Compressive strength prediction of veneer-based structural products

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Abstract: Veneer-based structural products, such as Laminated Veneer Lumber (LVL) or plywood, are commonly used in timber constructions. When a manufacturer wishes to use new timber species or optimise the use of its veneered stock, the nominal design values of the new products need to be determined from comprehensive and expensive experimental investigations. In an effort to cost-effectively determine these characteristics, this paper introduces a methodology to numerically predict the compressive strength of veneer-based structural products. The method combines a classical elastoplastic approach with a probabilistic strength prediction model of the wood veneers. The veneer strength is determined from its size and characteristics which can be measured in line. The accuracy of the approach is verified against experimental tests performed on twenty-four LVL samples manufactured from two different timber species and of various sizes. Results show that it accurately predicts the strength of the LVL samples with an overall predicted to experimental ratio of 1.05 and low coefficient of variation of 0.08. The methodology is then applied to determine the compressive strength distributions of LVL columns and plywood boards manufactured from a new resource, namely early to mid-rotation (juvenile) hardwood plantation logs. Three different species (Gympie messmate (*Eucalyptus cloeziana*), spotted gum (*Corymbia citriodora*) and southern blue gum (*Eucalyptus globulus*)) are considered in the approach. The modelled compressive design strength of the new products is found to be of the same order of magnitude of and up to 1.6 times greater than the strength of commercialised LVL columns and plywood boards.

- 28 **Keywords:** Laminated Veneer Lumber (LVL); Plywood; Veneer-based structural products;
- 29 Numerical modelling; Juvenile hardwood logs

INTRODUCTION

Veneer-based wood structural products are manufactured by gluing wood veneers together, generally with either the grain of each veneer orientated in the same direction (Laminated Veneer Lumber (LVL)) or the grain of adjacent veneers orientated at 90° to one another (plywood) (Bottle 1983). These products are commonly used in timber constructions. They have higher strength, less variability in material properties and can span longer distances than sawn timber structural products (Stark, et al. 2010). With the existing interest in timber as a more sustainable alternative to steel and concrete in constructions, their use is expected to further expand. Yet, when a manufacturer introduces a new product on the market, either by using new timber species due a response to variations in prices and product demand (Boughton and Crews 2013) or an optimisation strategy of its existing veneered stock, a costly experimental program must be undertaken. This program aims at accurately measuring the strength and stiffness distributions of the new product and ultimately determining its design properties. In the Australian/New Zealand standards (AS/NZS 2269.1 2012, AS/NZS 4357.2 2006), a minimum of 30 tests is required per design property. To reach a specific final product, an inefficient trail-and-error approach may be needed.

Nevertheless, expected strength and stiffness distributions of new veneer-based products can be cost-effectively predicted if a methodology is developed that combines classical elastoplastic constitutive equations with a probabilistic strength prediction model of the wood veneers (Clouston and Lam 2001). The veneer strength prediction model is based on the veneer size and characteristics which can be measured in line. This approach has seldom been applied to LVL and plywood structural products (Gilbert, et al. 2017b) and is followed in this paper to ultimately determine the expected compressive structural properties of veneer-based products manufactured from a new resource: early to mid-rotation (juvenile) subtropical hardwood plantation logs (Gilbert, et al. 2017a). Indeed, while it has been proven that hard-

wood juvenile logs result in high grade veneer-based structural products (Gaunt, et al. 2002, McGavin, et al. 2013, Monteiro de Carvalho, et al. 2004), the actual design properties of the products have not been evaluated.

Note that the new resource is harvested between 12 and 15 years after establishing the plantation and are about 15 to 30 cm in diameter at breast height. They can be either sourced from (i) the low quality trees (for instance, those that are crooked, smaller or have too many branches) removed in an operation referred to as “thinning” in “commercial” plantations primarily established for high quality solid wood markets or (ii) from the clear felt trees of plantations primarily established for pulpwood production. The former type of plantations represents 0.16 million hectares of Australia’s plantations and the latter 0.84 million hectares (Australian Government 2015, Gavran 2013). With an unfavourable market for pulpwood (McGavin, et al. 2014) and thinned logs deemed of poor quality, these small diameter logs currently have little to no commercial value in Australia (McGavin, et al. 2006).

To ultimately predict the compressive strength of the new products, the objectives of this paper are to (i) extend the work in Gilbert, et al. (2017b) to numerically predict the compressive strength of veneer-based structural products in a general form, (ii) illustrate the practicality of the proposed approach in product development and (iii) evaluate the compressive design properties of LVL columns and plywood boards manufactured from juvenile hardwood plantation logs. Specifically, the theoretical framework of the proposed method, with an industrial perspective in mind, is first explained. Its characteristics and limitations are discussed. Second the strength prediction equations of early to mid-rotation hardwood plantation veneers published in the literature (Gilbert, et al. 2017a) and used in this study to (i) validate the proposed methodology and (ii) illustrate its application are summarised. The resource consists of two species planted for solid timber end-products (Gympie messmate (GMS) - *Eucalyptus cloeziana* and spotted gum (SPG) - *Corymbia citriodora*) and one species traditionally grown for

pulpwood (southern blue gum (SBG) - *Eucalyptus globulus*). Third, the accuracy of the approach is verified against compressive experimental tests performed on twenty-four LVL samples manufactured from early to mid-rotation GMS and SPG veneers. Finally, the developed methodology is used to evaluate the compressive strength distributions and design properties of new products. Six commercially available LVL cross-sectional sizes and three types of plywood boards, all products manufactured from four different construction strategies and from GMS, SPG and SBG early to mid-rotation hardwood plantation logs, are considered as case studies.

While a model has been developed by the author and co-workers to predict the bending strength of LVL beams (Gilbert, et al. 2017b), the novelty of this paper lies in extending for the first time the published methodology to predict the compressive strength of veneer-based structural products. Determining the bending, tensile, compressive and shear capacities of these products require different constitutive equations, as different mechanical behaviours are involved. The accuracy of all predicting models must therefore be thoughtfully verified, as in the present paper. Additionally, for the first time, the theoretical framework of probabilistically predicting the strength of wood veneers is developed with an industrial perspective in mind. The unknown compressive design properties of LVL columns and plywood boards manufactured from juvenile hardwood plantation logs is also quantified in the paper.

THEORETICAL FRAMEWORK

The elastoplastic constitutive equations (Willam 2003) which constitute the first part of the proposed methodology are introduced first in this section. These equations enable the compressive strength of a final veneer-based structural product to be calculated from the known properties of its veneers. The second part of the proposed methodology, consisting of the general form of the probabilistic strength prediction model of individual veneers, is then devel-

oped with an industrial perspective in mind. This veneer strength prediction is based on characteristics which can be measured in line and the veneer size. Finally, the combination of the two previous items to cost-effectively predict the compressive strength distribution of new veneer-based structural products is detailed.

Constitutive equations

The compressive strength of veneer-based structural products is typically determined along the product principal axes and uniaxial compression assumption is consequently considered in the model. The elastic response of the i^{th} veneer within a product is therefore described by the Hookes's law. After yielding, the veneer plastic response is governed by:

$$d\sigma_i = E_{e,i}d\varepsilon_{e,i} + E_{p,i}(\varepsilon_{p,i})d\varepsilon_{p,i} \quad (1)$$

where σ_i is the veneer stress, $E_{e,i}$ and $E_{p,i}$ are the veneer elastic and plastic moduli, respectively, and $\varepsilon_{e,i}$ and $\varepsilon_{p,i}$ are the veneer elastic and plastic strains, respectively. The stiffness $E_{ep,i}$ of the i^{th} veneer, defined as a function of $\varepsilon_{p,i}$ as,

$$E_{ep,i}(\varepsilon_{p,i}) = \frac{E_{e,i}E_{p,i}(\varepsilon_{p,i})}{E_{e,i} + E_{p,i}(\varepsilon_{p,i})} \quad (2)$$

is referred to as the elastoplastic stiffness. $E_{ep,i}$ is tangent to the non-linear stress-stress curve, as illustrated in Figure 1. Hardening and softening occur when $E_{ep,i} > 0$ and $E_{ep,i} < 0$, respectively (Willam 2003).

If the strain-stress curve in the principal direction of loading of each veneer is known, then $E_{ep,i}$ is known and the incremental compressive load dN applied to a n -layer veneer-based product of width W can be calculated as,

$$dN = W \sum_{i=1}^n E_{ep,i}(\varepsilon_{p,i}) d\varepsilon_i \quad (3)$$

where t_i is the thickness of the i^{th} veneer and ε is the total strain. For each veneer, the relationship between its plastic strain $\varepsilon_{p,i}$ and the total strain is given in terms of the elastic and plastic moduli $E_{e,i}$ and $E_{p,i}$ of the veneer as,

$$d\varepsilon_{p,i} = \frac{E_{e,i}}{E_{e,i} + E_{p,i}(\varepsilon_{p,i})} d\varepsilon \quad (4)$$

Probabilistic strength prediction of individual veneers

General

Manufacturers typically predict the strength of timber elements from characteristics which can be measured in line, such as density, elastic modulus (also commonly referred to as Modulus of Elasticity (MOE)) or knot locations. The expected strength R_d of the element is calculated from a best fitted equation f as,

$$R_d = f(c_1, c_2, \dots, c_k) \quad (5)$$

where c_i is the i^{th} measured characteristic and k is the total number of measured characteristics. Due to wood being a natural material, a variation exists between the actual (or measured) strength of the element and its predicted value from Eq. (5). For a given resource, this variation is expressed in term of the probability distribution function (PDF) h (or cumulative distribution function (CDF) H) for the random variable corresponding to the actual to predicted strength ratio ($R_{d,actual}/R_{d,predicted}$). The mean of the random variable is expected to be 1.0. The strength of a timber element can then be probabilistically determined from its measured characteristics as,

$$R_{d,actual} = f(c_1, c_2, \dots, c_k) H^{-1}(P) \quad (6)$$

where H^{-1} is the inverse CDF (also referred to as “quantile function”) and P a random number in $[0, 1]$.

148 *Characteristics c_i and veneer grading*

149 All or parts of in line measured characteristics c_l to c_k are typically used to grade timber ele-
150 ments and sort them into bins. For veneer-based products, veneers are randomly taken from
151 one or more bins to manufacture a given grade of final product. For a given resource, the dis-
152 tributions of c_l to c_k are known from accumulated past data. Let's term g_i the PDF of charac-
153 teristic c_i and let's assume that in the j^{th} bin c_i ranges in $[C_{ij,L}, C_{ij,U}]$. The PDF g_{ij} of c_i in Bin j
154 is given by the conditional PDF of g_i as,

$$155 \quad g_{ij}(c_i) = \frac{g_i(c_i | C_{ij,L} \leq c_i < C_{ij,U})}{\int_{C_{ij,L}}^{C_{ij,U}} g_i(c_i) dc_i} \quad (7)$$

156 The value of characteristic c_i of a veneer randomly taken from Bin j can then be obtained
157 from the inverse CDF G_{ij}^{-1} as,

$$158 \quad c_i = G_{ij}^{-1}(P) \quad (8)$$

159 where P is a random number in $[0, 1]$.

160 Note that characteristics c_l to c_k are assumed herein not to be correlated. Multivariable
161 distributions can be used in the methodology above if two or more characteristics are correlat-
162 ed.

163 *Size effect*

164 The strength of a timber element is well known to be sensitive to its size (Barrett, et al. 1995,
165 Madsen and Buchanan 1986). This phenomenon is commonly referred to as “size effect”
166 (Isaksson 2003) and is most noticeable for tensile and bending brittle failure modes (Clouston
167 and Lam 2001). Yet, timber elements failing in a ductile compressive mode are also known to
168 be sensitive to size effects, but to a lower degree (ASTM D1900-16 2016, Barrett, et al. 1995,
169 Madsen 1990, Madsen and Buchanan 1986). Therefore, the strength of wood veneers predict-

ed in Eq. (5) is only valid for the tested volume from which it was determined (Clouston and Lam 2001) and must be adjusted to reflect the volume of the veneer in a final veneer-based product. The weakest link theory (Weibull 1939) is well accepted in timber structures to perform this adjustment (Isaksson 2003, Madsen and Buchanan 1986). Note that while the theory has been developed for brittle, isotropic and homogeneous material (Fonselius 1997), it still applies to the ductile compressive failure mode experienced by timber structures as the failure occurs in the weakest cross-section (Madsen and Buchanan 1986). Moreover, the strength of timber elements is typically more sensitive to size variations perpendicular to the grain than parallel to it (ASTM D1900-16 2016, Barrett, et al. 1995, Zhou, et al. 2015).

Let's assume that the strength R_{d1} of a veneer predicted by Eq. (5) was obtained at a volume $V_1 = L_1 \times W_1 \times H_1$ (with the grain parallel to the longitudinal direction L), the strength R_{d2} of the same veneer at volume $V_2 = L_2 \times W_2 \times H_2$ can be deduced from the weakest link theory as (Isaksson 2003),

$$R_{d2} = \left(\frac{L_1}{L_2} \right)^{1/k_{\parallel}} \left(\frac{W_1}{W_2} \right)^{1/k_{\perp}} \left(\frac{H_1}{H_2} \right)^{1/k_{\perp}} R_{d1} \quad (9)$$

where $k_{\parallel}$ and $k_{\perp}$ are the shape factors related to the dimension(s) parallel and perpendicular to the grain, respectively.

Numerical implementation for industrial applications

How a manufacturer can predict the compressive strength distribution of an n-ply veneer-based structural product manufactured from veneers randomly taken from selected bins is detailed in the following steps.

- Step 1 – *Assign veneer characteristics*: For each veneer l ($l \in [1, n]$) taken from Bin j , randomly assign all its characteristic values c_i from Eq. (8).

- Step 2 – *Assign veneer strength*: For each veneer l , randomly assign its strength value R_d from Eq. (6) and correct R_d from Eq. (9) to reflect the actual size of the veneer within the simulated veneer-based structural product.
- Step 3 – *Assign stress-strain curves*: Based on characteristic values in Step 1 and strength in Step 2, assign the known strain-strain curve to each veneer l .
- Step 4 – *Capacity prediction*: Solve the constitutive equations in Section “*Constitutive equations*” and find the strength of the simulated product.
- Step 5 – *Repeat*: Repeat Steps 1 to 4 to run Monte Carlo simulations and obtain the strength distribution of the final product.

Limitations

While wood veneers are also used in the manufacture of Parallel Strand Lumber (PSL) and Laminated Strand Lumber (LSL) structural products, these products differs from veneer-based products as they are not manufactured from full wood veneer sheets but from strands clipped from them. The proposed methodology does not apply to these products. Modelling of strand-based composites from strand properties can be found in Clouston and Lam (2001), Clouston and Lam (2002) and Amini, et al. (2017).

As a uniaxial compression assumption is made in the proposed methodology, only the compressive failure mode is considered.

VENEER PROPERTIES FROM LITERATURE

To validate the accuracy of the proposed numerical approach (Section “*Validation of the proposed numerical approach*”) and illustrate its application (Section “*Illustration: Practical industrial application*”), veneered resources for which the mechanical properties have been probabilistically published (Gilbert, et al. 2017a, Gilbert, et al. 2017b) are used. The key

equations in Gilbert, et al. (2017a) of the compressive strength prediction of early to mid-rotation GMS, SPG and SBG hardwood plantation veneers are summarised in the section for ease of reading. Other properties established in Gilbert, et al. (2017b) are also briefly introduced. The interested reader can refer to Gilbert, et al. (2017a) and Gilbert, et al. (2017b) for detailed information.

Strength prediction

The compressive strength of the GMS, SPG and SBG veneers is determined from two characteristics c_1 and c_2 which can be measured in line during manufacturing, namely the veneer dynamic MOE and its total knot area ratio (tKAR) (Isaksson 1999). The dynamic MOE can be obtained by measuring the propagation time of an ultrasonic wave along the width of the veneer ribbon (Achim, et al. 2011) and the tKAR can be measured with a linear camera which scans the veneer ribbon as it passes. Examples of such veneer tester machines are commercialised for instance by Metriguard (2017) and Camsensor Technologies Ltd (2009). The general strength best fit prediction in Eq. (5) is expressed in the form (Gilbert, et al. 2017a),

$$R_d = \alpha \cdot MOE^\beta (1 - \gamma \cdot tKAR) \quad (10)$$

where coefficients α , β and γ are given in Table 1 for each species. For the three species of interest, Eq. (10) predicted the observed strength with a coefficient of determination R^2 ranging from 0.63 (GMS) to 0.74 (SPG). The relationship between R_d and the veneer dynamic MOE for the GMS species found in (Gilbert, et al. 2017a) is shown in Figure 2 (a). Note that for each species, Eq. (10) was determined from tests performed on 90 veneer sheets. Each sheet was cut into three strips which were glued together to manufacture 3-ply LVL test samples. The samples of nominal dimensions $L_l = 630 \text{ mm} \times W_l = 100 \text{ mm} \times H_l = 7.5 \text{ mm}$ were prevented from lateral buckling every 55 mm by rollers (AS/NZS 2269.1 2012) and tested in compression, as shown in Figure 2 (b). Also note that while the influence of the knots on the capacity on timber structural products is principally considered for tension and bending fail-

ures (Fink and Kohler 2014, Johansson 2003), considering the $tKAR$ value in Eq. (10) was found to significantly improve the compressive strength prediction (Gilbert, et al. 2017a). The coefficient of determination R^2 was improved by 12% on average.

A two-parameter Weibull distribution was found to best fit the CDF H of the random variable corresponding to the actual to predicted strength ratio ($R_{d,actual}/R_{d,predicted}$) in the form,

$$H\left(\frac{R_{d,actual}}{R_{d,predicted}}\right) = 1 - e^{-\left(\frac{R_{d,actual}}{\lambda R_{d,predicted}}\right)^k} \quad (11)$$

where the shape factor k and the scale parameter λ (Fonselius 1997) are given in Table 1 for all species.

Veneer grading and characteristics

The three different veneer grades defined in Gilbert, et al. (2017a) and using the veneer MOE value as the sole grading indicator are used in the present paper. The MOE cut-off values between each grade are summarised in Table 2 and are based on the expected distributions of MOE encountered in a mill (McGavin, et al. 2015). The grades divide veneers into three bins, each with an equal number of veneers, and mimic a simple way a manufacturer could divide the veneers. The grades are referred to as “Low” (L), “Medium” (M) and “High” (H). While it is understood that how veneers are divided into bins would vary with both the final structural products and the specific strategies adopted by a manufacturer, the three grades above were arbitrary chosen for simplicity in Gilbert, et al. (2017a).

The distribution of the dynamic veneer MOE (characteristic c_l) has been quantified in McGavin, et al. (2015) for the resources analysed. This characteristic is modelled in this paper through a Weibull distribution and its overall CDF G_l is in the form,

$$G_l(MOE) = 1 - e^{-\left(\frac{MOE}{\lambda_1}\right)^{k_1}} \quad (12)$$

where k_I and λ_I are given in Table 3 for all species.

The distribution of the expected tKAR value of a veneer of length L (characteristic c_2) is defined in Gilbert, et al. (2017a). For each grade, a Weibull distribution was also found to best fit the distribution of the tKAR values. The CDF G_{2j} for characteristic c_2 in Bin j ($j = [L, M, H]$) is in the form (see Gilbert, et al. (2017a) for more details),

$$G_{2j}(1 - tKAR) = 1 - e^{-\frac{L}{L_{ref}} \left(\frac{1 - tKAR}{\lambda_{2j}} \right)^{k_{2j}}} \quad (13)$$

where $L_{ref} = 150$ mm. k_{2j} and λ_{2j} are given in Table 3 for all species and grades.

Stress-strain curves and size effect

When developing a numerical model to predict the strength of LVL beams (Gilbert, et al. 2017b), a tri-linear compressive stress-strain relationship (see Figure 1) was found to provide accurate results for the three species studied in this paper. The values of the slopes m_1 and m_2 , and yielding point (proportional limit) y_I in Figure 1 were derived in Gilbert, et al. (2017b) from the characteristic stress-strain relationship measured from compression test results and model calibration. Values of $m_1 = 50\%$, $m_2 = 7\%$ and $y_I = 1/1.2$ were adopted in Gilbert, et al. (2017b) and used in this paper.

Based on the literature and model calibration in Gilbert, et al. (2017b), the shape factors for the three species of interest in this study were derived in Gilbert, et al. (2017b) as $k_{II} = 2 \times k_{\perp} = k$, where k is given in Table 1 for each species. These values are adopted herein.

VALIDATION OF THE PROPOSED NUMERICAL APPROACH

Experimental program

The proposed numerical methodology is validated through two series of tests. The first series has been performed by McGavin, et al. (2013) on sixteen 13-ply LVL panels manufactured from early to mid-rotation GMS and SPG veneers. The second series has been performed as

part of this study on seven 15-ply and one 12-ply LVL panels manufactured from SPG veneers.

In the first series (McGavin, et al. 2013), eight SPG and eight GMS 13-ply LVL 1,080 mm $\times$ 1,800 mm panels were manufactured using four different construction strategies and 3.0 mm nominal thick veneers. Out of each panel, one nominal $L_2 = 234$ mm (long) $\times$ $W_2 = 55$ mm (wide) sample was cut for compression testing perpendicular to the grain. All samples were tested in compression parallel to the grain following the recommendations in the Australian/New Zealand standard AS/NZS 4357.2 (AS/NZS 4357.2 2006) at a constant loading rate to reach failure within 1 to 5 mins. Refer to McGavin, et al. (2013) for more details.

In the second series, the seven 15-ply LVL panels were manufactured from plies cut from five different 2.5 mm nominal thick veneer sheets, with three plies cut per sheet. Similarly, the 12-ply LVL panel was manufactured from four different 2.5 mm nominal thick veneer sheets, also with three plies cut per sheet. Six different construction strategies were used, with panels manufactured only with veneers of dynamic MOE (i) greater than 21 GPa (Panel 1), (ii) between 20 to 21 GPa (Panel 2), (iii) between 18 to 20 GPa (Panel 3), (iv) between 16 to 18 GPa (Panel 4), (v) less than 16 GPa (Panel 5) and (vi) random selection of veneers (Panels 6 to 8). Out of each panel, two nominal $L_2 = 90$ mm (long) $\times$ $W_2 = 80$ mm (wide) samples were cut for compression testing. The samples were tested in compression parallel to the grain in a universal 500 kN MTS testing machine at a stroke rate of 0.3 mm/min to reach failure in 3 to 5 mins. The samples were positioned between a fixed bottom platen and an upper platen mounted on a spherical seat so as to provide full contact between the platens and the specimens.

The different sample sizes and number of veneer sheets used in the two series of tests allow to more thoroughly verifying the accuracy of the model. Indeed, different size effects re-

sult from Eq. (9), equal to 1.32 for the first series and 1.16 for the second for the SPG samples.

In both series: (i) the veneers used in the manufacturing were different to the ones used in Gilbert, et al. (2017a) but are from the same resources, (ii) only the longitudinal dynamic MOE of each veneer (characteristic c_1) was acoustically measured prior to manufacturing, i.e. the tKAR value (characteristic c_2) of the wood veneers was not recorded, (iii) the LVL samples were manufactured using the same procedure as the test samples in Gilbert, et al. (2017a), and (iv) all samples were conditioned at 20°C and 65% relative humidity prior to testing.

Numerical simulations

10,000 Monte Carlo simulations are run per tested LVL sample to estimate the expected distribution of the sample compressive strength from the measured veneer MOE (characteristic c_1), the known distribution of the total knot area ratio (characteristic c_2) and Eqs. (6, 10). This is illustrated in the flowchart in Figure 3 based on the procedure detailed in Section “Numerical implementation for industrial applications”.

Results

Table 4 and Table 5 give the ratios of the simulated compressive strength at the 5th, 50th and 95th percentile to the measured one of each tested panel for the SPG and GMS panels, respectively. The measured strength is taken as the average of two tests for the second series of tests. The coefficient of variation (CoV) of the simulations is also given in the tables and provides an indication of the spread of the numerical results.

The proposed method is able to accurately predict the measured strength, with the ratio between the predicted 50th percentile strength to the measured one ranging from 0.90 (1st series and SPG) to 1.17 (2nd series and SPG). While the proposed approach tends to slightly overestimate the capacity, especially for the SPG 2nd series of tests, the average predicted 50th

percentile to experimental capacity ratio is close to 1.00 and equal to 1.03 and 1.06 for the tests performed SPG and GMS samples, respectively. The coefficient of variation of the predicted to experimental ratio is low and equals to 0.08 and 0.05 for the SPG and GMS samples, respectively. To better outline the accuracy of the model and the distribution of the simulated to experimental results, Figure 4 plots the CDF of the 50th simulated compressive strength to the experimental strength with the best fit normal distribution.

The overall accuracy of the proposed approach is further outlined by the low spread of the simulations, as outlined from their CoV in Table 4 and Table 5. These CoV correspond to a difference between the predicted 5th and 95th percentile strengths of only 5 to 7 MPa for the 1st series of tests and, due to a lower number of veneers, of 9 to 11 MPa for the 2nd series of tests. Indeed, in a veneer-based product, a higher number of veneers produces a more uniform final product, and therefore the more the number of veneers is, the lower the coefficient of variation in the final mechanical properties is (Sasaki and Kawai 1994).

The overall non-linear behaviour of the samples is also well captured. Figure 5 plots the simulated compressive stress-strain curves parallel to the grain versus the ones obtained experimentally for Panels 5 and 7 of the SPG 2nd series of tests. The simulated curves were randomly selected from simulations resulting in a compressive strength equal to the 50th percentile one at +/- 1%. Still in Figure 5, the experimental strain was obtained from the stroke displacement of the universal testing machine. While it is understood that this reading does not predict the actual deformation of the samples, as it also measures the overall stiffness of the testing machine and associated attachments, it still provides a sound indication of the overall shape of the stress-strain curve of the tested specimens. Consequently, the experimental stress-strain curves were adjusted herein by multiplying the strain values obtained from the universal testing machine by a constant so that the linear part of the experimental curves matches the one of the simulated curves. Only the overall shape of the curves is of interest.

Ignoring the initial part of the experimental stress-strain curves, corresponding to the upper platen adjusting to the tested specimens, the non-linear behaviour of the tested samples up to failure is well reproduced. When failure has fully developed, the experimental stress decreases at a faster rate than the numerical one. This phenomenon is explained by the actual material compressive stress-strain curve which decreases at a faster rate at large deformations than the tri-linear modelled curve, as presented in Figure 1.

ILLUSTRATION: PRACTICAL INDUSTRIAL APPLICATION

General

The application of the proposed numerical method and how a manufacturer could predict the compressive strength distributions and associated design strengths of veneer-based products manufactured from new species is illustrated in this section. Specifically, the strength distributions of six commercially available LVL sizes (Carter Holt Harvey Woodproducts 2015) and three plywood types (AS/NZS 2269.0 2012) are numerically investigated using Monte Carlo simulations. All products are considered to be either manufactured from early to mid-rotation GMS, SPG or SBG hardwood plantation veneers.

The LVL columns considered herein are all manufactured from 3.0 mm thick veneers and are (i) three 15-ply (45 mm thick) columns of width of 200 mm, 300 mm and 400 mm, and (ii) three 21-ply (63 mm thick) columns of width of 240 mm, 400 mm and 600 mm. The three plywood boards are (i) 5-ply of 3.0 mm thick veneers, i.e. nominal 15 mm thick boards, referred to as “15-30-5”, (ii) 7-ply of alternate 3.0 mm and 2.4 mm thick veneers with the 3.0 mm veneers used as the face veneers, i.e. nominal 19 mm thick boards, referred to as “19-30-7” and (iii) 9-ply also of alternate 3.0 mm and 2.4 mm thick veneers with the 3.0 mm veneers used as the face veneers, i.e. nominal 25 mm thick boards, referred to as “25-30-9”.

For all products, four different possible construction strategies that a manufacturer could consider are investigated herein:

- Low (L): the products are solely manufactured from the “Low” grade veneers mentioned in Section “*Veneer grading and characteristics*”.
- Medium (M): the products are solely manufactured from the “Medium” grade veneers.
- High (H): the products are solely manufactured from the “High” grade veneers.
- All (A): the products are manufactured by mixing the grades as (i) the LVL columns are manufactured with an equal number of veneers from each grade, (ii) the 5-ply plywood is manufactured with one “Low” veneer (middle one), two “Medium” veneers (adjacent to the middle one) and two “High” veneers (face veneers), (iii) the 7-ply plywood is manufactured with three “Low” veneer (middle ones), two “Medium” veneers (adjacent to the middle ones) and two “High” veneers (face veneers) and (iv) the 9-ply plywood is manufactured with an three “Low” veneer (middle ones), four “Medium” veneers (adjacent to the middle ones) and two “High” veneers (face veneers).

Parametric studies

Per studied configuration, 10,000 Monte Carlo simulations are run in reference to the flowchart in Figure 3 and Section “*Numerical implementation for industrial applications*”. The compression tests are simulated following the recommendations in the Australian/New Zealand standards AS/NZS 4357.2 (AS/NZS 4357.2 2006) for LVL and AS/NZS 2269.1 (AS/NZS 2269.1 2012) for plywood. The length of the simulated LVL columns is therefore six times the smaller nominal cross-sectional dimension. The plywood samples are 300 mm wide × 1,200 mm long and considered to be laterally restrained. For the plywood products, the compression tests are simulated parallel and perpendicular to the face grain. Following the recommendations in the AS/NZS 2269.1 (AS/NZS 2269.1 2012), the compressive strengths

of the plywood boards are determined by only considering the thickness of the plies parallel to the load in the calculation of the cross-sectional area.

For the plywood products, as the compressive stress-strain curves of the veneers perpendicular to the grain of the three studied species has not been quantified, its general form is extracted from the literature. When loaded perpendicular to the grain, the stress in a timber element typically increases linearly until plasticity occurs, which ultimately develops to the stress moderately and linearly increasing (Holmberg, et al. 1999). The MOE and strength perpendicular to the grain are about 12 to 35 times and about 6 to 12 times less than the ones parallel to the grain (Kretschmann 2010), respectively. In this study, a perfect elastic-plastic relationship is used for the plies loaded perpendicular to the grain with the compressive MOE and strength conservatively taken as $1/35$ and $1/12$ times the ones parallel to the grain, respectively, from the lower ratios on hardwood species reported in Kretschmann (2010). Note that ignoring the stiffness of the plies perpendicular to the grain (as in design practices) will decrease the design compressive strength calculated in Section “*Plywood results*” by 2.6% and 6.5% on average when tested parallel and perpendicular to the face grain, respectively. However, using higher range values for the MOE and strength perpendicular to the grain in the model, i.e. equal to $1/12$ (MOE) and $1/6$ (strength) times the ones perpendicular to the grain, would increase the design compressive strength in Section “*Plywood results*” on average by 4.9% and 14.8% when tested parallel and perpendicular to the face grain, respectively.

The uncertainty in the numerical method in predicting the actual compressive strength of the analysed structural products is also taken into account herein. The average predicted to actual strength ratio (Mean/Nominal = 1.05) and CoV (= 0.08), derived from the results reported in Section “*Validation of the proposed numerical approach*”, are used with an assumed normal distribution.

Note that while the proposed approach in this paper can predict the stiffness of the products, the MOE distribution of the new products is out of the scope of this study. Indeed, the dynamic MOE of the veneers, measured in line during manufacturing through an acoustic method and used in the constitutive equations as the veneer stiffness, is different to the static one. This effect is due to the viscoelastic nature of the wood (Banks, et al. 2011, Bruel and Kjaer 1982) and also maybe from hot pressing the veneers and gluing them during the manufacturing process. While using the veneer dynamic MOE in the elastoplastic constitutive equations does not change the compressive stress distribution, it creates inaccuracies in determining the static stiffness to be used for design. When the exact relationship between the dynamic MOE of the veneers and their associated static MOE within a glued veneer-based product is established, the static MOE of the analysed products can be accurately established.

LVL results

Table 6 gives the simulated design compressive strength, defined as the 5th percentile strength, for all investigated LVL columns. The design compressive strength is found to range from 34.4 MPa (600×63 Low SBG columns) to 67.2 MPa (200×45 High GMS columns). Due to the size effect and the length of the tested specimens increasing with their cross-sectional dimensions [4], the wider the column is, the lower its compressive design strength.

The values reported in Table 6 are of the same order of magnitude as, or superior to (up to 1.6 times), the design compressive strength of softwood LVL structural products commercialised in Australia, ranging from 35 MPa (Hyne timber 2016) to 42 MPa (Carter Holt Harvey Woodproducts 2015). Specifically, all columns manufactured from the “Medium” and “High” grade veneers, at the exception of the 600×63 SBG columns, have design strengths greater than 42 MPa. Still at the exception of the 600×63 SBG columns, all columns manufactured from the “Low” grade veneers have design strengths greater than 35 MPa. The GMS columns

result in the highest design strength, with values 5% to 7% and 15% to 20% greater than the SPG and SBG columns, respectively.

Figure 6 plots the simulated strength distributions of the 240×63 LVL columns manufactured from all grades and species. The simulations for all remaining columns show a similar trend. Lognormal distributions provide a good fit for all distributions, with a low Kolmogorov-Smirnov test result, typically lower than 0.04. The average mean to design strength ratio and associated CoV of the 72 analysed configurations are 1.15 and 0.086, respectively.

Plywood results

Table 7 provides the simulated design compressive strength, defined as the 5th percentile strength, for all investigated plywood boards. The design strength ranges from 33.9 MPa (15-30-5 Low SBG boards) to 62.3 MPa (25-30-7 High GMS boards). Similar to the LVL columns, boards manufactured from GMS and SBG veneers result in the highest and lowest compressive design strengths, respectively.

The Australian/New Zealand standard for plywood AS/NZS 2269.0 (AS/NZS 2269.0 2012) defines eight plywood grades, defined to as “F-grades”, based on the mechanical properties of the boards. The grades range from F7 (compressive design strength of 15 MPa) to F34 (compressive design strength of 75 MPa). Grades F11 and F14, which have design compressive strengths of 25 MPa and 30 MPa, respectively, correspond to the most commonly sold plywood boards. This likely aligns with the mechanical properties that can be obtained from the available softwood resources. In terms of compressive strength, all boards in Table 7 can be classified as grade F14 or better, and are equal or therefore superior to the most commonly available softwood plywood boards in Australia. All High SPG and GMS plywood boards are at least graded as F22, corresponding to a compressive design strength of 50 MPa.

Figure 7 plots the strength distributions of the 19-30-7 plywood boards manufactured from all grades and species. The simulations for all remaining boards show a similar trend.

Similar to the LVL columns, lognormal distributions provide a good fit for all distributions, with a low Kolmogorov-Smirnov test result, also typically lower than 0.04. The average mean to design strength ratio and associated CoV of the 72 analysed configurations are 1.19 and 0.10, respectively.

CONCLUSION

This paper proposed a numerical approach to accurately determine the compressive strength of veneer-based structural products from classical elastoplastic constitutive equations and a probabilistic strength prediction model of the individual veneers. The accuracy of the proposed approach was verified against experimental tests performed on twenty-four LVL samples of various sizes and manufactured from SPG and GMS veneers. Results showed that the proposed approach allows to accurately predicted the strength of the LVL samples with an overall predicted to experimental ratio of 1.05 and low coefficient of variation of 0.08.

The industrial applications of the proposed methodology were then demonstrated by determining the compressive strength distributions and design capacities of six commercially available LVL columns and three types of plywood boards. All manufactured using four different construction strategies and from GMS, SPG and SBG early to mid-rotation hardwood plantation logs. This resource is currently not used in the manufacturing of veneer-based structural products. An established database of the veneer mechanical properties was used for this purpose. Results showed that the LVL columns have design strengths of a similar order of magnitude of and up to 1.6 times greater than the ones of softwood LVL structural products commercialised in Australia. Plywood boards were found to achieve at least a F14 grade in terms of compressive strength. They are consequently of similar or higher grade than the most commonly used Australian plywood boards.

Acknowledgements:

The author would like to thank Dr Rob McGavin and Dr Henri Bailleres for sharing the test results to validate the proposed numerical method and technical discussions. The support provided by the Queensland Department of Agriculture and Fisheries (DAF) is also acknowledged as a critical part to the overall project. The author also expresses his gratitude to the Forest Product Innovation team at the Salisbury Research Facility for their help in preparing the test samples. Mr Alexander Mainey is also acknowledged for his valuable help in editing the paper. Discussions with Dr Dilum Fernando and Dr Nicholas Rohde's on key points of the paper were extremely appreciated.

This study was funded by the Australian Research Council under project DE140100212.

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Table 1: Coefficients α , β , γ and parameters k and λ to predict the compressive strength R_d of the three investigated species (Gilbert, et al. 2017a)

Species	α	β	γ	k	λ
SPG	0.490	0.506	0.437	15.60	1.035
SBG	0.810	0.437	0.246	11.74	1.039
GMS	0.680	0.474	0.388	16.09	1.031

Table 2: MOE cut-off values for each grade and investigated species in Gilbert, et al. (2017a)

Species	Low grade (MPa)	Medium grade (MPa)	High grade (MPa)
SPG	MOE < 14,000	14,000 ≤ MOE < 17,900	MOE ≥ 17,900
SBG	MOE < 14,100	14,100 ≤ MOE < 18,000	MOE ≥ 18,000
GMS	MOE < 14,600	14,600 ≤ MOE < 18,200	MOE ≥ 18,200

Table 3: Parameters k_1 and λ_1 to predict characteristic c_1 (extracted from McGavin, et al. (2015)) and parameters k_{2j} and λ_{2j} to predict characteristic c_2 for all grades (given in Gilbert, et al. (2017a)) for the three investigated species

Species	Characteristic c_1 (MOE)				Characteristic c_2 (tKAR)			
	k_1	λ_1	k_{2L}	λ_{2L}	k_{2M}	λ_{2M}	k_{2H}	λ_{2H}
SPG	4.69	17646	10.43	0.885	13.35	0.939	17.74	0.981
SBG	4.69	17465	22.67	0.948	25.39	0.974	43.13	0.980
GMS	4.30	17766	30.02	0.977	46.99	0.991	63.86	0.998

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Table 4: Proposed numerical approach validation for SPG panels: Ratios of simulated compressive strength at 5th, 50th and 95th percentile to experimental strength and CoV of the simulations

Series of test	Panel ID	5 th /Exp.	50 th /Exp.	95 th /Exp.	CoV simulation (%)
1 st (McGavin, et al. 2013)	1	1.03	1.08	1.12	2.40
	2	0.97	1.02	1.05	2.39
	3	0.90	0.94	0.98	2.58
	4	0.87	0.91	0.95	2.64
	5	0.86	0.90	0.93	2.58
	6	0.97	1.02	1.06	2.54
	7	1.05	1.09	1.13	2.48
	8	0.93	0.98	1.01	2.46
2 nd	1	1.06	1.13	1.19	3.70
	2	1.09	1.17	1.23	3.70
	3	1.00	1.07	1.13	3.72
	4	1.02	1.09	1.15	3.76
	5	0.96	1.03	1.09	3.78
	6	1.04	1.12	1.18	3.77
	7	0.97	1.04	1.09	3.74
	8	0.83	0.91	0.96	4.30
Average		0.97	1.03	1.08	
CoV (%)		7.93	8.14	8.51	

Table 5: Proposed numerical approach validation for GMS panels: Ratios of simulated compressive strength at 5th, 50th and 95th percentile to experimental strength and CoV of the simulations

Series of test	Panel ID	5 th /Exp.	50 th /Exp.	95 th /Exp.	CoV simulation (%)
1 st (McGavin, et al. 2013)	1	1.08	1.12	1.16	2.22
	2	1.06	1.11	1.14	2.25
	3	0.99	1.03	1.07	2.30
	4	0.93	0.97	1.01	2.30
	5	0.99	1.03	1.07	2.36
	6	1.00	1.04	1.08	2.36
	7	1.08	1.13	1.17	2.32
	8	0.98	1.02	1.06	2.31
Average		1.01	1.06	1.09	
CoV (%)		5.35	5.28	5.26	

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Table 6: Simulated design compressive strength (5th percentile of simulations) for LVL columns

LVL	Grade	SPG	SBG	GMS
200×45	L	45.4	42.4	48.8
	M	56.2	50.4	59.6
	H	64.6	55.7	67.2
	A	54.9	48.9	57.9
300×45	L	43.0	39.5	46.4
	M	53.3	47.1	56.8
	H	61.4	51.9	64.1
	A	52.3	45.8	55.0
400×45	L	41.4	37.7	44.6
	M	51.3	44.9	54.8
	H	58.9	49.5	61.7
	A	50.4	43.4	53.1
240×63	L	42.9	40.1	46.4
	M	53.2	47.4	57.1
	H	61.4	52.6	64.6
	A	52.3	46.2	55.5
400×63	L	40.3	36.6	43.7
	M	50.0	43.6	53.7
	H	57.5	48.1	60.6
	A	48.9	42.4	51.9
600×63	L	38.2	34.4	41.6
	M	47.4	40.7	51.0
	H	54.8	45.0	57.4
	A	46.5	39.5	49.5

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Table 7: Simulated design compressive strength (5th percentile of simulations) for plywood boards and F-grade classification in AS/NZS 2269.0 (AS/NZS 2269.0 2012) shown in brackets

Plywood	Grade	Load parallel to face veneer			Load perpendicular to face veneer		
		SPG	SBG	GMS	SPG	SBG	GMS
15-30-5	L	36.0 (F14)	33.9 (F14)	40.8 (F17)	36.6 (F14)	34.1 (F14)	41.5 (F17)
	M	46.5 (F17)	40.6 (F17)	51.5 (F22)	47.3 (F17)	41.0 (F17)	52.3 (F22)
	H	54.2 (F22)	45.1 (F17)	58.1 (F22)	55.2 (F22)	45.8 (F17)	59.3 (F22)
	A	47.8 (F17)	40.9 (F17)	51.7 (F22)	47.6 (F17)	41.4 (F17)	52.8 (F22)
19-30-7	L	36.5 (F14)	34.1 (F14)	41.2 (F17)	39.1 (F14)	36.6 (F14)	44.0 (F17)
	M	46.6 (F17)	41.0 (F17)	51.7 (F22)	49.6 (F17)	43.9 (F17)	54.9 (F22)
	H	54.5 (F22)	45.5 (F17)	58.3 (F22)	57.8 (F22)	48.7 (F17)	62.1 (F27)
	A	45.0 (F17)	39.1 (F14)	48.9 (F17)	46.2 (F17)	41.3 (F17)	51.5 (F22)
25-30-7	L	37.0 (F14)	34.4 (F14)	41.5 (F17)	39.6 (F14)	37.0 (F14)	44.3 (F17)
	M	46.9 (F17)	41.1 (F17)	51.8 (F22)	49.5 (F17)	44.2 (F17)	55.0 (F22)
	H	54.8 (F22)	45.8 (F17)	58.6 (F22)	58.0 (F22)	49.0 (F17)	62.3 (F27)
	A	47.6 (F17)	41.2 (F17)	51.9 (F22)	45.1 (F17)	41.1 (F17)	50.5 (F22)

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Figure 1: Stress-strain relationship for timber in compression

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(b)

Figure 2: (a) compressive strength versus veneer dynamic MOE relationship for GMS in Gilbert, et al. (2017a) and (b) veneer compression test set-up in (Gilbert, et al. 2017a) (schematic and actual)

Figure 3: Flowchart for validation and application illustration of the proposed numerical approach

Figure 4: CDF of 50th simulated compressive strength to experimental strength with normal distribution

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Figure 5: Stress-strain curves of simulations versus test results for Panels 5 and 7 of the SPG 2nd series of tests (Note, the strain of the experimental results is calculated from an adjusted universal testing machine stroke)

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Figure 6: Simulated compressive strength distributions for the 240×63 LVL columns

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Figure 7: Simulated compressive strength distributions for the 19-30-7 plywood boards, loaded paral-

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lel to the grain of the face veneers