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A MODIFIED THEORY OF COMPOSITE MECHANICS TO PREDICT TENSILE MODULUS OF RESINATED WOOD

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ABSTRACT

In this work, a modified theory (model) of composite mechanics was developed to predict the tensile modulus of elasticity (MOE) of resinated wood with the consideration of glue penetration. Variables built into the model included species, glue solids spread (*GS*), wood thickness and compression ratio (*CR*). The results showed that the effect of glue on the wood tensile MOE differed from species to species. With the increase of glue dosage, thOE first increased linearly and then leveled off at a threshold level of *GS*. Further increase of glue dosage made the MOE exhibit either a small increase or a decrease depending on the wood and glue properties. With a normal range of *GS* (50 to 90 $g.m^{-2}$), the effect of glue on the wood tensile MOE became negligible if wood thickness was larger than 1.4 mm. Also, an increase in *CR* resulted in a predictable increase of the wood MOE. The model prediction showed a good agreement with the published experimental results. Further validation of the model is underway.

KEYWORDS: Composite mechanics, tensile MOE, resinated wood, glue penetration.

INTRODUCTION

The classical theory of composite mechanics has been widely applied to predict mechanical properties of fibre-reinforced composites in which fibres are in a discontinuous or dispersed phase and matrix is in a continuous phase (Fan and Enjily 2009). By comparison, wood composites are made by consolidating resinated wood elements (veneers or strands) with heat and pressure, which can be viewed as a mixture: Glue as the reinforcement agent for the wood elements. Their modulus of elasticity (MOE) may be predicted by using MOE values of their constituents. Thus, a study of the elastic behavior of resinated wood elements is needed to further understand the mechanical properties of wood composites. To apply the classical theory of composite mechanics to wood composites, Gereke et al. (2012) presented a multi-scale model comprising unit cell modeling and macro-scale analysis. Using this model, an increase in volume fraction of the glue slightly decreased the longitudinal Young's modulus, which seemed to be opposite to the experimental results obtained by Wu et al. (2005). Indeed, a modified theory of composite mechanics to predict the tensile MOE of resinated wood is required.

Based on wood elements used, wood composites can be classified into two categories: Veneer-based and non veneer-based. The former, represented by plywood and laminated veneer lumber (LVL), is made from multiple layers of wood veneers. The latter, by contrast, broadly categorized into oriented strand board (OSB), particleboard, and fibreboard, is made from discontinuous wood elements, such as strands, particles, and fibres. Regardless of the product type, adhesive bonding is essential for the integrity of wood composites. Glue penetration is inevitably induced due to various voids present between elements or within each element (Dai et al. 2005).

Needless to say, wood is a porous material with many unique anatomical characteristics. Major cells in wood are longitudinal tracheids in softwood species, and vessels and longitudinal fibres in hardwood species. Due to its porous structure, glue can penetrate into wood to a certain extent (Laborie 2002). Glue penetration in wood, commonly classified into gross penetration and cell wall penetration, has been a subject of several published studies (Hare and Kutshca 1974, Sernek 1999, Gindl et al. 2000, Gindl 2001, Rijckaert et al. 2001, Buckley et al. 2002, Furuno et al. 2004, Cyr et al. 2006). The gross penetration results from the flow of glue liquid into most of cell lumens; and the cell wall penetration occurs when glue diffuses into the cell wall or flows into micro fissures (Marra 1992). The gross penetration can happen with most types of glue at a low viscosity, while the cell wall penetration only takes place with glue having a small molecular weight (MW) component (Tarkow et al. 1996, Marcinko et al. 1998, Laborie 2002, Frazier 2003). Kamke and Lee (2007) reviewed the previous studies and proposed that glue penetration into wood occurred in two scales: Micro-penetration through cell lumens and pits and nano-penetration in cell wall. One may also envision macro-penetration of glue through process-induced cracks, e.g., lathe checks in veneer. Glue penetration into wood is limited by occlusions in the pits or lumens and high glue MW. This conglomeration layer of glue and wood substance is commonly called the "interphase region" (or wood-glue mix phase) which varies with many factors, such as wood anatomy, porosity, permeability, glue viscosity, surface energy, consolidation pressure and others, mainly depending on wood species and glue properties (Laborie 2002). Marra (1992) proposed a classic chain-link analogy for an adhesive bond (Fig.1).

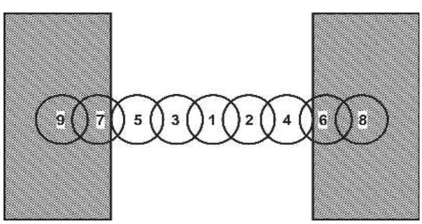


Fig. 1: A chain link analogy for an adhesive bond in wood (Marra 1992).

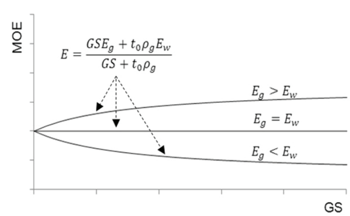


Fig. 2: Dynamic change of tensile MOE of resinated wood based on the classical theory.

Link 1 was the pure adhesive phase, unaffected by substrates. Links 2 and 3 represented the adhesive boundary layer that might have cured under the influence of the substrates. Links 4 and 5 represented the interface between the boundary layer and the substrate and constitute the "adhesion" mechanism. Links 6 and 7 represented wood cells that have been modified by the process of preparing the wood surface or the bonding process itself. Furthermore, Links 8 and 9 represented the unadulterated wood.

It was concluded by Marra (1992) and Pizzi (1994) that all of the potential adhesion mechanisms were influenced by glue penetration. Indeed, the bonding mechanism of wood is very complicated. Up to now, there have been no established theories to well explain the mechanism of adhesive bonding of wood and wood composites.

Many studies have been carried out to explore the relationship between mechanical properties of veneer-based products and their assembly patterns of veneers (Curry 1957, Okuma 1976, Bodig and Jayne 1982, Booth 1990, Booth and Hettiarachchi 1990, Zhang et al. 1994, DeVallance et al. 2011, Wang and Chui 2012a, b). Classical lamination theory (CLT) was applied analytically to predict stiffness and strength of LVL and plywood (Perry 1948). Okuma (1976) proposed that the portion of veneer where glue penetrated could be seen as a glue line in the plywood. However, the effect of the glue line was generally overlooked although it could not be neglected when it was very thick and its cross area fraction was relatively large (Okuma 1976, Booth and Hettiarachchi 1990). Also, the MOE of the glue line was higher than that of each component, and the MOE of the veneer in the plywood panel was slightly larger than that of corresponding solid wood owing to hot pressing. Wang (2007) conceptualized the glue line as a wood-glue mix layer in the modeling of heat and mass transfer of veneer-based products. It consisted of both wood and glue, representing about 12.5 % of the thickness of aspen veneer (3.2 mm). However, the contribution of the glue line to the product properties has not been documented.

For the non veneer-based products, numerous studies have been undertaken to predict their stiffness or strength (Fan and Enjily 2009, Shaler and Blankenhorn 1990, Xu and Suchsland 1998, Lee and Wu 2003, Bejo and Lang 2004, Clouston 2007, Weight and Yadama 2007, Arwade et al. 2009), particularly for OSB and oriented strand lumber (OSL). Analytical models, such as those established by the rule of composites mechanics (Fan and Enjily 2009), or by the Haplin-Tsai equation (Shaler and Blankenbor 1990, Lee and Wu 2003), or by applying a modified lamination theory (Lee and Wu 2003, Stürzenbecher et al. 2010) as well as numerical models using the finite element method (Wu et al. 2004), were developed to simulate the mechanical behavior of OSB and OSL. Bejo and Lang (2004) proposed a model to account for the effect of strand densification and strand orientation. Stürzenbecher et al. (2010) simulated the macroscopic elastic properties of OSB and OSL using continuum micromechanics and lamination theory. Resinated and compacted strand was the constituent element considered in this micromechanical model. While glue usually provides a thin coating or coverage on the strand surface, glue penetration into the strand inevitably forms a hard surface which may affect its elasticity or thickness swelling (Cai et al. 2007). Nevertheless, information pertaining to the effect of glue penetration on mechanical properties of strands has not been available (Wu et al. 2005, Lee and Wu 2003, Cai et al. 2007), and characteristics of resinated wood have not been fully understood.

The key objectives of this work were to: 1) develop a modified theory (model) to analytically predict the tensile MOE of resinated wood; 2) present typical prediction results and the effect of key variables on the tensile MOE of resinated wood. Although the glue penetration was considered, the interaction between wood and the glue, particularly in the cell wall, was not emphasized in the model.

Modeling of tensile modulus of resinated wood

Classical theory of composite mechanics

The tensile MOE of a unidirectional composite, E, is commonly described by the rule of mixture (Gibson 2011):

$$E = v_a E_a + v_b E_b \tag{1}$$

where: v_a and v_b - the volume fractions of components *a* and *b*, respectively,
E_a and E_b - the MOE of components *a* and *b*, respectively.

Eq. (1) is derived based on the following assumptions: 1) two components and are strained by the same amount (homogeneous strain); 2) the components can be rearranged and reshaped as homogeneous materials connected in parallel, and the interfacial bond is perfect; and 3) the differences in the Poisson's ratio and the thermal contraction between the components are small.

This classical theory assumed that there was no glue penetration in wood and all the glue was coated on the wood surface (Gereke et al. 2012). Thus, the tensile MOE of resinated wood in the fibre direction based on Eq. (1) can be expressed as,

$$E = v_g E_g + v_{\mathrm{w}} E_{\mathrm{w}} \tag{2}$$

where: v_g - the volume fraction of glue solids,
E_g - the MOE of glue solids,
v_{w} - the volume fraction of dry wood,
E_{w} - the MOE of dry wood.

And v_g and v_{w} can be calculated as follows:

$$v_g = \frac{GS/\rho_g}{GS/\rho_g + t_0} \tag{3a}$$

$$v_w = \frac{t_0}{GS/\rho_g + t_0} \tag{3b}$$

where: *GS* - the glue solids spread (namely, glue solids weight per area), which can be calculated by glue liquid spread multiplying by glue solids content,
ρ_g- the density of glue solids, and
t_0- the thickness of wood.

Thus, combining Eqs. (2) and (3) leads to:

$$E = \frac{GS\,E_g + t_0 \rho_g E_w}{GS + t_0 \rho_g} \tag{4}$$

To examine how E changes with GS in Eq. (4), we take its derivative as,

$$\frac{dE}{dGS} = \frac{t_0 \rho_g (E_g - E_w)}{(GS + c)^2} \tag{5}$$

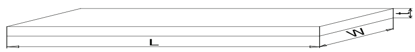
It is well known that the sign of $\frac{dE}{dGS}$ controls the monotonicity of Eq. (4). An increase in GS results in an increase in the tensile MOE of resinated wood when $E_g > E_w$; vice versa, E decreases with increasing GS when $E_g < E_w$. The dynamic change of tensile MOE of resinated wood based on the classical theory can be shown in Fig. 2.

Based on the classical theory, the MOE enhancement of wood composites requires that the MOE of glue solids is greater than the MOE of wood.

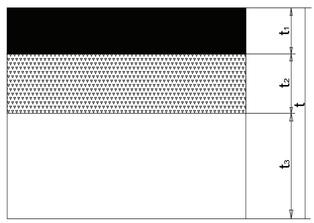
A modified theory of composite mechanics

Simplifications and assumptions

There is no doubt that glue will penetrate into wood for bonding. This work simplified the chain link analogy by assuming that the resinated wood could be categorized into the following three phases: pure glue, wood-glue mix (glue line), and unadulterated wood, as shown in Fig. 3.



a) Resinated wood



a) Cross section of resinated wood

Fig. 3: A typical representation of resinated wood.

Glue covering on the wood surfaces (pure glue) was equivalent to Links 1 and 2, and wood-glue mix phase comprised Links 4 and 6. The remaining phase was represented by unadulterated wood (Link 8). The thicknesses of the three phases above were t_1, t_2, and t_3, respectively. Note that in some cases, wood elements are coated (or impregnated) by both sides, leading to double glue lines. However, for theoretical modeling, double glue lines could be radically converted to an equivalent single glue line. Also, in the revised theory, the interaction between wood and the glue in the cell wall was not considered.

Modeling tensile MOE of wood

Wood is a porous material comprising of wood substance (cell wall) and voids (air and water). The mechanical performance of wood is only provided by wood substance. According to the theory of composite mechanics, the tensile MOE of wood in the fibre direction, E_w, is defined as

$$E_W = v_f E_f + v_v E_v \tag{6}$$

where: E_f - the MOE of wood fibres or cell walls,
E_v - the MOE of voids, viewed as zero here,
v_f and v_v - denote the volume fractions of wood fibres and voids, respectively, meeting the following condition:

$$v_f + v_v = 1 \tag{7}$$

where: v_f can be calculated based on the constant weight of dry wood by the following equation:

$$v_f = \frac{V_f}{V} = \frac{\rho_0}{\rho_f} \tag{8}$$

where: V_f - the volume of dry wood fibres,
V - the bulk volume of dry wood,
ρ_0 - the oven-dried density of wood,
ρ_f - the cell wall density of dry wood, generally 1.490-1.570 kg.m^{-3}.

Combining Eqs. (7) and (8), Eq. (6) becomes:

$$E_w = \frac{\rho_0}{\rho_f}E_f + (1 - \frac{\rho_0}{\rho_f})E_v = \frac{\rho_0}{\rho_f}E_f \tag{9}$$

Eq. (9) reveals the relationship between macroscopic mechanical property of wood (E_w) and microscopic mechanical property of wood (E_f).

Modeling tensile MOE of wood-glue mix phase

It was assumed that there existed no voids in wood-glue mix phase. According to the classical theory of composite mechanics, the tensile MOE of wood-glue mix phase, E_m, is given by:

$$E_m = \frac{\rho_0}{\rho_f}E_f + (1 - \frac{\rho_0}{\rho_f})E_g \tag{10}$$

Modeling tensile MOE of resinated wood

Resinated wood with the three phases can also be viewed as a composite. Neglecting volume change of wood due to the difference in moisture content (MC), the tensile MOE of resinated wood, E, can be expressed as,

$$E = v_1 E_g + v_2 E_m + v_3 E_w \tag{11}$$

where: the coefficients, v_1, v_2, and v_3 - denote the volume fractions of pure glue phase, wood-glue mix phase and unadulterated wood phase, respectively. They can be obtained as follows:

$$v_1 = \frac{t_1}{t} \tag{12a}$$

$$v_2 = \frac{t_2}{t} \tag{12b}$$

$$v_3 = \frac{t_3}{t} \tag{12c}$$

where: t - the thickness of resinated wood;
t_1, t_2 and t_3 - the thicknesses of pure glue phase, wood-glue mix phase (the depth of glue penetration in wood) and unadulterated wood phase, respectively (Fig. 3), and $t_2 + t_3 = t_0$, namely.

Combining Eqs. (11) and (12) gives:

$$E = \frac{t_1}{t}E_g + \frac{t_2}{t}E_m + \frac{t_3}{t}E_w \tag{13}$$

In general, the amount of polymeric glue to bond wood can be separated into two parts: one covering on the wood surface to form the pure glue phase and the other penetrating into wood to form the wood-glue mix phase, which leads to:

$$GS = [t_1 + t_2(1 - \frac{\rho_0}{\rho_f})]\rho_g \tag{14}$$

Thus, we have

$$t_1 = \frac{GS}{\rho_g} - t_2(1 - \frac{\rho_0}{\rho_f}) \tag{15}$$

Polymeric glue is generally non-Newtonian fluid (Levenspiel 1984). The flow of the fluids through cell lumens and pits is torturous, with significant entrance and exit effects on the capillary pathway. Polymerization and chemical interaction between glue and cell wall also restrict the flow (Kamke and Lee 2007). These considerations lead to an assumption that the maximum depth of glue penetration, namely t_ρ, is constant for the specific wood and glue based on wood permeability and glue properties. To theoretically describe the dynamic change of tensile MOE with glue solids spread (GS), assumptions were made that glue penetrates into wood with no glue coverage at first until the depth of glue penetration, t_2, achieved its maximum, t_ρ. At this moment, GS reached its threshold level. When glue dosage continued to increase, but glue penetration into wood thereby ceased, resulting in glue coverage on the wood surface. Thus, mathematical descriptions can be made based on Eq. (13).

When $t_1 = 0$, $t_2 < t_\rho$, the glue starts to penetrate into wood and the tensile MOE of resinated wood can be expressed by,

$$E = \frac{\rho_0}{\rho_f} E_f + \frac{GS}{t_0 \rho_g} E_g \tag{16}$$

When $t_1 = 0$, $t_2 = t_\rho$, the maximum glue penetration depth is achieved. At this stage, glue dosage reaches its threshold level, which is given by,

$$GS = t_p \rho_g (1 - \frac{\rho_0}{\rho_f}) \tag{17}$$

And, at this GS threshold, the tensile MOE of resinated wood can be given by,

$$E = \frac{\rho_0}{\rho_f} E_f + \frac{t_p}{t_0}(1 - \frac{\rho_0}{\rho_f}) E_g \tag{18}$$

When $t_1 > 0$, $t_2 = t_\rho$, the glue starts to cover or coat on wood surface, the tensile MOE of resinated wood is thus given by,

$$E = \frac{GS E_g + t_0 \rho_g E_w}{GS - t_p \rho_g (1 - \frac{\rho_0}{\rho_f}) + t_0 \rho_g} \tag{19}$$

This is the most common case of resinated wood with both glue penetration ($t_2 \neq 0$) and glue coverage ($t_1 > 0$).

Changes of tensile MOE with glue solids spread (GS)

To simplify Eq. (19), three terms, *a*, *b*, and *c*, are introduced as follows:

$$a = E_g \tag{20a}$$

$$b = t_0 \rho_g E_w \tag{20b}$$

$$c = -t_p \rho_g (1 - \frac{\rho_0}{\rho_f}) + t_0 \rho_g \tag{20c}$$

So Eq. (19) can be simplified as,

$$E = \frac{aGS + b}{GS + c} \tag{21}$$

Similarly, a derivative is taken as,

$$\frac{dE}{dGS} = \frac{ac-b}{(GS+c)^2} \tag{22}$$

where: $ac - b = [t_0 - t_p(1 - \frac{\rho_0}{\rho_f})]\rho_g E_g - t_0 \rho_g E_w$

The sign of $\frac{dE}{dGS}$ in the Eq. (22), namely the value of $ac - b$, is governed by the properties of wood and glue, such as wood thickness, wood density, wood permeability, and elastic behaviors of wood and glue. The dynamic change of tensile MOE of resinated wood based on the modified theory can be shown in Fig. 4.

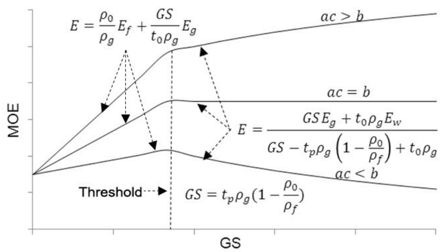


Fig. 4: Dynamic change of tensile MOE of resinated wood based on the modified theory.

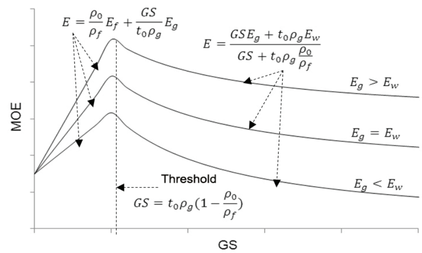


Fig. 5: Dynamic change of tensile MOE of resinated wood based on the modified theory ($t_p = t_0$).

One extreme case is that all of wood voids are saturated with glue solids by high-pressure impregnation or other methods, namely $t_p = t_0$. In this case, we have

$$\frac{dE}{dGS} = \frac{t_0\rho_g(\frac{\rho_0}{\rho_f}E_g - E_w)}{(GS+c)^2} = \frac{t_0\rho_g(E_g - E_m)}{(GS+c)^2} \tag{23}$$

The MOE of glue-saturated wood (or wood-glue mix), E_m - higher than that of each component (glue solids MOE or dry wood MOE), so the sign of $\frac{dE}{dG_s}$ is always negative in Eq. (23). This demonstrates that E decreases with increasing GS after crossing the threshold level given by $GS = t_0\rho_g(1 - \frac{\rho_0}{\rho_f})$, as shown in Fig. 5.

Changes of tensile MOE with compression ratio (CR)

During manufacturing of wood composites, compression is generally required to consolidate resinated wood elements and bring them into intimate contact and thus enhance composite properties, leading to a change in wood density and thickness. Wang (2007) measured the LVL density profile by X-ray and demonstrated that there was no obvious high density area of pure glue solids. Thus, the thickness of pure glue solids between wood element could be assumed as zero ($t_1 = 0$). Note that $t_1 = 0$ means glue solids partially or fully fill the voids of the wood-glue mix phase, including the wood surface process-induced cracks. Here, we introduce the compression ratio (CR) into the Eq. (16).

When $t_1 = 0$, $CR \neq 0$, the tensile MOE of compressed resinated wood is theoretically given by,

$$E = \frac{\rho_0}{\rho_f(1-CR)}E_f + \frac{GS}{t_0(1-CR)\rho_g}E_g \tag{24}$$

The Eq. (24) can be used to predict the tensile MOE of resinated wood before reaching the maximum glue depth or the threshold level of GS. To express the ratio of glue dosage and dry wood mass, a new term, namely, glue solids uptake (glue solids weight/dry wood mass, *GSU*) can be introduced to replace *GS*. Note that *GS* is equal to $\frac{GSU}{t_0}$.

RESULTS AND DISCUSSION

Prediction results from classical theory of composite mechanics

In an attempt to predict the MOE of parallel strand lumber, Gereke et al. (2012) proposed a multi-scale model based on the classical theory of composite mechanics with an assumption of no glue penetration into resinated strands. Input parameters for the model were: E_w and E_g, being 13.000 MPa and 7.600 MPa, respectively, and ρ_0 and ρ_g , being 580 kg.m^{-3} and 1.400 kg.m^{-3},, respectively and t_0 being 5 mm. According to the prediction performed by Gereke et al. (2012), increasing the volume fraction of glue solids led to a decrease in the tensile MOE of strands, which was generally not true and opposite to the experimental results (Wu et al. 2005). As seen in Fig. 6, the prediction from the Eq. (19) in this work showcased that, at a lower level of glue solids uptake (GSU), the tensile MOE of resinated strand increased linearly with the increase of GSU. Once the GSU exceeded about a certain level 7 % in this case, the tensile MOE of resinated strand started to drop nonlinearly at a slower rate, the same trend as observed in Fig. 4 ($ac < b$). In contrast, the prediction from the classical theory (Eq. (4)) showed that the tensile MOE of resinated strand decreased with GSU nonlinearly, which is intuitively not true.

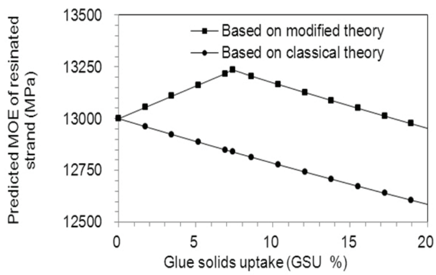


Fig. 6: Comparison of the predictions between the classical and modified theories of composite mechanics.

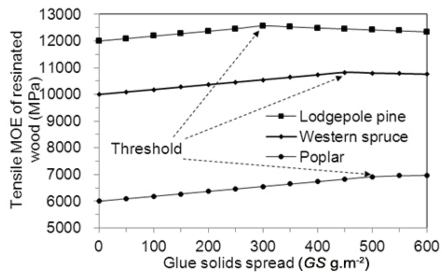


Fig. 7: The relationship between tensile MOE of resinated wood and glue solids spread (GS).

All above results indicated that glue penetration has a drastic effect on the tensile MOE of resinated wood. To accurately model the tensile MOE change of resinated wood, the classical theory of composite mechanics has to be modified, and glue penetration into porous wood has to be considered.

Typical prediction results

This work studied the effect of glue penetration into wood (veneer or strand) on its tensile MOE. Wood species, glue solids spread (*GS*) or glue solids uptake (*GSU*), wood thickness and compression ratio (*CR*) were identified as key variables affecting the tensile MOE of resinated wood.

Tensile MOE with regard to wood species and glue solids spread (GS)

Three wood species, namely lodgepole pine (*Pinus contorta*), western spruce (*Picea glauca*

(Moench)), and poplar (*Populus euramericana*) were selected with input parameters given in Tab. 1.

Tab. 1: Input parameters of the three wood species.

Species	Tensile MOE (MPa)	Wood density ($kg.m^{-3}$)	Wood thickness (10^{-3} m)	Maximum glue penetration depth (10^{-3} m)
Lodgepole pine	12.000	480	3.2	0.3
Western spruce	10.000	380	3.2	0.4
Poplar	6.000	350	3.2	0.5

Density and MOE of PF glue solids were assumed to be 1.500 $kg.m^{-3}$ and 8.800 MPa, respectively (Lu et al. 2002). The maximum glue penetration depth was assumed for the three wood species, which was determined by wood density and permeability.

Fig. 7 shows the relationship between the tensile MOE of resinated wood and (GS). In general, the tensile MOE increases with increasing in *GS*, but the magnitude and trend are species dependent. For each species, there is a threshold level of *GS* in which the pattern of the tensile MOE changes. The *GS* threshold levels of the three species are found to be 300 $g.m^{-2}$ (GSU=20 %), 450 $g.m^{-2}$ (GSU=37 %) and 500 $g.m^{-2}$ (GSU=45 %), respectively. Those threshold levels are generally wood density, permeability and glue related. Before the threshold level, the MOE of resinated wood increases linearly with *GS*. Right at this level, the wood-glue mix phase reaches the maximum depth of penetration and all voids in this phase are fully saturated with glue solids. Once the *GS* exceeds this level, the tensile MOE of resinated wood starts to level off. For example, the tensile MOE of lodgepole pine and western spruce tend to decrease but that of poplar still increases slightly. It can be concluded that when the MOE of dry wood is smaller than that of glue solids, increasing *GS* can improve the tensile MOE of resinated wood. But if the MOE of dry wood is larger than that of glue solids, increasing *GS* may improve the tensile MOE of resinated wood only before the voids within the maximum glue penetration depth are fully saturated with glue solids.

Tensile MOE with regard to wood thickness and compression ratio (CR)

Based on the input parameters selected by Lu et al. (2002), curves were drawn to describe the relationship between the tensile MOE of resinated wood and *CR*, as seen in Fig. 8. When dry wood thickness was larger than 1.4 mm, all three curves were close to each other. On the contrary, when dry wood thickness was 0.5 mm, the tensile MOE increased more than others for any given *CR*. This indicated that dry wood thickness is a critical factor affecting the MOE of resinated wood.

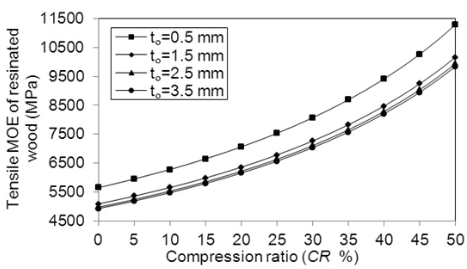
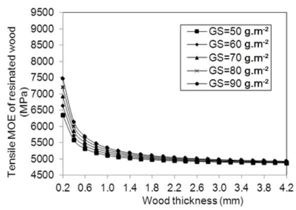


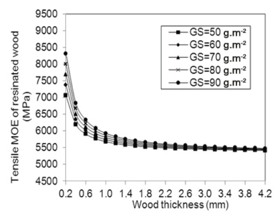
Fig. 8: The tensile MOE of resinated wood versus compression ratio (CR).

To achieve the target panel performance, the optimum level of glue solids spread (*GS*) needs to be established for OSB and LVL or plywood manufacturing. To further reveal the relationship between the tensile MOE of resinated wood and dry wood thickness, five levels of *GS* from 50 to 90 g.m^{-2} were selected for case studies, which cover the normal range of *GS* for plywood and LVL manufacturing. The other input data were cited from the paper of Lu et al. (2002).

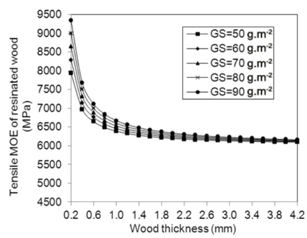
Fig. 9 shows the relationship of the tensile MOE of resinated wood with regard to wood thickness at three typical levels of *CR* (0, 10 and 20 %). For any given *CR*, an increase in dry wood thickness resulted in a decrease in the tensile MOE of resinated wood owing to the increase of the volume fraction of wood. Higher level of *GS* leaded to a greater tensile MOE of resinated wood, but the effect of glue on resinated wood decreased gradually, depending on wood thickness. It was obvious that the effect of the glue on tensile MOE of resinated wood was significant only when dry wood thickness was less than 1.4 mm. This trend was also observed by early analytical modeling of plywood along with experimental results (Okuma 1976, Booth and Hettiarachchi 1990).



d) $CR = 0\%$



e) $CR = 10\%$



f) $CR = 20\%$

Fig. 9: The relationship between tensile MOE of resinated wood and thickness (CR).

As indicated by Eq. (24), wood compression can also significantly improve the tensile MOE of resinated wood. It was reported that veneer MOE enhancement was 1.2 when veneer CR was 19.7 % (Wang and Dai 2005). As demonstrated, this enhancement ratio in dry wood MOE can also be predicted by the modified theory.

Preliminary validation of the modified theory of composite mechanics

Lu et al. (2002) proposed a simplified model to predict the tensile MOE of resinated veneer. In that work, the glue was assumed to fully penetrate into veneer. However, in most cases, due to the permeability of wood, the glue penetration was largely limited. Thus, the glue coverage on the wood surface must be considered. In this work, the data from Lu et al. (2002) were used to validate the modified theory at the early stage (Eq. (24)).

Tab. 2: Input parameters for the model.

Veneer sheet No.	Veneer thickness (10^{-3} m)	Compression ratio (*CR*, %)	Veneer density (kg.m^{-3})	Glue solids spread (*GS*, kg.m^{-2})
1	1.7	11.4	390	109
2	1.8	29.8	530	213
3	1.8	5.5	390	157
4	2.6	1.2	510	121
5	2.7	5.8	500	141
6	2.6	2.7	580	133
7	3.6	34.2	530	52
8	3.6	5.6	480	62
9	3.5	1.3	440	102
10	3.4	7.3	460	121

Tab. 2 summarizes the partial input parameters for the model. For input, the tensile MOE of poplar cell wall (E_f) was 18.000 MPa and the MOE of glue solids (E_g) was 8.800 MPa. Fig. 10 shows that a good correlation exists between the predicted and measured tensile MOE of the dry impregnated poplar veneer, giving an R^2 of 0.88, which demonstrates the feasibility of the modified model to predict the tensile MOE of resinated wood.

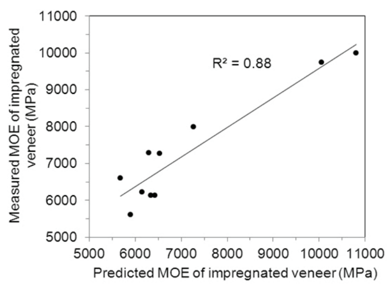


Fig. 10: Comparison between the predicted and measured tensile MOE of impregnated veneer (Lu et al. 2002).

Further validation is underway to deal with both glue penetration and coverage. Various species with different levels of permeability will be used to: 1) characterize the effect of glue dosage on resulting tensile MOE of resinated wood; 2) examine the maximum glue penetration into wood with an SEM or X-ray technology.

CONCLUSIONS

A modified theory (model) of composite mechanics was proposed to predict the tensile MOE of resinated wood (veneer or strand) by incorporating a wood-glue mix phase from glue penetration into wood.

The key variables affecting the tensile MOE of resinated wood were investigated using the modified model. The model predictions showed that the tensile MOE first increases linearly with an increase in glue solids spread (*GS*) or glue solids uptake (*GSU*), but the magnitude is species dependent. For each species, there is a threshold level of GS in which the pattern of the tensile MOE changes. This level is governed by wood species, density, permeability, and glue penetration. This model could also predict how wood compression improves the tensile MOE of resinated wood. In addition, the thickness of dry wood was found to significantly affect the tensile MOE of resinated wood. With a normal range of GS for plywood and LVL manufacturing (50 to 90 $g.m^{-2}$), the model demonstrated that the effect of glue on the tensile MOE of resinated wood could be neglected if the wood thickness was larger than 1.4 mm. This result was in a good agreement with that found by others (Okuma 1976, Booth and Hettiarachchi 1990). Further, with a full glue penetration, the model prediction agreed well with the published experimental results (Lu et al. 2002). Thus, this model could accurately capture the trend of the tensile MOE of resinated wood, and provides a useful tool to understand how properties of wood composites develop in terms of resinated wood element. Further validation of the model is underway to deal with both glue penetration and coverage.

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