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

Benoit P. Gilbert⁽¹⁾, Julien M. Husson⁽²⁾, Henri Bailleres⁽³⁾, Robert L. McGavin⁽⁴⁾, Maxime F. Fischer⁽⁵⁾

⁽¹⁾ Benoit P. Gilbert, School of Engineering and Built Environment, Griffith University, QLD 4222, Australia, b.gilbert@griffith.edu.au (Corresponding author)

⁽²⁾ Julien M. Husson, School of Engineering and Built Environment, Griffith University, QLD 4222, Australia

⁽³⁾ Henri Bailleres, Salisbury Research Facility, Queensland Government, Salisbury, QLD 4107, Australia, henri.bailleres@daf.qld.gov.au

⁽⁴⁾ Robert L. McGavin, Salisbury Research Facility, Queensland Government, Salisbury, QLD 4107, Australia, robbie.mcgavin@daf.qld.gov.au

⁽⁵⁾ Maxime F. Fischer, School of Engineering and Built Environment, Griffith University, QLD 4222, Australia

ABSTRACT: This paper quantifies the mechanical properties perpendicular to the grain and in shear of **glued** rotary peeled veneers, as would be encountered in veneer-based structural products (i.e. by including both the effects of hot pressing the veneers and the glue used during the manufacturing process), of three species recovered from juvenile (early to mid-rotation) subtropical hardwood plantation logs. This underutilised resource has currently little to no commercial value in Australia but proven potential to produce attractive veneer-based structural products. Determining these unknown properties is important as they constitute essential input data to ultimately predict the behaviour and design properties of veneer-based structural products in cost-effective numerical simulations. Two species planted for solid timber end-products (Gympie messmate - *Eucalyptus cloeziana* and spotted gum - *Corymbia citriodora*) and one species traditionally grown for pulpwood (southern blue gum - *Eucalyptus globulus*) are considered in the paper. The dynamic Modulus of Elasticity, compressive and tensile strengths perpendicular to the grain of **veneer-based elements, each manufactured from single veneer sheets**, were experimentally measured and are analysed herein.

These properties are found to have no to weak correlation to the **parent veneer sheet** dynamic Modulus of Elasticity parallel to the grain, a value which is commonly measured in line to grade veneers. The Shear Modulus (in the longitudinal-tangential plane), also referred to as “Modulus of Rigidity”, through-the-thickness and rolling shear strengths were also experimentally measured and the results are discussed in the paper. Little to no correlation to the **veneer sheet** dynamic Modulus of Elasticity parallel to the grain is also found for these properties. Weibull distributions are fitted to all test results and presented to probabilistically consider the investigated properties in numerical simulations of veneer-based structural products.

KEYWORDS: Veneer mechanical properties; Veneer-based structural products; Perpendicular to grain; Shear; Juvenile plantation hardwood.

INTRODUCTION

When a manufacturer of engineered wood products wishes to introduce new veneer-based structural products on the market, such as those manufactured from new timber species (Boughton and Crews 2013) or from an optimisation strategy of the existing veneered stock, an experimental campaign must be undertaken. The campaign aims at determining the strength and stiffness distributions of the new products and ultimately derive the design properties. A minimum of 30 and 32 tests per design property is required in the Australian/New-Zealand (AS/NZS 2269.1 2012, AS/NZS 4357.2 2006) and European (EN 1058 2009) standards, respectively. A costly trial-and-error procedure may therefore be needed to achieve targeted design properties.

Nevertheless, to efficiently determine and optimise the mechanical properties of new veneer-based structural products, numerical models which aim at determining the properties of a final product from the properties of its individual wood components can be taken advantage of. These models, combined with a probabilistic data base of the mechanical properties of individual veneers, can ultimately predict the strength and stiffness distributions of the new products through cost-effective Monte Carlo simulations. Such approach is described for instance in Clouston and Lam (2001), Gilbert, et al. (2017b) and Gilbert (2018). Consequently, the initial establishment of a probabilistic data base of the mechanical properties of the **glued veneers within a final product** is essential.

The approach above is currently followed (Gilbert 2018, Gilbert, et al. 2017a, Gilbert, et al. 2017b) to determine the mechanical properties of Laminated Veneer Lumber (LVL) and plywood panels manufactured from Australia's underutilised hardwood plantation forest resources in structural applications, namely juvenile (early to mid-rotation) hardwood plantation logs. The methodology will also be extended to derive the design properties of innovative veneer-based hollow structural products manufactured from the same resource (Gilbert, et al. 2014, Gilbert, et al. 2017c, Gilbert, et al. 2018). The new resource consists of the trees either harvested during the thinning operation (Nolan, et al. 2005) in plantations established for high quality solid wood markets or clear felled, with no prior pruning or thinning, in plantations primarily established for pulpwood production. These plantations

cover just under one million hectares in Australia (Australian Government 2017). In both plantation types, the trees of interest are harvested between 12 to 15 years after establishing the plantation, are about 30 cm in diameter at breast height, and, due to a high proportion of defects (knots, gum veins, grain deviation, etc.), have little to no commercial value. Nevertheless, manufacturing veneer-based products from juvenile hardwood logs has proven to produce structural products superior in their mechanical properties to currently commercialised softwood ones (Gaunt, et al. 2002, Gilbert 2018, Gilbert, et al. 2017b, McGavin, et al. 2013, Monteiro de Carvalho, et al. 2004, Rahayu, et al. 2015). This offers a viable market for the new resource.

While the tensile and compressive strengths parallel to the grain of **glued** rotary peeled veneers recovered from three species of the above juvenile hardwood logs have been quantified in Gilbert, et al. (2017a), their mechanical properties perpendicular to the grain and in shear still need to be investigated. Two of these species were planted for solid timber end-products (Gympie messmate (GMS - *Eucalyptus cloeziana*), spotted gum (SPG - *Corymbia citriodora*)) and one species for pulpwood (southern blue gum (SBG - *Eucalyptus globulus*)). These properties represent essential data that would then be entered into numerical models to compute, for instance, the embedment, bearing or shear strengths of various configurations of veneer-based structural products. The objectives of this paper are therefore to experimentally and statistically quantify for the first time (i) the dynamic Modulus of Elasticity (MOE) perpendicular to the grain (in the tangential direction of the wooden material), (ii) the tensile and compressive strengths perpendicular to the grain (also in the tangential direction), (iii) the Shear Modulus (in the longitudinal-tangential plane of the wooden material), also referred to as “Modulus of Rigidity”, and (iv) the through-the-thickness and rolling shear strengths of **glued** veneers recovered from the GMS, SPG and SBG species. The test methodologies, aiming at quantifying the properties of the veneers as would be encountered in veneer-based structural products (i.e. by including both the effects of hot pressing the veneers and the glue used during the manufacturing process), are explained. The correlations between the investigated properties and reference values, commonly used to grade veneers or veneer-based structural products,

such as the MOE parallel to the grain and veneer density, are analysed. Distributions are fitted to the test results and presented to probabilistically consider the investigated properties in future numerical simulations.

Note that the distributions of veneer qualities expected from veneer processing of the three species of interest have been quantified in McGavin, et al. (2015a).

MATERIAL AND METHODS

Sample preparation

As part of collaborative projects between industry and the Queensland Government to enhance the value of early to mid-rotation hardwood plantations logs, 1.3 m long logs originated from (i) one site in South-east Queensland for the GMS species, (ii) two different sites in Northern New South Wales and one site in South East Queensland for the SPG species and (iii) three different sites in Victoria for the SBG species were delivered at the Salisbury Research Facility, Brisbane, Australia (McGavin, et al. 2015a). The logs were then rotary peeled using a spindle-less lathe to produce veneers with a dried nominal thickness of 2.5 mm. The details (age of the trees, breast height diameter, number of trees, etc) of the overall resources peeled during these projects can be found in McGavin, et al. (2015a), (2015b).

90 seasoned veneer sheets of nominal dimensions of 1.2 m wide $\times$ 1.2 m long were selected per species out of all peeled logs to best represent the range of veneer MOE encountered for each species. In total, the veneer sheets come from 20, 44 and 43 different trees for the GMS, SPG and SBG species, respectively.

Each veneer sheet was cut parallel to the grain into three 400 mm wide $\times$ 1.2 m long strips. The three strips per veneer sheet were then glued together to form a 3-ply LVL of 7.5 mm nominal thickness using standard gluing procedures and a readily available commercial Phenol-Formaldehyde adhesive system (Momentive Specialty Chemical PP1158). To ensure defects were randomised, the middle strip was glued upside-down and the other two strips were glued with their tight side (i.e. the

side not in contact with the knife as the log is being peeled) as the outer faces of the LVL. The manufacturing of the 3-ply LVL to determine the properties of each veneer sheet is important as it allows quantifying the mechanical properties of each veneer (or sheet) as would be encountered in veneer-based structural products, i.e. by including the effects of both hot pressing the veneers and the glue used during the manufacturing process.

After manufacture, the 3-ply LVL were sawn into samples to determine the different mechanical properties as:

- One 630 mm (along grain) $\times$ 100 mm sample and one 1,130 mm (along grain) $\times$ 150 mm sample for compression and tension parallel to the grain, with the results reported in Gilbert, et al. (2017a).
- Three 100 mm (along grain) $\times$ 150 mm samples for compression and MOE perpendicular to grain, tension perpendicular to grain and rolling shear, respectively.
- One 150 mm $\times$ 150 mm sample for Shear Modulus and through-the-thickness shear.

The samples were conditioned at 20°C and 65% relative humidity before testing, following the recommendations in the Australian standard AS/NZS 4357.2 (AS/NZS, 2006). For samples tested perpendicular to the grain and in shear through-the-thickness, selected samples were weighed immediately after being tested to calculate the moisture content of the timber at the time of testing. The oven-dry methodology in the Australian and New Zealand standard AS/NZS 1080.1 (AS/NZS, 2012) was followed. Moisture content measurements were not possible for samples tested in rolling shear, as the nature of the tests (see Section “Material testing”) does not allow samples large enough to be cut after testing to determine the moisture content.

Note that due to the cutting direction and the log orientation of rotary peeled veneers: (i) the perpendicular direction to the grain investigated in this study corresponds to the tangential direction of the wooden material and (ii) the through-the-thickness strength and Shear Modulus corresponds to the longitudinal-tangential plane of the wooden material.

While all 90×3 -ply LVL per species were used in Gilbert, et al. (2017a) to determine the mechanical properties parallel to the grain, only 45×3 -ply LVL per species were selected in this study to assess the perpendicular to grain and shear properties of the veneers. 45 samples per species were deemed a reasonable number to capture the variability in each investigated mechanical property while preparing for and performing a realistic number of tests. In total, 270 non-destructive and 540 destructive tests were performed as part of this study. In some cases, due to manipulation errors or broken samples, the number of tested samples may be less than 45 per mechanical property and species.

Material testing and correlations

As no specific test methods is published to investigate the mechanical properties of the 3-ply LVL (each manufactured from the same veneer sheet), the test methods for LVL and clear timber specimens in the Australian standards, ASTM and European standards were first reviewed. The most appropriate method was used in the study as discussed in each sub-section below.

Note that correlations are derived in this paper between mechanical properties as detailed in following sections. Principally, as both the veneer dynamic MOE parallel to the grain and the veneer density are commonly measured in line to grade veneers (e.g. Metriguard veneer tester Model 2805 DME (Metriguard 2017)), they would constitute reference values based on which veneers will be selected to manufacture veneer-based structural products with targeted structural properties. These two properties are also often used as reference values to predict other mechanical properties, such as in Kretschmann (2010) and Guitard and El Amri (1987). Finding the correlations between the investigated properties in this paper and the veneer density or dynamic MOE parallel to the grain is important. Indeed, similarly to the production phase, in numerical simulations, the density or the MOE of the veneers would also be used as reference values and all mechanical properties would be statistically derived from these references values and realistically assigned to each ply. This approach is taken throughout the paper for all investigated properties.

Compressive strength and MOE perpendicular to the grain

The 100 mm × 150 mm 3-ply LVL pieces reserved for compression testing perpendicular to the grain were cut into two strips of 48 mm (along grain) × 150 mm (across grain). The dynamic MOE perpendicular to the grain of one strip out of two was determined by simply supporting the strip on rubber bands and impacting it with a hammer in bending. The sample natural frequency was recorded using a microphone and analysed using the software BING® (Beam Identification by Non-destructive Grading) (Brancheriau and Bailleres 2002, CIRAD 2012). The dynamic MOE (E_{T_LVL}) perpendicular to the grain of each 3-ply LVL is compared in the study to (i) the one parallel to the grain (E_{L_Veneer}) of the parent single veneer sheet, i.e. measured before gluing and also from a non-destructive acoustic resonance method (Gilbert, et al. 2017a), and (ii) the veneer density, i.e. also measured before manufacturing the LVL. Note that due to the nature of the veneers, measuring the dynamic MOE of the veneers (i.e. before gluing) did not provide conclusive and was not performed.

The two strips were then glued together with polyurethane structural adhesive to form 6-ply LVL samples of 15 mm nominal thickness. The Australian and New-Zealand standard AS/NZS 4357.2 (AS/NZS, 2006) does provide a methodology to assess the compressive strength perpendicular to the grain of LVL samples. The ASTM D5456 (2017) recommends samples of height of 51 mm in the plane of the veneers and in the direction of the load to be tested. The European standards (EN 408 2010, EN 14374 2004) recommend samples of height of 90 mm. In this study, as the thickness of the samples was less than the one recommended in both the ASTM D5456 (2017) and the EN 14374 (2004), the samples had to be cut to 40 mm (height) × 42 mm (wide) × 15 mm (thick) to avoid global buckling during testing. The orientation of the samples is shown in Figure 1. The samples were tested in compression (in the tangential direction) in a 30 kN capacity Lloyd universal testing machine at a stroke rate of 1.2 mm/min to reach failure between 3 to 5 mins. The bottom platen of the testing machine was fixed while the top platen was mounted on a spherical bearing, which could rotate to provide full contact between the platen and the samples. The test set-up is shown in Figure 1.

The compressive plastic stress perpendicular to the grain moderately increased after the elastic response but not to large strains, as typically observed in wood elements (Holmberg, et al. 1999). Instead the load reached a peak before the samples ultimately crumbled to pieces. Yet, enough plastic deformation was observed before reaching the maximum load to calculate the compressive strength f_{c_T} perpendicular to the grain following the 1% strain offset method in the European standard EN 408 (2010). f_{c_T} is therefore calculated in this study as,

$$f_{c_T} = \frac{F_{1\%}}{wt} \quad (1)$$

where $F_{1\%}$ is the load corresponding to the intersection of the load-displacement curve and a straight line parallel to the elastic part of the curve with a 1% strain offset, and w and t are the measured width and thickness of the sample, respectively.

Correlations between f_{c_T} and the veneer dynamic MOE parallel to the grain (E_{L_Veneer}), 3-ply LVL MOE perpendicular to the grain (E_{T_LVL}) and veneer density are established in this paper through linear regression analyses.

The variability in the MOE and compressive strength perpendicular to the grain is also discussed in terms of 2-parameter Weibull distributions (Weibull 1939), also fitted through regression analyses. The use of Weibull distributions is well accepted to characterise the variability in mechanical properties of timber elements (Gibson and Ashby 1999, Madsen and Buchanan 1986). The Cumulative Distribution Function (CDF) F of a Weibull distribution is given for the random variable V as,

$$F(V) = 1 - e^{\left(-\left(\frac{V}{m}\right)^k\right)} \quad (2)$$

where m and k are the Weibull scale and shape parameters, respectively.

Tensile strength perpendicular to the grain

The tensile strength perpendicular to the grain was determined following a similar method to the one described for clear timber specimens in the ASTM D143-14 (2014). This procedure differs from

the one described in the European standards (EN 408 2010, EN 14374 2004) for LVL samples in which steel plates (or timber blocks) are glued to cuboid samples. The former procedure was deemed to be better suited for the size of the analysed samples and is used in the literature for LVL samples (Ardalany, et al. 2011).

The samples were cut to the dimensions given in Figure 2 (a) and were then fastened to a specially made jig, as shown in Figure 2. The jig was clamped in the jaw a 30 kN capacity Lloyd universal testing machine which was driven in displacement control at a stroke rate of 0.3 mm/min to reach failure between 2 to 5 mins.

The tensile strength f_{t_T} parallel to the grain of a sample is calculated as,

$$f_{t_T} = \frac{F_{\max}}{wt} \quad (3)$$

where $F_{\max}$ is the maximum applied force, and w and t are the measured width and thickness of the sample, respectively. w is measured at the minimum cross-sectional width in Figure 2, with nominal w equal to 25 mm.

Similar regression analyses and distribution fittings to the ones described in Section “Compressive strength and MOE perpendicular to the grain” are applied to the results for tension perpendicular to the grain.

Through-the-thickness shear strength and Shear Modulus

The through-the-thickness shear was assessed following a methodology similar to the one described in the Australian and New-Zealand AS/NZS 4357.2 (AS/NZS, 2006), European (EN 408 2010, EN 14374 2004) and ASTM D2719-13 (2013) standards, but adapted for the size of the 3-ply LVL samples. The 150 mm × 150 mm pieces selected for through-the-thickness shear tests were clamped between serrated steel plates (as shown in Figure 3), leaving a shear area of 50 mm × 150 mm. The grain of the 3-ply LVL samples was orientated along the transverse (short) direction of the shear area, as shown in Figure 3. The angle θ between the applied load F and the longitudinal (long) direction of the shear area was set to 14°, as specified in the standards.

Out of the 45 samples per species, 15 were fitted at their centre point with a 30 mm single strain gauge, orientated at 45° to the longitudinal direction of the shear area, as shown in Figure 3, to measure the Shear Modulus. The sample were tested in a 30 kN capacity Lloyd universal testing machine at a stroke rate of 0.5 mm/min to reach failure in 3 to 6 mins.

The through-the-thickness shear strength f_{s_LT} of each sample is calculated as (ASTM D2719-13 2013),

$$f_{s_LT} = \frac{F_{\max} \cos \theta}{Lt} \quad (4)$$

where $F_{\max}$ is the maximum applied load, and L and t are the measured length and thickness of the shear area, respectively. The Shear Modulus G_{LT_LVL} is calculated by performing a linear regression on the linear part of the shear stress (τ)-strain (ϵ) curve (ASTM D2719-13 2013) as,

$$\tau = \frac{F \cos \theta}{Lt} = 2G_{LT} \epsilon \quad (5)$$

where ϵ is the strain recorded by the strain gauge.

The ASTM D2719-13 (2013) offers the possibility or not to correct the Shear Modulus by a factor to take into account non-uniform stress distributions. As the correction factor of 1.19 suggested in the ASTM may not be accurate for the size of the tested samples, the values of G reported in this paper have not been corrected.

Correlations between f_{s_LT} and properties E_{L_Veneer} , veneer density, E_{T_LVL} and G_{LT_LVL} are established in this paper through regression analyses. Similar correlations are also established for G_{LT_LVL} . Similarly to the perpendicular to grain results, the variability in the through-the-thickness shear strength is discussed in terms of 2-parameter Weibull distributions (Weibull 1939), also fitted through regression analyses.

Rolling shear strength

The rolling shear strength was determined following the “Planar Shear Loaded by Plates” methodology described in the ASTM D2718-00 (2011). This method is similar in philosophy to the one proposed in the Australian standard AS/NZS 4357.2 (2006) for LVL. The 100 mm × 150 mm

pieces reserved for rolling shear tests were glued using two-part structural epoxy between two 170 mm (length) $\times$ 100 mm (width) $\times$ 10 mm (thickness) steel plates. A knife edges was machined to the end of each plate. Both knife edges were positioned in V-blocks and loaded in compression in a 500 kN capacity MTS universal testing machine, as shown in Figure 4. The tests were performed in displacement control at a stroke rate of 0.4 mm/min to reach failure between 3 and 5 mins.

The 3-ply LVL were glued so that the knife checks produced by the peeling lathe were orientated in opposite directions, as shown in Figure 4 (explanations on LVL layout are given in Section “Sample preparation”). Therefore, during testing and whatever the orientation of the sample is, at least one knife check opened and the remaining one(s) closed. Therefore, as specified in the ASTM D2718-00 (2011), a “checks open” failure mode is possible regardless the direction of loading and the samples were randomly orientated during testing.

The rolling shear strength f_{s_RT} of each sample is calculated as (ASTM D2718-00 2011),

$$f_{s_RT} = \frac{F_{\max}}{wL} \quad (6)$$

where $F_{\max}$ is the maximum applied load, and w and L are the measured width and length of the samples, respectively.

Similar regression analyses and distribution fittings to the ones described in Section “Through-the-thickness shear strength and Shear Modulus” are applied to the rolling shear results.

RESULTS AND DISCUSSION

Moisture content

The average oven dry moisture content at the time of testing for all test configurations and species is summarised in Table 1. Also are given in the table, the number of samples on which the average moisture content was calculated and associated Coefficient of Variations (CoV). The results display consistent moisture content between tests.

MOE perpendicular to the grain

The Coefficients of Determination between E_{T_LVL} and properties E_{L_Veneer} and veneer density are summarised in Table 2 for all analysed species. The MOE perpendicular to the grain of the 3-ply LVL is found to have little to no correlation with the MOE parallel to the grain of the veneer sheet from which they were manufactured, with R^2 less than 0.06 (GMS) for all three species. A weak correlation is found between the MOE perpendicular to the grain and the density, with R^2 ranging between 0.10 (SPG) and 0.28 (GMS). These results follow the correlation trends quantified by judgment and documented in the JCSS Probabilistic model code (JCSS 2006). In this code, a “low” correlation is reported between the MOE perpendicular and parallel to the grain, while a “medium” correlation is reported between the MOE perpendicular to grain and the density. However, as the dynamic MOE perpendicular to the grain is determined from the measured density and the natural frequency of the tested sample, the correlation between E_{T_LVL} and density may be biased towards the measuring method.

The values of the measured MOE perpendicular to the grain are found to range between 200 MPa to 1,300 MPa for all species, with average values of 826 MPa, 756 MPa and 482 MPa for the GMS, SPG and SBG species, respectively. The CoV on the measured values are 27.6%, 27.4% and 36.2% for the GMS, SPG and SBG species, respectively. The average E_{T_LVL} values for the GMS and SPG samples are 1.65 and 1.40 times lower, respectively, than the predicted values in Guitard and El Amri (1987) which are based on experimental statistical models from wood density versus wood mechanical properties measured on clear sawn specimen. The presence of lathe checks on the veneers may weaken the tangential properties when compared to clear sawn wood (Pot, et al. 2015). Note that the average density of the tested samples is used herein in Guitard and El Amri (1987)’s prediction equation. For the SBG samples, the predicted value of the MOE perpendicular to the grain is 3.20 higher than the average measured one.

As no clear correlation is found between the MOE perpendicular to the grain and either the one parallel to the grain or the timber density, the MOE perpendicular to the grain may be treated as a

random variable in numerical simulations. Figure 5 shows the CDF of the random variable E_{T_LVL} and best fit Weibull distributions (Eq. (2)). Values of Weibull parameters m and k found by regression analysis are reported in Table 3 for all species. The distributions fit the experimental data with a Kolmogorov-Smirnov test less than 0.12. Note that Normal distributions would fit the experimental data with Kolmogorov-Smirnov tests no more than 4% different to the tests of the Weibull distributions.

Compressive strength perpendicular to the grain

The compressive strength f_{c_T} for the SBG samples is plotted in Figure 6 (a) against the veneer dynamic MOE parallel to the grain, in Figure 6 (b) against the measured veneer density and in Figure 6 (c) against the 3-ply LVL dynamic MOE perpendicular to the grain. The linear regression curves are also plotted on the figures with associated Coefficients of Determination (R^2).

The Coefficients of Determination between f_{c_T} and properties E_{L_Veneer} , veneer density and E_{T_LVL} are summarised in Table 2 for all analysed species. For all species, the correlation between f_{c_T} and E_{L_Veneer} is weak, with R^2 less than 0.20 (GMS). The correlation between either f_{c_T} and density or f_{c_T} and E_{T_LVL} is weak to moderate and varies within species, with R^2 between f_{c_T} and density ranging from 0.18 (SPG) to 0.46 (SBG) and R^2 between f_{c_T} and E_T ranging from no correlation (SPG) to 0.71 (SBG). Apart from the correlation between f_{c_T} and E_{T_LVL} , these results follow somehow the correlation trends quantified by judgment in the JCSS Probabilistic model code (JCSS 2006) of (i) a “low” correlation between f_{c_T} and MOE parallel to grain, (ii) a “high” correlation between f_{c_T} and density and (iii) and “very low” correlation between f_{c_T} and MOE perpendicular to grain.

The average compressive strength perpendicular to the grain is found to be 7.9 MPa, 8.4 MPa and 4.7 MPa for the GMS, SPG and SBG species, respectively. The CoV on the measured values are 13.6%, 16.1% and 26.5% for the GMS, SPG and SBG species, respectively. Note that the above average compressive strength values, calculated herein using the 1% strain offset method in the EN 408 (2010), are 1.5 to 2.3 times lower than the maximum recorded strength values.

In numerical simulations, if the veneer MOE parallel to grain is used as the reference mechanical property to predict f_{c_T} , and as no clear correlation is found between the two values, the Weibull distribution for each species is first fitted herein on the random variable f_{c_T} . The CDF $F(f_{c_T})$ are plotted in Figure 7 (a) for all species with best fit Weibull distributions. On the other hand, if the density is used as the reference property to predict f_{c_T} in numerical simulations, and as some correlation is found between the two values (especially for SPG and SBG), the Weibull distribution for each species is second fitted on the random variable $f_{c_T} / \text{Density}$. The CDF $F(f_{c_T} / \text{Density})$ are plotted in Figure 7 (b) for all species with best fit Weibull distributions. Values of Weibull parameters m and k (Eq. (2)) for random variables f_{c_T} and $f_{c_T} / \text{Density}$ are reported in Table 3 for all species. The distributions fit the experimental data with a Kolmogorov-Smirnov test less than 0.15.

Figure 7 (a) shows that SBG has the lower compressive strength perpendicular the grain and SPG, the highest.

Note that due to samples initially cut too long and globally buckling, all test results were not processed and the numbers of valid tests is low for the GMS species and equal to 23.

Tensile strength perpendicular to the grain

The Coefficients of Determination between f_{t_T} and properties E_{L_Veneer} , veneer density and E_{T_LVL} are summarised in Table 2 for all analysed species. Apart for the SBG, little to weak correlations are found between f_{t_T} and the latter properties, with a maximum R^2 of 0.16. A stronger correlation is found either between f_{t_T} and E_{T_LVL} or f_{t_T} and veneer density for the SBG samples, with a maximum R^2 of 0.36. Yet, this correlation is still weak. These results agree well with the correlation trends in the JCSS Probabilistic model code (JCSS 2006) which reports a “low” correlation between f_{t_T} and all previously analysed properties.

The tensile strength perpendicular to the grain is about 4 to 6 times lower than the compressive strength perpendicular to the grain with average strengths of 1.06 MPa, 1.39 MPa and 1.29 MPa for the GMS, SPG and SBG species, respectively. The CoV on the measured values are large and equal to 64.8%, 47.6% and 65.0% for the GMS, SPG and SBG species, respectively.

In view of the correlations reported in Table 2, the compressive strength f_{t_T} can be considered as random in numerical simulations. Figure 8 shows the CDF of the random variable f_{t_T} and best fit Weibull distributions (Eq. (2)). Values of Weibull parameters m and k found by regression analysis are reported in Table 3 for all species. The distributions fit the experimental data with a Kolmogorov-Smirnov test less than 0.16.

Shear Modulus

For all species, the Shear Modulus G_{LT_LVL} shows little to weak correlations with both the veneer MOE parallel to the grain and the veneer density, with R^2 being less than 0.18 for all cases, as shown in Table 4. On the other hand, a strong correlation is found between G_{LT_LVL} and the 3-ply LVL MOE perpendicular to the grain E_{T_LVL} , with R^2 ranging from 0.39 (SBG) to 0.59 (GMS), as shown in Table 4. Note that in the JCSS Probabilistic model code (JCSS 2006), a “medium” correlation is reported between the Shear Modulus and either MOE parallel to grain, MOE perpendicular to grain or veneer density. Figure 9 plots the relationship between Shear Modulus G_{LT_LVL} and MOE perpendicular to the grain for species.

The average observed value for the Shear Modulus G_{LT_LVL} is found to be 748 MPa, 711 MPa and 523 MPa for the GMS, SPG and SBG species, respectively. The CoV on the measured values are equal to 20.9%, 17.0% and 15.6% for the GMS, SPG and SBG species, respectively. The average G_{LT_LVL} values are between 1.50 (GMS) and 1.69 (SBG) times lower than the predicted values, based on the timber density, in Guitard and El Amri (1987). The presence of lathe checks may also influence the value G_{LT_LVL} when compared to clear sawn wood (Pot, et al. 2015).

As the number of samples to quantify the Shear Modulus is low (15) and may not be significant enough, no Weibull distributions are plotted for this value herein.

Through-the-thickness shear strength

The through-the-thickness shear strength f_{s_LT} for the SPG samples is plotted in Figure 10 (a) and (b), against the 3-ply LVL dynamic MOE perpendicular to the grain and the Shear Modulus,

respectively. The linear regression curves are also plotted on the figures with associated Coefficients of Determination (R^2).

The Coefficients of Determination between f_{s_LT} and properties E_{L_Veneer} , veneer density, E_{T_LVL} and G_{LT_LVL} are summarised in Table 4 for all analysed species. The correlation between either f_{s_LT} and E_{L_Veneer} or f_{s_LT} and veneer density is null or weak, especially for the GMS and SPG species, with R^2 less than 0.29 (SBG and f_{s_LT} versus veneer density). However, a stronger correlation is found between either f_{s_LT} and E_{T_LVL} or f_{s_LT} and G_{LT_LVL} , with R^2 ranging from 0.36 (SBG and f_{s_LT} versus E_T) to 0.63 (SPG-SBG and f_{s_LT} versus G_{LT_LVL}). In the JCSS Probabilistic model code (JCSS 2006), (i) a “low” correlation is reported between f_{s_LT} and MOE parallel to grain which somehow agrees with the present results and (ii) a “medium” correlation is reported between either f_{s_LT} and density, f_{s_LT} and the MOE perpendicular to grain or f_{s_LT} and the shear modulus.

The average through-the-thickness shear strength is found to be 7.5 MPa, 8.4 MPa and 6.8 MPa for the GMS, SPG and SBG species, respectively. The CoV on the measured values are 18.9%, 15.3% and 26.7% for the GMS, SPG and SBG species, respectively.

Similarly to the discussion on the compressive strength perpendicular to the grain, Weibull distributions are derived herein for the through-the-thickness shear strength with two different random variables. First, let's assume that either the **veneer dynamic** MOE parallel to grain or the veneer density is used as the reference mechanical property in numerical simulations to predict f_{s_LT} . As no clear correlation is found between either f_{s_LT} and E_{L_Veneer} or f_{s_LT} and veneer density, the Weibull distribution for each species is first fitted herein on the random variable f_{s_LT} . The CDF $F(f_{s_LT})$ are plotted in Figure 11 (a) for all species with best fit Weibull distributions. Second, if the MOE perpendicular to the grain is used as the reference property to predict f_{s_LT} in numerical simulations, and a strong correlation is found between the two values, the Weibull distribution for each species is fitted on the random variable f_{s_LT} / E_{T_LVL} . The CDF $F(f_{s_LT} / E_{T_LVL})$ are plotted in Figure 11 (b) for all species with best fit Weibull distributions. Values of Weibull parameters m and

k (Eq. (2)) for random variables f_{s_LT} and f_{s_LT} / E_{T_LVL} are reported in Table 5 for all species. The distributions fit the experimental data with a Kolmogorov-Smirnov test less than 0.15.

Rolling shear strength

Failure was observed to occur in some samples at the glued interface between the steel plates and the timber samples. In this section, only the results from the samples failing in the timber are reported. This represents 32, 28 and 26 valid tests for GMS, SPG and SBG species.

The Coefficients of Determination between f_{s_RT} and properties E_{L_Veneer} , veneer density and E_{T_LVL} are summarised in Table 4 for all analysed species. Table 4 shows no to weak correlations between the rolling shear strength and all analysed properties. The maximum R^2 value of 0.29 is found between f_{s_RT} and veneer density for the SPG species.

The average rolling shear strength is found to be 2.56 MPa, 2.85 MPa and 2.26 MPa for the GMS, SPG and SBG species, respectively. The CoV on the measured values are 16.1%, 24.4% and 24.5% for the GMS, SPG and SBG species, respectively.

Weibull distributions are fitted on the random variable f_{s_RT} for each analysed species and the corresponding CDF $F(f_{s_RT})$ are plotted in Figure 12. Values of Weibull parameters m and k (Eq. (2)) for the random variable f_{s_RT} are reported in Table 5 for all species. The distributions fit the experimental data with a Kolmogorov-Smirnov test less than 0.16.

CONCLUSION

This paper presented the experimental results to quantify the MOE perpendicular to the grain, the compressive and tensile strengths perpendicular to the grain, the Shear Modulus, the through-the-thickness and rolling shear strengths of veneer-based elements, each glued from a single rotary peeled veneer sheet, of three species of early to mid-rotation (juvenile) hardwood plantation logs. The methodology allows to investigate the properties of veneers as would they be encountered in veneer-based structural products, i.e. by including the effects of both hot pressing the veneers and the glue used during the manufacturing process. The results were presented in the form of Weibull

distributions which can be used as random variables in numerical simulations to predict the overall properties of veneer-based structural products. The correlation between the investigated mechanical properties and the veneer sheet dynamic MOE parallel to the grain, the veneer-based element dynamic MOE perpendicular to the grain and veneer density are also reported and discussed. Results showed that in general, no to weak correlations are found between the different properties at the exception of the compressive strength perpendicular to the grain and veneer density, and the through-the-thickness strength and veneer-based element dynamic MOE perpendicular to the grain. The values of the measured MOE perpendicular to the grain were found to range between 200 MPa to 1,300 MPa for all analysed species. The average compressive strength perpendicular to the grain was found to be 7.9 MPa, 8.4 MPa and 4.7 MPa for the GMS, SPG and SBG species, respectively, and the tensile strength perpendicular to the grain was about 4 to 6 times lower than the compressive strength perpendicular to the grain. Regarding the shear, the average through-the-thickness shear strength was 7.5 MPa, 8.4 MPa and 6.8 MPa for the GMS, SPG and SBG species, respectively, while the average rolling shear strength was 2.56 MPa, 2.85 MPa and 2.26 MPa for the GMS, SPG and SBG species, respectively.

ACKNOWLEDGEMENTS

The authors would like to thank the *Australian Research Council* for its financial support through project DE140100212.

The support provided by the Queensland Department of Agriculture and Fisheries (DAF) through the provision of the unique Salisbury Research Facility is also acknowledged. The authors also express their gratitude to the Forest Product Innovation team at the Salisbury Research Facility for their invaluable help in preparing the 3-ply LVL.

CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

REFERENCES

- Ardalany, M., Deam, B., Fragiaco, M., and Crews, K. I. (2011). "Tension perpendicular to grain strength of wood, Laminated Veneer Lumber (LVL), and Cross-Banded LVL (LVL-C)." *Proceedings of the 21st Australasian Conference on the Mechanics of Structures and Materials (ACMSM21)*, 891 - 896.
- AS/NZS 1080.1 (2012). "Timber - Methods of test - Moisture content." Standards Australia, Sydney, Australia.
- AS/NZS 2269.1 (2012). "Plywood - Structural, Part 1: Determination of structural properties - Test methods." Standards Australia, Sydney, Australia.
- AS/NZS 4357.2 (2006). "Structural laminated veneer lumber, Part 2: Determination of structural properties - Test methods." Standards Australia, Sydney, Australia.
- ASTM D143-14 (2014). "Standard Test Methods for Small Clear Specimens of Timber." ASTM International, Pennsylvania, USA.
- ASTM D2718-00 (2011). "Standard Test Methods for Structural Panels in Planar Shear (Rolling Shear)." ASTM International, Pennsylvania, USA.
- ASTM D2719-13 (2013). "Standard test methods for structural panels in shear through-the-thickness." ASTM International, Pennsylvania, USA.
- ASTM D5456 – 17e1 (2017). "Standard Specification for Evaluation of Structural Composite Lumber Products." ASTM International, Pennsylvania, USA.
- Australian Government (2017). "Australia's forests at a glance 2017, with data to 2015–16." Australian Bureau of Agricultural and Water Resources, ed., Australian Bureau of Agricultural and Water Resources,.
- Boughton, G. N., and Crews, K. I. (2013). *Timber design handbook in accordance with the Australian Limit State Design Code AS 1720.1-2010*, Standards Australia, Sydney, Australia.
- Brancheriau, L., and Bailleres, H. (2002). "Natural vibration analysis of clear wooden beams: a theoretical review." *Wood Science and Technology*, 36, 347–365.
- CIRAD (2012). "BING® (Beam Identification by Nondestructive Grading) software." <<https://www.picotech.com/library/application-note/non-destructive-testing-of-wood>>. (25/09/2015).
- Clouston, P. L., and Lam, F. (2001). "Computational Modeling of Strand-Based Wood Composites." *ASCE Journal of Engineering Mechanics*, 127(8), 844-851.
- EN 408 (2010). "Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties." The European Union Per Regulation, Brussel, Belgium.
- EN 1058 (2009). "Wood-based panels - Determination of characteristic 5-percentile values and characteristic mean values." The European Union Per Regulation, Brussel, Belgium.
- EN 14374 (2004). "Timber structures. Structural laminated veneer lumber. Requirements." The European Union Per Regulation, Brussel, Belgium.

- Gaunt, D., Penellum, B., and McKenzie, H. M. (2002). "Eucalyptus nitens laminated veneer lumber structural properties." *New Zealand Journal of Forestry Science*, 33(1), 114-125.
- Gibson, L. J., and Ashby, M. F. (1999). "Wood (Chapter 10)." *Cellular solids - Structure and properties - Second edition*, D.R. Clarke, S. Suresh, and I.M. Ward FRS, eds., Cambridge university press, UK.
- Gilbert, B. P. (2018). "Compressive strength prediction of veneer-based structural products." *ASCE Journal of Materials in Civil Engineering (Accepted)*.
- Gilbert, B. P., Bailleres, H., Fischer, M. F., Zhang, H., and McGavin, R. L. (2017a). "Mechanical properties of rotary veneers recovered from early to midrotation subtropical-hardwood plantation logs for veneer-based composite applications." *ASCE Journal of Materials in Civil Engineering*, 29(10), 04017194.
- Gilbert, B. P., Bailleres, H., Zhang, H., and McGavin, R. L. (2017b). "Strength modelling of Laminated Veneer Lumber (LVL) beams." *Construction and Building Materials*, 149, 763-777.
- 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., Underhill, I. D., Fernando, D., and Bailleres, H. (2017c). "Structural solutions to produce long timber Veneer Based Composite hollow sections." *Construction and Building Materials*, 139, 81-92.
- Gilbert, B. P., Underhill, I. D., Fernando, D., Bailleres, H., and Miller, D. (2018). "Structural behaviour of hardwood veneer-based circular hollow sections of different compactness." *Construction and Building Materials*, 170, 557-569.
- Guitard, D., and El Amri, F. (1987). "Modèles prévisionnels de comportement élastique tridimensionnel pour les bois feuillus et les bois résineux (in French)." *Annals of Forest Science*, 44(3), 335-358.
- Holmberg, S., Persson, K., and Petersson, H. (1999). "Nonlinear mechanical behaviour and analysis of wood and fibre materials." *Computers & Structures*, 72(4-5), 459-480.
- JCSS (2006). "JCSS Probabilistic model code, Part 3: Resistance models." JCSS, ed.
- Kretschmann, D. E. (2010). "Mechanical properties of wood (Chapter 5)." *Wood handbook, Wood as an engineering material - Centennial Edition*, Forest Products Laboratory - United States Department of Agriculture Forest Service, Madison, Wisconsin, U.S.A.
- Madsen, B., and Buchanan, A. H. (1986). "Size effect in timber explained by a modified weakest link theory." *Canadian Journal of Civil Engineering*, 13, 218-232.
- McGavin, R. L., Bailleres, H., Fehrmann, J., and Ozarska, B. (2015a). "Stiffness and Density Analysis of Rotary Veneer Recovered from Six Species of Australian Plantation Hardwoods." *BioResources*, 10(4), 6395-6416.
- McGavin, R. L., Bailleres, H., Hamilton, M. G., Blackburn, D., Vega, M., and Ozarska, B. (2015b). "Variation in Rotary Veneer Recovery from Australian Plantation Eucalyptus globulus and Eucalyptus nitens." *BioResources*, 10(1), 313-329.

McGavin, R. L., Bailleres, H., Lane, F., and Fehrmann, J. (2013). "High value timber composite panels from hardwood plantation thinnings." Fisheries and Forestry Department of Agriculture, ed., Department of Agriculture, Fisheries and Forestry, Brisbane, Australia.

Metriguard (2017). "Model 2805 DME." <<https://metriguard.com/product/model-2800-dme>>. (30/01/2018).

Monteiro de Carvalho, A., Rocco Lahr, F. A., and Bortoletto, G. J. (2004). "Use of brazilian eucalyptus to produce LVL panels." *Forest Products Journal*, 54(11), 61-64.

Nolan, G., Greaves, B., Washusen, R., Parsons, M., and Jennings, S. (2005). "Eucalypt Plantations for Solid Wood Products in Australia – A Review ‘If you don’t prune it, we can’t use it’." Forest & Wood Products Research & Development Corporation, Melbourne, Australia.

Pot, G., Denaud, L.-E., and Collet, R. (2015). "Numerical study of the influence of veneer lathe checks on the elastic mechanical properties of laminated veneer lumber (LVL) made of beech." *Holzforschung*, 337.

Rahayu, I., Denaud, L., Marchal, R., and Darmawan, W. (2015). "Ten new poplar cultivars provide laminated veneer lumber for structural application." *Annals of Forest Science*, 72(6), 705-715.

Weibull, W. (1939). "A statistical theory of strength of materials." Generalstabens litografiska anstalts förlag, Stockholm.

Table 1: Average measured moisture content for all tested configurations and species. The numbers in brackets indicate the number of samples on which the average and Coefficient of Variations (CoV) are calculated

Configuration	Species	MC (%)	CoV (%)
Compression perpendicular to grain	GMS	11.5 (1)	--
	SPG	10.8 (3)	4.9
	SBG	11.7 (7)	3.1
Tension perpendicular to grain	GMS	10.6 (3)	2.6
	SPG	10.1 (7)	7.0
	SBG	10.7 (7)	6.2
Through-the-thickness shear	GMS	10.7 (19)	4.6
	SPG	10.1 (14)	6.7
	SBG	10.4 (15)	6.9

Table 2: Coefficient of Determination (R^2) matrix for perpendicular to grain properties

	MOE perp. To grain (E_{T_LVL})			Compression strength (f_{c_T})			Tensile strength (f_{t_T})		
	GMS	SPG	SBG	GMS	SPG	SBG	GMS	SPG	SBG
E_{L_Veneer}	0.06	0.02	0.04	0.20	<0.01	0.13	0.16	0.01	0.02
Density	0.28	0.10	0.22	0.39	0.18	0.46	0.04	0.07	0.24
E_{T_LVL}	--	--	--	0.32	<0.01	0.71	0.16	0.13	0.36

Table 3: Weibull distribution parameters for perpendicular to grain properties

	MOE perp. to grain (E_{T_LVL})			Comp. strength (f_{c_T})			Comp. strength to Dens. ($f_{c_T}/\text{Density}$)			Tensile strength (f_{t_T})		
	GMS	SPG	SBG	GMS	SPG	SBG	GMS	SPG	SBG	GMS	SPG	SBG
m	904.5	825.0	531.3	8.24	8.85	5.00	10.3e ⁻³	10.9e ⁻³	7.5e ⁻³	1.14	1.56	1.39
k	3.73	3.74	2.93	8.93	7.10	4.69	11.48	7.82	6.01	1.67	1.91	1.64
KT	0.11	0.11	0.12	0.15	0.13	0.11	0.09	0.13	0.14	0.10	0.16	0.09
Test ⁽¹⁾												

⁽¹⁾ Kolmogorov-Smirnov test

Table 4: Coefficient of Determination (R^2) matrix for shear properties

	Shear Modulus (G_{LT_LVL})			Through-the-thk shear strength (f_{s_LT})			Rolling shear strength (f_{s_RT})		
	GMS	SPG	SBG	GMS	SPG	SBG	GMS	SPG	SBG
E_{L_Veneer}	0.18	0.10	0.01	<0.01	0.07	0.26	0.10	0.10	0.05
Density	0.11	0.09	0.17	0.14	0.04	0.29	0.20	0.29	0.02
E_{T_LVL}	0.59	0.57	0.39	0.47	0.51	0.36	0.16	0.09	0.17
G_{LT_LVL}	--	--	--	0.48	0.63	0.63	--	--	--

Table 5: Weibull distribution parameters for shear properties

	Through-the-thk shear strength (f_{s_LT})			Through-the-thk shear strength to MOE perp. to grain (f_{s_LT} / E_{T_LVL})			Rolling shear strength (f_{s_RT})		
	GMS	SPG	SBG	GMS	SPG	SBG	GMS	SPG	SBG
m	8.00	8.86	7.37	10.2e ³	12.3e ³	16.3e ³	2.71	3.06	2.38
k	6.26	7.38	4.39	5.50	5.79	4.76	6.53	4.30	5.21
KT	0.10	0.09	0.15	0.11	0.12	0.10	0.14	0.16	0.14
Test ⁽¹⁾									

⁽¹⁾ Kolmogorov-Smirnov test

Figure 1: Compressive perpendicular to grain test set-up

Figure 2: Tension perpendicular to grain test set-up, (a) schematic and (b) photo

Figure 3: Through-the-thickness shear test set-up, (a) schematic and (b) photo

Figure 4: Rolling shear test set-up

Figure 5: CDF of 3-ply LVL dynamic MOE perpendicular to the grain ($E_{T,LVL}$) with associated 2-parameter Weibull distributions

(a)

(b)

(c)

Figure 6: Compressive strength perpendicular to the grain ($f_{c,T}$) versus (a) veneer dynamic MOE parallel to the grain ($E_{L,Veneer}$), (b) veneer density and (c) 3-ply LVL dynamic MOE perpendicular to the grain ($E_{T,LVL}$) - Plotted for SBG

(a)

(b)

Figure 7: CDF of (a) Compressive strength perpendicular to the grain (f_{c_T}) and (b) Compressive strength perpendicular to the grain to Veneer density ratio, both with associated 2-parameter Weibull distributions

Figure 8: CDF of tensile strength perpendicular to the grain ($f_{t,T}$) with associated 2-parameter Weibull distributions

Figure 9: 3-ply LVL Shear Modulus ($G_{LT,LVL}$) versus 3-ply LVL dynamic MOE perpendicular to the grain ($E_{T,LVL}$) - Plotted for all investigated species

(a)

(b)

Figure 10: Through-the-thickness shear strength ($f_{s,LT}$) versus (a) 3-ply LVL dynamic MOE perpendicular to the grain ($E_{T,LVL}$) and (b) 3-ply LVL shear Modulus ($G_{LT,LVL}$), - Plotted for SPG

(a)

(b)

Figure 11: CDF of (a) Through-the-thickness shear strength ($f_{s_{LT}}$) and (b) Through-the-thickness shear strength to 3-ply LVL MOE perpendicular to grain ratio, both with associated 2-parameter Weibull distributions

Figure 12: CDF of rolling shear strength (f_{s_RT}) with associated 2-parameter Weibull distributions