AN ULTRASONIC TECHNIQUE FOR PREDICTING TENSILE STRENGTH OF SOUTHERN PINE LUMBER

B. Rajeshwar, D. A. Bender, D. E. Bray, K. A. McDonald

ABSTRACT. *The goal ofthis research was to develop nondestructive evaluation (NDE) technology to enhance mechanical stress rating of lumber. An ultrasonic NDE technique was developed that is sensitive to grain angle and edge knots in lumber - two primary determinants of lumber strength. The presence of edge knots increased the acoustic wave travel time and selectively attenuated the higher frequency ultrasonic energy. NDE measurements and tension tests were performed on 200 pieces of nominal 50 × 150 mm Southern Pine lumber. Statistical models were developed from localized stress wave indices to predict lumber tensile strength. The ultrasonic method compared favorably with other NDE methods, including static modulus of elasticity (MOE), impact stress wave MOE and transverse vibration MOE.*
Keywords. Lumber, Grades, Ultrasound, Southern pine.

The strong demand for wood together with timber harvest restrictions and escalating raw material costs have accentuated the need for efficient utilization of wood resources. In the case of lumber, efficiency dictates that it be accurately sorted into grades, each having an acceptable range of quality for the intended uses.

Current methods for grading structural lumber include visual stress rating (VSR), machine stress rating (MSR), and machine evaluating lumber (MEL). Both visual and mechanical lumber grading methods inherently have some limitations. The VSR categorizes lumber strength by surface characteristics alone, resulting in relatively wide variabilities of mechanical properties within grades. The MSR and MEL use nondestructively measured properties of modulus of elasticity (MOE) and density, respectively, to predict lumber strength, followed by a visual check for certain defects in the lumber. Linear correlations between MOE or density and lumber strength typically range from 0.6 to 0.8. Since predictions of lumber strength are not 100% accurate, visual grading rules and machine grading thresholds are conservatively set to minimize the probability of assigning a piece of lumber a grade that is too high.

Research is needed to develop innovative stress rating technology for more accurate grading of lumber, leading to better utilization of timber resources. Another incentive for developing new lumber grading technology is the cost of present grading machines, which is prohibitive for many of the small lumber mills which account for more than 50% of the lumber production in United States.

Article was submitted for publication in July 1996; reviewed and approved for publication by the Structures & Environment Div. of ASAE in April 1997.

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OBJECTIVES

The overall goal of this research was to develop an ultrasonic nondestructive evaluation (NDE) technique to enhance mechanical stress rating of lumber. Specific objectives were: (1) to develop an ultrasonic NDE technique that is sensitive to grain angle and edge knots – two natural growth characteristics that have profound influences on lumber strength; (2) to determine the statistical correlation between localized stress wave indices and lumber tensile strength; and (3) to compare the stress wave technique with other NDE measurements including static MOE, impact stress wave, and transverse vibration.

LITERATURE REVIEW

Among the technologies approved for stress rating lumber by the American Lumber Standard Committee (ALSC, 1996), stress wave nondestructive methods have excellent potential, as reviewed by Szymani and McDonald (1981), Gerhards (1982), Falk et al. (1988) and Ross and Pellerin (1991). Jayne (1959) hypothesized that stress wave energy storage and dissipation are controlled by the same mechanisms that determine the static behavior of wood materials.

Stress waves can be initiated through mechanical impact (sonic) or with piezoelectric transducers operating at higher, controlled frequencies (e.g., ultrasonic). Ultrasonic transducers in the nominal frequency range of 20 to 500 kHz have been successfully applied to wood (e.g., Szabo, 1978; McDonald, 1978). Among the various methods for stress wave excitation, ultrasonic transducers give the most repeatable measurements with the best resolution.

Ultrasonic inspection is typically performed using one of the following basic procedures: (1) normal beam pulse-echo; (2) normal beam through-transmission; (3) angled-beam pulse-echo; or (4) angled-beam through-transmission (Bray and Stanley, 1989). Among these methods, through-transmission is most useful for lumber grading since wood is a highly attenuative material. The pulse-echo method uses the same transducer for sending and receiving and the through-transmission technique uses two transducers, one as the sender and another as the receiver.

Gerhards (1982) reviewed the factors affecting the use of stress waves for lumber stress grading, focusing most of his attention on wave velocity. He reported wave distortions caused by knots, and grain deviations caused problems in timing stress waves (excited by a mechanical impact source). He concluded that stress wave velocity was ideal for rapid lumber grading; however, more research was needed on the method of exciting the stress wave. Further, he stated that emphasis should be placed on short lumber spans.

Szymani and McDonald (1981) reviewed the applicability of ultrasonic and other testing methods for automated defect detection system. They indicated that the ultrasonic method was sensitive to many natural defects in lumber and is capable of operating at production speeds. However, some lumber defects, such as stain, may require an optical scanning system. They concluded that a comprehensive lumber defect detection system would require a combination of NDE methods.

PILOT STUDY

A pilot study was conducted to determine the effect of grain angle and edge knots on ultrasonic wave velocity. These two growth characteristics significantly influence the parallel-to-grain tensile strength of lumber. The information gained in this study was used later in designing the ultrasonic testing procedure. The following issues were considered: (1) confirm effect of grain angle on ultrasonic wave velocity; and (2) examine if the difference between wave velocities along the two opposing narrow faces of lumber was a good indicator of edge knots.

Equipment used for ultrasonic testing included two *Panametrics* 0.5 MHz, 12.7-mm diameter longitudinal wave transducers, *Panametrics 5058PR* high voltage pulser-receiver, and a personal computer with A/D board and *Testpro* software.

CONFIRMATION OF EFFECT OF GRAIN ANGLE ON ULTRASONIC WAVE VELOCITY

Lee (1958), Elvery and Nwokoye (1970), and Gerhards (1982) studied the effect of grain angle on longitudinal stress wave velocity and found that the velocity perpendicular to the longitudinal axis was approximately one-third of that along the longitudinal axis. Stress wave velocity loss was over 1% per degree in grain angle up to about 30°, the most apparent loss taking place at grain angles less than 20°. The stress wave velocities observed by Gerhards (1982) agree with observed MOEs parallel and perpendicular to the longitudinal axis. The MOE parallel to the grain is commonly more than 10 times the MOE perpendicular to the grain (Gerhards, 1982), hence stress wave velocity parallel to the grain should be more than three times that perpendicular to the grain since MOE is proportional to the square of wave velocity.

The effect of grain angle on MOE and tensile strength can be approximated by the Hankinson-type formula (USDA, 1987):

$$N = \frac{PQ}{P \sin^n\theta + Q \cos^n\theta} \qquad (1)$$

where

N = strength property at an angle from the fiber direction

Q = strength perpendicular to the grain

P = strength parallel to the grain

n = empirical value

Figure 1 graphically depicts the Hankinson-type formula for both tensile strength and MOE for varying grain angles using typical values of n and Q/P for tensile strength. Values of n and Q/P used were 1.75 and 0.055 for tensile strength and 2.0 and 0.08 for MOE. The values of n and Q/P were taken from the Wood Handbook (USDA, 1987). Wave velocities at varying grain angles presented in figure 1 were approximated by taking the square root of the MOE value at that particular grain angle. As observed in the figure 1, tensile strength is most affected by the grain angle. The maximum permissible slope of grain is 1:4 (i.e., grain angle 14°) for stress rated lumber. At a grain angle of 14° the respective decreases in tensile strength, MOE, and wave velocity are approximately 60%, 30%, and 15% of the peak values at 0°.

The schematic layout of the experimental procedure carried out on the 15 specimens is shown in figure 2. The specimens were clear, straight-grained pieces of nominal

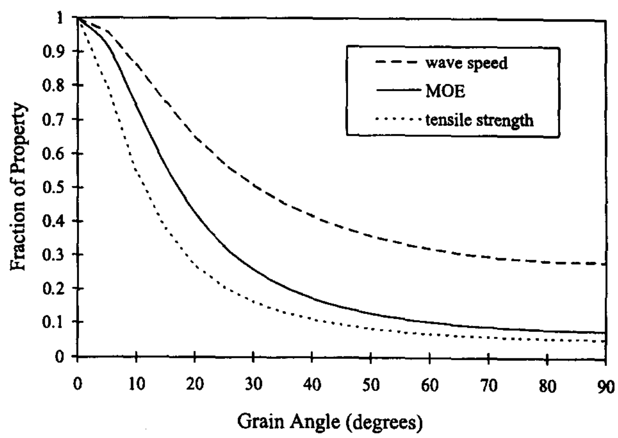

Figure 1–Effect of grain angle on wood properties (USDA, 1987).

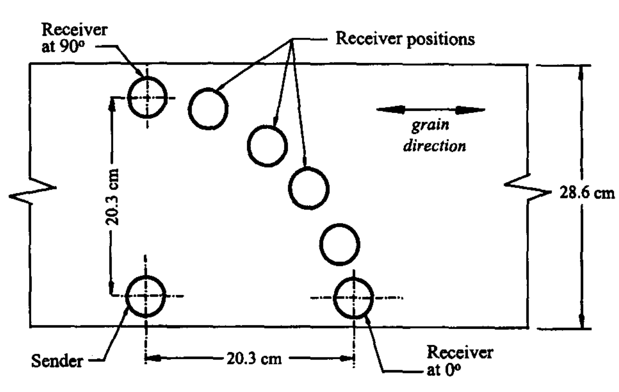

Figure 2–Schematic of the grain angle experiment.

50 × 300 mm Southern Pine lumber, conditioned to an equilibrium moisture content of approximately 10%. Ultrasonic wave velocities were obtained at angles of 0" to 90° at intervals of 5° using 0.5 MHz longitudinal-wave transducers. The distance between the sending and receiving transducers was held constant at 20.3 cm. Wave velocities were normalized by dividing the wave velocity at each grain angle by the wave velocity at 0°.

The plot of average and range of normalized wave velocities for 15 boards at each grain angle are shown in figure 3. The results of the wave velocity test with respect to grain angle substantiate those reported by Lee (1958), Elvery and Nwokoye (1970), and Gerhards (1982), and also were similar to the results obtained from the Hankinson-type formula.

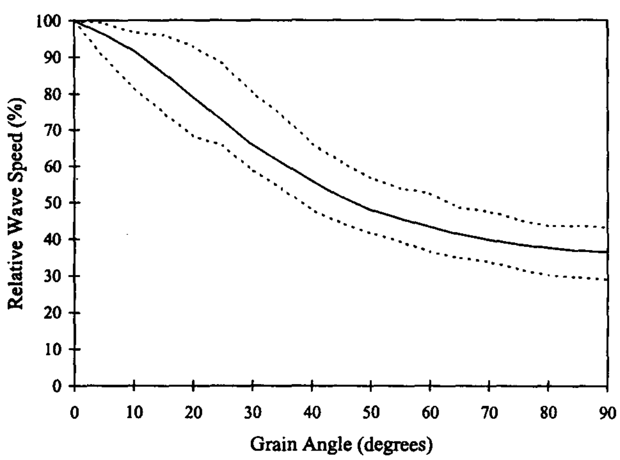

Figure 3–Effect of grain angle on relative acoustic wave speed. The solid line is the average response for the 15 specimens and the dotted lines represent an envelope of the data range.

Detection of Edge Knots Using the Wave Velocity

This experiment was performed to determine if the difference between wave velocities along the two opposing edges of lumber was a good indicator of edge knots and associated grain distortions. The secondary objective was to examine two spacings between transmitting and receiving transducers to determine which was more sensitive to edge knots.

Eleven pieces of nominal 50 × 150 mm Southern Pine lumber were selected which contained an edge knot of approximately 2.5 cm diameter on one edge and clear on the other edge. Aside from edge knots, no effort was made to restrict any other naturally occurring defect in the lumber (e.g., slope of grain). Testing was performed using the through-transmission technique with 0.5 MHz longitudinal transducers. A schematic of the experiment is shown in figure 4. Transmitting transducers were located on narrow faces of the lumber at locations labeled as 1, 2, 3, and 4 and the receiving transducers were placed at locations 1´, 2´, 3´, and 4´ in figure 4. Passage times were sequentially recorded for these locations and the corresponding wave velocities were calculated.

The relative differences in wave velocities between the edge propagations 1-1' and 3-3' at 30.5 cm intervals, and between edge propagations 2-2' and 4-4' at 61 cm intervals for each piece of lumber are summarized graphically in figure 5. Relative differences were calculated by dividing the velocity difference by the average velocity for each piece of lumber. As hypothesized, knots significantly slowed the ultrasonic waves, relative to the clear wood along the lumber edges. It is also seen that the relative difference in velocities is much greater for 30.5 cm transducer intervals, as compared to the 61 cm transducer intervals (except Specimen 3 which had gross grain deviations that masked the presence of the knot). Hence, the 30.5 cm interval spacing was selected for the final ultrasonic investigation.

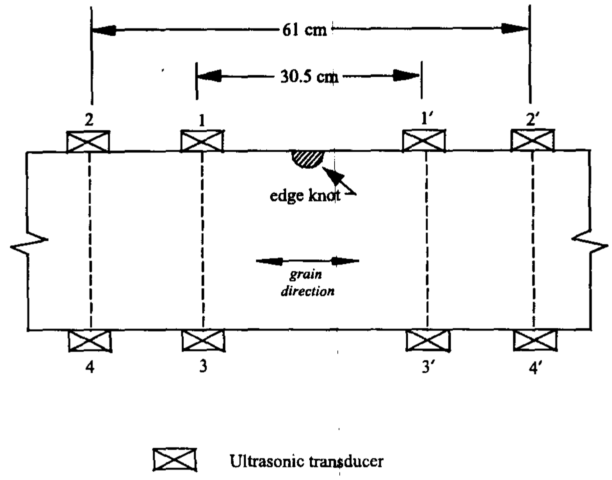

Figure 4–Schematic of ultrasonic experiment for edge knot detection.

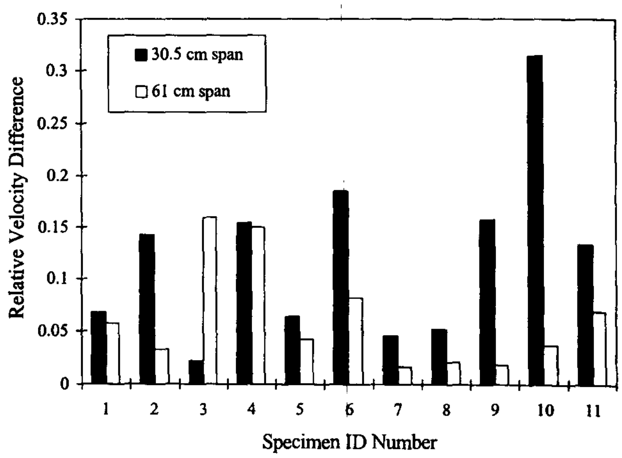

Figure 5–Relative differences between wave velocities along opposing edges of lumber specimens containing edge knots, at transducer spans of 30.5 and 61 cm.

The received signals of the ultrasonic waves along the clear edge and knot edge for Specimen 10 at the 30.5 cm interval are shown in figure 6. The acoustic wave fronts were detected at 54.8 and 75.3 µs, resulting in wave velocities of 5560 and 4050 m/s, respectively. It can been seen in figure 6 that the edge knot and associated grain deviation slowed and attenuated the acoustic wave in the early portion. Figure 7 shows the frequency spectra of ultrasonic signals (between 50 and 150 µs time period) from Specimen 10. A comparison of frequency spectra shows that edge knot and associated grain distortion selectively attenuated the higher frequency components of the signal.

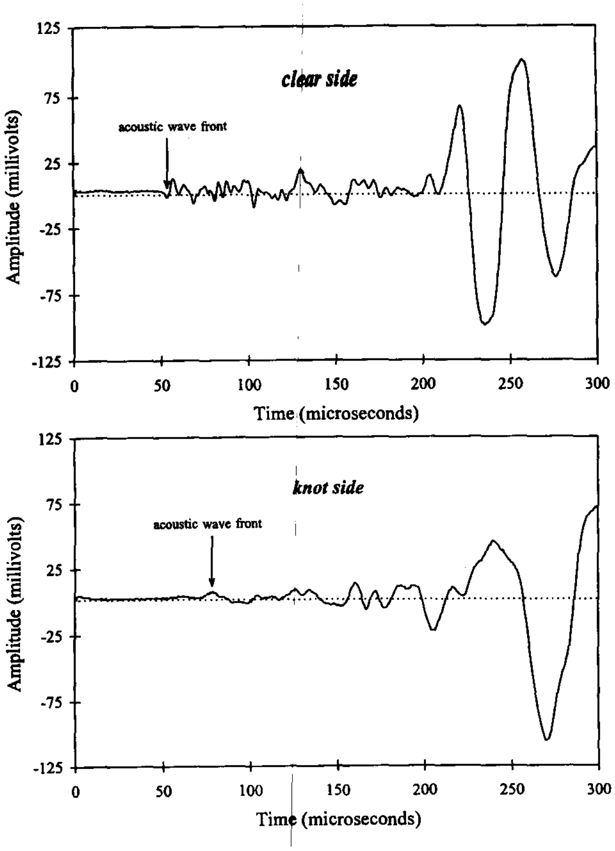

Figure 6–Ultrasonic signals for Specimen 10 along the clear and knot edges at 30.5 cm transducer spacing are shown in the top and bottom plots, respectively. The acoustic wave fronts were detected at 54.8 and 75.3 µs. The large, trailing signal is due to reflected wave energy. The edge knot and associated grain deviation slowed and attenuated the acoustic wave in the early portion.

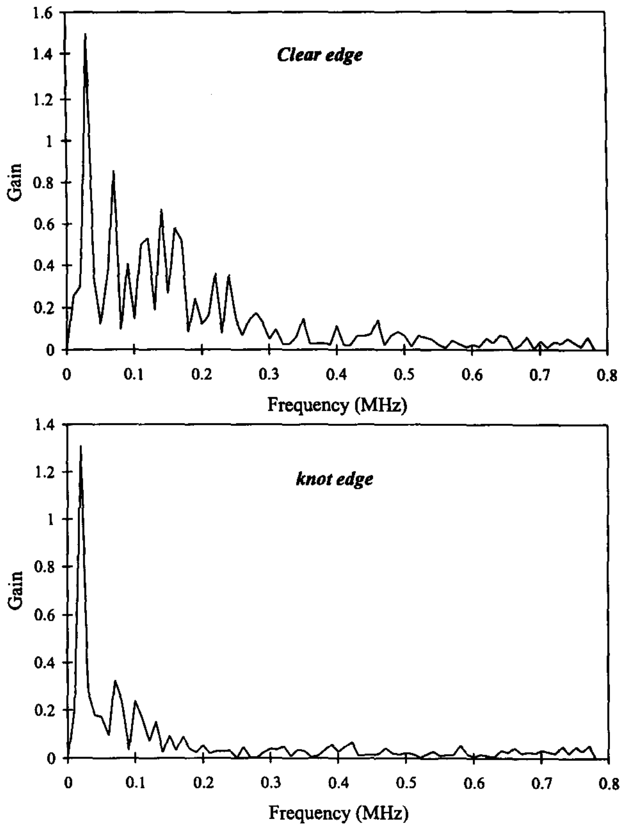

Figure 7–Frequency spectra of the ultrasonic signals from figure 6, gated between 50 and 150 µs. The edge knot and associated gain deviation attenuated the higher frequency components.

MATERIALS AND METHODS

Forty pieces of nominal 50 × 150 mm Southern Pine lumber (4.27 m long) were randomly sampled from each of five different lumber grades (302-24*, No. 1 Dense, No. 1 Medium, No. 2 Dense, add No. 2 Medium) for a total of 200 pieces. Each piece was given an identification number that indicated its specimen number and grade. Each specimen was divided and marked into four 61-cm segments. The first of these segments always began 91.5 cm from the "zero" end. The testing procedures are summarized as follows:

1. The lumber was conditioned to an average equilibrium moisture content of 10.3% (dry basis) inside an environmentally controlled laboratory. Moisture contents were measured with a resistance-type moisture meter calibrated with data from oven tests. The length of each lumber specimen was measured to the nearest 3 cm. The width and the depth of the specimens were measured to the nearest 2 mm and 0.02 mm respectively with a digital calipers. This was done as MOE calculations are more sensitive to changes in depth than to changes in width. The width and depth were recorded as the average of two readings taken at 1.2 m from both ends. The weight of each specimen was measured with a digital scale to the nearest 45 g.
2. Localized static bending MOE was measured on 4 contiguous 61 cm segments within each board using flatwise bending over a 1.83 m span with third-point loading. The test followed ASTM Standard D198-94 (ASTM, 1996). The influence of shear was minimized by measuring deflection relative to the load head, over the center 61 cm portion of the total 1.83 m span.
3. Long-span dynamic MOEs, using transverse vibration and impact stress wave methods, were measured for each board. Transverse vibration test was done using the *Metriguard Model 340 E-Computer*. Transverse vibration is based on flexural vibration, while impact stress wave test is based on longitudinal wave velocity. These dynamic methods are described by several sources, e.g., Bodig and Jayne (1982).
4. Ultrasonic testing was done on Segments 1 and 4, as explained in the section below. After ultrasonic testing was performed, Segments 1 and 4 were destructively tested in tension according to Test T119 from the AITC 200-92 Inspection Manual (AITC, 1992) using *Metriguard Model 422 tension tester*. The tensile strength data was used to develop statistical models to predict tensile strength using the localized stress wave indices.

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* 302-24 is a high quality lumber grade used in the glued-laminated timber industry.

Due to the gripping requirements of the tension test machine, only Segments 1 and 4 were tension tested. Prior to destructive testing, localized bending and localized ultrasonic testing was done for Segments 1 and 4 in order to correlate with tensile strength data.

The pilot study substantiated that velocity differences along the edges of lumber could be used to detect the presence of edge knots and that velocity differences diagonally across the lumber could be used to detect gross grain angle. With the above considerations, the ultrasonic transducer configuration shown in figure 8 was designed.

Tests were performed on the 61-cm segments 1 and 4, which were subsequently tested to failure in tension. Transducers were positioned on the narrow face of the board, as this would give more details about the edge knots. Figure 8 shows eight paths between the transmitting and receiving transducers. Measurements along the edges and diagonally across the lumber were conceptualized to provide information about the edge knots and grain deviation respectively. Paths 1, 3, 5, and 7 are along the edges of the board and paths 2, 4, 6, and 8 are across the board. Ultrasonic signals were then sequentially collected for Paths 1 to 8 for all boards. Transit times were recorded for each acoustic wave path.

Results and Discussion

Long-span lumber properties are summarized in table 1. Average specific gravities and dynamic MOEs for each grade were generally in good agreement with nominal values published in AITC 200-92 (1992). Short-span (61 cm) lumber properties are summarized in table 2. As expected, short-span and long-span MOEs were similar, even though the measurement techniques and test spans differed. Average tensile strengths were higher than previously published (Marx and Evans, 1986, 1988), due in part to the relatively short span tested (Taylor et al., 1992).

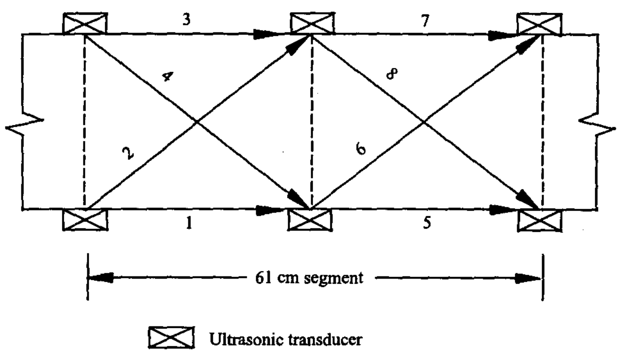

Figure 8–Schematic of ultrasonic wave paths.

Table 1. Statistical summary of long-span lumber properties

Grade	Sample Size	Gross Specific Gravity*		Transverse Vibration MOE (GPa)		Impact Stress Wave MOE (GPa)	
		Mean	COV	Mean	COV	Mean	COV
302-24	40	0.57	0.08	17.42	0.14	17.09	0.14
1D	40	0.56	0.08	15.61	0.13	15.60	0.14
1M	40	0.51	0.10	13.33	0.20	13.39	0.22
2D	40	0.52	0.06	12.93	0.13	13.09	0.14
2M	40	0.48	0.08	10.77	0.19	10.90	0.19

* Specific gravity calculated from gross dry weight (using measured weight and moisture content) and dimensions at ambient conditions.

Table 2. Statistical summary of short-span (61 cm segment) lumber properties X

Grade	Sample Size*	Short-span Bending MOE (GPa)		Ultimate Tensile Stress (MPa)	
		Mean	COV	Mean	COV
302-24	80	17.09	0.15	88.04	0.25
1D	80	15.66	0.14	62.76	0.21
1M	80	13.35	0.22	53.31	0.38
2D	80	13.00	0.16	36.98	0.37
2M	80	10.79	0.22	30.67	0.58

* Two samples per board.

As previously discussed, differences among the edge velocities were expected to provide the information on the presence of edge knots and other anomalies on the edges (e.g., localized grain deviation). Similarly, differences among crossing velocities were expected to provide the information on gross grain angle within the lumber. With these considerations in mind, the variables listed in table 3 were derived as candidate predictor variables for the ultimate tensile stress (UTS) regression model.

The “R-Square Selection” method (SAS, 1988) was used for selecting the optimum’ set of predictor variables. The “R-Square Selection” method searches all possible combinations of two predictor variables along with the corresponding R^2 values. Then the subset size is increased by one, and all combination6 of three variables are searched. This continues until all possible sizes and variable combinations have been checked. Subsequently, “Forward Selection” was performed on the set of best predictor variables (SAS, 1988). The “Forward Selection” method enters each predictor variable into the model and gives the corresponding parameter estimates, coefficient of determination, mean squared error (MSE) and C_k (Mallow’s Statistic). Mallow’s Statistic is the normalized expected total error of estimation. Values of C_k near or below the number of parameters, including the intercept, are generally desirable.

Table 3. Variables used in ultimate tensile stress (UTS) regression models

Variable	Description of Variable	Formula
ρ	Gross lumber density	$\frac{\text{Mass}}{\text{Volume}}$
V_{av}	Average velocity of 4 edge waves, i.e., paths 1, 3, 5, 7 shown in figure 8.	$\frac{V1 + V3 + V5 + V7}{4}$
MOE_{ult}	Ultrasonic MOE using V_{av} and ρ, and assuming plane wave mode of propagation.	$\rho \times V_{av}^2$
DVV	Ratio of velocity difference with average velocity along two paths. There are 5 combinations along edges and 4 combinations along crossings respectively. For example DVV13 is the ratio of absolute difference of V1 and V3 and the average of VI and V3.	$DVV13 = \frac{\lvert V1 - V3\rvert}{\left(\frac{V1 + V3}{2}\right)}$
DVE_{max}	Max of DVV13, DVV15, DVV57, DVV37 (4 combinations along edges).	---------
DVC_{max}	Max of DVV24, DVV26, DVV68, DVV48 (4 combinations along crossings).	---------
DVV_{2648}	Ratio of absolute difference of averages of V2, V6 and V4, V8 with the average of V2, V4, V6, V8.	$\frac{\left\lvert \frac{(V2 + V6)}{2} - \frac{(V4 + V8)}{2} \right\rvert}{\left[\frac{(V2 + V6) + (V4 + V8)}{4}\right]}$

A logarithmic transformation was used in modeling the ultimate tensile stress (UTS) data. This is a common transformation for regression modeling of lumber tensile strength (e.g., Woeste et al., 1979), and eliminated the possibility of predicting negative UTS values. Parameters MOE_{ult}, DVE_{max}, V_{av}, DVC_{max}, and DVV_{2648} were selected as the optimum set of predictor variables with a ciefficient of determination value of 0.603. The linear correlation between the actual and predicted UTS was 0.728. The regression model is given by:

$$UTS = \exp[5.856 + 0.1207 MOE_{ult} - 0.6945 V_{av} - 1.763 DVE_{max} - 5.189 DVC_{max} + 4.266 DVV_{2648}] \quad (2)$$

where the parameter units are

UTS = ultimate tensile stress (MPa)
MOE_{ult} = ultrasonic MOE (GPa)
V_{av} = edge average velocity (km/s)
DVE_{max} DVC_{max}, DVV_{2648} = dimensionless ratios

The ultrasonic model was compared to short-span bending MOE, as well as the impact stress wave MOE and transverse vibration MOE measurement methods recognized by ALSC (1996) for MSR lumber production. The linear correlations between UTS and short-span bending, impact stress wave, and transverse vibration MOE values were 0.721, 0.6977, and 0.725, respectively. The linear coefficient of the ultrasonic model, 0.728, is slightly better than short-span bending, impact stress wave, and transverse vibration measurements, although the practical significance of the improvement would depend on the specific application.

In comparing the ultrasonic technique with the other NDE methods, it should be emphasized that lumber strength was measured over a relatively short-span. Hence, the portion of the lumber tested, in many instances, did not contain the grade-limiting defect. Future research should focus on performing the localized ultrasonic measurements on the entire span of lumber; this eliminates the possibility of testing a lumber section which does not contain the grade limiting defect. Then the corresponding long-span tensile strength should be measured.

SUMMARY AND CONCLUSIONS

The goal of this research was to develop nondestructive evaluation (NDE) technology for improving lumber stress rating. Two naturally-occurring growth characteristics that significantly affect lumber strength are gross grain angle and secondly, edge knots with associated localized grain distortions. A pilot study was conducted to confirm the effect of grain angle and edge knots on ultrasonic stress wave propagation. Based on this information, an ultrasonic transducer configuration was devised for measuring wave propagation diagonally across the wide face of the lumber and along both narrow faces.

Difference in wave velocities diagonally across the wide face of the lumber was a good indicator of gross grain angle. Similarly, edge knots were found to decrease wave velocity and selectively attenuate the higher frequency ultrasonic energy. Hence, by comparing wave properties on opposing sides of the lumber, gross grain angle and edge knots were detected. A regression model was formulated using the ultrasonic parameters to predict parallel-to-grain tensile strength of Southern Pine lumber. The resulting linear correlation between predicted and actual tensile strength was 0.728. Based on a comparison with other NDE measurements (static bending, impact stress wave and transverse vibration MOE), the ultrasonic technique is a comparable and promising technology for improving lumber stress rating, especially for detecting edge knots and grain distortions.

Research is needed to refine the ultrasonic technique by continuously scanning the lumber along its full length, and developing advanced signal processing algorithms (time and frequency domains). The practical value of new stress rating technologies needs to be evaluated, perhaps by simulating lumber grading systems and comparing lumber grade recoveries.

ACKNOWLEDGMENTS. This study was funded through grant No. 92-37500-8209 of the USDA NRI Competitive Grants Program. Appreciation is also extended to the American Institute of Timber Construction for their cooperation in supplying lumber specimens.

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