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A Comparative Study on the Mechanical Properties of Laminated Veneer Lumber (LVL) Produced from Blending Various Wood Veneers

Robert L. McGavin,[a,]* Hoan H. Nguyen,[b] Benoit P. Gilbert,[b] Tony Dakin,[a] and Adam Faircloth [a]

Rotary veneers from spotted gum (*Corymbia citriodora*) and white cypress pine logs (*Callitris glaucophylla*) recovered from the native forest in Queensland, as well as Queensland plantation hoop pine (*Araucaria cunninghamii*) logs were used to manufacture LVL products following six different lay-up strategies including blended species LVL. The different lay-up strategies were to determine the opportunities for improving the mechanical performance of plantation softwood LVL by including native forest veneers. The manufactured products were evaluated for their bending performance, tension, bearing strength perpendicular to the grain, and longitudinal-tangential shear strength. The all-spotted gum LVL showed superior performance in all testing compared to other construction strategies. Blending even a small amount of spotted gum veneer with plantation hoop pine veneer resulted in improved mechanical performance, especially in flatwise bending. Opportunities exist to develop more optimised construction strategies that target specific product performances while optimising the use of the variable veneer qualities generated from log processing.

Keywords: Laminated veneer lumber; Hardwood; Cypress; Veneer; Rotary peeling

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INTRODUCTION

Australia's native forest resources cover approximately 137 million hectares and constitute approximately 90% of Australian forests (ABARES 2018). For many years, mainly larger diameter logs from these forests have been transformed using traditional sawmilling technologies, into a range of end-products such as beams, bridge members, flooring, decking, and landscaping timbers. However, despite there being a significant volume of small diameter logs potentially available to the timber industry from the sustainable management of these forests, these logs yield poor recovery rates when processed by traditional sawmilling technology. This has resulted in much of this resource being under-utilised and under-valued, despite the wood properties being well-suited to a range of high-value products (McGavin and Leggate 2019). Recently, spindleless veneering technologies have been capable of efficiently processing small-diameter plantation and native forest logs and hence offering the potential of utilising these resources for veneer-based products, such as laminated veneer lumber (LVL) (McGavin 2016; McGavin and Leggate 2019).

An appropriate commercialisation pathway for rotary veneer produced from small-diameter native logs may be through blending with existing commercial plantation softwoods. Blending may support efficient use of the veneer qualities while enabling high-value and high-performance LVL to be manufactured for structural applications. Blending resources in product manufacturing has been identified in previous research as advantageous, as these products have advantages when compared to traditional sawn products, including increased product performances, efficient resource utilisation, and compatibility with modern building systems (Keskin 2004; Kilic and Celebi 2006; Burdurlu *et al*. 2007; Kilic *et al*. 2012; Xue and Hu 2012). More importantly, these products allow the increased use of lower cost, low-grade, and low-density wood veneers as core veneers in mixed-species LVL products to reduce product cost (Keskin and Musa 2005; Burdurlu *et al*. 2007; Xue and Hu 2012; Wang and Dai 2013) and increase the mechanical properties of predominately low-density wood LVL (Wong *et al*. 1996; H'ng *et al*. 2010; Xue and Hu 2012; Bal 2016; Ilce 2018).

According to Wong *et al.* (1996), it is possible to increase the use of low-grade wood veneers from fast-growing trees such as rubberwood (*Hevea brasiliensis*) into high-performance products by processing them into mixed-species structural LVL with higher quality mangium (*Acacia mangium*) veneers. The study showed that the mechanical properties of rubberwood LVL can increase up to 13% in the modulus of elasticity (MOE) and 12% in the modulus of rupture (MOR) by positioning mangium veneers in the surface or face layers. Another study on manufacturing 7-ply LVL in 8 different lay-up strategies that blended higher-density Austrian pine (*Pinus nigra*) veneers and lower-density Lombardy poplar (*Populus nigra*) veneers was conducted by Kilic *et al.* (2010). Results showed that as the ratio of Austrian pine veneers increase in mixed-species LVLs, the MOR and MOE increased up to 40% and 69% on average, compared to LVL manufactured only with Lombardy poplar.

Burdurlu *et al*. (2007) investigated the MOE and MOR of LVL manufactured from beech (*Fagus orientalis* L.) and Lombardy poplar (*Populus nigra* L.) veneers through eight different lay-up strategies and reported that increasing the proportion of high-density beech veneers leads to an increase in the MOE and MOR and that the flatwise MOE and MOR of LVL with two beech veneers on each outer layer was 49% and 27% higher on average compared to the LVL manufactured from poplar alone. The results were consistent with the study conducted by Xue and Hu (2012) which considered ten-ply LVL manufactured from poplar (*Populus ussuriensis* Kom.) as the core layers, and birch (*Betula platyphylla* Suk.) as the outer layers. The authors also reported that the bending strength of LVL with high strength birch veneers on the outer layers is much greater than LVL with low strength poplar veneers on the surface layers.

Although manufacturing LVL from blending different wood species has been advanced in other countries, the opportunities for adopting this approach in Australia are not well understood. The key objectives of this study were to examine the structural performance of LVL products manufactured from rotary veneers recovered from small-diameter selected Australian native forest species, an Australian commercial plantation grown softwood, and various blends of veneers from these species. The study aims to provide an insight into the opportunities to improve the performance of plantation pine LVL through the inclusion of native forest sourced veneers.

EXPERIMENTAL

Materials

Rotary veneers

Spotted gum (*Corymbia citriodora*), white cypress pine (*Callitris glaucophylla*), and hoop pine (*Araucaria cunninghamii*) were selected for this study. The spotted gum (SPG) and white cypress pine (CYP) veneers were sourced from the small diameter log processing trials previously undertaken and reported by McGavin and Leggate (2019), and represent two different resources commercially available to the timber industry from Australia's native forests. These species represent a high-density, durable hardwood (SPG) and a mid-density, durable softwood (CYP). The processing was completed using a spindleless rotary veneer lathe that targeted a nominal dried veneer thickness of 3.0 mm. The hoop pine (HP) veneers were recovered from approximately eight logs peeled by a commercial veneer producer during standard commercial operations and also targeted a nominal dried veneer thickness of 3.0 mm.

Methods

Veneer properties

To evaluate the distribution of dynamic properties such as the elastic modulus parallel to the grain direction (E_{L_Veneer}), the acoustic properties of the SPG, CYP, and HP veneers were measured using a non-destructive grading device (Brancheriau and Baillères 2002) on sample strips (approximately 1200 mm × 200 mm) removed from a subset of recovered veneers, as reported by McGavin and Leggate (2019). Sample strips were positioned on elastic supports and a simple percussion was then induced in the direction of the grain at one end of the sample, while at the other end, a Lavalier type microphone recorded the vibrations before transmitting the signal *via* an anti-aliasing filter (low-pass) to an acquisition card that included an analog-to-digital converter to provide a digitized signal (Fig. 1). A fast Fourier transform algorithm processed the signal to convert the information from the time to the frequency domain. The mathematical processing of selected frequencies was undertaken using BING (beam identification using non-destructive grading) software (Version 9.7.2, Montpellier, France) in combination with the geometrical characteristics and the weight of the specimen to provide the dynamic MOE, among other specific mechanical characteristics (CIRAD 2018).

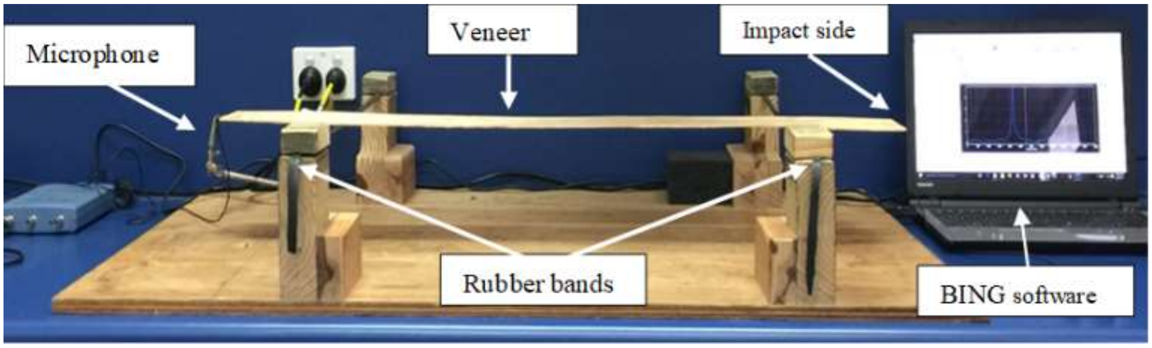


Fig. 1. Experimental setup for the acoustic properties testing

Veneer grading

The veneer quality was assessed by visual grading in accordance with AS/NZS 2269.0:2012 (2012). This standard is widely used across the Australian veneer industry and follows the same principles as other international veneer visual grading classification systems. The standard separates structural veneers into four veneer surface grades with each grade corresponding to a quality group in accordance with the standard. The grading was based on visual characteristics of the veneers such as splits, various knot types, and roughness.

Target LVL construction strategies

Six different LVL construction lay-up strategies were implemented to manufacture 12-ply LVL from the three species to demonstrate the construction strategy impact on the manufactured product mechanical properties. The strategies were comprised of three single-species reference LVLs and three blended-species LVLs (Fig. 2).

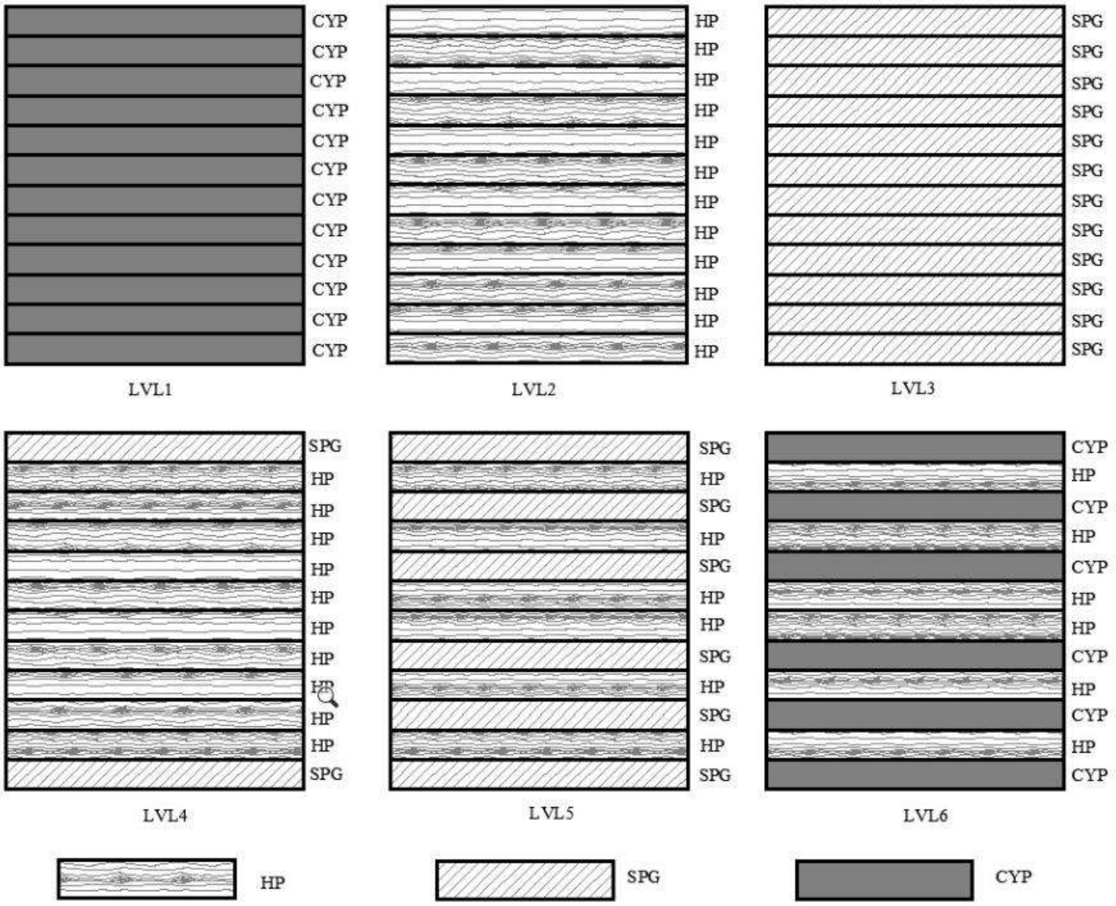


Fig. 2. LVL panel construction lay-up types

The construction strategies are outlined below, with the veneer selection process explained in the following section:

- LVL1 - 12 CYP veneers throughout the panel thickness;
- LVL2 - 12 HP veneers throughout the panel thickness;

- LVL3 - 12 SPG veneers throughout the panel thickness;
- LVL4 - SPG veneers on the outside faces and 10 HP veneers for the internal core;
- LVL5 - alternating SPG and HP veneers with SPG veneers on the outside faces; and
- LVL6 - alternating CYP and HP veneers with CYP veneers on the outside faces.

Veneer selection and allocation

The strategy to select individual veneers from the available stocks and their placement within the LVL panels had the following main objectives:

- To minimise the within-species veneer MOE variation for veneers included in the LVL panel manufacturing;
- To target “average” structural quality veneers (*i.e.* veneers with MOEs that were similar to the mean veneer MOE of the available stocks of each species);
- To ensure individual veneers were in the optimum position within the allocated panel to maximise the panel mechanical properties (*i.e.* biasing higher MOE veneers towards the outer layers of the LVL panels);
- To minimise the within-species variation between LVL panels of the same construction type.

The veneer selection and placement followed these steps:

1. From the available veneers of the three species, veneers that did not achieve a visual grade of D-grade or better were discarded. While the veneer visual grading wasn’t used as the primary selection method to influence the LVL mechanical performance, the criteria of D-grade or better was adopted to ensure a commercially relevant quality criteria, in terms of surface roughness, representation of visual defects and splitting, *etc*.
2. For the remaining veneer sheets, the mean dynamic MOE of the veneer population was calculated and used to guide the veneer selection. Given the study objective of assessing the mechanical performance of the manufactured LVL, the veneer MOE was used as the primary veneer selection method. This approach is common practice in commercial LVL manufacture using equipment such as Metriguard produced by the Raute Group.
3. Veneers within each population were sorted by their MOE in descending order.
4. The required subset of each species (the number of veneers required from each species to manufacture the required LVL panels including contingency veneers) were taken as a series of consecutive veneers to minimise MOE variation. Then, the mean dynamic MOE (as per Step 1) was calculated for each possible subset.
5. The veneer subset that had a mean MOE closest to the entire population MOE mean were selected for panel manufacturing.
6. The veneers from each subset were systematically distributed among the final panels of each construction type. Veneers were distributed, in order of decreasing MOE, starting with the outer layers of all panels and progressing to the core. This ensured that veneers were optimally located from a structural perspective with higher MOE veneers

located towards the panel periphery, and that consistency was achieved across the panels of the same construction type. Once all the veneers were assigned, the statistics for the desired combinations of panels and positions were reviewed to ensure the objectives were achieved.

LVL panel manufacturing

A total of 18 LVL panels (approximately 1200 mm × 1200 mm × 36 mm) were manufactured with three panels for each construction type. A melamine urea formaldehyde adhesive was selected to achieve a B-bond glue line, which are the service conditions outlined in AS/NZS 2754.1 (2016).

The adhesive was applied to each face of the veneers targeting a total spread rate of 400 gsm (grams per square metre) per glue line. The assembly stage included an open assembly time of approximately 22 min (measured from adhesive application to the first veneer to when pressure was applied in the press). Pre-pressing was undertaken at 1 MPa for a duration of 8 min. Once the pre-pressing was complete, the panels were transferred to the hot press and pressed at 1.1 MPa for 26 min at 135 °C.

Test samples and mechanical properties test method

Figure 3 illustrates the LVL panel cutting pattern and test sample locations. Six samples per construction lay-up type (*i.e.* 2 samples per panel) were cut from each panel to experimentally evaluate their 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}), longitudinal-tangential shear strengths (f_s), and bearing strength perpendicular to the grain strength ($f_{c\_\perp}$). For tension perpendicular to the grain ($f_{t\_\perp}$), nine samples per construction lay-up type (*i.e.* 3 samples per panel) were tested.

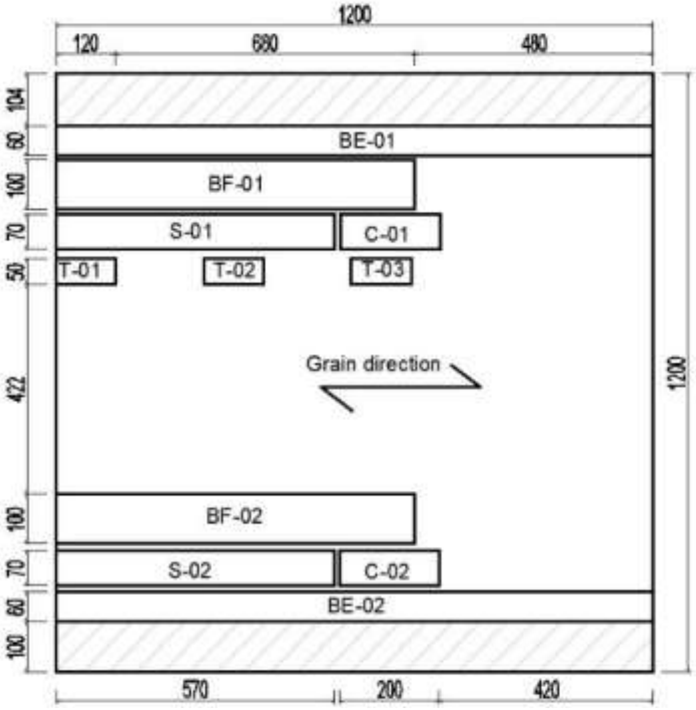


Fig. 3. The LVL cutting pattern for the property tests (BE-edgewise bending tests, BF-flatwise bending tests, S-longitudinal-tangential shear bending tests, C-compression perpendicular to the grain test, and T-tension perpendicular to the grain tests)

After the test samples were removed from the LVL panels, they were conditioned at 20 °C at a relative humidity of 65% in accordance with AS/NZS 4357.2 (2006), which targeted a sample moisture content of approximately 12%.

All testing was undertaken within the test laboratory at the Department of Agriculture and Fisheries' Salisbury Research Facility (Salisbury, Australia) or the testing laboratory at Griffith University (Southport, Australia). The testing methodology for each test are described in Nguyen *et al*. (in press) and summarised as below:

(i) Static bending was tested following AS/NZS 4357.2 (2006) using a four-point bending test configuration. From each panel, two 60 mm (height) × 1200 mm (length) samples were tested in the edgewise bending, and two 100 mm (width) × 800 mm (length) samples were tested in flatwise bending. A 100 kN Shimadzu universal testing machine (AG-100X, Kyoto, Japan) was used with a constant load application rate of 5 mm/min, for failure to be achieved within 3 to 5 min as per the standards specifications (Fig. 4).

(ii) The bearing strength perpendicular to the grain was measured using the bearing strength test method from AS/NZS 4063.1 (2010) on 70 mm (height) × 200 mm (length) test samples. A 100 kN Shimadzu universal testing machine was used and the load was applied at a constant rate of 1.0 mm/min for failure to be achieved within 2 to 5 min and therefore tested in accordance with the standard (Fig. 5).

(iii) The tensile strength perpendicular to the grain was measured following the configuration in ASTM D143-14 (2014), which was devised for solid timber specimens. The procedure has been previously applied to LVL samples and proven successful (Ardalany *et al*. 2011; Gilbert *et al*. 2018). The sample dimensions are shown in Fig. a. The samples were inserted into an aluminium jig as demonstrated in Fig. 6b. The jig was gripped in the jaw of a 30 kN capacity Lloyd universal testing machine (LR30k, West Sussex, UK) which ran in displacement control at a stroke rate of 2.5 mm/min for failure to be achieved within 1 to 3 min.

(iv) The longitudinal-tangential shear strength testing was undertaken following AS/NZS 4063.1 (2010). In this method, a three-point bending test configuration was used as illustrated in Fig. 7. The stroke rate was set to ensure failure was achieved within 2 to 5 min, as specified by the standard. Two 70 mm (height) x 570 mm (length) samples were cut per panel for testing.

Fig. 4. Testing configuration for flatwise (left) and edgewise bending (right)

Fig. 5. Testing configuration for bearing strength perpendicular to the grain

(a) (b)

Fig. 6. Testing configuration for tensile strength perpendicular to the grain

Fig. 7. Testing configuration for longitudinal shear strength

RESULTS AND DISCUSSION

Veneer Properties and Selection

The veneer population statistics for each species are shown in Table 1, and the statistics of the selected subset of veneers for the LVL panel manufacturing are presented in Table 2. The SPG yielded much higher veneer stiffness, with over 85% of the veneers exceeding the maximum MOE recorded for HP. This highlights the opportunities to use SPG and other high-density Australian hardwoods to manufacture veneer-based products, such as LVL, to achieve structural performances superior to that possible from plantation softwood resources. The CYP recorded a lower average MOE (8998 MPa) compared to HP (12169 MPa) and the SPG (22437 MPa). Comparative statistics for veneers allocated to each LVL panel are shown in Table 3.

Table 1. Veneer Population Statistics

	Spotted Gum	White Cypress Pine	Hoop Pine
Veneer Count	127	91	246
Average MOE (MPa)	22,437	8,998	12,169
Std. Dev. MOE (MPa)	3,541	1,509	2,338
Coeff. Of Variation (%)	15.8%	16.8%	19.2%
Min MOE (MPa)	13,407	6,070	4,655
Max MOE (MPa)	29,679	11,813	18,716

Table 2. Veneer Subset Statistics

	Spotted Gum	White Cypress Pine	Hoop Pine
Veneer Count	70	63	119
Average MOE (MPa)	22,449	9,015	12,174
Std. Dev. MOE (MPa)	1,724	964	779
Coeff. Of Variation (%)	7.7%	10.7%	6.4%
Min MOE (MPa)	19,955	7,513	10,699
Max MOE (MPa)	25,684	11,014	13,485

Table 3. Panel Statistics for Each Investigated Construction Lay-up

Construction Lay-up	Panel	Average Veneer MOE (MPa)	Std. Dev. MOE (MPa)	Coeff. Of Variation (%)	Min. Veneer MOE (MPa)	Max. Veneer MOE (MPa)
LVL1 (CYP)	1	9,428	1,845	19.6%	6,435	11,604
	2	9,380	1,356	14.5%	7,292	11,479
	3	9,405	1,697	18.0%	6,948	11,628
LVL2 (HP)	1	12,364	993	8.0%	11,037	14,457
	2	12,842	1,310	10.2%	11,030	15,079
	3	12,275	826	6.7%	10,955	13,454
LVL3 (SPG)	1	22,378	2,352	10.5%	19,918	26,885
	2	22,536	2,750	12.2%	19,579	26,558
	3	23,014	2,232	9.7%	20,229	26,546
LVL4 (SPG face & HP core)	1	13,953	4,949	35.5%	8,966	26,280
	2	13,854	4,833	34.9%	8,997	25,684
	3	13,929	4,429	31.8%	8,455	24,298
LVL5 (SPG & HP alternate)	1	17,616	5,458	31.0%	10,936	24,134
	2	17,580	5,666	32.2%	8,889	24,679
	3	17,666	4,968	28.1%	11,496	23,493
LVL6 (CYP & HP alternate)	1	11,000	2,234	20.3%	7,888	16,095
	2	11,046	2,494	22.6%	8,031	16,271
	3	10,912	2,013	18.4%	8,091	13,683

Mechanical Properties Testing

Table 4 provides the test results of MOE and MOR in both flatwise and edgewise bending, tension strength, bearing strength, and shear strength for the six different LVL construction lay-ups. The results show relatively narrow variation within the construction lay-ups, which is reflective of the veneer selection and positioning strategies adopted during the LVL panel manufacturing. However, there was a wide variation between the six LVL constructions which highlights the substantial differences between fundamental wood properties of the species included.

Table 4. Mechanical Properties of Mixed-Species LVL

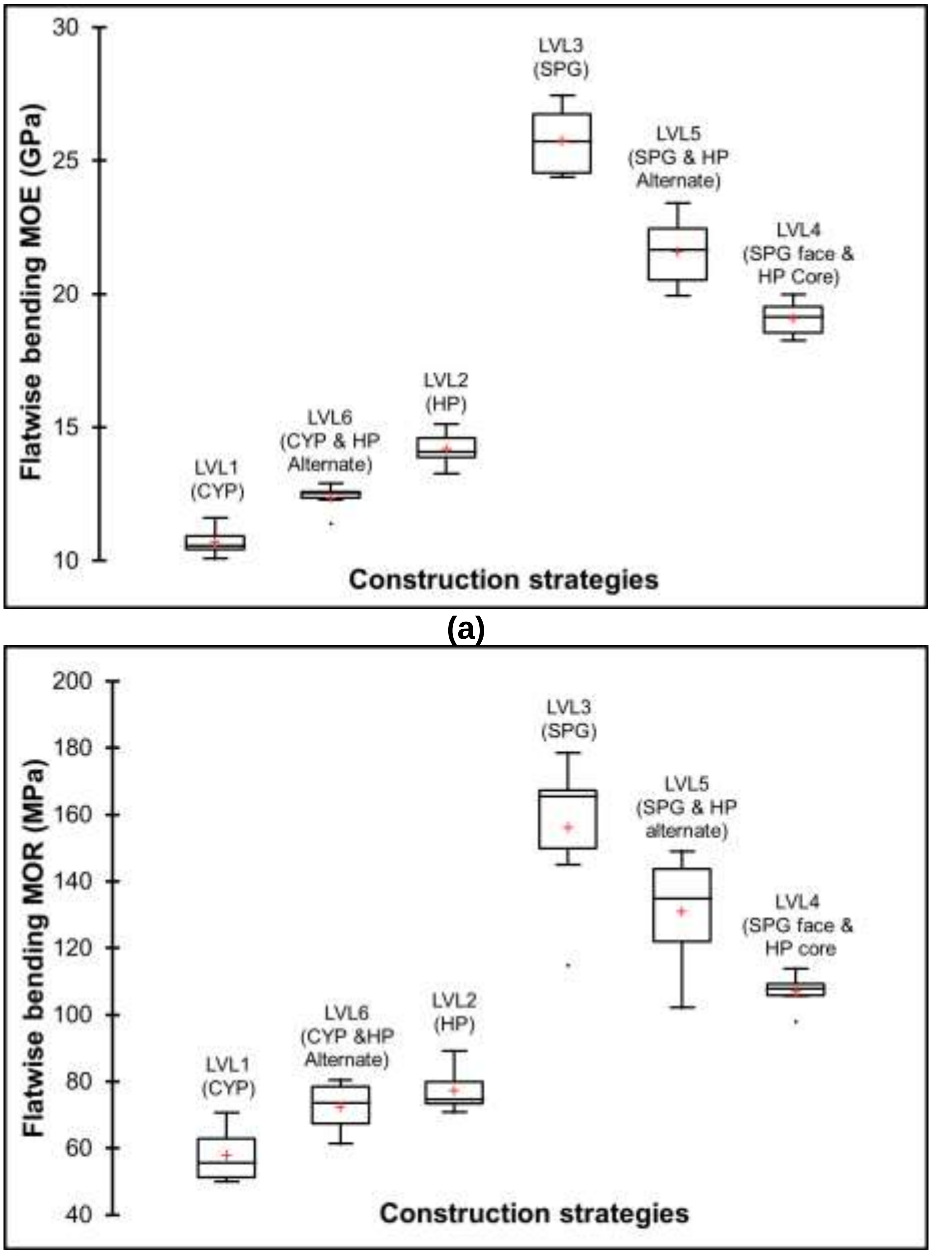
Type	Panel	Flatwise Bending		Edgewise Bending		Tension Strength ($f_{t\_\perp}$) (MPa)	Bearing Strength ($f_{c\_\perp}$) (MPa)	Shear Strength (f_s) (MPa)
		MOE (E_{b_e}) (GPa)	MOR (f_{b_e}) (MPa)	MOE (E_{b_f}) (GPa)	MOR (f_{b_e}) (MPa)			
LVL1 (CYP)	1	11.1	60.7	10.2	55.5	2.01	29.7	6.0$^{\#}$
	2	10.3	50.1	9.7	48.7	1.80	30.7	6.4$^{\#}$
	3	10.7	62.7	9.6	44.3	2.16	31.8	5.5$^{\#}$
	Mean	10.7	57.8	9.8	49.5	2.0	30.7	5.9$^{\#}$
LVL2 (HP)	1	14.3	72.5	12.0	68.3	2.89	16.0	7.0$^{\#}$
	2	14.2	81.1	12.2	69.4	2.78	16.1	6.5$^{\#}$
	3	14.1	78.3	11.5	62.2	2.38	15.9	5.8$^{\#}$
	Mean	14.2	77.3	11.9	66.6	2.7	16.0	6.4$^{\#}$
LVL3 (SPG)	1	25.7	161.8	25.4	143.7	3.65	40.9	14.9$^{\#}$
	2	25.6	139.4	23.4	140.0	3.54	40.9	13.5$^{\#}$
	3	25.9	167.1	22.7	134.2	3.40	40.8	13.9
	Mean	25.8	156.1	23.9	139.3	3.5	40.8	14.1$^{\#}$
LVL4 (SPG face & HP core)	1	19.3	110.2	14.2	76.6	2.72	17.7	7.0$^{\#}$
	2	19.2	109.2	12.0	65.0	3.19	17.9	7.3$^{\#}$
	3	18.8	101.8	14.6	83.2	2.67	17.9	7.3$^{\#}$
	Mean	19.1	107.1	13.6	74.9	2.9	17.8	7.2$^{\#}$
LVL5 (SPG & HP alternate)	1	21.2	141.1	17.6	100.9	3.56	32.1	10.4$^{\#}$
	2	22.2	141.3	19.3	108.5	3.05	30.4	10.5$^{\#}$
	3	21.4	110.2	17.5	101.3	2.82	29.0	10.6
	Mean	21.6	130.9	18.1	103.6	3.1	30.5	10.5$^{\#}$
LVL6 (CYP & HP alternate)	1	12.7	69.1	11.8	66.6	2.78	24.2	4.7$^{\#}$
	2	12.0	70.6	12.1	68.3	2.56	22.9	7.1$^{\#}$
	3	12.5	77.6	11.2	66.7	2.26	24.4	5.2$^{\#}$
	Mean	12.4	72.4	11.7	67.2	2.5	23.8	5.7$^{\#}$
Note: # represents failure in bending modes								

Flatwise bending tests

The static flatwise bending test results for the six LVL construction lay-ups are shown in Fig. 8. For single species LVL, the construction with all-SPG veneers (LVL3) yielded the highest performance with an average MOE of 25.8 GPa and an average MOR of 156.1 MPa. The all-HP construction (LVL2) had an average MOE of 14.2 GPa and an average MOR of 77.3 MPa. The all-CYP construction (LVL1) provided the lowest test result with an average MOE of 10.7 GPa and an average MOR of 57.8 MPa.

The constructions that utilised a blend of both SPG and HP veneers performed in between and in line with the proportion of the blend. The construction (LVL5) that included an alternate mix of both species (6 SPG and 6 HP veneers) had an average MOE of 21.6 GPa and an average MOR of 130.9 MPa, while the SPG face and HP core construction lay-up (LVL4) provided a slightly lower average MOE of 19.1 GPa and an average MOR of 107.1 MPa. The construction that alternated CYP veneers with HP veneers (LVL6) performed between the LVL1 (all-CYP) and LVL2 (all-HP) constructions.

When tested in the flatwise direction, the construction lay-up LVL4 clearly demonstrated that substantial performance improvements can be achieved with the substitution of even a small amount of higher performing veneers when positioned in the optimal location within the LVL cross-section.



(a)

(b)

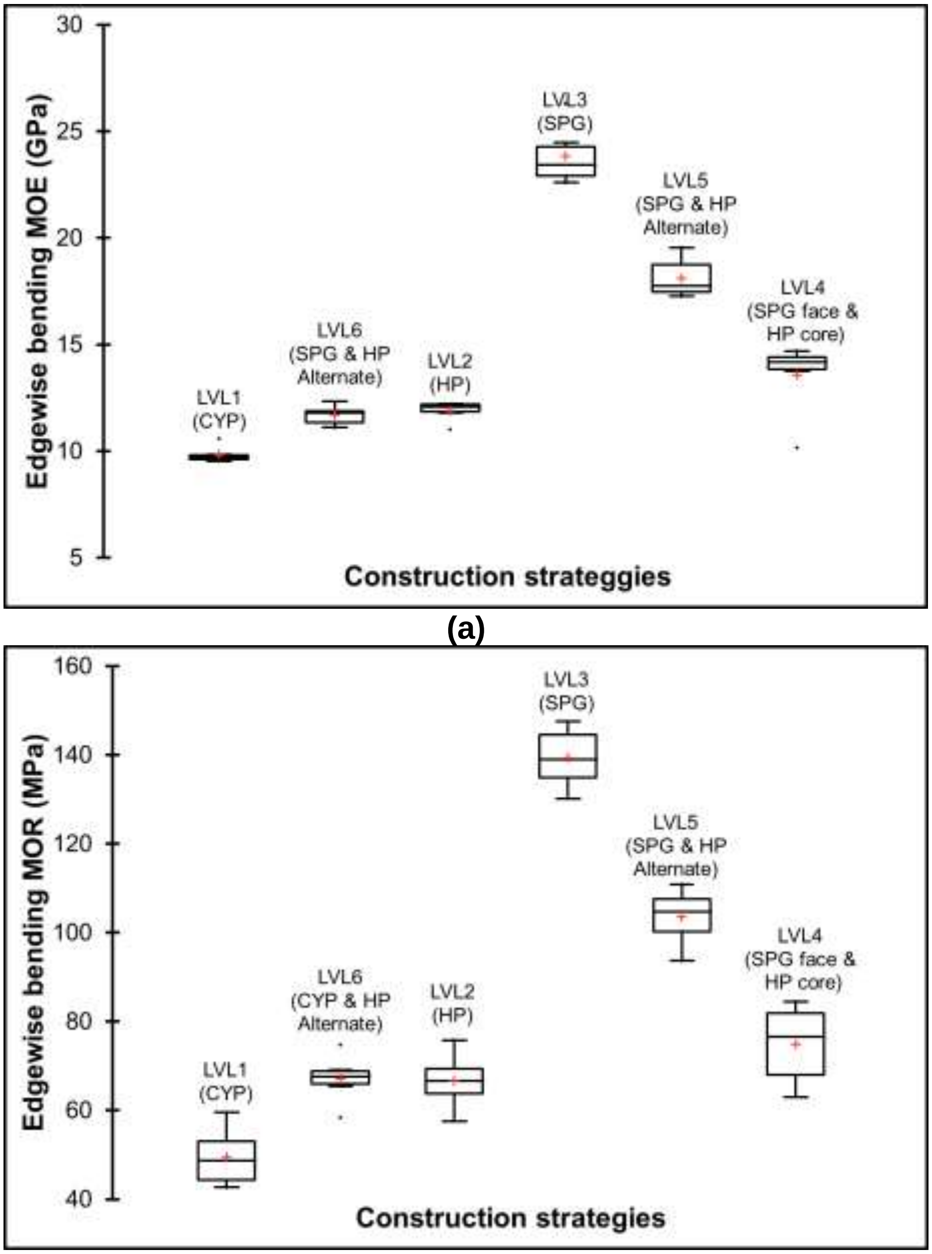
Fig. 8. Flatwise bending MOE (a), and flatwise bending strength (MOR) (b) per LVL construction lay-up

Edgewise bending tests

The static edgewise bending test results for the six LVL construction lay-ups are further reported in Fig. 9. The trend of edgewise bending results between construction lay-up types was similar to the flatwise bending results with the LVL3 (all-SPG) construction providing the highest performance with an average MOE of 23.9 GPa and an average MOR of 139.3 MPa, and the LVL1 (all-CYP) construction provided the lowest performance with an average MOE of 9.8 GPa and an average MOR of 49.5 MPa. The all-HP construction (LVL2) was slightly better than the all-CYP (LVL1) with an average MOE of 11.9 GPa and an average MOR of 66.6 MPa.

The blended constructions performed in between the relevant single species lay-up constructions. The construction lay-up type LVL4 (SPG face and HP core) was found to have a higher MOE (up to 34.5%) and higher MOR (up to 38.5%) than the single species HP lay-up (LVL2). However, compared to the single species SPG lay-up (LVL3), the bending properties of LVL4 was up to 43% (MOE) and up to 46% (MOR) lower.

Compared to the flatwise bending tests, the performance improvements with the blended species construction lay-ups remained, although they were not as strong as the flatwise bending tests because the strategic positioning of the higher performing veneers towards the outer laminations had less of an impact when tested in the edgewise direction. Instead, all the veneers within a construction type equally contributed to the final beam performance.



(a)

(b)

Fig. 9. Edgewise bending MOE (a) and edgewise bending strength (MOR) (b) per LVL construction lay-up type

Tensile strength perpendicular to the grain

Figure 10 further shows the tension strength perpendicular to the grain for all investigated products. The rank of the single-species products was similar to the bending performance in both the edgewise and flatwise mode. Particularly, the LVL3 construction lay-up (SPG) displayed the highest average tensile strength of 3.5 MPa followed by the all-HP construction LVL2 with a mean tensile strength of 2.7 MPa. The all-CYP LVL1 had the lowest tensile strength of 2.0 MPa which was partly due to the high proportion of natural defects in the CYP veneers.

The tensile strength of the blended-species constructions performed in between the relevant single species constructions. To illustrate, the tensile strength of the construction LVL5 (six SPG and six HP veneers) was observed to be 15% higher than the single-species HP LVL2, but 13% lower than the single-species SPG LVL3.

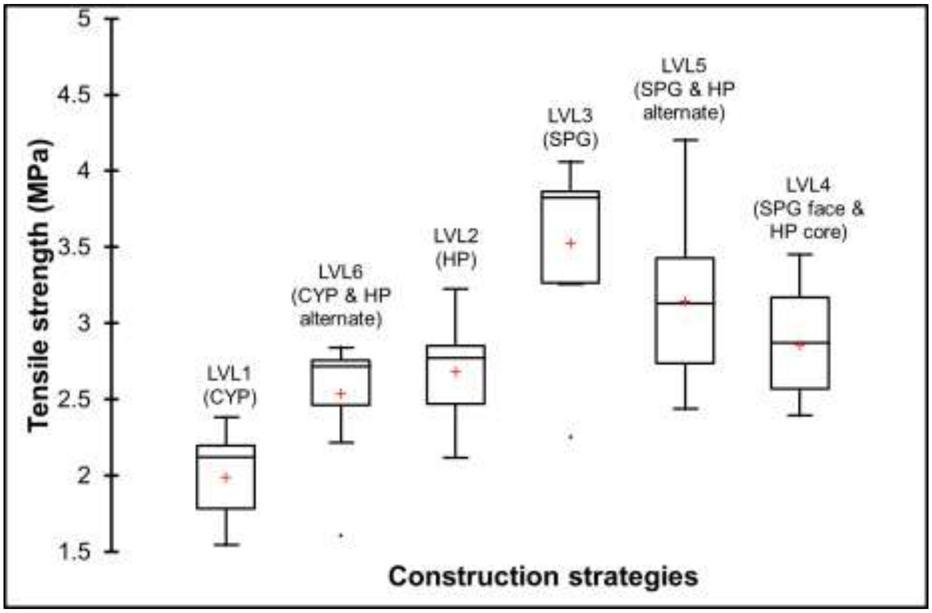


Fig. 10. Comparison of tension strength perpendicular to the grain for all the investigated products

Bearing strength perpendicular to the grain

Figure 11 further presents the bearing strength (perpendicular to the grain) test results conducted on the six LVL constructions. Compared to the tensile strength, the bearing strength values of all the construction strategies were approximately 6 to 17 times higher.

The all-SPG LVL3 was again the highest performing construction type, achieving a mean bearing strength of 40.8 MPa. The second ranked construction was the all-CYP LVL1 achieved an average bearing strength of 30.7 MPa, which was then followed by the construction that alternated spotted gum with hoop pine (LVL5) (30.5 MPa).

The all-HP LVL2 achieved the lowest mean result of 16.0 MPa. Minimal gains in bearing strength were observed when positioning SPG on the faces and using HP in the cores (LVL4) compared with the all HP construction (LVL2) with the former achieving a mean bearing strength result of 17.8 MPa.

While the all-CYP LVL1 did not perform well in other mechanical tests, the specimens did perform well in the bearing strength testing with a mean bearing strength of

30.7 MPa, which is approximately two times higher than the bearing strength value of single species HP LVL2. This could be an attractive asset for this species for the manufacture of products that require high bearing strength.

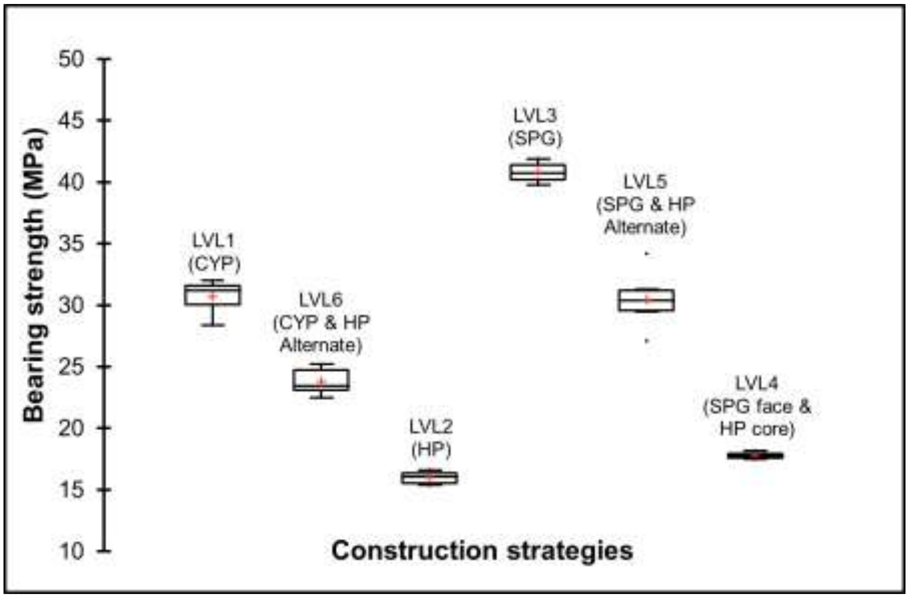


Fig. 11. Bearing strength perpendicular to the grain between investigated products

Longitudinal-tangential shear strength

The adopted shear strength test method had a propensity for inducing failure in bending rather than shear. As a result, the actual shear strength of the LVL specimens was unknown. The results presented were calculated based on the shear stress present in the sample at the time of failure, whether it was in bending or in shear. The maximum shear stresses reached during the tests are conservatively reported in Table 4 and Fig. 12 and therefore represents lower band values of the possible shear strengths.

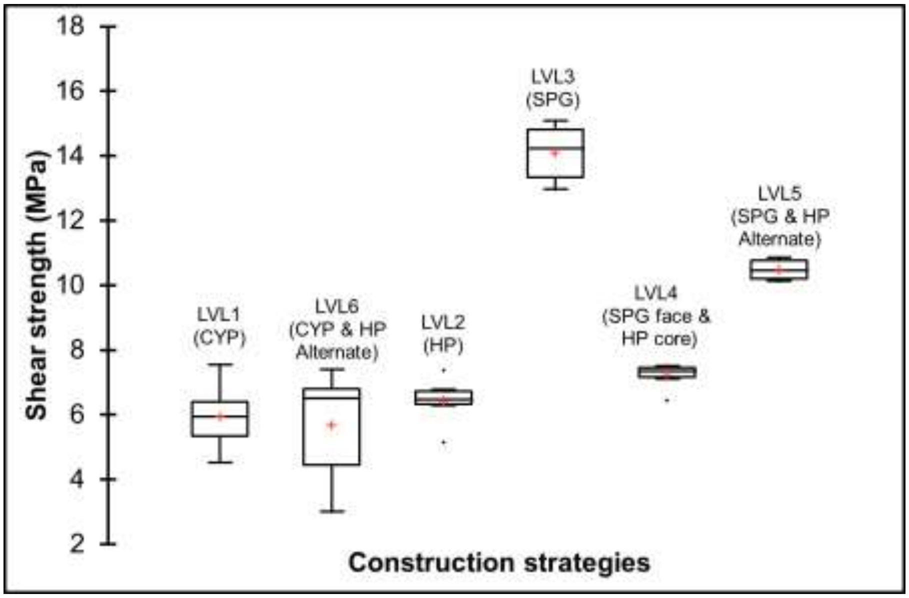


Fig. 12. Shear strength results per construction lay-up type

A failure as a result of bending may also indicate beam shear need not be taken into consideration as a failure criterion, as outlined in the AS/NZS 4063.1 (2010) standard.

The all-SPG construction lay-up (LVL3) performed the best with an average beam shear strength greater than 14 MPa. The three construction types not containing SPG veneers (all-CYP LVL1, all-HP LVL2, and LVL6 [CYP and HP alternating]) showed varying, yet similar results, with all displaying an average beam shear strength greater than 5.7 MPa. The LVL4 (SPG face and HP core) performed only marginally better than the all-HP construction LVL2 (average of 7.2 MPa *versus* 6.4 MPa), as the better performing SPG veneers were not positioned optimally to counteract the shear stress. Including more SPG veneers throughout the LVL beam, such as the SPG and HP alternating construction lay-up (LVL5), improved the shear strength performance (average 10.5 MPa).

CONCLUSIONS

1. This study demonstrated that there was a considerable difference in dynamic veneer MOE between native hardwood species and either native softwood or softwood plantation species. The SPG veneers showed superior stiffness properties (an average of 22.4 GPa), followed by HP veneers and CYP veneers (an average of 12.2 GPa and 9.0 GPa, respectively).
2. The LVL products were manufactured from the three included species using a variety of different construction strategies. The adopted construction strategies used veneers with MOEs close to the population mean for each species, which suggests that opportunities exist to manufacture LVL products targeting specific performances while optimising the use of the variable veneer qualities generated from log processing.
3. For both edgewise and flatwise bending, the all-SPG construction lay-up (LVL3) performed the best among the investigated single-species construction types (25.8 GPa for MOE and 156.1 MPa for MOR for flatwise bending), while the lowest values were found in all-CYP LVL1 (10.7 GPa for MOE and 57.8 MPa for flatwise bending). The construction strategy that included all-SPG consistently outperformed the other construction strategies across all mechanical testing. The substitution of only two SPG veneers on the faces of the HP 12-ply LVL yielded an increase of up to 34.5 % (MOE) and 38.5% MOR compared with the all HP LVL2. Replacing every second HP veneer with SPG (LVL5) resulted in a flatwise MOE increase of 52% compared with the all HP construction (LVL2).
4. The bearing strength perpendicular to the grain was approximately 6 to 17 times higher than tensile strength perpendicular to the grain, with the all-SPG LVL3 having the highest tensile and bearing strength. The lowest tension strength was observed in the single-species CYP LVL1, however this configuration ranked second for bearing strength. On average, the tensile and bearing strengths of the mixed-species LVL were superior to the reference single-species HP LVL and the single-species CYP LVL.
5. The majority of samples tested for longitudinal-tangential shear strength failed in bending rather than shear. The highest shear strength was observed in the single-species SPG LVL3 with an MPa greater than 14, and the mixed-species LVL5 with an average MPa greater than 10.5.
6. The study demonstrated that SPG is capable of producing high mechanical performing

LVL, however is also able to boost the mechanical performance of plantation softwood LVL through the addition of even small quantities of SPG within the LVL construction strategy.

7. With an accurate product performance criterion, construction strategies that minimise manufacturing cost, and product weight, and maximize variable feedstock utilisation could be achieved, while still manufacturing fit-for-purpose products. The exploration of construction strategy modelling would provide guidance for developing the most efficient construction strategies taking into account the various constraints and objectives, and the targeted product performance.

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