Predicting Plywood Properties with Wood-Based Composite Models

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Abstract

Previous research revealed that stress wave nondestructive testing techniques could be used to evaluate the tensile and flexural properties of wood-based composite materials. Regression models were developed that related stress wave transmission characteristics (velocity and attenuation) to modulus of elasticity and strength. The developed regression models accounted for over 94% of these materials' observed elastic properties and for over 90% of their observed strength. The original models were developed using wood-based particle composite specimens. The study presented in this paper investigated use of the developed statistical model to predict the modulus of elasticity and strength of veneer laminated materials, specifically plywood.

Introduction

In a previous study on the subject of nondestructive testing of wood-based composites conducted by Ross and Pellerin (1988), strong correlations ($r^2 > 0.90$) were drawn between dynamic modulus of elasticity (MOE), static flexural MOE, and modulus of rupture (MOR). At the time of the study, the use of ultrasonic stress wave propagation time as a non-destructive inspection tool for wood composites was not widespread. Since that study, ultrasonic inspection has become an accepted mean of assessing and evaluating wood and wood composites. The wood-based composites used in the original study did not include plywood.

Fundamental Hypothesis and First Studies

Jayne (1959) theorized that the mechanisms that controlled the dynamic properties of wood, such as stress wave speed and attenuation, also govern important static mechanical properties. The theory implied that identifiable relationships exist between stress wave behavior and mechanical properties of wood and wood-based composites; therefore, useful analytical models could be developed and used to nondestructively estimate the mechanical properties of these materials.

This concept has served as the working hypothesis for many studies, and resulting applications, that have focused on the use of dynamic properties as nondestructive indicators of the performance of wood-based materials and composites.

The first reported study that investigated use of stress wave speed to estimate the properties of wood-based particle composites was conducted by Pellerin and Morschauser (1974). They used stress wave speed to predict the flexural properties of underlayment particleboard. Szabo (1978) published a reference that covered many aspects of the use of ultrasonic inspection on wood-based composites including anisotropy, coupling issues, wave types, attenuation, basic ultrasonic testing setups, transducer descriptions, and the advantages and disadvantages of higher frequency usage.

Koch and Woodson (1968) first reported on the use of stress wave technique to evaluate the properties of veneer to be used in laminated veneer lumber (LVL) based on results of a study conducted in cooperation with Washington State University. Kunesh (1978) reported on the industrial use of these concepts to grade veneer. Based on the results of an extensive field, laboratory and equipment development effort, he demonstrated that ultrasonic inspection was capable of grading wood veneer at rates usable on a production line. Sharp (1985) reported similar results and conclusions, and described the process of relating ultrasonic stress wave velocity to LVL strength and grade.

Development of Predictive Models for Elasticity and Strength

Subsequent to these early studies, there has been extensive research conducted on the use of ultrasonic test methods to inspect or grade wood-based composites. A literature review on the subject can be found in Senalik and others (2014). A critical analysis of that review revealed the following:

1. Most studies were aimed at investigating the possibility of adapting existing technologies that were developed for other materials to specific problems associated with wood-based composite materials,
2. A lack of investigations linking fundamental physical phenomena with composite product performance.

In an effort to develop a strong, fundamental model relating nondestructive parameters to mechanical properties, Ross and Pellerin (1988) developed an analytical model that was a marriage between theoretical and empirical approaches and was applicable to a broad spectrum of wood composites. Using a wide range of wood-based particle composites (Table 1) including particleboard, oriented strand board, and a high strength structural composite, they developed a model that predicted static properties at levels of accuracy thought at the time to be unattainable. It is important to note the following concerning their model:

1. The model is based on the assumption of a linear positive relationship between wave speed and static properties and an inverse relationship between wave attenuation and static properties;
2. No wood veneer products (plywood or laminated veneer lumber) were used in its development;

The fundamental form of the model they developed is expressed as Equation (1).

$$P = K N_0^x N_1^y N_2^z \qquad (1)$$

Where
P is property being estimated,

K, *x*, *y*, and *z* are empirical constants, and
N_0, N_1, and N_2 are nondestructive parameters

The nondestructive parameters examined were specific gravity, wave attenuation, and wave speed. Given the wide range of values for the properties being estimated, natural log scale was used to express the relationship. Taking the natural logarithm of Equation (1) separated the nondestructive parameters, as shown in Equation (2), and allowed for further linear regression to be performed to determine which parameter had the highest correlation to flexural MOE and MOR.

$$\ln P = \ln K + x \ln N_0 + y \ln N_1 + z \ln N_2 \qquad (2)$$

The dynamic MOE was found to have the combination of highest correlation and lowest standard error of the estimate. Dynamic MOE is the product of the wood density and the square of the wave speed, and is shown in Equation (3). Wood density is proportional to the specific gravity; therefore, dynamic MOE combined two nondestructive parameters into a single parameter.

$$E_d = \rho c^2 = \rho_{H_20} SG_w c^2 \qquad (3)$$

Where
E_d is the dynamic modulus of elasticity (MOE),
ρ is the density of the wood specimen,
c is the wave speed through the wood specimen,
ρ_{H_20} is the density of water (practically constant), and
SG_w is the specific gravity of the wood specimen.

The model shown in Equation (1) was implemented using the dynamic MOE as the sole nondestructive parameter. The model with reduced number of parameters is shown in Equation (4).

$$\ln P = \ln K + x \ln E_d \qquad (4)$$

A linear regression analysis determined the values for the unknown empirical constants, K and x, for flexural MOE and MOR. The values for the constants and the related coefficients of determination, r^2, are given in Table 1. The research reported herein was conducted to examine use of this fundamental model to assess the properties of plywood products.

Table 1—Values predicted using dynamic modulus of elasticity as the nondestructive parameter

Parameter (P)	ln(K)	x	r^2 (Ross 1988)	r^2 (Reconstructed)[a]
Flexural Modulus	-0.109	0.934	0.92	0.93
Modulus of Rupture	8.321	1.211	0.85	0.89

[a] Reconstructed data had slightly higher coefficients of correlation than that of Ross and Pellerin (1988).

Materials and Methods

Specimens of untreated plywood were cut from six separate panels. The panels were previously unused and undegraded. The cut specimens had widths of 76 mm (3 in.) and lengths of 508 mm (20 in.). The panels had a variety of thickness between 11 mm (0.42 in.) to 18 mm (0.71 in.). The specimens were conditioned for 15 days at 24°C (75°F) and 65% relative humidity. At the end of the conditioning period, the specimens were assumed to contain 12% moisture content. Prior to destructive testing, the dimensions, mass, and dynamic wave speed were measured. The dynamic wave speeds were measured using a Metrigaurd 239A across a span of 457 mm (18 in.).

The specimens were then subjected to four point static bending tests in accordance with ASTM D3043. Load and deflection were recorded during testing. From the data, flexural MOE and MOR were extracted. The extracted values were compared against the values predicted using the dynamic MOE and the relationships given in Table 1.

Original data were no longer available from the Ross and Pellerin (1988) study. The diagrams from the paper were imported into AutoCAD. The diagrams were scaled within the 2D space and an estimate of location of each data point was made. The estimated data points were used to construct the diagrams in this report. While close to the original data, the reconstructed data did have some differences. The r^2 values of the reconstructed data were slightly higher than those of the original study, but did not exceed the original values by more than 5%. The r^2 values from the original study and the reconstructed data are given in Table 1.

Results

The relationship between the predicted flexural MOE and the flexural MOE from the specimen testing is shown in Figure 1. The data shown in Figure 1 was reconstructed from the original study. The r^2 value of the reconstructed data, 0.9271, was slightly higher than the original value of 0.92. In Figure 2, the flexural MOE results from the plywood tests were added to the reconstructed data shown in Figure 1. The additional data raises the r^2 value from 0.9271 to 0.9345. It can be concluded that the model accurately predicted the values of the flexural MOE from the dynamic MOE. Further, the additional plywood data strengthened the cumulative relationship between the predicted and tested values.

The relationship between the predicted MOR and the MOR from the specimen testing is shown in Figure 3. The data shown in Figure 3 was reconstructed from the original study. The r^2 value of the reconstructed data, 0.8865, was slightly higher than the original value of 0.85. In Figure 4, the results from the MOR results from the plywood tests were added to the reconstructed data shown in Figure 3. The additional data raises the r^2 value from 0.8865 to 0.9023. It can be concluded that the model accurately predicted the values of the MOR from the dynamic MOE.

Further, the additional plywood data strengthened the relationship between the predicted and tested values.

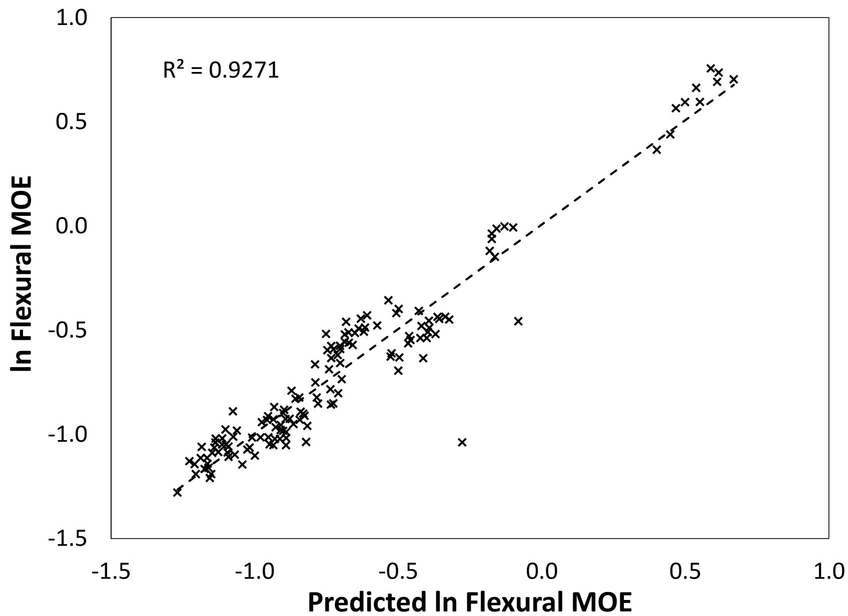

Figure 1—Natural logarithm of the predicted flexural modulus of elasticity (MOE) versus tested flexural MOE. Original data reconstructed from Ross and Pellerin (1988).

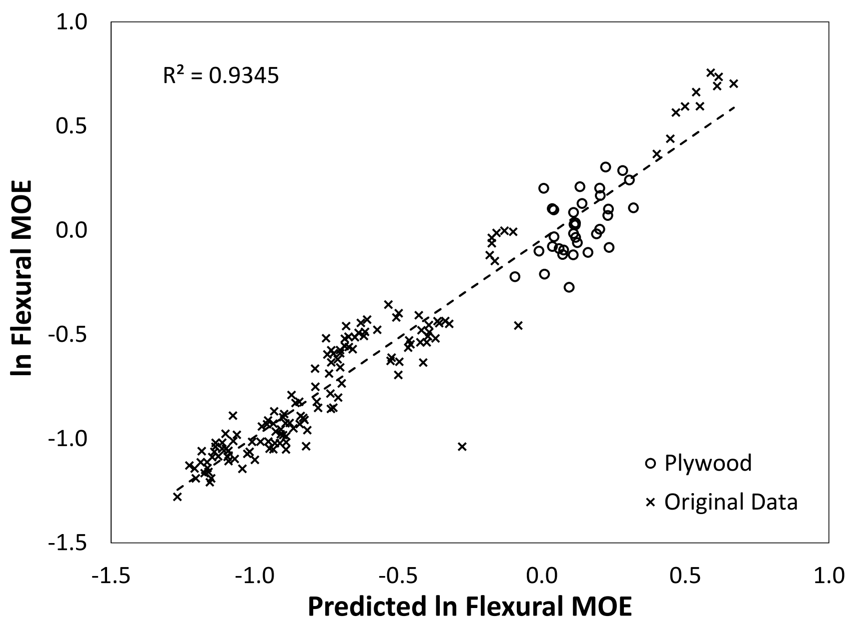

Figure 2—Natural logarithm of the predicted flexural modulus of elasticity (MOE) versus tested flexural MOE for the plywood. specimens. Plywood results are marked with “o”. Original data, marked with “x”, reconstructed from Ross and Pellerin (1988).

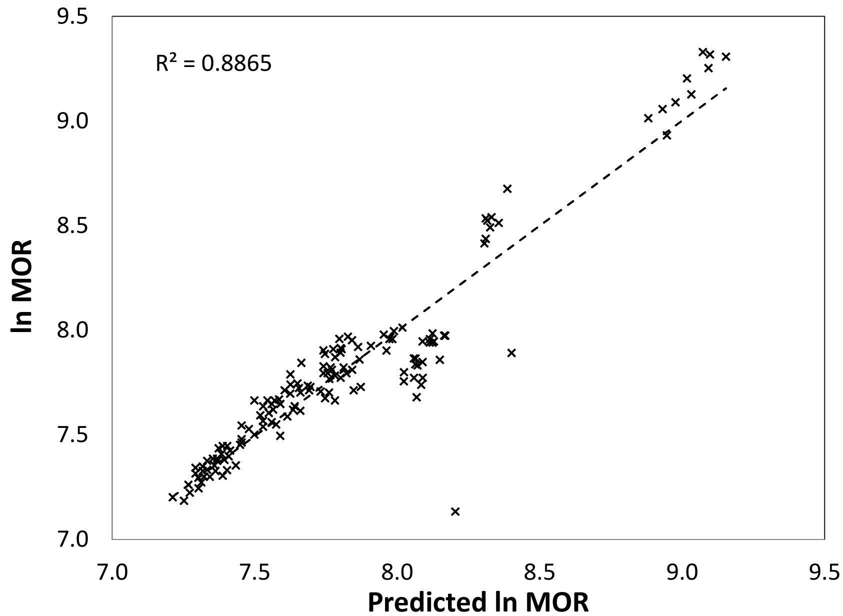

Figure 3—Natural logarithm of the predicted modulus of rupture (MOR) versus tested MOR. Original data reconstructed from Ross and Pellerin (1988).

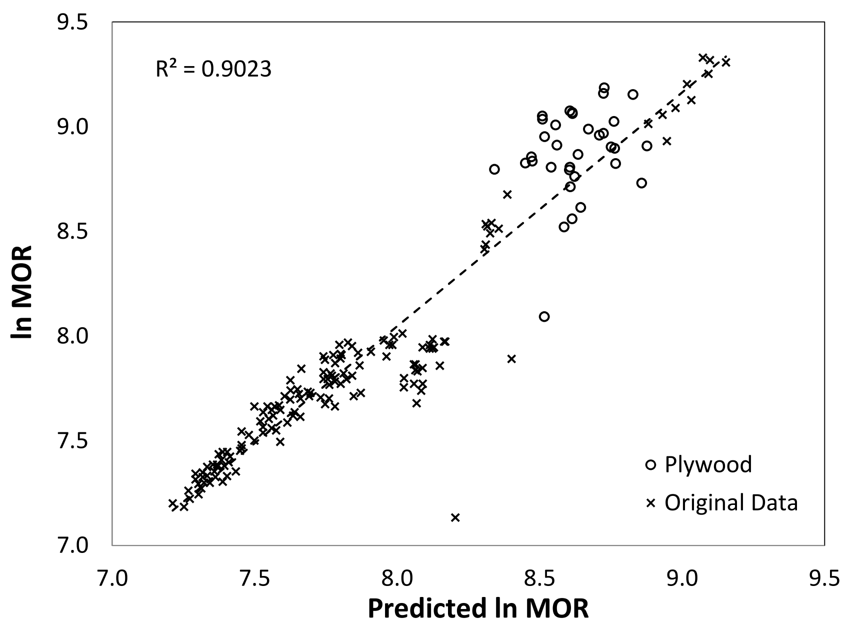

Figure 4—Natural logarithm of the predicted modulus of rupture (MOR) versus tested MOR for the plywood specimens. Plywood results are marked with "o". Original data, marked with "x", reconstructed from Ross and Pellerin (1988).

Conclusions

In this study, a model relating nondestructive parameters to mechanical properties for wood composites was applied to plywood specimens. Plywood was not among the wood composites originally used to develop the model. The nondestructive parameter used as the basis for predicting material properties was the dynamic modulus of elasticity (MOE). From the dynamic

MOE, flexural MOE and modulus of rupture (MOR) were predicted. The data used to create the original model was reconstructed using diagrams from the original report. The coefficients of determination, r^2, of the reconstructed data were slightly higher than those of the original data, but did not exceed the original values by more than 5%. In the predictions of both the flexural MOE and also the MOR, the inclusion of the plywood data caused the r^2 values to increase. The increase indicated that not only did the model accurately predict the mechanical properties of the plywood, but also the inclusion of the plywood to the body of data strengthened the correlation between the predicted values and the mechanical properties.

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