

PREDICTING BENDING STIFFNESS OF RANDOMLY ORIENTED HYBRID PANELS

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Abstract. This study was conducted to develop a simple model to predict the bending modulus of elasticity (MOE) of randomly oriented hybrid panels. The modeling process involved three modules: the behavior of a single layer was computed by applying micromechanics equations, layer properties were adjusted for densification effects, and the entire panel was modeled as a three-layer symmetric composite using laminate theory. The model accounts for panel vertical density distribution and the inclusion of two fiber reinforcements. Model inputs were experimentally determined from physical and mechanical tests on hot-pressed resinated strands and bark. Experimental verification was conducted using laboratory panels of wood strands and bark from fire-impacted trees at an 80:20 wood:bark weight ratio. Comparisons with experimental data showed that MOE of hybrid panels was adequately predicted with deviations of 13-23% compared with observed MOE. Results validated application of micromechanics equations and laminate theory to predict the MOE of randomly oriented hybrid oriented strandboard of wood strands and bark. This study also contributes to the knowledge of predicting and tuning stiffness properties of hybrid panel-based composites, thereby promoting utilization and sustainable use of plant-based raw materials.

Keywords: Hybrid panels, stiffness modeling, laminate theory, wood strands, bark.

INTRODUCTION

The modulus of elasticity (MOE) is regarded as one of the most important mechanical properties of oriented strandboard (OSB) because of the impact on service life and structural perfor-

mance. The mechanical behavior of OSB mainly depends on constituent materials (eg wood strands and resin) and on the manufacturing process. The elastic moduli of OSB can be experimentally determined or predicted from mathematical models. Literature devoted to modeling the elastic properties of wood composites includes, among others: statistical models based on empirical results; semiempirical, analytical models using micromechanical equations; and laminate theory.

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Statistical models were used by Geimer et al (1975) to predict the bending MOE of three-layer particleboard. In the prediction, empirical relationships between density and tensile stiffness for each of the three layers were first established, and then successive 0.8-mm-thick lamina were measured for density to predict values of lamina MOE. The panel-effective MOE was then calculated with multilayer analyses. Hoover et al (1992) used regression equations to model various mechanical properties of OSB by accounting for flake dimensions, board density, and flake alignment factor. Predicted MOE deviated less than 5 and 17% in the aligned and cross-aligned direction, respectively, from experimental data. A semiempirical model was developed by Barnes (2000) to predict composite modulus of rupture (MOR) and MOE from wood properties and eight major manufacturing parameters. Predictions fell within $\pm 10\%$ of measured values for both properties.

Micromechanics equations from composite theories were applied by Shaler and Blankenhorn (1990) to predict MOE of flakeboards. Longitudinal and transverse rule of mixtures (ROM) and Halpin-Tsai equations were used to predict the bending MOE of flakeboard. Vertical density gradients and inhomogeneities were not considered in the model, which showed an average deviation of 25% from the experimental MOE. Mundy and Bonfield (1998) proposed a modified ROM for short-fiber composites to predict the strength and stiffness of chipboard. Close predictions were obtained, however several model assumptions would be violated in most flake-based composites (eg the assumed parallel alignment of chips to the direction of applied stress and the assumed cylindrical particle geometry). Xu and Suchsland (1998) developed a volumetric ROM based on energy analyses to predict the MOE of single-layer OSB with a uniform vertical density profile (VDP). Later, Xu (1999) broadened this work and applied laminate theory in combination with a range of VDP to calculate composite stiffness, but predictions were not verified with experimental data. Painter et al (2006) adapted the model of

Xu and Suchsland (1998) using, as input parameters, density, flake dimensions, and flake orientation from a simulated panel. The predicted MOE deviated -25 to $+22\%$ from MOE of commercial OSB in parallel- and perpendicular-to-grain directions, respectively.

Laminate analysis was used by Suo and Bowyer (1995) to model particleboard-effective MOE as a function of layer stiffness. The bending MOE of each layer was determined from flake stiffness and adjusted for layer density. The underlying assumption was that layer stiffness is a linear summation of individual strands and predictions agreed well with experimental data. Using classical laminate theory, Lee and Wu (2003) predicted the elastic constants of OSB, observed significant differences from experimental values, and attributed the discrepancy to the unrealistic assumption of uniform VDP. Benabou and Duchanois (2007) applied classical laminate theory and the Mori-Tanaka multiscale approach to model the hygroelastic behavior of OSB. The model accounted for particle shape and strand alignment but not for panel density. Contrary to the findings of Lee and Wu (2003), the MOE predictions were close to data provided by manufacturers. Recently, Chen et al (2008) developed a numerical model based on laminate theory to predict the bending stiffness of typical three-layer OSB by taking into account VDP, strand angle distribution, and published MOE values of wood parallel- and perpendicular-to-grain. The model overestimated bending stiffness values by less than 10% compared with measured values for all the angles considered.

Although modeling of mechanical properties has been extensively reported for OSB with single-component wood furnish, no studies have been reported for hybrid intraply OSB, ie OSB made of two or more types of fibrous materials closely mixed together within the same layer. Hybrid intraply composites, which have often been reported in the plastics composites literature, are very attractive because they permit partial replacement of high-value fibrous materials with those less valuable. Fu et al (2001)

employed a rule of hybrid mixtures (RoHM) and evaluated the hybrid effect on the tensile properties of hybrid short carbon- and glass-fiber plastic composites. No hybrid effects were found for the tensile elastic modulus. Mirbagheri et al (2007) used the RoHM equation to predict the tensile elastic modulus of wood flour/kenaf fiber/polypropylene composites. The hybrid composite was considered as a system comprising two single composites with no interaction between them. A high coefficient of determination ($R^2 = 0.988$) between experimental and predicted MOE was reported, suggesting that the RoHM is a suitable approach to predict the stiffness of hybrid wood composite materials (eg OSB).

Tree bark has become increasingly attractive as a second fibrous component in the manufacturing of engineered wood (hybrid) composites from growing interests in alternative fiber sources for composite production. Previous studies (Blanchet et al 2000; Nemli et al 2004) established the technical viability of 20-25% bark addition to particleboard, however predictive models that include bark as a second reinforcement for OSB are not in the literature. The main objective of this study was to develop a simple model based on laminate theory to predict the bending stiffness of randomly oriented hybrid OSB. Specific objectives include: 1) to determine the elastic properties of strands and bark; 2) to examine the effect of hot-pressing and resin application on density and bending properties of strands; and 3) to validate the model by comparing predicted and experimental data.

MATERIALS AND METHODS

Materials and Specimen Preparation

The strands and bark used in this study were produced from 55-yr-old red pine (*Pinus resinosa*) trees that had each been exposed to a wildfire. A total of eight trees classified as unburnt (BL1), lightly burnt (BL2), moderately burnt (BL3), and severely burnt (BL4) were debarked and used to produce strands with aver-

age dimensions of 76 mm long, 25 mm wide, and 0.65 mm thick. Strands from each log were bagged separately. Additional details were given in a previous article (Moya et al 2008).

Strands. From each log, 48 strands were randomly selected from a population of more than 500. The selected strands were conditioned at 65% RH and 20°C for at least 4 wk. Moisture content of all conditioned strands was 7.5-10.3%. Strands from each log were divided into three groups: 12 controls (unpressed), 18 hot-pressed, and 18 hot-pressed with resin. All strands were labeled and their fiber angle with respect to length was measured. Width and thickness were measured at three points along the length using a digital caliper. Strands to be resinated were sprayed with 3.5% polymeric diphenylmethane diisocyanate resin based on oven-dry weight. The resinated strands were individually wrapped in aluminum foil sprayed with a release agent to prevent sticking. The same wrapping procedure was performed on nonresinated strands to be hot-pressed except that no release agent was applied. Supplementary red pine strands were added to prepare eight (560 × 560 × 150 mm) randomly oriented mats. The furnish of each panel was equally divided into four parts (by weight) to form top, core (two parts), and bottom layers to permit wrapped strands to be distributed through the mat thickness at desired locations. Then, 12 wrapped strands were placed in the top, core, and bottom layers of each panel (Fig 1). The strand mats were hot-pressed under similar conditions as OSB prepared in our previous research (Moya et al 2008) to a target thickness of 12.7 mm. The strand specimens were collected from the pressed mat and conditioned at 65% RH and 20°C for at least 4 wk before testing.

Bark. Bark samples for compression testing were prepared from only BL1 and BL4 trees so that analyses could be focused on extreme cases, ie unburnt and severely burnt. The samples were obtained from two 50-mm-thick disks that were cross-cut from the stem of corresponding tree samples at about 1.50 and 3.0 m

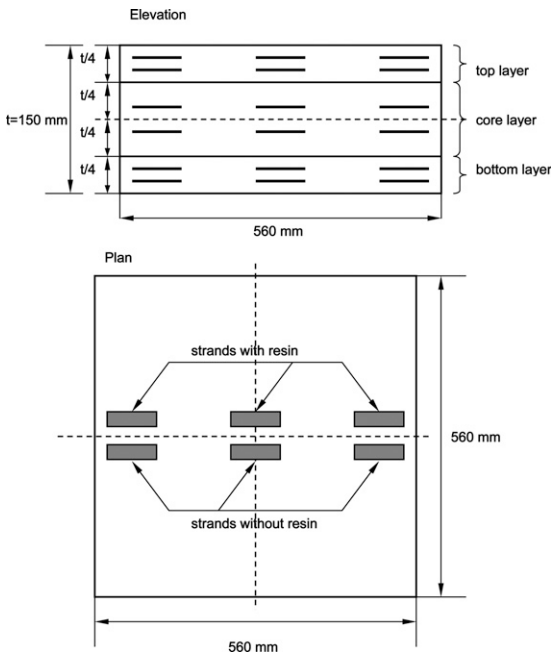


Figure 1. Strand location before hot-pressing within the panel mat to determine the effects of hot-pressing on strand properties.

from the forest floor. Bark from each disk was cut along the grain for two identical sets of 10 specimens each of $5 \times 8 \times 15$ mm, in radial, tangential, and longitudinal orientations, respectively. The compression specimens were equilibrated at 65% RH and 20°C for 4 wk before being tested.

Mechanical Tests

Strands. Three-point bending tests were conducted to determine MOE and MOR for control, hot-pressed, and hot-pressed resinated strands. Specimen dimensions and testing procedures were in accordance with the Deomano and Zink-Sharp (2004) procedure. One specimen 5 mm wide and 40 mm long was cut from each strand along the flake length. Actual dimensions were measured with a digital caliper and used for stiffness and strength calculations. The span of testing was 25 mm given a span-to-depth ratio of approximately 40:1 at a nominal specimen (flake) thickness of 0.65 mm.

The experimental MOE of an individual strand (MOE_x) represents an effective MOE along the length of the strand having grain angle, θ . MOE_x values were converted to MOE in the material principal directions: MOE_1 (longitudinal direction) and MOE_2 (transverse direction) by Hankinson's formula:

$$MOE_x = \frac{MOE_1 \times MOE_2}{MOE_1 \sin^2 \theta + MOE_2 \cos^2 \theta} \quad (1)$$

The bending stiffness ratio (MOE_2/MOE_1) was estimated using tensile moduli (E) relationships among longitudinal (L), tangential (Tan), and radial (R) directions of red pine wood (FPL 1999): $E_{Tan}/E_L = 0.044$; $E_R/E_L = 0.088$. Assuming transverse isotropy (isotropic nature in the transverse plane of wood), the tangential and radial ratios were averaged:

$$MOE_2 = 0.066(MOE_1) \quad (2)$$

Combining Eqs 1 and 2:

$$MOE_1 = \frac{MOE_x(\sin^2 \theta + 0.066 \cos^2 \theta)}{0.066} \quad (3)$$

The effective transverse stiffness of the strand (MOE_y) was then determined by the Hankinson equation, similar to Eq 1 with an angle ($90^\circ - \theta$).

Bark. Bark specimens were tested in compression following procedures suggested by Martin and Crist (1968) to determine parallel to the grain values of maximum compression strength (MCS) and Young's modulus (E_{1-bark}). The Young's modulus perpendicular to the grain (E_{2-bark}) was estimated from the bark compression study of Eberhardt (2007), who reported moduli ratios of $E_{Tan}/E_L = 0.4$ and $E_R/E_L = 0.022$. An average value from tangential and radial ratios was used assuming transverse isotropy:

$$E_{2-bark} = 0.211(E_{1-bark}) \quad (4)$$

After testing, all strand and bark specimens were oven-dried for moisture content and density determination in accordance with ASTM D2395-97 (ASTM 2000a). Volumetric measurements followed Method A for strand density determination and Method B, Mode I, for

bark basic density (based on swollen volume) determination.

Adjustment of stiffness and density by moisture content. OSB properties from Moya et al (2008), hereafter referred to as “actual OSB,” were used as reference values for strand and bark properties adjustments and the modeling process. Stiffness and strength of individual strands and individual bark specimens were adjusted to the same moisture content of the actual OSB as per ASTM D 2915-97 (ASTM 2000b):

$$P_{M2} = P_{M1} \left[\frac{(\alpha - \beta \times M_2)}{(\alpha - \beta \times M_1)} \right] \quad (5)$$

where P_{M1} is the property (stiffness or strength) measured at moisture content M_1 (in percentage), P_{M2} is the property (stiffness or strength) adjusted to moisture content M_2 (in percentage), and α and β are moisture constants.

Strands and bark densities were adjusted to the same moisture content of the actual OSB (FPL 1999):

$$\rho_2 = \frac{\rho_1}{[1 - 0.265(30 - M_2)/100\rho_1]} \quad (6)$$

where ρ_2 is the density at the desired moisture content M_2 (in percentage) and ρ_1 is the basic density (based on oven-dry weight and swollen volume).

Modeling Process

A flowchart of the three module-based modeling processes of the OSB is presented in Fig 2.

Determining modulus of elasticity of individual layers (Steps 1-8). The thickness (t) of each panel was divided into three layers, top ($t/4$), core ($t/2$), and bottom ($t/4$), based on the experimentally determined VDP of the actual OSBs (Fig 1). At the lamina level, the in-plane randomly oriented layer was considered as a discontinuous short fiber composite. Here, it was assumed that the bending stiffness (MOE) of the strand (span-to-depth ratio of approximately 40:1) is a close approximation of

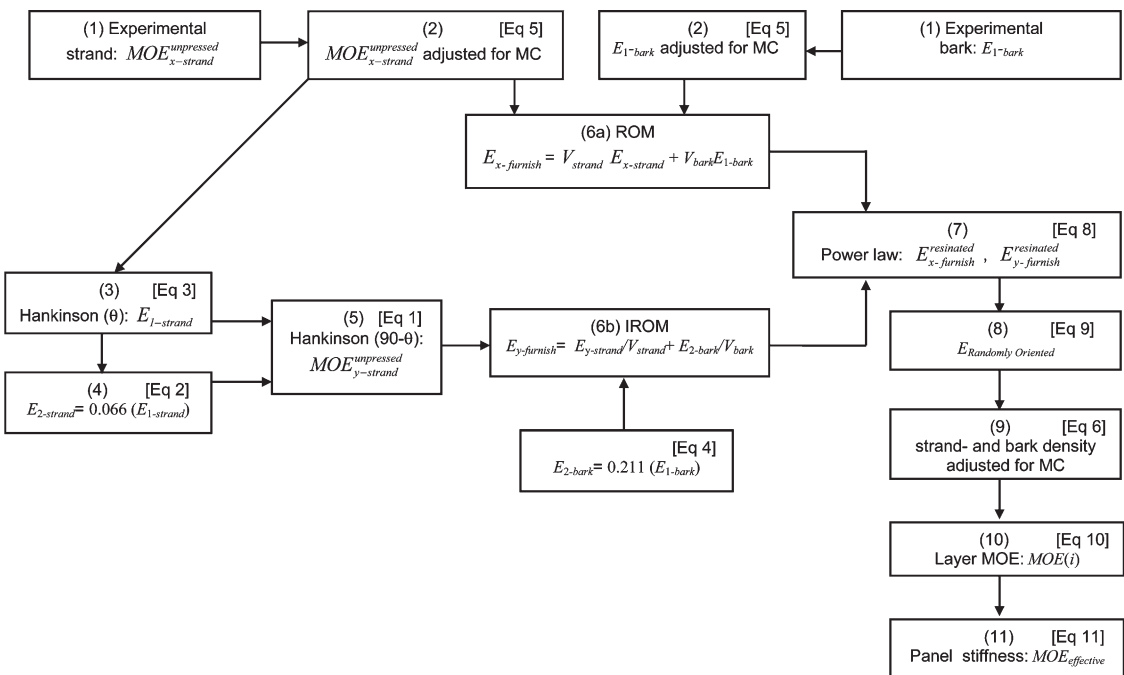


Figure 2. Flowchart of the modeling process of randomly oriented hybrid oriented strandboards.

Young's modulus (E), which is typically determined using uniaxial loadings (tensile or compression). The experimental MOE of individual strands was first adjusted to the same moisture content of actual OSB (6.97-7.61%) by Eq 5. Strand longitudinal stiffness ($E_{1\text{-strand}}$) and transverse modulus ($E_{2\text{-strand}}$) were obtained by Eqs 3 and 2, respectively. Similarly, for bark, the experimental longitudinal modulus ($E_{1\text{-bark}}$) was adjusted to the same moisture content of actual OSB, and then, the transverse modulus ($E_{2\text{-bark}}$) was obtained by Eq 4.

The longitudinal modulus of nonresinated furnish ($E_{x\text{-furnish}}$) when both strands and bark were aligned longitudinally was estimated using the longitudinal moduli of the strands ($E_{x\text{-strand}}$; with grain angle, θ) and bark ($E_{1\text{-bark}}$; no off-axis alignment) through the ROM (Step 6a). The ROM requires values of volumetric ratio that could be calculated, as detailed in the Discussion section, from the strand and bark density and their weight ratio. The density of the resulting furnish was also estimated using the ROM:

$$\rho_{\text{furnish}} = V_{\text{strand}}\rho_{\text{strand}} + V_{\text{bark}}\rho_{\text{bark}} \quad (7)$$

The in-plane transverse modulus of non-resinated, uniaxially aligned furnish ($E_{y\text{-furnish}}$) was estimated by the inverse rule of mixture (IROM) (Step 6b). The IROM estimation involved the use of in-plane moduli in a direction perpendicular to the longitudinal axis of strands ($E_{y\text{-strand}}$) and bark ($E_{2\text{-bark}}$). The estimation also required volumetric ratios as described for Step 6a.

The combined effect of hot-pressing and resin on the furnish was estimated by a power-law equation:

$$E_{\text{furnish}}^{\text{resinated}} = E_{\text{furnish}} \left[\frac{\rho_{\text{strand}}^{\text{resinated}}}{\rho_{\text{strand}}} \right]^N \quad (8)$$

where $E_{\text{furnish}}^{\text{resinated}}$ is the modulus of the pressed, resinated furnish, in their x ($E_{x\text{-furnish}}^{\text{resinated}}$) or y direction ($E_{y\text{-furnish}}^{\text{resinated}}$), E_{furnish} is the modulus of the unpressed furnish (unpressed strands and

bark) in the x or y direction, $\left(\frac{\rho_{\text{strand}}^{\text{resinated}}}{\rho_{\text{strand}}}\right)$ is the densification ratio (DR), and N is a coefficient that combines effects of resin and hot-pressing on the strands. Note that Eq 8 involves values of N and densification ratio from the strands. By adopting this approach, it was assumed that both wood strands and bark were subjected to the same DR and the same effects of hot-pressing and resin (N). This assumption was necessary because there were no density and stiffness values available in this study for hot-pressed individual bark specimens. These input values were not available because hot-pressing of brittle bark specimens would result in small broken pieces that were impossible to test subsequently.

Stiffness of the in-plane, randomly oriented hybrid layer was individually computed (Agarwal and Broutman 1990) (Step 8):

$$E_{\text{Randomly Oriented}} = \frac{3}{8}E_{x\text{-furnish}}^{\text{resinated}} + \frac{5}{8}E_{y\text{-furnish}}^{\text{resinated}} \quad (9)$$

By using Eq 9, it was assumed that the two resinated, reinforcement materials are randomly dispersed ensuing a macroscopically isotropic layer.

Adjusting modulus of elasticity by density (Steps 9-10). The layer stiffness was adjusted to MOE(i) by a compaction ratio (CR) to account for the difference between furnish and layer densities:

$$\text{MOE}(i) = E_{\text{Randomly Oriented}} \times \text{CR} \quad (10)$$

where CR is the quotient of density of the layer (obtained from VDP) and the density of hot-pressed resinated furnish constituting the layer. These two densities were obtained from corresponding locations (eg the density of panel face layer corresponds to the density of face furnish). Before computing the CR, strand and bark densities were adjusted to the same moisture content of the actual OSB using Eq 6 (Step 9).

Determining panel modulus of elasticity (Step 11). The effective MOE of the panel was calculated from the stiffness of the three individual layers (Bodig and Jayne 1993):

$$MOE_{\text{effective}} = \frac{1}{I} \sum_{i=1}^3 MOE(i) \left[I_0^i + A^i (d^i)^2 \right] \quad (11)$$

where I and I_0^i are the moment of inertia of the cross-section of the panel and of the i^{th} layer with respect to the panel's neutral plane, respectively; A^i is the cross-section area of the i^{th} layer and d^i is the centroidal distance of the i^{th} layer with respect to the neutral plane.

Data Analysis

One-way analyses of variance (ANOVA) was performed on experimental data to test significant differences among burning levels for strand and bark physical and mechanical properties. Student's t tests were also used to evaluate the differences between properties of the three groups of strands (ie control, hot-pressed, and hot-pressed resinated strands). All tests were conducted at the 95% confidence level ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Original Strand Properties

Mean values of bending properties, density, and moisture content of strands from the four burnt levels are summarized in Table 1. The grain angle, θ , of the bending strands ranged 0° - 12° with an average angle of 5° - 7° . After being

adjusted to 12% MC and 0° (MOR_L), the strand MOR values were 76-82 MPa, which approximated the published value (76 MPa) for red pine small clear specimens (FPL 1999) at the same moisture content level. The MOE values of strands, after adjustment to 12% MC and 0° (MOE_L), varied 7.09-7.82 GPa, which is 30-37% lower than the published value (11.2 GPa). Price (1976) attributed the stiffness reduction of strands to the occurrence of damage during strand manufacture, grain slope through the thickness of each strand, and inaccuracy of strain measurements. The density values of strands adjusted to 12% MC were 500-520 kg/m^3 , which were higher than the reported 460 kg/m^3 for red pine at the same moisture content (FPL 1999).

Effect of burning on wood. ANOVA results showed no statistical differences ($p < 0.05$) in bending properties, density, and moisture content of strands from different burning levels (Table 1). These results suggest that the heat exposure during the forest fire did not significantly affect the mechanical and physical properties of wood, and this outcome could be attributed to the insulating properties of bark (Neilson 1998 as cited in Watson and Potter 2004).

Hot-Pressed Strand Properties

Effect of hot-pressing. To further investigate the effect of heat on the mechanical properties

Table 1. Bending properties and density of red pine strands.^{a,b}

BL ^c	Values at specific moisture content				Values adjusted to 12% MC		
	MOE (GPa)	MOR (MPa)	Density (kg/m^3)	Moisture content (%)	MOE (GPa)	MOR (MPa)	Density (kg/m^3)
1	7.06 (1.93)	78.0 (14.1)	530 (10)	7.95 (1.81)	6.62 (1.82)	71.2 (13.5)	520 (10)
2	7.37 (2.48)	78.5 (22.2)	520 (10)	9.37 (0.43)	7.06 (2.36)	73.7 (20.6)	520 (10)
3	6.22 (1.84)	71.7 (18.9)	520 (8)	9.12 (1.57)	5.93 (1.75)	67.1 (18.3)	510 (8)
4	6.44 (2.32)	70.7 (20.4)	510 (10)	8.95 (1.78)	6.14 (2.29)	65.8 (19.8)	500 (10)

^a Mean values. Numbers in parentheses are standard deviations. No significant differences among burnt levels (BL) were found for MOE, MOR, and density; $p = 0.05$.

^b Grain angle varied 0° - 12° with an average angle of 5° - 7° .

^c BL = Burnt Level. Assessment of fire damage to standing tree before harvest: 1 = unburnt; 2 = lightly burnt outer bark; 3 = moderately burnt outer bark; 4 = severe-char damage to outer bark.

MOE = modulus of elasticity; MOR = modulus of rupture.

of strands, hot-pressed strands, with and without resin, from trees of four burnt levels were preliminarily analyzed (Fig 3). To reduce variability, the bending properties of these strands were adjusted to approximately the same moisture content (7%) and density (510-530 kg/m³), which were the conditions of the OSB panel. Figure 3 shows that when hot-pressed strands from the same location (eg face strands) were compared, the bending properties were statistically similar among different burnt levels of trees and between resinated and nonresinated

strands. While implications of density adjustment will be subsequently examined, the preliminary results presented so far suggest that it was sufficient for subsequent analyses to focus on experimental data from two extreme cases: BL1 and BL4. Additionally, similar results of physical and mechanical properties were found for the bottom- and top-layer strands (data not shown), which were averaged and analyzed as “face” layers. A DR was also determined for each hot-pressed specimen of strands to account for the degree of strand densification. Subsequent analyses were then performed on the effect of hot-pressing by examining mean values (Table 2) of MOE, MOR, density, and DR of strands (from BL1 and BL4) on the same basis of moisture content (approximately 7%).

The effect of hot-pressing on strand density was observed from values of DR (Table 2). It was evident that the combined effect of hot-pressing and resin increased the density of strands. As a general observation, strands with resin experienced higher densification than those without resin (eg 2.0 vs 1.6 for face strands). The difference can be attributed to a higher densification (reduced springback) in resinated strands, because it has been suggested that cured resin prevents springback (Yadama and Wolcott 2006). Location through the panel thickness was another influential factor on densification of strands. For hot-pressed resinated strands, face layers were compressed about 30% (22-39%) on average more than those located in the core. A similar trend was observed in the hot-pressed strands in the absence of resin (Table 2).

Although the data presented in Table 2 had been preadjusted to the panel (approximately 7% MC), attempts were also made in this study to analyze values of strand moisture content. Student's *t*-tests of initial strand moisture content revealed no statistical differences for hot-pressed strands in the presence or absence of resin (data not shown). However, consistently lower moisture content values were observed in resinated pressed strands (3.4-4.5%) compared with nonresinated pressed strands (4.5-5.13%).

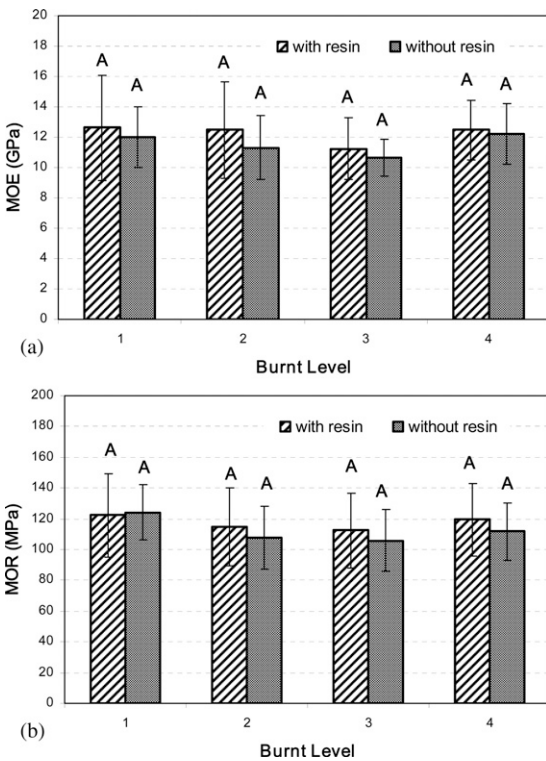


Figure 3. Comparison of bending properties of hot-pressed red pine face strands as affected by burnt level: (a) MOE^a and (b) MOR^a. ^aValues adjusted to the panel moisture content (approximately 7%) and density of oriented strandboard panels. Burnt Level: assessment of fire damage to standing tree before harvest: 1 = no char damage to outer bark and green needles; 2 = low char damage to outer bark and brown needles; 3 = moderate char damage to outer bark with brown needle; 4 = severe char damage to outer bark and no needles; bars indicate standard deviation; same letter denotes statistically similar results between burnt levels ($\alpha = 0.05$).

Table 2. Bending properties and density of hot-pressed red pine strands.^{a,b}

Hot-Pressed without resin									
BL ^c	Board ID	Faces				Core			
		MOE (GPa)	MOR (MPa)	Density (kg/m ³)	DR ^d	MOE (GPa)	MOR (MPa)	Density (kg/m ³)	DR ^d
1	A	9.57	98.6	860	1.61	6.76	76.1	700	1.31
		(2.44)	(19.9)	(18)	(0.38)	(1.89)	(16.7)	(12)	(0.26)
4	C	9.46	98.3	860	1.62	6.79	68.0	710	1.34
		(1.77)	(16.1)	(9)	(0.20)	(1.21)	(14.3)	(10)	(0.22)
	F	9.70	87.7	800	1.55	5.84	68.7	670	1.30
		(3.26)	(25.9)	(15)	(0.33)	(0.80)	(14.1)	(5)	(0.11)
	G	9.99	95.3	810	1.56	6.63	72.8	660	1.27
		(1.84)	(9.6)	(15)	(0.33)	(2.56)	(12.1)	(12)	(0.25)
Hot-Pressed with resin									
BL ^c	Board ID	Faces				Core			
		MOE (Gpa)	MOR (MPa)	Density (kg/m ³)	DR ^c	MOE (GPa)	MOR (MPa)	Density (kg/m ³)	DR ^d
1	A	12.54	126.3	1050	1.97	9.08	110.7	880	1.66
		(3.98)	(33.9)	(17)	(0.37)	(3.01)	(26.7)	(8)	(0.17)
4	C	12.68	118.3	1200	2.26	8.35	88.3	860	1.61
		(2.79)	(26.3)	(10)	(0.22)	(0.97)	(6.1)	(4)	(0.10)
	F	12.69	121.3	1050	2.02	8.74	89.1	780	1.51
		(2.51)	(24.8)	(4)	(0.10)	(2.93)	(27.9)	(11)	(0.23)
	G	13.01	126.6	1020	1.97	8.77	111.0	850	1.63
		(1.33)	(24.7)	(8)	(0.17)	(1.93)	(37.9)	(10)	(0.21)

^a Mean values adjusted to about 7% MC of OSB panels. Numbers in parentheses are standard deviations.

^b Grain angle varied 0°-12° with an average angle of 5°-7°.

^c BL = Burnt Level. Assessment of fire damage to standing tree before harvest: 1 = unburnt; 4 = severe char damage to outer bark.

^d DR: Density Ratio = final density/initial density.

Unpressed strands of BL1 had average MOE = 7.06 GPa, MOR = 78.0 MPa, density = 530 kg/m³ after adjusted to 7% MC.

Unpressed strands of BL4 had average MOE = 6.44 GPa, MOR = 70.7 MPa, density = 510 kg/m³ after adjusted to 7% MC.

MOE = modulus of elasticity; MOR = modulus of rupture; OSB = oriented strandboard.

The effect of hot pressing on the strand mechanical properties is shown in Table 2. Hot-pressing in the absence of resin increased the mean MOE and MOR values of strands located in the face layer by about 40% (32-50%) and 24% (19-29%), respectively (Table 2) compared with the unpressed (control) strands (Table 1). Such significant increases were not observed for the core strands in the absence of resin (Fig 4). This lack of significant MOE or MOR increase between control strands and hot-pressed (without resin) core strands can be attributed to possible damage to the strands during hot-pressing. In other words, although the strands were densified (DR approximately 1.30), the positive effects of such a small extent of densification was offset by the damage. In the presence of resin, hot-pressing increased the bending properties of strands in both face and core layers. In the face layers, hot-pressed resinated strands showed about

85 and 60% increase in mean values of MOE and MOR, respectively, compared with the control strands. In the core layers, hot-pressed resinated strands exhibited mean MOE and MOR values that were, respectively, 27 and 30% higher than the unpressed strands. This favorable effect of hot-pressing on core strands was not observed in nonresinated strands, as mentioned previously, and the postulated effect of strand damage, in addition to lower densification, will be examined subsequently.

Comparing pressed and resinated strands (face and core combined) showed about a 32-35% increase in mean MOE compared with non-resinated strands. To explain this, the MOE of nonresinated pressed strands was adjusted to the density of resinated strands by assuming a directly proportional MOE-density relationship. On adjustment for density, the stiffness

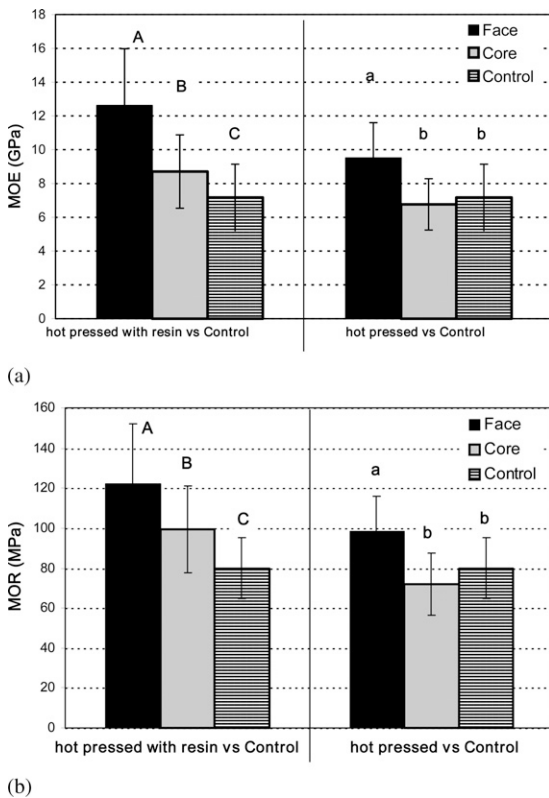


Figure 4. Comparison of modulus of elasticity (MOE) and modulus of rupture (MOR) of red pine unburnt strands^a. ^aValues adjusted to the same panel moisture content (7%). Bars indicate standard deviation; same letter denotes statistically similar results ($\alpha = 0.05$).

superiority of pressed resinated strands (over nonresinated pressed stands) decreases from approximately 35-8% or lower, making the effects of resination insignificant as discussed earlier for Fig 3. This observation suggests that the higher MOE observed in resinated strands was largely because of a higher density, which presumably was a result of springback reduction from resin curing.

Comparing strands that were hot-pressed in the presence of resin, face strands were stiffer and stronger than core strands, 45 and 25% higher in MOE and MOR, respectively. After adjustment to the density of face strands by the DR, these differences decreased to 12% for MOE but became insignificant for MOR. This suggests

that factors other than density also play a role in causing a lower MOE in core strands. To further investigate this, the density dependence of MOE for resinated strands of two locations was compared with reference to controls. Using Eq 8 for the data in Table 2, the power constants (N) were found to be 0.9 on average for face strands and 0.5 for the core. The respective N values could be used to estimate the combined effects of resin and hot-pressing on wood strands under similar manufacturing conditions. In addition, the smaller N value for the core layers suggests that mechanical enhancement benefits of densification diminish in the core, where mat temperature is expected to be lower than that in the face layers during hot-pressing. It has been reported that a higher temperature can reduce damage by plasticizing the wood to a greater degree or can repair pressing-related damage by causing lignin to flow (Geimer et al 1985). The higher temperature in the face layer could also plasticize face strands to obtain higher densification.

Bark Properties

Table 3 lists the average values of E , MCS, density, and moisture content for BL1 and BL4. Mean values of E and MCS of BL1 and BL4 specimens at 10-11% MC agreed with the respective values at 10% MC of (unburnt) southern pine bark (Eberhardt 2007). The average basic density of bark was slightly higher than the 243 kg/m³ reported by Lamb and Marden

Table 3. Red pine bark properties.^a

	Values at specific moisture content				Values adjusted to 7% moisture content		
	E^c (MPa)	MCS ^d (MPa)	Density (kg/m ³)	MC (%)	E^c (MPa)	MCS ^d (MPa)	Density (kg/m ³)
BL ^b							
1	385 (140)	6.02 (1.57)	283 (5)	10.63 (1.11)	408 (128)	7.00 (1.28)	285 (4)
4	350 (116)	5.66 (1.03)	277 (7)	11.34 (0.76)	375 (106)	6.79 (0.83)	279 (6)

^a Mean values. Numbers in parentheses are standard deviations. No significant differences among burnt levels (BL) were found for E , MCS, and density; $p = 0.05$.

^b BL = Burnt Level. Assessment of fire damage to standing tree before harvest: 1 = unburnt; 4 = severe char damage to outer bark.

^c Modulus of elasticity in compression parallel to grain.

^d Maximum compression strength parallel to grain.

(1968) for red pine bark. When density was adjusted to the same moisture content of the actual OSB (6.9-7.4%) by using Eq 6, the resulting value was 280 kg/m³. ANOVA showed no statistical differences (*p* < 0.05) between the two burning levels for E, MCS, and density (Table 3). This could be explained in that our bark specimens were sampled from trees at 1.5- and 3.0-m height, where presumably, the impact of the fire on bark was not significantly different between the two burning levels. Another possibility is the constraint in bark sampling in which materials of BL4 were inclined to be collected from portions of bark that were still intact (not broken from charring), thereby leading to the insignificant property differences. This second possibility will be verified subsequently when we examine the outcome of using data of unburnt bark and severely burnt bark for MOE prediction of OSB.

Model Predictions

Table 4 summarizes the parameters required in the modeling process. In using micromechanics formulae, a 68:32 wood:bark volumetric ratio was used ($V_{strand}^{resinated} = 0.68$ and $V_{bark}^{resinated} = 0.32$). This ratio was determined from the weight ratio of 80:20 based on density values of pressed resinated strands (1200-780 kg/m³) and pressed resinated bark (570-420 kg/m³, projected using the same densification ratio as the strands) in accordance with:

$$V_{bark}^{resinated} = \left(\frac{20}{SG_{bark}^{resinated}} \right) \times \left(\frac{1}{\frac{80}{SG_{strand}^{resinated}} + \frac{20}{SG_{bark}^{resinated}}} \right) \tag{12}$$

$$V_{strand}^{resinated} = 1 - V_{bark}^{resinated} \tag{13}$$

Because the density of pressed resinated strand and bark have different values, a ROM was used to predict the density of the pressed strand-bark mixture ($\rho_{furnish}$) before adjusting for the OSB layer density to predict the layer MOE (Steps 6a and 6b).

Experimental and predicted properties of OSB are summarized in Table 5. Face layer densities of hybrid OSBs were about 26-27% higher than those for the core. Face layer densities were on average higher compared with the respective layer for bark-free panels (810 vs 780 kg/m³), indicating that bark addition increased the degree of densification of the OSB face layer. This could be explained by, among other reasons, bark having a lower density (higher compressibility) and a smaller particle size compared with strands. In our model, the density difference between wood and bark was considered when determining $\rho_{furnish}$ as discussed in the previous paragraph. For verification of the stiffness model, the predicted MOE was compared with experimentally measured values reported by Moya et al (2008). Comparisons between experimental and predicted values

Table 4. Parameters required in the modeling process.

Material property	Value	Source
Strand MOE: face	Table 2	Hot-press resinated
Strand MOE: core	Table 2	Hot-press resinated
Strand angle (°)	5-7	
Bark E _L	Table 3	
Density of strands (unpressed) adjusted to the approximately 7% MC of OSB panels (kg/m ³)	510-530	
Face strands DR	Table 2	Hot-press resinated
Core strands DR	Table 2	Hot-press resinated
Density of panel face layer	Table 5	Vertical density profile
Density of panel core layer	Table 5	Vertical density profile

MOE = modulus of elasticity; OSB = oriented strandboard; DR = densification ratio.

Table 5. Experimental and predicted properties of red pine hybrid OSB.^a

BL ^b	Panel ID	Experimental				Predicted MOE (GPa)	[Pred-Exp]/Exp (%)
		MOE (GPa)	Density (face) (kg/m ³)	Density (core) (kg/m ³)	MC (%)		
1	A-d	4.82 (0.44)	840 (4)	660 (3)	7.41 (0.07)	4.21	-13
	C-d	5.15 (0.42)	830 (4)	660 (5)	7.61 (0.02)	4.11	-20
4	F-d	4.96 (0.58)	810 (4)	640 (4)	6.97 (0.13)	3.83	-23
	G-d	4.18 (0.73)	740 (4)	690 (3)	7.45 (0.20)	3.58	-14

^a Mean values. Numbers in parentheses are standard deviations.

^b BL = Burnt Level. Assessment of fire damage to standing tree before harvest: 1 = unburnt; 4 = severe char damage to outer bark.

MOE = modulus of elasticity; MC = moisture content.

showed that the model predicted bending stiffness with deviations of 13-23% from the observed value. The deviation could be attributed to the (bending) test method used in this study to determine strand MOE, which is typically determined using uniaxial loadings for modeling purposes. In this case, the prediction is adequate compared with the variability (coefficient of variation of up to 17%) of the actual OSB stiffness. The deviations of MOE predictions were similar for furnish (strand and bark) from both unburnt and severely burnt trees (Table 5). This observation agrees with the earlier conclusion (in the “bark properties” section) that bark of BL1 and BL4 were similar in stiffness.

CONCLUSIONS

A simple approach to predict the bending stiffness of randomly oriented hybrid OSB was presented. The modeling process involved: determination of individual layer stiffness, adjustment of layer properties from densification effects, and determination of panel MOE based on layer properties and lamination theory. Model results were compared with laboratory panels made of wood strands and bark from fire-impacted trees. Conclusions of this study include:

- The bending properties and density of red pine wood from fire-impacted trees were not significantly affected by the forest fire. Sub-

sequent exposure of strands to heat during the manufacturing process did not produce different effects on bending properties of strands from different burnt levels.

- Three groups of strands, unpressed, hot-pressed nonresinated, and hot-pressed resinated, were tested in bending to compare the effect of hot-pressing and resin on stiffness and strength of strands. Our findings with red pine strands support published results for other wood species that hot-pressing increases strand stiffness from densification and plasticization. This effect also depended on the strand location in the mat during hot-pressing. Strands located in face layers showed significantly higher mechanical properties compared with strands in the core layer.
- Unpressed strands were 30-37% lower in MOE than documented in the Wood Handbook, possibly from wood damage during strand production. Additionally, the effects of hot-pressing and resin on MOE of strands could be predicted from unpressed strands using a target densification ratio through the power-law equation. These findings suggest that the modeling approach proposed in this study could potentially, and hence conveniently, rely on documented data as inputs for the furnish after making adjustments.
- Comparison between model results and experimental data showed that the model adequately predicted the effective MOE with deviations of 13-23% from observed values.

Results of this study validate the application of micromechanics equations and lamination theory to predict the MOE of randomly oriented hybrid panels of wood strands and bark.

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