

Nondestructive Evaluation of Green Wood Using Stress Wave and Transverse Vibration Techniques

by Udaya B. Halabe,* Gangadhar M. Bidigalu,† Hota V.S. GangaRao,* and Robert J. Ross‡

List of Symbols

E_{swg}	Green stress wave longitudinal modulus of elasticity
E_{swd}	Dry stress wave longitudinal modulus of elasticity
E_{cmpe}	Green dynamic longitudinal modulus of elasticity
E_{cmpl}	Dry dynamic longitudinal modulus of elasticity
E_{bg}	Green static bending longitudinal modulus of elasticity
E_{bd}	Dry static bending longitudinal modulus of elasticity
FSP	Fiber saturation point
MC	Moisture content
MOE	Longitudinal modulus of elasticity
MOR	Modulus of rupture
n	Number of observations
P_{max}	Maximum load
R^2	Coefficient of determination
V_{pg}	Green stress wave longitudinal velocity
V_{pd}	Dry stress wave longitudinal velocity

Abstract

Longitudinal stress wave and transverse vibration nondestructive testing (NDT) techniques have proven to be accurate means of evaluating the quality of wood based products. Researchers have found strong relationships between stress wave and transverse vibration parameters (e.g., wave velocity and modulus of elasticity predicted using NDT measurements) with the actual static bending properties (e.g., modulus of elasticity from static bending tests) of dry as well as green wood based materials. Therefore, these techniques may be used to presort or grade structural wood prior to drying, provided that cross correlation equations are developed to relate wood properties in the dry state with NDT measurements in the green state. Discarding wood with inferior properties prior to drying can result in significant cost savings in the drying process.

This paper presents the results of an experimental program designed to examine the relationships between stress wave and transverse vibration characteristics (i.e., stress wave velocity, and modulus of elasticity predicted from stress wave velocity and transverse vibration measurements) with the static bending modulus of elasticity (MOE) and modulus of rupture (MOR) of green as well as dry southern pine dimension lumber. Also, cross correlations have been developed between green stress wave and transverse vibration properties with the dry static bending MOE and MOR. Such cross correlations are important for grading wood in the green state itself, so that drying costs can be minimized. This research resulted in good cross correlation relationships between the static bending MOE values of dry southern pine and the

nondestructive parameters in the green state (e.g., stress wave velocity and derived MOE, and transverse vibration based MOE values for green wood). Also, ultrasonic tests were conducted over limited distances (300 mm [12 in.]) at three locations on the 2.4 m (8 ft) long specimens to see if good correlations can be achieved. The low coefficients of determination lead to the conclusion that ultrasonic testing is not suitable for grading of 1.8 to 2.4 m (6 to 8 ft) long dimension lumber.

Keywords: dynamic testing, green wood, modulus of elasticity, modulus of rupture, nondestructive testing, stress wave, timber, ultrasonic testing, vibration, wood.

Introduction

Predicting the material properties of wood through nondestructive testing (NDT) techniques is a matter of considerable importance for the timber industry. Conventional Machine Stress Rated (MSR) equipment (continuous type) dramatically increases the grading accuracy over visual methods but is quite costly. Therefore, only a few lumber companies are using the MSR rating technique. Recent advances in NDT techniques have resulted in small and low cost grading units that are based on transverse vibration and stress wave propagation methods. Although these units do not improve grading accuracy over conventional MSR units, they provide higher grading accuracy over visual methods.

Considerable amounts of resources are required for drying green wood suitable for construction. The grading of wood is usually done only after drying is completed. Significant savings can be achieved if the wood is tested using NDT techniques (e.g., transverse vibration or stress wave techniques) in the green state to predict the stiffness and strength properties after drying, and wood with inferior properties is discarded prior to drying. To enable the prediction of stiffness and strength properties in the dry state from stress wave velocity and transverse vibration measurements in the green state, cross correlation equations based on experiments conducted in both green and dry states are needed.

The objectives of this study are twofold:

- to determine the relationships between static bending properties [bending modulus of elasticity (MOE) and modulus of rupture (MOR)] and measured NDT parameters (e.g., stress wave velocity, MOE predicted using stress wave and transverse vibration techniques) through linear regressions.

- to develop cross correlation equations using linear regressions to predict static bending properties for dry wood (e.g., MOE and MOR) from nondestructive measurements conducted on green wood. Use of these cross correlation equations will enable the sorting of green wood before it is dried.

This study has been conducted using over 100 specimens of southern pine, a softwood species commonly used in construction. The study can easily be extended to other species.

Background

Several researchers have explored the behavior of stress waves (longitudinal rod waves) in lumber and developed relationships to predict the modulus of elasticity and strength properties from measured wave parameters.

*West Virginia Univ., Dept. of Civil and Environmental Engineering, Constructed Facilities Center, PO Box 6103, Morgantown, WV 26506-6103; (304) 293-3031 X617; fax (304) 293-7109; e-mail halabe@cemr.wvu.edu.

†Tri-State Engineering & MC Inc., 237 E Thistle Ct., New Martinsville, WV 26155.

‡USDA Forest Service, Forest Products Laboratory, One Gifford Pinchot Dr., Madison, WI 53705-2398.

James (1964) presented regression data for relating modulus of rupture and ultimate crushing strength (UCS) to stress wave longitudinal MOE (E_{sw}) for clear Douglas fir at different moisture contents (MC) ranging from 2 to 28 percent. The coefficient of determination (R^2) given by James (1964) was greater than 0.64 for an MC of 15 percent or less. Gerhards (1975) found that stress waves, if used for lumber grading, may overestimate the static modulus of elasticity of incompletely dried lumber. However, overestimation may not be significant unless there are substantial portions of wet pockets (i.e., if MC is well above the fiber saturation point).

Several researchers (e.g., Green and McDonald, 1993; Ross and Pellerin, 1991) have developed regression relationships correlating NDT parameters (e.g., stress wave velocity or derived modulus, dynamic modulus predicted using transverse vibration measurements) to the experimental static bending modulus of elasticity for different species of dry wood. The R^2 value of such regressions range from 0.61 to 0.9. However, a lower R^2 value (0.34 to 0.56) has been obtained when the MOR was correlated to the static bending modulus of elasticity or the dynamic modulus using E-computer (e.g., Green and Evans, 1987; Green and McDonald, 1993). Ross and Pellerin (1991) conducted a preliminary study to assess the MOE of green lumber and concluded that stress wave techniques may be useful to predict dry static MOE by measuring the stress wave velocity in green wood. The current study thoroughly investigates the cross correlation relationships between properties of dry wood (MOE and MOR) and measured NDT parameters in green wood for southern pine, a commonly used softwood species.

MATERIALS AND TESTING EQUIPMENT

This study involved the testing of over 100 samples (50 mm \times 100 mm \times 2.4 m [2 in. \times 4 in. \times 8 ft]) of southern pine in the green and dry states. The samples were procured and wrapped to avoid moisture loss before being surfaced on all four faces using a Wadkin molder planer to final nominal dimensions (\approx 38 mm \times 76 mm \times 24 m [15 in. \times 3 in. \times 8 ft]).

The velocity of longitudinal stress waves in the above samples was measured over a distance of 2.4 m (8 ft) using a stress wave timer (manufactured by Metriguard, Pullman, WA) consisting of an impact hammer, a receiving accelerometer, and a timer which measured the wave travel time in wood between the impact hammer and the receiving accelerometer. Dynamic bending MOE was determined through a transverse vibration test using equipment manufactured by Metriguard, Pullman, WA. This test involved simply supporting the wooden sample over two tripods (one at each end). One of the tripods had a sensor at the top (just under the wooden sample) which fed the sample weight and transverse vibration signal to a computer. Since the computer is programmed to directly display the dynamic modulus, it is commonly referred to as an E-computer. Ultrasonic wave velocities were also measured using an electronic signal generator, a broadband receiver, 25 mm (1 in.) diameter transmitting and receiving transducers (125 kHz central frequency), and a digital oscilloscope to view and acquire output signals from the test specimen. The mechanical static bending apparatus used in this study conforms to ASTM Standard D198-84 (for four point bending test) and uses a Baldwin model BTE II hydraulic testing machine with a capacity of 27,000 kg (60,000 lb). A weighing balance to measure the density and an electrical resistance moisturemeter to measure the MC (at dry state) were also used. The density value was used to compute MOE from the stress wave velocity.

LABORATORY EXPERIMENTS

Green southern pine specimens (50 mm \times 100 mm \times 24 m [2 in. \times 4 in. \times 8 ft]) were machined to final nominal dimensions (\approx 38 mm \times 76 mm \times 24 m [15 in. \times 3 in. \times 8 ft]). The following measurements were made on each specimen in the green state:

- Measurement of exact specimen dimensions.
- Weight measurement to determine the density.
- Travel time and velocity measurement for an impact induced stress wave traveling along the length of the specimen (24 m [8 ft] distance).
- Dynamic MOE determined using the commercial device for

flatwise transverse vibration in vertical direction (i.e., section depth less than section width so as to minimize lateral or horizontal vibrations) with the ends simply supported at 2.38 m (7.8 ft) apart.

■ Ultrasonic wave velocity measurement over transducer center-to-center distance of 300 mm (12 in.) along the specimen's length with the 125 kHz transducers placed on the same wide face of the specimen, with the same measurement conducted at three locations on each specimen (two at the ends and one at the center).

■ Static bending MOE determined by loading the specimen edge-wise (i.e., section depth greater than section width) in a four point bending setup to approximately 20 percent of its failure load.

The green southern pine specimens were then end-coated with a waterproofing paint and stacked up in the kiln and left to dry at about 32 °C (90 °F). Two 750 mm (30 in.) long specimens were used as moisture reference test pieces. These reference pieces were tested for moisture content every day. The average moisture content for the two pieces was used as a reference to increase or decrease the temperature in the kiln. The wood specimens were removed from the kiln after the reference pieces reached approximately 12 percent moisture content and were immediately placed in the conditioning chamber. All the specimens were conditioned at 70 percent relative humidity and 23 °C (73 °F) to produce a uniform MC of 12 percent

Upon removal from the conditioning chamber, the experiments described earlier were repeated for dry specimens. A hand held resistance moisture meter was used to determine the moisture content of every specimen prior to testing. The moisture content at green state for each specimen was determined using the dry and green weights of the specimens. All the specimens were loaded to failure by placing them edgewise (i.e., section depth greater than section width) in four point bending setup to obtain the maximum load (P_{max}), which was used to compute the MOR

RESULTS AND DISCUSSIONS

The moisture content range for the 115 specimens of green southern pine tested in this study was found to be 25-125 percent, and the corresponding average moisture content and standard deviation were 75 and 27 percent, respectively. The moisture content for dry southern pine was about 12 percent. The derived regression equations relating bending MOE and MOR with measured NDT parameters (e.g., stress wave velocity and predicted MOE, dynamic MOE obtained using transverse vibration technique, etc.) are given in Tables 1 to 3. Regression lines for bending MOE versus measured NDT parameters are shown in Figures 1 to 10. The following sections discuss the results obtained in this study. More details can be found in Bidigalu (1994).

RESULTS AND DISCUSSIONS OF STRESS WAVE TIMER TESTS

Linear regression can be conducted between MOE and stress wave velocity instead of using the square of the stress wave velocity, because the measured data lie in a very small segment of the second degree parabola, which can be assumed to be a straight line. Hence, most researchers (e.g., Ross and Pellerin, 1991) have conducted linear regression between the bending MOE and velocity instead of the square of velocity. The same approach has been followed here. Results of the regressions using the stress wave timer test are presented next.

Static Bending MOE vs. Stress Wave Velocity

Figures 1 and 2 show the coefficient of determination (R^2) value between static bending MOE (E_s) and stress wave velocity (V_s) as 0.61 and 0.45 for the green and dry cases, respectively (also see Table 1). A comparison between Figures 1 and 2 indicate that the velocity and bending MOE is significantly higher for dry wood compared to green wood. The elastic modulus is lower for green wood because the fibers of the cellulose absorb water molecules (which are then chemically bound) thereby softening the cell walls. In addition, the velocity of stress waves in water is slower than in cell wall material resulting in a lower velocity for green wood. When the moisture level in wood increases above the fiber saturation point (FSP), the cells begin to retain free water. The alternating relative motion between the cell walls and trapped free water causes a

decrease in velocity and stiffness but at a slower rate than what is observed below the FSP (Gerhards, 1975; Sakai et al., 1990).

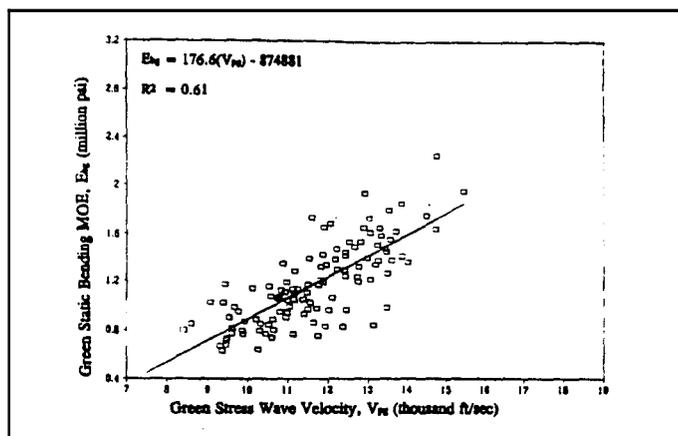


Figure 1 – Static bending modulus of elasticity, E_{bg} vs. stress wave velocity, V_{pg} (green southern pine).

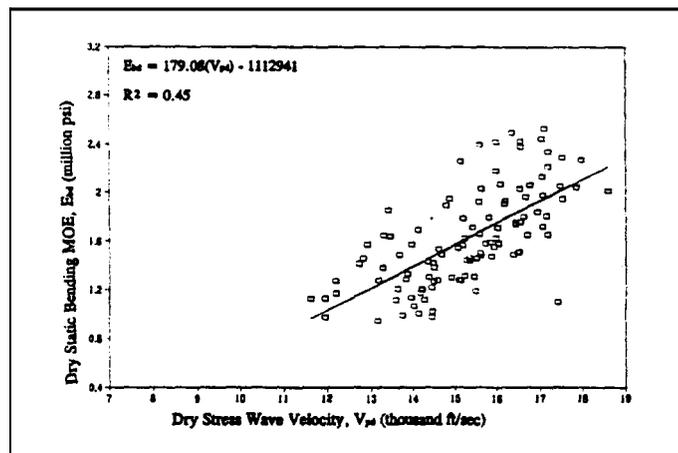


Figure 2 – Static bending modulus of elasticity, E_{bd} vs. stress wave velocity, V_{pd} (dry southern pine).

Static Bending MOE vs. Stress Wave MOE

Figures 3 and 4 show the regression results for static bending longitudinal MOE (E_b) versus stress wave longitudinal MOE (E_{sw}) with coefficients of determination of 0.73 and 0.74 in the green and dry states, respectively (also see Table 1). This indicates that 74 percent of the observed behavior was accounted for by the regression model.

Table 1 Regression relationships for green and dry southern pine (MOE in lb/in²; velocity in ft/s)*

Relationships	Moisture Condition	n	Coefficient of Determination	A (slope)	B (intercept)
$E_b = A(V_p) + B$	Green	114	0.61	176.63	-874,881
	Dry	108	0.45	179.08	-1,112,941
$E_b = A(E_{sw}) + B$	Green	114	0.73	0.8135	57,508.3
	Dry	108	0.74	0.883	189,242.4
$E_b = A(E_{cmp}) + B$	Green	115	0.82	1.24	90,155.5
	Dry	109	0.70	0.962	370,147.4
$E_{sw} = A(E_{cmp}) + B$	Green	115	0.90	1.37	178,401.6
	Dry	109	0.86	1.07	230,555.7

* 1 lb/in.² = 6,895 N/m²; 1 ft/s = 0.3048 m/s.

Figures 3 and 4 also show that the stress wave longitudinal MOE is higher than the bending MOE ($E_{swg}/E_{bg} = 1.1$ to 1.20) in high moisture green wood whereas it is about the same ($E_{swd}/E_{bd} = 0.94$ to 1.05) in dry wood. This is stress wave MOE calculated from the elementary longitudinal stress wave formula (MOE = ρV_p^2 where ρ is the density) is highly dependent on MC over the 15 to 150 percent range. In fact, above the hygroscopic moisture range or FSP (i.e., above approximately 30 percent MC or when water is

present in cell cavities as free water), stress wave MOE can yield a value which is much higher compared to the static bending MOE (Gerhards, 1975).

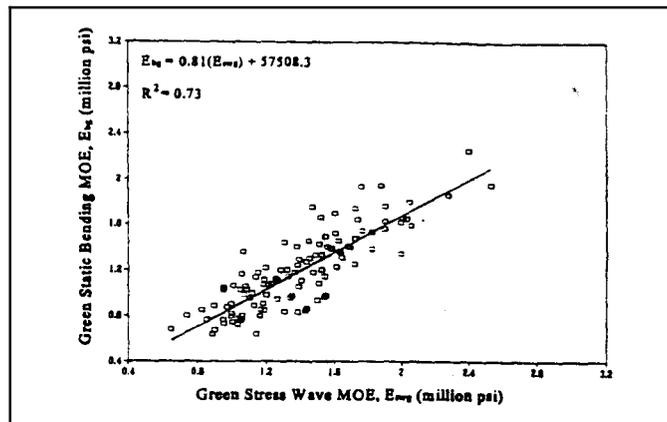


Figure 3 – Static bending modulus of elasticity, E_{bg} vs. stress wave modulus of elasticity, E_{swg} (green southern pine).

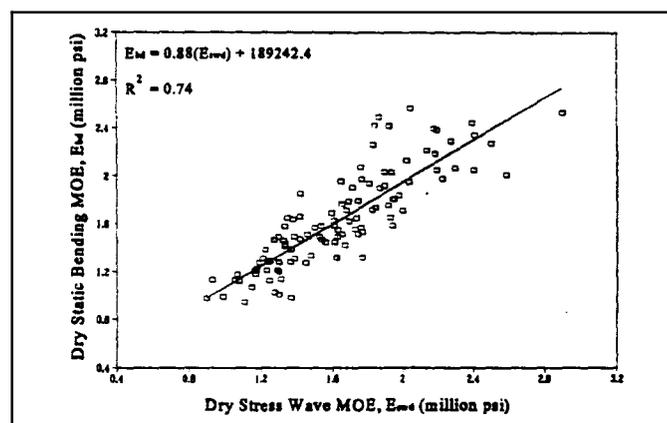


Figure 4 – Static bending modulus of elasticity, E_{bd} vs. stress wave modulus of elasticity, E_{swd} (dry southern pine).

Gerhards (1975) showed that the bending MOE remains constant above approximately 30 percent MC, whereas the stress wave MOE increases due to an increase in density. To study the impact of MC on the R^2 value, additional regression analyses were conducted between green bending MOE and green stress wave MOE calculated by normalizing the density to 30 percent MC. This regression analysis showed that the R^2 value did not improve but actually dropped to 0.63 from the original value of 0.73 as shown in Figure 3.

The fact that the stress wave MOE in wood is usually higher than the static bending MOE can also be explained by considering wood as a highly damping and viscoelastic material. For a vibrating lumber specimen, the elastic restoring force is proportional to the displacement and the dissipative force (damping) is proportional to the velocity. Therefore, when a force is applied for a very short duration, the material behaves like an elastic solid, while for longer duration, the behavior is like that of a viscous liquid. This behavior is more prominent for long duration static bending tests as compared to stress wave tests. Therefore, the modulus of elasticity predicted by stress waves is usually higher than the static bending MOE.

Dry Static Bending MOE vs. Green Stress Wave Velocity and MOE

The cross correlation between the dry static bending MOE (E_{bd}) versus the green stress wave velocity (V_{pg}) gave an R^2 value of 0.62 (Figure 5 and Table 2). The R^2 value for dry static bending MOE (E_{bd}) versus green stress wave MOE (E_{swg}) was 0.72 (Figure 6 and Table 2). The difference in R^2 values in the above two relationships is small. Moreover, these R^2 values are considered good in terms of

nondestructive evaluation of wood as noted by other researchers (e.g., James 1964). In practice, it is much easier to determine the stress wave velocity rather than the stress wave MOE which involves the determination of density of each lumber sample. The results of this research show that the relationship between dry static bending MOE versus green stress wave velocity can directly be used to predict the dry static bending MOE.

Table 2 Cross correlation between dry bending MOE with green parameters for southern pine (MOE in lb/in.²; velocity in ft/s)

Relationships	n	Coefficient of Determination	A (slope)	B (intercept)
$E_{bd} = A(V_{pg}) + B$	106	0.62	211.15	-837,313
$E_{bd} = A(E_{swg}) + B$	107	0.72	0.95	321,370
$E_{bd} = A(E_{cmpg}) + B$	108	0.78	1.44	360,802
$E_{bd} = A(E_{bdg}) + B$	109	0.77	1.06	361,549.2

* 1 lb/in.² = 6,895 N/m²; 1 ft/s = 0.3045 m/s.

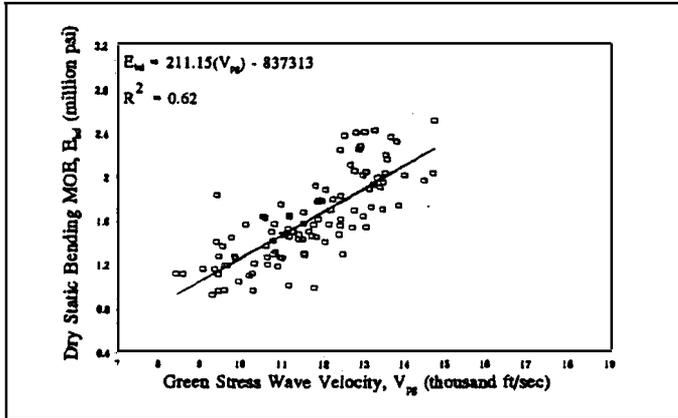


Figure 5 – Dry static bending modulus of elasticity, E_{bd} vs. green stress wave velocity, V_{pg} (southern pine).

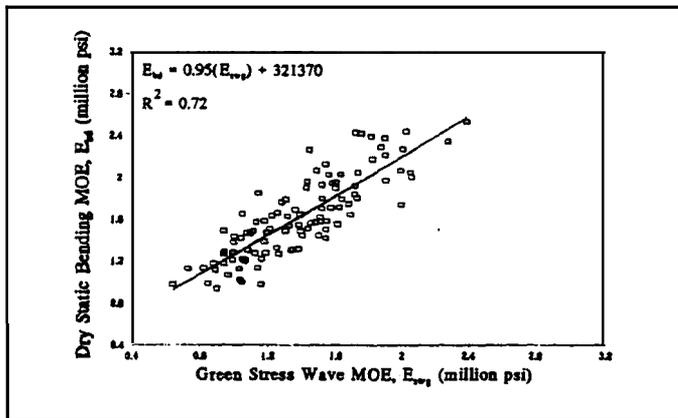


Figure 6 – Dry static bending modulus of elasticity, E_{bd} vs. green stress wave modulus of elasticity, E_{swg} (southern pine).

MOR vs. Stress Wave Velocity and Stress Wave MOE

As shown in Table 3, the R^2 values for MOR versus green and dry stress wave velocity (V_p) were 0.22 and 0.06, respectively. The R^2 values for MOR versus green and dry stress wave MOE were 0.25 and 0.31, respectively. These low R^2 values are due to the fact that the stress wave impact measurements used in this study resulted in low stress levels which depend on mechanical properties only in the elastic range, while the MOR behavior is usually at a high stress and strain level (far beyond the elastic limit). Also, the MOR behavior is primarily affected by the behavior of edge fibers and the presence of edge knots, whereas the stress wave velocity and stress wave MOE are also affected by the fibers at the center of the section. The MOR values show better correlation with stress wave MOE compared to stress wave velocity (specially in the dry case). This behavior is similar to that observed for static bending MOE discussed earlier.

RESULTS AND DISCUSSIONS OF COMPUTER TESTS

Static Bending vs. Dynamic Modulus of Elasticity

The regression results for static bending MOE (E_b) versus dynamic MOE from a computer (E_{cmp}) showed coefficients of determination (R^2) of 0.82 and 0.70 (Figures 7 and 8) for southern pine in green and dry conditions, respectively (also see Table 1). From Figures 7 and 8, it is obvious that static bending MOE values are higher than dynamic MOE obtained from a computer. This behavior is inconsistent with the viscoelastic behavior, but conforms to the results obtained by Gerhards (1975). The cross correlation between the dry static bending MOE (E_{bd}) versus the green dynamic MOE (E_{cmpg}) gave a R^2 value of 0.78 (Figure 9 and Table 2). Interestingly, the correlation between stress wave MOE (E_{sw}) and dynamic MOE (E_{cmp}) was found to have a R^2 value of 0.9 and 0.86 in green and dry states, respectively (figure not shown, see Table 1). This shows that the NDT parameters correlate well among themselves, which indicates that the material response to NDT measurements is very good.

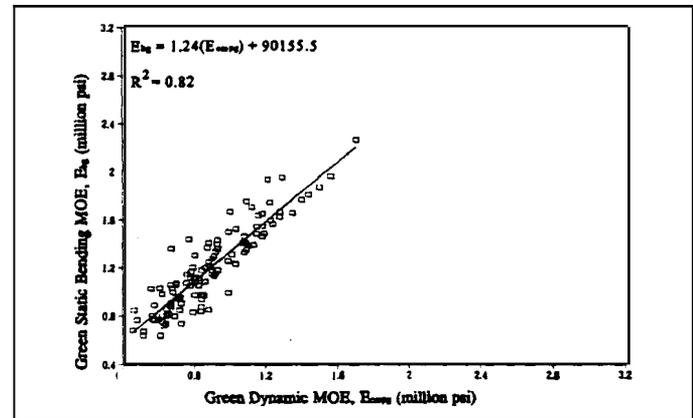


Figure 7 – Static bending modulus of elasticity, E_{bg} vs. dynamic modulus of elasticity, E_{cmpg} (green southern pine).

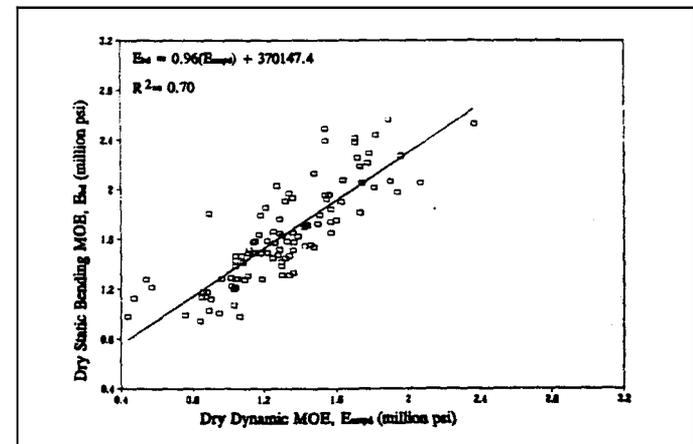


Figure 8 – Static bending modulus of elasticity, E_{bd} vs. dynamic modulus of elasticity, E_{cmpd} (dry southern pine).

Modulus of Rupture vs. Dynamic Modulus of Elasticity

The R^2 values for MOR versus green and dry dynamic MOE obtained from a computer were 0.41 and 0.28, respectively (see Table 3). These R^2 values are low because the stress induced in the material during the dynamic test is very low; that is the nondestructive dynamic measurements are based on mechanical properties only in the elastic range. MOR behavior is at a high stress and strain level (far beyond the elastic limit) and therefore resulted in poor correlation with NDT parameters. Also, it should be noted that MOR behavior can be significantly affected by the presence of edge knots.

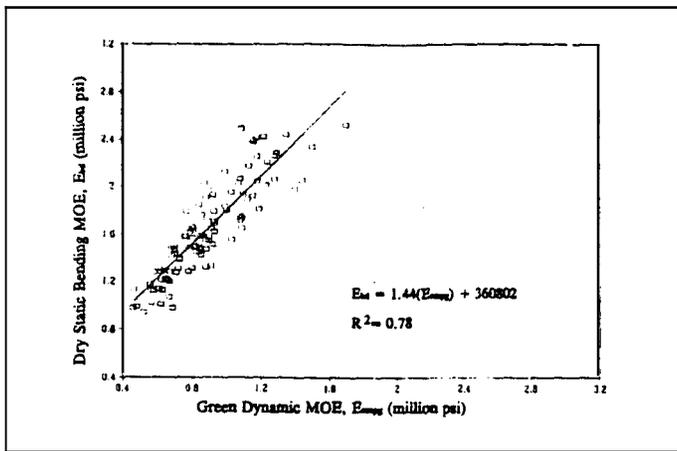


Figure 9 – Dry static bending modulus of elasticity, E_{bsd} vs. green dynamic modulus of elasticity, E_{dmg} (southern pine).

Table 3 Regression relationships between MOR and green and dry parameters for southern pine (MOR in lb/in.²; velocity in ft/s)

Relationships	Moisture Condition	n	Coefficient of Determination	A (slope)	B (intercept)
MOR = $A(V_p) + B$	Green	108	0.22	0.8700	-3,667
	Dry	109	0.06	0.4200	-32
MOR = $A(E_{sw}) + B$	Green	109	0.25	0.0037	1,249
	Dry	109	0.31	0.0037	281
MOR = $A(E_{cmp}) + B$	Green	109	0.41	0.0069	271
	Dry	108	0.28	0.0041	1,149
MOR = $A(E_b) + B$	Green	109	0.45	0.0053	125
	Dry	109	0.52	0.0047	-1,202

* 1 lb/in.² = 6,895 N/m²; 1 ft/s = 0.3048 m/s.

RESULTS AND DISCUSSIONS OF STATIC BENDING TESTS

Dry vs. Green Static Bending Modulus of Elasticity

The R^2 value for dry static bending MOE versus green static bending MOE was 0.77 (Figure 10 and Table 2). The bending MOE in the dry state was 24 to 50 percent higher than bending MOE in the green state. When the fibers of the cellulose absorb water molecules, the cell walls become soft, and therefore the elastic modulus decreases for green wood.

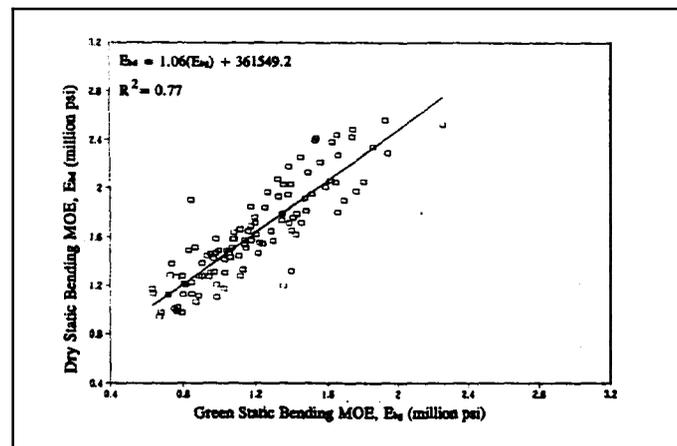


Figure 10 – Dry static bending modulus of elasticity, E_{bsd} vs. green bending modulus of elasticity, E_{bg} (southern pine).

Modulus of Rupture vs. Static Bending Modulus of Elasticity

The R^2 values for MOR versus green and dry static bending MOE were 0.45 and 0.52, respectively (see Table 3). The R^2 value obtained here is comparable to those obtained by other researchers (e.g., Green and Evans, 1987; Green and McDonald, 1993).

It can be noted that the MOR values correlate better with static bending MOE compared to stress wave or dynamic MOE (obtained using a computer) reported earlier. The reason for this is that static

bending is a direct measurement technique, whereas NDT measurements are indirect.

RESULTS AND DISCUSSIONS OF ULTRASONIC TESTS

Static Bending Modulus of Elasticity vs. Ultrasonic Velocity

The regression between bending MOE and ultrasonic P-wave velocity (average of velocities obtained at three locations on the specimen over 300 mm (12 in.) distances in the longitudinal direction) gave an R^2 value of 0.29 and 0.05 in green and dry states, respectively.

Since timber is a highly heterogeneous material, the P-wave velocity could vary appreciably over a distance of inches. The fact that stiffness from the static bending tests and the ultrasonic tests did not involve the same region of the material of the specimens (1.5 m [5 ft] for static bending tests versus 300 mm [12 in.] for ultrasonic tests) could have contributed to the low R^2 values for southern pine. The distance in the ultrasonic tests had to be limited because of the high attenuation inherent with high frequency waves.

Modulus of Rupture vs. Ultrasonic Velocity

The R^2 value for MOR versus dry ultrasonic velocity (V_p) was 0.06.

CONCLUSIONS

Linear regression relationships were developed between stress wave velocity, stress wave MOE, dynamic MOE using a computer, and static bending MOE and MOR for green as well as dry southern pine. The main objective of this research was to develop regression equations to predict bending properties (MOE and MOR) in the dry state based on nondestructive measurements in the green state. The results of this research show that the relationship between dry static bending MOE versus green stress wave velocity or the corresponding (derived) green MOE can directly be used to predict the dry static bending MOE. The R^2 values for MOR regressions presented in this paper, although low, are typical of most wooden species as reported in the literature.

Ultrasonic P-wave velocity did not give good correlation with static bending MOE. The fact that stiffness from the bending tests and the ultrasonic tests did not involve the same region of the material of the specimens (1.5 m [5 ft] for static bending tests versus 300 mm [12 in.] for ultrasonic tests) could have contributed to the low R^2 values. Due to higher attenuation, ultrasonic travel distances are small. The stress wave impact technique, on the other hand, uses low frequency waves which can travel larger distances, thus providing an average of the material property of a specimen over its entire length. Also, the low frequency and high wavelength stress waves (rod longitudinal waves) interact with the entire cross-section in contrast to short wavelength ultrasonic P-waves. Therefore, the stress wave technique is more suitable for grading of 1.8 to 24 m (6 to 8 ft) long dimension lumber.

Acknowledgments

The authors would like to thank Mike Wolcott, formerly Assistant Professor of Wood Science, West Virginia University, for making arrangements for surfacing and drying of the southern pine specimens used in this research. The financial support for this research project from Forest Products Laboratory, US Department of Agriculture, Grant No. FP-93-1956, is gratefully acknowledged.

References

- Annual Book of Standards, Vol. 04.09, 1988. ASTM, Philadelphia, PA.
- Bechtel, F.K., Use of the Metriguard Model 239A Stress Wave Timer, Jun. 25, 1986. Metriguard, Inc., Pullman, WA.
- Bidigalu, G.M., "Nondestructive Evaluation of Green Wood Using Stress Wave and Transverse Vibration Techniques," Master's thesis, Department of Civil Engineering, West Virginia University, Morgantown, WV, 1994.
- Bodig, J., and B.J. Jayne, Mechanics of Wood and Wood Composites, 1982. Van Nostrand Reinhold Company, New York, NY.
- Forest Products Laboratory Research Paper, Linear Methods for Forest Research, US Dept. of Agriculture, Forest Service, FPL 17, Madison, WI, Dec. 1964.
- Gerhards, C.C., "Longitudinal Stress Waves for Lumber Stress Grading: Factors Affecting Applications: State of the Art," Forest Products Journal, Vol. 32, No. 2, 1982, pp 20-25.

- Gerhards, C.C., "Stress Wave Speed and MOE of Sweetgum Ranging from 150 to 15 Percent MC," *Forest Products Journal*, Vol. 25, No. 4, 1975, pp 51-57.
- Green, D.W., and J.W. Evans, *Mechanical Properties of Visually Graded Lumber, Vol. 1: A Summary*, Publication PB-88-159-389, 1987. National Technical Information Service, US Dept. of Agriculture, Springfield, VA.
- Green, D.W., and K.A. McDonald, "Investigation of the Mechanical Properties of Red Oak 2 by 4's," *Wood and Fiber Science*, Vol. 25, No. 1, 1993, pp 35-45.
- James, W.L., "Vibration, Static Strength, and Elastic Properties of Clear Douglas-Fir at Various Levels of Moisture Content," *Forest Products Journal*, Vol. 14, No. 9, 1964, pp 409-413.
- Jayne, B.A., "Vibrational Properties of Wood," *Forest Products Journal*, Vol. 9, No. 11, 1959, pp 413-416.
- Ross, R.J., and R.F. Pellerin, "NDE of Green Material with Stress Waves: Preliminary Results Using Dimension Lumber," Technical Note, *Forest Products Journal*, Vol. 41, No. 6, 1991, pp 57-59.
- Sakai, H., A. Minamisawa, and K. Takagi, "Effect of Moisture Content on Ultrasonic Velocity and Attenuation in Woods," *Ultrasonics*, Vol. 28, No. 11, 1990, pp 382-385.
- USDA Forest Service, *Wood Handbook*. US Dept. of Agriculture Handbook No. 72, 1987. Forest Products Laboratory, Madison, WI.