ORTHOTROPIC STRENGTH AND ELASTICITY OF HARDWOODS IN RELATION TO COMPOSITE MANUFACTURE PART III: ORTHOTROPIC ELASTICITY OF STRUCTURAL VENEERS

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ABSTRACT

Structural veneers approximately 3.2 mm (⅛ in.) in thickness are widely used as basic constituents in structural composites such as plywood, laminated veneer lumber (LVL), and parallel strand lumber (PSL). The veneer processing operation (peeling) may adversely alter the mechanical properties of the wood substance by introducing compression-set, cracks, and splits, etc. The modulus of elasticity (MOE) in tension of five hardwood species, which are potential raw materials for composite manufacture, was investigated in veneer form. The experimental work included dynamic MOE determination using ultrasound stress wave timing and static MOE measurements for comparison purposes. The orthotropy of MOE in the longitudinal-tangential (LT) plane was also a target of the investigation. Theoretical models were fitted to experimental data that may predict the MOE of the constituents according to their position within the consolidated composites. Experimental and analytical results indicated that a combined model including the Hankinson's formula and an orthotropic tensorial approach is the best estimator for MOE of veneers having inclined grain orientation. Furthermore, the

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relationship between static and dynamic MOE values may be obtained by second-order polynomial models.

Keywords: Orthotropy, hardwood, tensile MOE.

INTRODUCTION

A long-term research project to investigate different hardwood species as potential raw materials for structural composites is under progress. The cooperative international research focuses on the exploration of mechanical properties of five hardwoods, including three Appalachian and two East European species: quaking aspen (*Populus tremuloides*), red oak (*Quercus rubra*), yellow-poplar (*Liriodendron tulipifera*), turkey oak (*Quercus cerris*), and true poplar (*Populus x. Euramericana cv. Pannonia*), respectively. A detailed description of the project, justification, and research need have already been discussed previously in related publications (Lang et al. 2000; Lang et al. 2002).

The work presented here is the third paper of a series further exploring the mechanical properties for hardwood species used in structural composite production. The orthotropy of MOE in tension for structural veneers was the target of the present investigation.

The objectives included:

1. The experimental determination of modulus of elasticity (MOE) of veneer sheets using an ultrasonic technique.
2. Investigation of the correlation between dynamic and static MOE values.
3. Development of model(s) that are capable of estimating the MOE values of structural veneers at different grain orientations.
4. Experimental validation of the model(s) for screening out the possible best prediction equation for further modeling purposes.

This paper provides a review of relevant literature and discusses possible theoretical approaches for estimating the direction-dependent modulus of elasticity of structural veneers. Furthermore, it describes the experimental and analytical works performed, along with conclusions and further modeling possibilities.

LITERATURE REVIEW

The orthotropic tensile properties of thin wood plates (veneers) are difficult to assess by common testing methods because of the low stiffness and strength properties perpendicular to the grain. Usually no standard ASTM testing procedures can be used for measuring the tension strength and modulus of elasticity of veneers. Therefore, limited research has been done on the tensile orthotropy of thin wooden plates. Gerhards (1988) examined the effect of sloping grain on the tensile strength of Douglas-fir. At small angle deviations (less than 20°), he found that the modified Hankinson's formula (Kollman and Côté 1968) provided an acceptable fit. In another work that included the full grain orientation range (Woodward and Minor 1988), the authors found that the same theory worked well, but provided a worse prediction than a hyperbolic formula. Pugel (1990) developed an angle-to-grain tensile setup for thin specimens. Tensile test results of Douglas-fir and southern pine, measured by this new technique, showed reasonable agreement with the original Hankinson's formula. These studies dealt with the tensile strength only, and did not address the effect of sloping grain on the modulus of elasticity.

Nondestructive testing is a simple and inexpensive alternative to static tests. Its advantages are obvious: the specimen is not destroyed during the measurement, which is usually fast and less labor-intensive. Furthermore, nondestructive evaluation is often much simpler than the static test. Vibration methods are particularly suitable for quantitative, as well as qualitative evaluation, of materials. The relationship of vibration properties to the elastic characteristics of materials was recognized as early as 1747 by Riccati. Researchers started to apply this relationship for wood in the early 1950s (Pellerin 1965).

Vibration methods include two subtypes:

transverse and longitudinal (stress-wave) vibration. Furthermore, different measuring techniques may include low or high frequency (ultrasonic) stress waves for measuring mechanical and/or physical properties of materials. According to theory, measured transverse vibration frequency and wave propagation velocity are related to the bending and uniaxial MOE, respectively. Many studies verified these relationships experimentally, typically with excellent results. Researchers also endeavored to find empirical correlations between vibration and strength properties. Many considered the damping characteristics of wood to be promising for evaluation of mechanical properties, but their experiments were not invariably successful. Pu and Tang (1997) gave an excellent overview of the research conducted in this area.

The application of static tension tests to angle-to-grain veneer specimens is limited due to the inherent fragility of thin wooden plates across the grain. The mechanical properties of veneer can be very different from those of the wood it originated from, and assessment of veneer properties is sometimes desirable.

There are two areas where vibration testing (stress-wave grading) of veneers can be particularly useful: 1. relating the mechanical properties of logs to those of the veneer peeled from them (Ross et al. 1999; Rippy et al. 2000) and 2. veneer classification prior to Laminated Veneer Lumber manufacture to engineer or improve the consistency of the product's end properties (Koch and Woodson 1968; Jung 1982; Kimmel and Janiowak 1995; Shuppe et al. 1997). The latter gained practical application, too, and a commercial tool is now widely used for classifying veneer sheets according to their stress-wave characteristics (Sharp 1985).

Other studies about veneer testing by stress-waves include that of Jung (1979), who presented a comprehensive study of stress-wave application on veneers. He examined the potential of this technique to detect knots and slope of grain, and investigated the effect of specimen size and different testing devices. Hunt et al. (1989) correlated the tensile and stress-wave MOE of veneer with acceptable results. Most recently, Wang et al. (2001) investigated the potential of two stress-wave techniques to detect lathe checks and knots in veneer. Stress-wave propagation parameters were sensitive to defects, when measuring perpendicular to grain.

Few studies dealt with the effect of sloping grain on nondestructive testing parameters. Kaiserlik and Pellerin (1977) attempted to predict tensile strength of woods containing sloping grain. Divos et al. (2000) used ultrasonic propagation velocity and attenuation parameters to predict grain slope. They showed that both ultrasonic velocity and the magnitude of the first received amplitude are good indicators of grain deviation. Attenuation is better to detect small grain angles, while propagation velocity—which is a function of the direction-dependent MOE—is a better estimator for the entire grain orientation range. Jung (1979) examined (among other factors) the effect of sloping grain on the stress-wave characteristics of veneers. He found that at small angles ($<5°$) there is little change in stress-wave velocity, but at slightly larger angles it decreases rapidly. There appears to be no study in the literature that uses vibration methods to describe the relationship between MOE and grain angle in wood.

THEORETICAL BACKGROUND

The propagation velocity of longitudinal stress-waves in a material is directly related to the modulus of elasticity and the bulk density of the substance:

$$E_d = v^2\rho \qquad (1)$$

where:

E_d — dynamic Modulus of Elasticity (Pa)
v — propagation velocity (m/s)
ρ — density (kg/m^3)

The above equation holds true for so-called one-dimensional bodies only, that is, where the dimensions perpendicular to the wave propagation are at least one magnitude smaller than the wave length. In veneer sheets, where one cross-sectional dimension is larger than the wave length (two-dimensional body), the above equation is modified with the Poisson's ratio:

$$E_d = v^2\rho(1 - \nu_{xy}{}^2) \qquad (2)$$

where:

ν_{xy} = Poisson's ratio (*x*—propagation direction; *y*—perpendicular in-plane direction).

Unfortunately, reliable information concerning ν_{xy} is seldom available. In past investigations, stress-wave MOE measured on veneer was invariably calculated using Eq. (1). The results of Jung's investigations (1979) indicate that the correction introduced in Eq. (2) appears to be negligible in red oak wood veneers. Other researchers also reported the negligible effect of Poisson's ratio in evaluation of thin wooden plates (Divos and Tanaka 2000).

Because of the viscoelastic nature of wood, measured dynamic MOE depends on the rate of stress-development. During dynamic testing, stresses develop much faster than they do during static testing and the difference between the resulting MOE values is significant. For this reason, MOE calculated from longitudinal or transverse vibration characteristics is called dynamic MOE.

Divos and Tanaka (2000) proposed the following empirical equation to calculate the ratio of dynamic and static MOE:

$$\frac{E_d}{E_s} = 1 + 0.017 \log\left(\frac{t_s}{t_d}\right) \qquad (3)$$

where:

E_d; E_s — dynamic and static MOE, respectively

t_d; t_s — characteristic time of the dynamic and static MOE determination, respectively.

Note that t_d is the period (T) of the applied stress wave when vibration method is used to determine dynamic properties and t_s is the elapsed time to develop 10% of failure stress level by any applicable static testing procedure.

PREDICTION MODELS

Several models and theories were developed for estimating the direction-dependent engineering properties of orthotropic materials. Many of these approaches include hard to measure material constants like modulus of rigidity or Poisson's ratios. The model selection criteria for this research included: simplicity, reliability, and easy adaptability. The following three models were involved in this investigation.

Tensor approach

The compliance matrix of an orthotropic material can be converted into a four-dimensional tensor (Szalai 1994). Transforming the first element of this tensor results in an equation that can be used to estimate the stiffness of the material in any direction inclined to its principal material coordinates. The interested reader can find the detailed description and derivation of this model in an earlier, related publication (Lang et al. 2002). The general equation applied to MOE in the LT plane only, where the grain angle (φ) controls the property, reduces to the following form:

$$\hat{E}_O = 1 \Bigg/ \left[\frac{1}{E_L}\cos^4\varphi + \frac{1}{E_T}\sin^4\varphi + \left(\frac{4}{E_{LT}^{R45°}} - \frac{1}{E_L} - \frac{1}{E_T}\right)\sin^2\varphi\,\cos^2\varphi\right] \qquad (4)$$

where:

$\hat{E}_O$ — predicted MOE at grain angle φ;

E_i — experimentally determined MOE in the principal anatomical directions ($i = L, T$);

$E_{LT}^{R45°}$ — experimentally determined MOE in the LT plane, at φ = 45°.

Equation (4) needs three predetermined E values for predicting the modulus of elasticity in the LT plane. Besides its demonstrated theoretical basis, the experimentally determined midpoint (i.e., $E_{LT}^{R45°}$) may provide improved accuracy compared to other models.

Hankinson's formula

The most widely used equation for predicting the effect of sloping grain on unidirectional strength and MOE is the experimental Hankinson's formula (Hankinson 1921). For MOE in the LT plain, the equation can be written as follows:

$$\hat{E}_H = \frac{E_L E_T}{E_L \sin^2\varphi + E_T \cos^2\varphi}, \tag{5}$$

where $\hat{E}_H$ is the predicted MOE at grain angle φ, and the other notations are as in Eq. (4).

The Hankinson's formula, though empirical, is simpler than the tensor approach and uses only two predetermined MOE values for the estimation.

Hyperbolic formula

Woodward and Minor (1988) reported that a hyperbolic formula provides excellent fit to tensile strength data. Although no experimental data were provided regarding the stiffness prediction, it may provide reasonable estimation of elasticity values. The equation applied in the LT plane takes the following form:

$$\hat{E}_{Hyp} = \frac{2E_L E_T}{e^{0.01\varphi}(E_T + E_L) + e^{-0.01\varphi}(E_T + E_L)}, \tag{6}$$

where e is the base of the natural logarithm, and the other notations are as in Eq. (4). Similarly to that of Hankinson's formula, it represents a simple approach that requires only two predetermined elastic constants. During this research, the applicability and prediction accuracy of these models were investigated by the following experimental and analytical methods.

MATERIALS AND METHODS

Experimental material consisted of 3.2-mm-(⅛-in)-thick structural veneer sheets of three Appalachian hardwood species: quaking aspen (*Populus tremuloides*), red oak (*Quercus rubra*), and yellow-poplar (*Liriodendron tulipifera*), and two European species: turkey oak (*Quercus cerris*), and true poplar (*Populus x. Euramericana cv. Pannonia*). Structural composite plants in West Virginia and in Europe prepared the veneer sheets from logs. The veneer sheets used for specimen fabrication were processed as in actual manufacturing including peeling, drying, and clipping. Consequently, specimens included all the random discrepancies such as cracks, compression-set, etc. that may develop during structural veneer manufacturing. However, studying the effects of further composite manufacturing processes such as densification and resin penetration on the mechanical properties was beyond the scope of this investigation.

Dynamic MOE was determined using a stress-wave measuring equipment. The device consists of an ultrasonic timer and two piezoelectric accelerometers. The transducers used a 127 V, 45 kHz impulse that lasted for 30 μs. The subsequent impulses were generated at one-second intervals. Surface pressure of 3–4 MPa between the transducers and the veneer sheets provided adequate coupling, using sandpaper as a coupling material.

Figure 1a and 1b show the details and schematic of the ultrasonic equipment, respectively. The distance between the transducer and the receiver was 160 mm. The material was clamped on a special table, which was covered with a 4-mm-thick rubber sheet, to avoid bridging of the signal between the transducer and the receiver. A commercial hand-clamp provided adequate surface pressure between the transducers and the material.

Figure 2 demonstrates the operation principle of the ultrasonic timer. Timing starts when the excitation impulse rises, and stops when the received signal reaches a threshold value above the noise level. The advantage of this method is that there is minimal delay between the reception of the signal and the stoppage of the timer. The measured time was cora.

b.

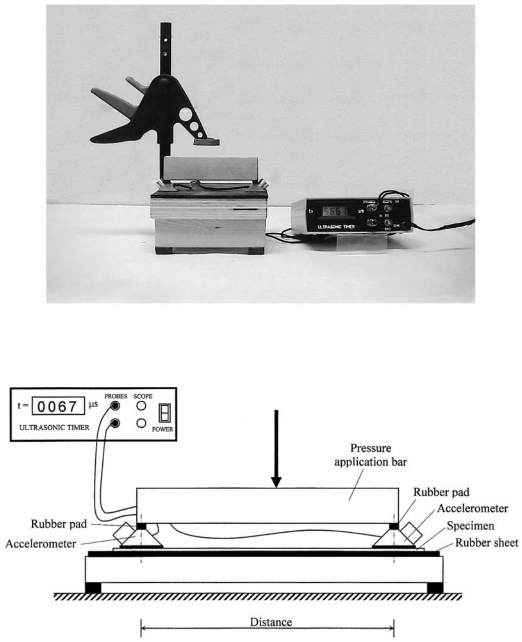

FIG. 1. View (a.) and schematic (b.) of the ultrasonic timing device.

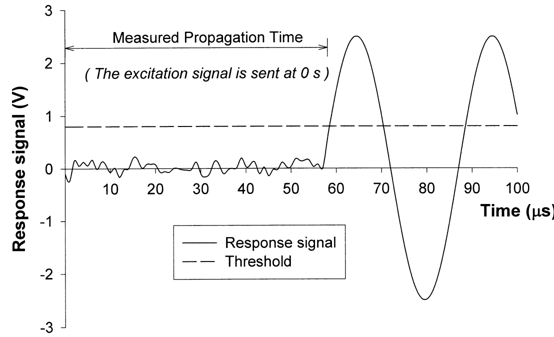

FIG. 2. Operation principle of the ultrasonic timer. Explanation of propagation time and threshold signal.

rected to account for travelling time in the transducer housing.

Because peeled structural veneers represent two-dimensional bodies, the applicability of Eq. (1) or (2) was investigated. Preliminary measurements were executed on 300-mm × 300-mm × 3.2.-mm veneer sheets using various grain orientations. The exact location of the accelerometers was marked and thin veneer strips, that included the marked measurement locations, were cut from the sheet. Propagation times measured on veneer strips (i.e., one-dimensional body) were no different from those obtained from measuring large sheets. This led to the conclusion that Eq. (1) is sufficient for dynamic MOE determination.

Material preparation for the exploration of dynamic MOE started with the splitting of large veneer sheets along the grain. This provided a base line for cutting the 200-mm × 200-mm specimens using a large paper shear. Furthermore, the split-side of the specimen served as the 0° grain direction to which the inclined directions could be measured and marked. Both sides of the specimens were marked by 15° increment of grain orientation using a precision protractor having ±1° of accuracy.

The precut and marked specimens were conditioned in a controlled environment of 20°C and 65% relative humidity. Approximately six days of conditioning resulted in constant weight of the veneer sheets. Twenty control specimens were used to establish the physical properties of the experimental materials. Table 1 contains the summary statistics of these properties obtained by standard measurements (ASTM D-2394 and ASTM D-4442; 1996b, c). The comparatively low standard deviations of physical properties indicate that the natural variability wood was limited by selecting defect-free and straight-grained veneer specimens.

After conditioning and immediately prior to dynamic MOE evaluation, the exact dimensions and weight of the specimens were measured and recorded for bulk density calculations. The accuracies of dimension and weight measurements were 0.01 mm and 0.01 g, respectively. The ultrasonic propagation time was assessed in the marked directions on both faces of each specimen.

Data evaluation started with calculating the density of the specimens, and the propagation time (average of two sides) in each direction on each sheet. The propagation velocity was calculated by dividing the transducer distance by the corrected propagation time. Finally, Eq.

TABLE 1. *Summary statistics of the measured physical properties of structural veneers.*

Species	N[a]	Moisture content (%)		Specific gravity		Bulk density (kg/m^3)	
		$\bar{x}$[b]	Std[c]	$\bar{x}$	Std	$\bar{x}$	Std
Aspen	20	11.8	0.32	0.37	0.01	385	18.0
Red oak	20	10.5	0.38	0.50	0.01	523	19.5
Yellow-poplar	20	11.5	0.61	0.42	0.02	450	17.3
True poplar	20	11.3	0.59	0.38	0.04	397	17.6
Turkey oak	20	11.7	0.45	0.65	0.03	670	19.4

[a] Sample size.
[b] Mean value.
[c] Standard deviation.

(1) provided the E_d values in each direction for each specimen. Because every specimen was tested in each direction, this situation corresponds to a randomized complete block (RCB) design.

A relationship between the dynamic and static MOE was established by testing veneer and solid wood specimens of each species (conditioned the same way as above), at four grain angle levels (0°, 15°, 30°, and 45°). Sample sizes were set to 5 for these analyses for each variable combination. The target dimensions were 300 mm in length and 25 mm in width. Solid wood specimens had the same dimensions except the thickness was set to 12 mm. Dynamic MOE was measured in a similar manner as described above. Static MOE was measured using an MTS servo-hydraulic testing machine. Load and strain values were collected using a data acquisition system, with a data collection frequency of 1 second. The top tension-grip of the experimental setup had a self-aligning, rotational free coupling to the load cell (Fig. 3). Thus, the majority of bias introduced by the twisting of angle-to-grain specimens has been alleviated. Testing speed and other testing parameters were in accordance with the relevant ASTM standard (ASTM D 143-94; 1996a).

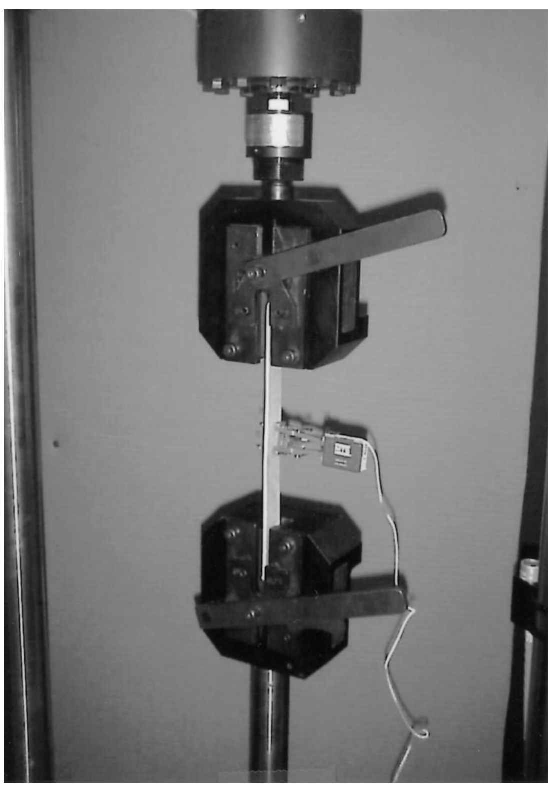

FIG. 3. The experimental setup for static MOE measurements parallel to the grain.

RESULTS AND DISCUSSION

Table 2 shows the summary statistics of the dynamic MOE of each species at different grain angle levels. Figures 4a through 8a demonstrate these data by box plots as a function of grain orientation (φ).

In general, measured dynamic MOE values decreased sharply with increasing grain angle, under 45° grain orientation. Above this angle, MOE leveled off, and there was little additional decrease. These observations agree well with the results of orthotropic compression MOE determination (Lang et al. 2002). One-way ANOVA revealed that grain orientation significantly affects the MOE of each species.

TABLE 2. *Summary statistics of the measured dynamic MOE values.*

Species		Grain angle (ϕ°) 0°	15°	30°	45°	60°	75°	90°	n
		Dynamic modulus of elasticity (GPa)							
Quaking aspen	Mean	11.976	7.056	2.658	1.279	1.048	1.035	1.030	20
	Std.	0.888	0.752	0.287	0.135	0.045	0.045	0.047	
Red oak	Mean	10.651	5.770	1.997	1.396	1.387	1.383	1.382	23
	Std.	1.201	0.827	0.348	0.046	0.039	0.039	0.044	
Yellow-poplar	Mean	13.529	7.631	2.589	1.254	1.149	1.145	1.142	21
	St.	1.020	0.735	0.254	0.112	0.050	0.060	0.062	
Turkey oak	Mean	12.221	8.435	3.989	1.878	1.158	0.807	0.685	11
	Std.	0.852	0.897	0.417	0.258	0.195	0.071	0.125	
True poplar	Mean	10.638	7.208	3.476	1.850	1.158	0.870	0.750	12
	Std.	0.839	0.825	0.371	0.159	0.154	0.106	0.132	

n—sample size.
Std.—standard deviation.

Tukey's multiple comparison tests, however, failed to detect statistically significant differences between the MOE values above 45° and 60° grain angles for the Appalachian and European species, respectively.

As a first approach to evaluating the prediction models, correlation analysis was used on the data, without regard to blocking. Table 3 lists the r^2 values by species and model types.

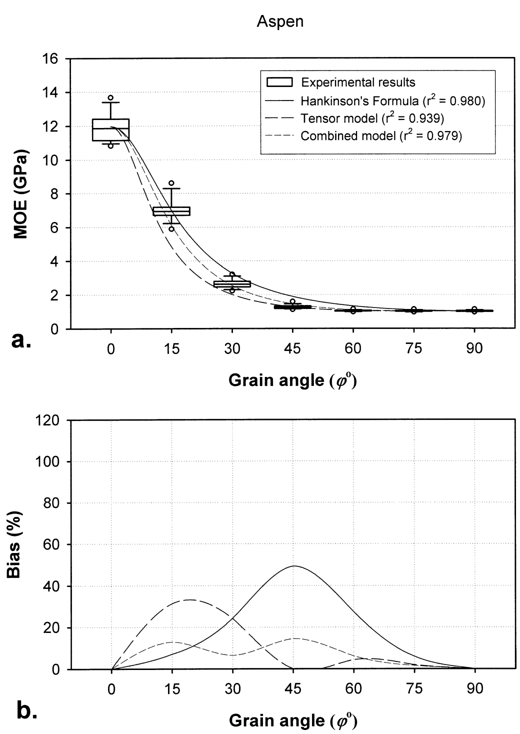

FIG. 4. Dynamic MOE values as a function of grain orientation for aspen (*Populus tremuloides*). a. Comparison of experimental and model predicted values. b. The average absolute percentage of bias of the models.

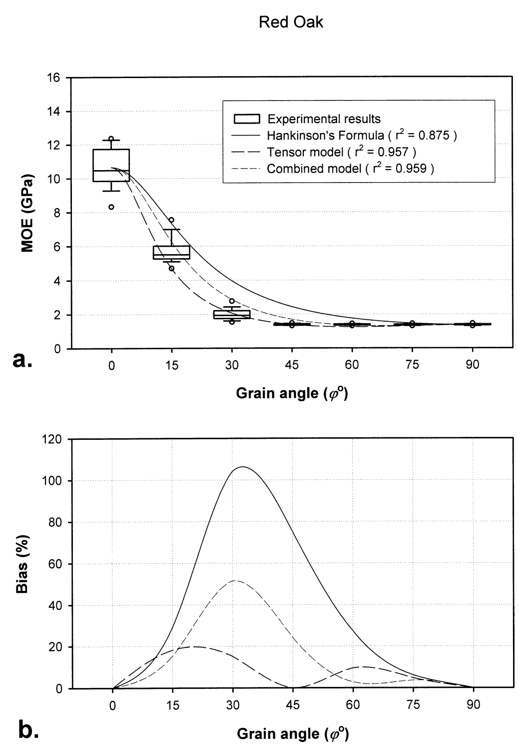

FIG. 5. Dynamic MOE values as a function of grain orientation for red oak (*Quercus rubra*). a. Comparison of experimental and model predicted values. b. The average absolute percentage of bias of the models.

TABLE 3. *r^2 values provided by the different prediction models.*

	Hankinson's formula	Orthotropic tensor model	Hyperbolic formula	Combined model
Quaking aspen	0.98	0.94	0.92	0.98
Red oak	0.88	0.96	0.93	0.95
Yellow-poplar	0.97	0.93	0.93	0.98
Turkey oak	0.90	0.99	0.72	0.96
True poplar	0.94	0.98	0.79	0.98

In all but one case, the hyperbolic formula provided less precise prediction than either of the other two models. Thus, it was eliminated from further evaluations. The fit of Hankinson's formula resulted in higher r^2 values in the cases of aspen and yellow-poplar, while the orthotropic tensor approach (Eq. 4) seems to work better for red oak and for the Hungarian species. For the Appalachian species, the former appears to work better in the lower grain angle region, while the latter is very accurate in the higher range.

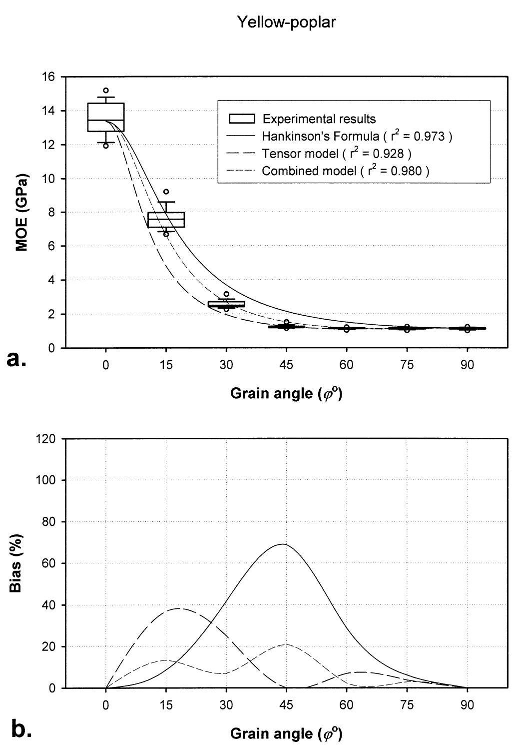

FIG. 6. Dynamic MOE values as a function of grain orientation for yellow-poplar (*Liriodendron tulipifera*). a. Comparison of experimental and model predicted values. b. The average absolute percentage of bias of the models.

In complex modeling that requires several input parameters, the calculated results can be seriously impaired if the uncertainties of the parameters are high. Our goal was to screen out the possible best prediction equation for MOE determination of structural veneers as a function of grain orientation for further modeling purposes. Thus, the prediction equation introduces only limited uncertainties that propagates into the final model prediction. Based on the above discussion, a combination of the two models appeared to improve the MOE prediction throughout the whole range. Following is a possible combination that works well:

$$\hat{E}_C = \hat{E}_H \frac{\sqrt{\pi/2} - \sqrt{\varphi}}{\sqrt{\pi/2}} + \hat{E}_O \frac{\sqrt{\varphi}}{\sqrt{\pi/2}}, \quad (7)$$

where: $\hat{E}_H$, $\hat{E}_O$ and $\hat{E}_C$ are the dynamic MOE values predicted at grain angle φ, by the Hankinson formula, the orthotropic tensor approach, and the above combination, respectively. It is obvious that the value of $\hat{E}_C$ will be close $\hat{E}_H$ at lower grain angles, and approaches $\hat{E}_O$ rapidly, as φ increases. Figures 4a through 8a, along with r^2 values given in Table 3, show that the combined model provides improved prediction for almost all examined species. One should note that Eq. (7) does not provide a new approach to predict the direction-dependent MOE of structural veneers. Rather, it exploits the fact that the evaluated two models have different accuracies over the lower and higher grain angle domains.

For a more rigorous evaluation of prediction accuracy, all three models were applied to

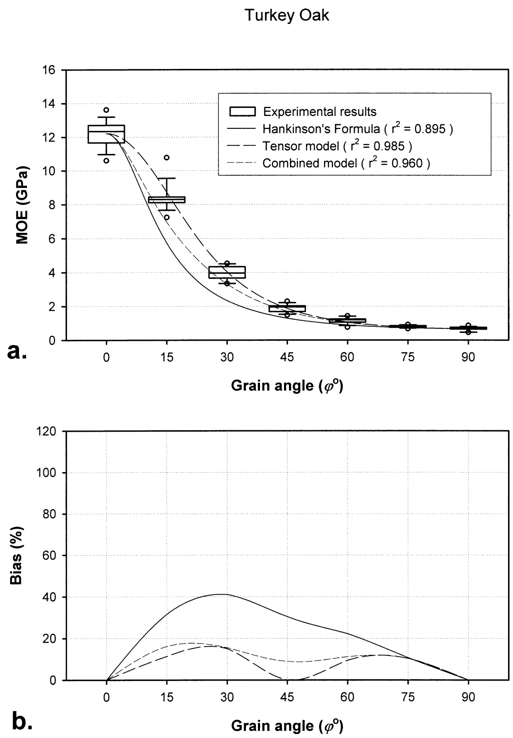

FIG. 7. Dynamic MOE values as a function of grain orientation for turkey oak (*Quercus cerris*). a. Comparison of experimental and model predicted values. b. The average absolute percentage of bias of the models.

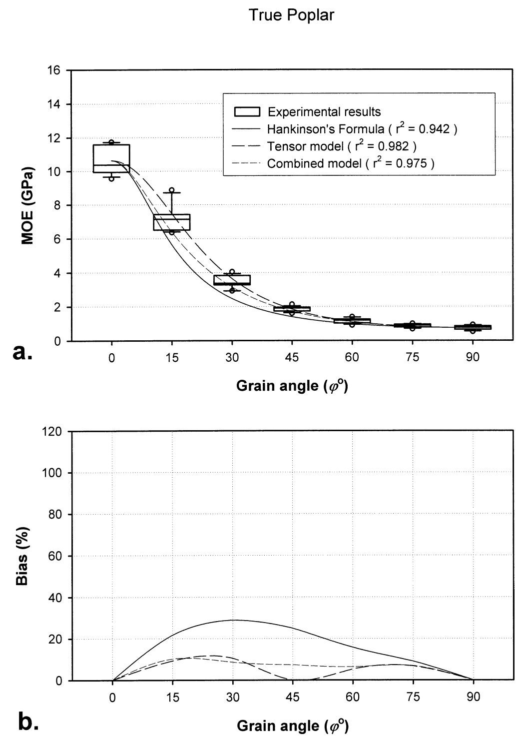

FIG. 8. Dynamic MOE values as a function of grain orientation for true poplar (*Populus x. Euroamericana cv. Pannonia*). a. Comparison of experimental and model predicted values. b. The average absolute percentage of bias of the models.

each specimen individually. The following formula calculated the average percentage bias of the prediction for a given grain angle and prediction model:

$$\text{Bias} = \frac{\sum \dfrac{\hat{E}_{\varphi i} - E_{\varphi i}}{E_{\varphi i}}}{n} \times 100\% \qquad (8)$$

where:

$\hat{E}_{\varphi i}$ — dynamic MOE value predicted at grain angle φ by applying Eqs. (4), (5), or (7) to data obtained from specimen i;

$E_{\varphi i}$ — dynamic MOE measured on specimen i at grain angle φ.

n — total number of specimens.

Figures 4b through 8b show the *average absolute percentage bias* of the different prediction models. The analysis revealed that the bias of the Hankinson's formula is at maximum close to 45° (~30 to 100%), then decreasing sharply towards 0° and 90°.

The tensor approach gives the most accurate prediction for red oak and for the European species, where its bias is always less than 20%. This model follows experimental results very closely above 45° grain angle for every species. The maximum bias is usually at 15° grain angle, approaching 40% for aspen and yellow-poplar. This translates into a large absolute bias, since MOE is relatively high at this grain angle. Note that at 45° grain angle this model has 0 bias because Eq. (4) includes the actual MOE at this grain orientation.

While it was not always the best model, the combined formula provided consistently good performance, in terms of both r^2 values and

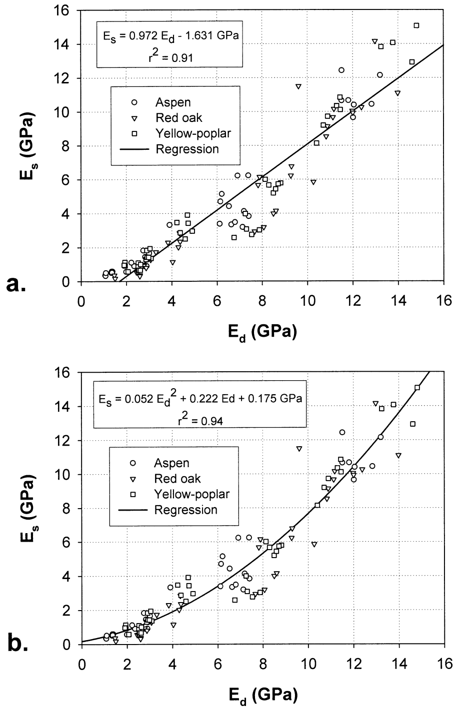

FIG. 9. Association between experimentally measured dynamic and static MOE values. Regression models and r^2 values are listed. a. First-order regression model. b. Second-order regression model.

bias. With the exception of red oak, the bias remained below 20%. It does appear that this model offers satisfactory predictions for each species, and might be more useful for dynamic MOE estimation for further model developments.

Figure 9 shows the association between the experimentally measured dynamic and static MOE. This graph includes the data points measured both on veneer and on solid wood, for all North American species. It was assumed that the relationship should depend only on the characteristic time of the test procedure (Eq. 3). Because the ratio of t_s to t_d is independent from species or orientation, the relationship should be linear with uniform slope for every species, and the regression line should pass through the origin. From Fig. 9a it is apparent that this is not so. The regression line does not pass through the origin, and the linearity of the data is questionable. The cause of this anomaly is most likely the high damping effect in veneer and wood in non-longitudinal directions, which might have influenced the measurements. A serious problem with the first order regression model depicted on Fig. 9a is that, according to its equation, dynamic MOE values measured at higher grain angles correspond to negative static MOE.

Figure 9b shows the scatter plot to which a second-order polynomial was fitted. As the improved r^2 value indicates, this model describes the relationship significantly better than did the linear regression depicted in Fig. 9a. It is also apparent that, using the quadratic model, positive static MOE values are calculated for any dynamic MOE value. While there is no real justification for using a second-order regression model, it appears that this equation might be better for estimating the static MOE from its dynamic counterpart.

SUMMARY AND CONCLUSIONS

The analytical and experimental works aimed at exploring the orthotropic nature of MOE in tension of structural veneers have been presented. Results indicated that a combined model including the Hankinson's equation and a model based on tensorial approach could predict the stiffness of structural veneers as a function of inclined grain orientation with reasonable accuracy. Although this combination does not represent a new theoretical approach for angle-to-grain MOE prediction, it may reduce bias errors that can propagate to the results of complex calculations. Ultrasonic stress-wave timing does appear to be a good technique for assessing the dynamic MOE of veneers. A second-order polynomial regression model may be used to estimate the static modulus of elasticity values after obtaining the dynamic ones.

The developed experimental methods and models will be used to generate input MOE data for simulation models. The overall simulation process will include the effect of further composite processing parameters such as densification during consolidation, resin penetration, etc. These combined stochastic/deterministic models are under development for predicting the flexural strength and stiffness of structural composites in which the veneer constituents are aligned randomly or systematically.

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