers on the faces than in the core, LVL_2 had the average highest flatwise MOR value of 144 MPa, followed by LVL-C1 with the value of 126.4 MPa. However, both the edgewise and flatwise bending MOR values of single-species HP LVL1 were observed to be higher (up to 8.2%) than the cross-banded LVL-C2. The LVL-C2 also showed an edgewise and flatwise MOR about 19% and 39% lower than LVL_2, as detailed in Table 3. These results were in agreement with previous studies on single-species LVL-C (Kawazoe *et al.* 2006; Kobel *et al.* 2014).

When compared to commercial LVL-C products (Table 3), the average flatwise bending MOE and MOR, of the two investigated LVL-C were found to be up to 72% and 251% higher than the single cross-banded Kerto-Q LVL, with thickness of 27 mm to 69 mm, (Metsä Wood company 2019) and single cross-banded STEICO LVL-*X* (STEICO group 2019). The values for edgewise bending were up to 44% (MOE) and 191% (MOR) higher than the commercialised LVL_C products.

Table 3. Mechanical Properties of Investigated Products *versus* Commercial LVL-C Products

Type	Panel	Flatwise bending		Edgewise bending		Tension strength ($f_{t\_\perp}$) (MPa)	Bearing strength ($f_{c\_\perp}$) (MPa)	Shear strength (f_s) (MPa)
		MOE (E_{b_f}) (MPa)	MOR (f_{b_f}) (MPa)	MOE (E_{b_e}) (MPa)	MOR (f_{b_e}) (MPa)			
LVL_1	1	13,911	94.7	14,233	89.1	2.72	14.05	9.6
	2	14,481	112.6	14,314	84.9	2.92	15.85	12.2
	3	14,433	120.6	14,094	81.7	2.56	18.56	10.7
	Ave.	14,274 (4%)	109.3 (11.4%)	14,213 (1.2%)	85.2 (6.4%)	2.74 (11.6%)	16.15 (13.6%)	10.8 (22.6%)
LVL_2	1	20,575	131.1	16,411	92.5	3.66	19.83	16.9
	2	20,214	155.5	15,431	95.2	2.97	19.98	9.3
	3	19,605	146.6	16,764	93.4	3.15	18.29	10.1
	Ave.	20,131 (5%)	144.4 (9.5%)	16,202 (4%)	93.6 (2.87%)	3.26 (12.14%)	19.13 (4.8%)	12.1 (31.5%)
LVL-C1	1	18,870	138.7	14,404	85.0	7.31	23.50	10.3
	2	17,387	114.0	15,956	101.9	9.84	23.37	9.2
	Ave.	18,128 (6.2%)	126.4 (11.5%)	15,180 (6.08%)	93.4 (11.4%)	8.58 (19.4%)	23.44 (2.41%)	9.8 (7.7%)
LVL-C2	1	16,250	104.3	14,866	84.6	9.34	23.50	7.7
	2	16,318	103.1	13,777	72.9	10.42	23.11	9.2
	Ave.	16,284 (5.4%)	103.7 (13.2%)	14,321 (4.5%)	78.7 (9.5%)	9.88 (14.35%)	23.30 (3.12%)	8.4 (13.2%)
Kerto® -Q	-	10,500	36	10,500	32	6.0	-	-
STEICO *LVL X*	-	10,600	36	10,600	36	5.0	-	-

The coefficient of variation (%) is represented in bracket next to each average number.

Tensile Strength Perpendicular to the Grain

Table 3 shows the tensile strength perpendicular to the grain ($f_{t\_\perp}$) for all the investigated products. On average, the tensile strengths of LVL-C products (LVLC-1 and LVL-C2) was observed to be about 3 times higher than that of single-species HP LVL and mixed-species LVL. This is explained by the positive effect of the cross-layer veneers in LVL-C products that results in a substantial improvement in tensile strength. Specifically, LVL-C2 had the highest tensile strength value of 9.88 MPa, whereas the lowest value of

2.74 MPa was found for single-species HP LVL. There was no significant difference in $f_{t\_\perp}$ between the mixed-species LVL and the single-species HP LVL.

When compared to commercial cross-banded LVL-C in Table 3, the average $f_{t\_\perp}$ of the investigated LVL-C were up to 97% superior to the cross-banded Kerto-Q LVL and STEICO LVL-*X*.

Bearing Strength Perpendicular to the Grain

Table 3 depicts the bearing strength perpendicular to the grain ($f_{c\_\perp}$) for all the investigated products. There was a difference by up to 45% between LVL-C products and LVL products in the average $f_{c\_\perp}$, but no major difference between the two mixed-species LVL-C products. The average $f_{c\_\perp}$ was found to be 17.2 MPa, 19.1 MPa, 23.4 MPa, and 23.3 MPa for LVL_1, LVL_2, LVL-C1, and LVL-C2, respectively. In addition, the average bearing strength value for LVL-C2 was observed to be 21% superior to that of mixed-species LVL_2, which was manufactured from the exact same veneer sheets.

Longitudinal-Tangential Shear Strength

All three-point bending test performed to investigate the longitudinal-tangential shear strength failed in bending. The maximum shear stresses reached during the tests are conservatively reported in Table 3 and therefore represents lower band values of the shear strengths.

The LVL_2 had the highest shear strength with an average shear strength greater than 12 MPa, followed by single species HP LVL_1 with 10.8 MPa. The shear strength of LVL-C1 (9.7 MPa) was higher than that of mixed-species LVL-C2 (8.4 MPa). Due to the presence of the cross-layered veneers, one would expect the shear strength value of the LVL-C to be higher than the one of the LVL. This counter-intuitive result is likely due to the observed bending failure and to the bending MOR of LVL-C being lower than that of LVL (see Table 3). Bending failure likely occurred in the LVL-C before the shear failure would have occurred.

CONCLUSIONS

1. D-grade was the dominant grade for the spotted gum (SPG) veneers and accounted for around 70% of the veneers recovered from the peeling process. About 21% of the veneers were graded as F-reject. Limited correlation between visual grading and dynamic modulus of elasticity (MOE)-based grading was found, meaning that visual grading may not be the most appropriate method to guide the manufacture of veneer-based products (VBP) of targeted MOE from the native forest SPG veneers.
2. For both edgewise and flatwise bending, the average MOE and modulus of rupture (MOR) values of cross-banded laminar veneer lumber (LVL) were found to be (i) up to 19% (MOE) and 28% (MOR) lower than the investigated LVL but (ii) up to 72% (MOE) and 251% (MOR) higher than commercially available LVL-C.
3. The average bearing strength perpendicular to the grain of LVL-C was found to be 23% and 160% higher than the investigated LVL and commercial LVL-C, respectively. The tensile strength perpendicular to the grain of the investigated LVL-C products was observed to be approximately 3 times higher on average than the other investigated LVL products.

4. Regarding the longitudinal-tangential shear strength, all the samples were observed to fail in bending rather than shear. The LVL-C showed a shear strength of at least 8.4 MPa.
5. In view of the reported characteristics, the mixed-species LVL-C manufactured showed mechanical properties superior to commercially available LVL-C and could represent a potential market for the manufactured veneers.

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REFERENCES CITED

Ardalany, M., Deam, B., Fragiacomo, M., and Crews, K. (2011). "Tension perpendicular to grain strength of wood, laminated veneer lumber (LVL), and cross-banded LVL (LVL-C)," in: *Proceedings of the 21st Australasian Conference on the Mechanics of Structures and Materials (ACMSM21)*, Melbourne, Australia, pp. 891-896.

AS/NZS 2269.0 (2012). "Plywood-structural- Part 0: Specification," Australian Standard/New Zealand Standard, Sydney, Australia.

AS/NZS 2754.1 (2016). "Adhesives for timber and timber products, Part 1: Adhesives for manufacture of plywood and laminated veneer lumber (LVL)," Australian Standard/New Zealand Standard, Sydney, Australia.

AS/NZS 4063.1 (2010). "Characterization of structural timber- Part 1- Test methods," Standards Australia, Sydney, Australia.

AS/NZS 4357.2 (2006). "Structural laminated veneer lumber (LVL)- Part2 - Determination of structural properties -Test methods," Standards Australia, Sydney, Australia.

ASTM D143-14 (2014). "Standard methods of testing small clear specimens of timber," ASTM International, West Conshohocken, PA, United States.

Bootle, K. R. (2005). *Wood in Australia: Types, Properties and Uses*, 2nd Ed., McGraw-Hill, Sydney.

Brancheriau, L., and Baillères, H. (2002). "Natural vibration analysis of clear wooden beams: A theoretical review," *Wood Science and Technology* 36(4), 347-365.

CIRAD (2018). "Beam identification by nondestructive grading (BING) software," https://www.picotech.com/library/picoapp/bing-software, Accessed on 23.04.18

Gilbert, B. P., Underhill, I. D., Bailleres, H., El Hanandeh, A., and McGavin, R. L. (2014). "Veneer based composite hollow utility poles manufactured from hardwood plantation thinned trees," *Construction and Building Materials* 66, 458-466.

Gilbert, B. P., Husson, J. M., Bailleres, H., McGavin, R. L., and Fischer, M. F. (2018a). "Perpendicular to grain and shear mechanical properties of veneer-based elements glued from single veneer sheets recovered from three species of juvenile subtropical hardwood plantation logs," *European Journal of Wood and Wood Products* 76(6), 1637-1652. DOI:10.1007/s00107-018-1350-8

Gilbert, B. P., Underhill, I. D., Fernando, D., Bailleres, H., and Miller, D. (2018b). "Structural behaviour of hardwood veneer-based circular hollow sections of different compactness," *Construction and Building Materials* 170, 557-569.

Kawazoe, M., Tuchiya, Y., Mori, T., and Komatsu, K. (2006). "Effect of crossbanded laminates on the bearing properties of mechanical joints of laminated veneer lumber with a drift pin," *Mokuzai Gakkaishi* 52(4), 221-227.

Kobel, P., Steiger, R., and Frangi, A. (2014). "Experimental analysis on the structural behaviour of connections with LVL made of beech wood," in: *Materials and Joints in Timber Structures: Recent Developments of Technology*, Vol. 9, S. Aicher, H. W. Reinhardt, and H. Garrecht (eds.), Springer, Dordrecht, Netherlands, pp. 211-220.

Leggate, W., McGavin, R. L., and Bailleres, H. (2017). "A guide to manufacturing rotary veneer and products from small logs," *Australian Centre for International Agricultural Research*, Canberra.

McGavin, B. H, Lane, F., and Fehrmann, J. (2013). *High Value Timber Composite Panels from Hardwood Plantation Thinnings (Project Report)*, Department of Agriculture, Fisheries and Forestry (DAFF), Queensland, Australia.

McGavin, L. W. (2019). "Comparison of processing methods for small-diameter logs: Sawing *versus* rotary peeling," *BioResources* 14(1), 1545-1565. DOI: 10.15376/biores.14.1.1545-1565

McGavin, R. L., Bailleres, H., Lane, F., Blackburn, D., Vega, M., and Ozarska, B. (2014a). "Veneer recovery analysis of plantation eucalypt species using spindleless lathe technology," *BioResources* 9(1), 613-627. DOI: 10.15376/biores.9.1.613-627

McGavin, R. L., Bailleres, H., Lane, F., Fehrmann, J., and Ozarska, B. (2014b). "Veneer grade analysis of early to mid-rotation plantation eucalyptus species in Australia," *BioResources* 9(4), 6562-6581. DOI: 10.15376/biores.9.4.6562 -6581.

McGavin, R. L., Nguyen, H. H., Gilbert, B. P., Dakin, T and Faircloth, A. (2019). "A comparative study on the mechanical properties of laminated veneer lumber (LVL) produced from blending various wood veneer," Manuscript under preparation to *BioResources*.

Metsä Wood Company (2019). *Brochures Kerto for Load-bearing Structures*, Revontulenpuisto 2, Finland.

Nguyen, H. H., Gilbert, B. P., McGavin, R., and Bailleres, H. (2019). "Optimisation of cross-banded Laminated Veneer Lumber manufactured from spotted gum and southern pine veneers," *European Journal of Wood and Wood Products*, 77(5), 783-797

STEICO Group (2019). *Brochures STEICO LVL for Construction Elements*, Feldkirchen, Germany.

Wang, B. J., and Dai, C. (2013). "Development of structural laminated veneer lumber from stress graded short-rotation hem-fir veneer," *Construction and Building Materials* 47, 902-909. DOI: 10.1016/j.conbuildmat.2013.05.096

Walker, J. C. (2006). *Primary Wood Processing: Principles and Practice*, Springer Science & Business Media, Netherlands.

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