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# Nondestructive Evaluation of Tensile Properties of Structural Lumber from the Spruce–Pine–Fir Species Grouping

## Relationship between Modulus of Elasticity and Ultimate Tension Stress


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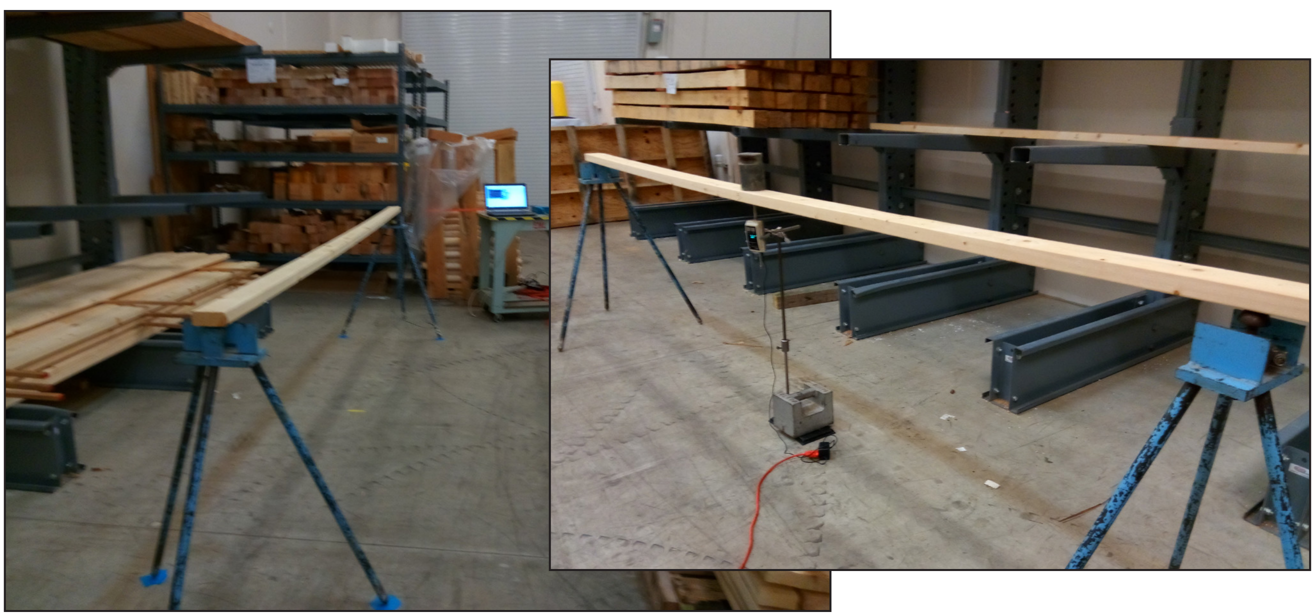


Forest Service

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Research Note FPL–RN–0383

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## Abstract

The study summarized in this research note was conducted to examine the relationships between nondestructive evaluation (NDE) parameters, tensile modulus of elasticity (MOE), and strength of spruce–pine–fir structural lumber. Samples were procured from a local lumber yard using a random selection process and were conditioned at the USDA Forest Service, Forest Products Laboratory, to 10% equilibrium moisture content. Static bending and vibration (transverse and longitudinal) nondestructive tests were conducted on each specimen and MOE was calculated. The relationship between static and dynamic modulus values was examined, and empirical models were developed using statistical regression analysis techniques. Results revealed excellent correlative relationships among MOE values. Coefficients of determination obtained were 0.92, 0.96, and 0.93 for MOE of static transverse vibration, MOE of static longitudinal vibration, and MOE of longitudinal transverse vibration, respectively. Correlative relationships were also observed between NDE parameters and tensile strength. Coefficients of determination were similar to those observed for strength predication models developed for other species.



Keywords: nondestructive evaluation, modulus of elasticity, spruce–pine–fir lumber, tension, strength


## Contents




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# Nondestructive Evaluation of Tensile Properties of Structural Lumber from the Spruce–Pine–Fir Species Grouping

## Relationship between Modulus of Elasticity and Ultimate Tension Stress

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## Introduction

The tensile strength of wood and lumber products is important in the design of engineered components and systems. For example, the bottom chord of a wood truss is stressed in tension as are the undersides of large glued-laminated timbers. The tensile strength of wood is 20 to 50 times higher along the grain (fibers generally aligned with the long axis of a lumber specimen) than in the radial or tangential directions for softwood species and species groupings that are commonly used in structural applications. The grain angle is the angle between the wood fibers and the edges of a piece of wood. Variations in grain direction are especially great around knots and are a major factor governing the strength of a piece of lumber in tension.

## Literature Review

A search of the literature conducted of the Forest Products Laboratory's library collection, Web of Science, and Engineering Index yielded several technical papers that investigate the use of nondestructive testing (NDT) techniques to predict the ultimate tensile stress (UTS) of structural lumber. Hoyle (1968) summarized early research efforts from a variety of laboratories that resulted in the technology that is referred to as machine stress rating (MSR) of lumber. He presented results from several studies specifically designed to examine the relationship between the modulus of elasticity (MOE) (measured in a flatwise orientation, using a center-span dead load) and the corresponding strength of softwood structural lumber. He reported that the statistical models relating MOE and UTS yielded correlation coefficients ranging from 0.74 to 0.82.

Orosz (1977) and Green and McDonald (1993a, 1993b) used transverse vibration NDT techniques to measure the MOE of structural lumber. Green and McDonald reported correlation coefficients for the models relating MOE to UTS that ranged from 0.46 to 0.60.

Kaiserlik and Pellerin (1977) examined the use of a longitudinal vibration NDT method to evaluate the UTS of softwood lumber. They reported a correlation coefficient of 0.84 when MOE was compared with UTS values. In addition to measuring the longitudinal MOE, they measured the attenuation rate of the wave as it travelled through the lumber specimens. After incorporating this additional parameter in their prediction equation, they reported a correlation coefficient of 0.9.

Cramer and Fohrell (1990) reported on a series of studies that developed fundamental information on the physical and mechanical properties of wood in knots and fiber deviation observed around knots. Knots significantly decrease the UTS of structural lumber. Although this work provided excellent information on stress distributions in the vicinity of knots, it did not provide a commercially useful methodology for evaluating lumber properties.

Rajeshwar and others (1997) provided details of the use of an ultrasonic technique for estimating the strength of Southern Pine structural lumber. Ultrasound through transmission measurements were made at several locations in the vicinity of knots and were used to predict strength.

One NDT method for measuring grain direction is based on the difference in dielectric constant (permittivity) of wood between the directions of parallel (lower dielectric constant) and perpendicular (higher dielectric constant) to the grain. The dielectric constant is simply the ability of a material to concentrate an applied electric field. Measuring a material's dielectric constant can be as simple as measuring the current flow between two conductors with an alternating voltage applied. At low moisture content levels, wood can be considered a dielectric material (Kellogg 1981, James and Hamill 1965, Lin 1967, Skaar 1948). The dielectric constant of a nonconducting material determines the amount of electric potential energy that is stored in a given volume of the material within an electric field. It is expressed as the ratio of the dielectric permittivity of the material relative to that of a vacuum or dry air. Experimentally, it is determined as the ratio of the capacity of a condenser with the material acting as the dielectric relative to the capacity of the condenser when the space between the plates is dry air. The dielectric constant for wood varies with grain (fiber) direction, and commercial equipment has been developed that uses this fact to determine fiber orientation in wood products. It has been reported that knots, spiral grain, and other defects can be detected by measuring dielectric properties (Martin and others 1987).

Pellerin and Ross (2015) provided a review of the concept and development of tension proof loading, a technology that focuses on testing each piece of lumber to a predetermined load level near its design load. Pieces of lumber with a strength below the set design load would fail, thereby eliminating them from the lumber to be used.

The preceding review reveals the following: (1) there has not been a systematic evaluation of the relationships between widely used NDT parameters and the tensile properties of structural lumber, and (2) there is no reported research focused on the potential of using combinations of these techniques to predict the strength of structural lumber.

The overarching objective of our cooperative work is to systematically evaluate relationships among several NDT parameters and the tensile properties of softwood structural lumber. This report summarizes our examination of the relationships among several measurements of MOE of a sample of spruce–pine–fir lumber and UTS.

**Figure 1. Lumber specimens used in this study.**

# Materials and Methods

## Materials

One hundred nominal 2 by 4 lumber specimens were obtained from a local lumber yard (standard metric dimensions were 38 by 88 mm). The specimens were 12 ft long (mean length of 3.66 m) and were visually grade No. 2 or better of the spruce–pine–fir species group. All specimens were stickered and equilibrated at a temperature of 21 °C (70 °F) and relative humidity of 50% (Fig. 1) to achieve an equilibrium moisture content of approximately 12%.

## Nondestructive Test Methods

The following briefly describes the test setups that were used for measurement of MOE. Detailed descriptions of each setup, and subsequent analysis, are presented in Ross (2015).

### *Flatwise Bending*

Figure 2 illustrates the center point loading test setup that was used. Each specimen was simply supported at both ends, a load was applied, and the midspan deflection that resulted from the load was measured. A span of 0.35 m was used. A load of 4.54 kg was applied at midspan, and the specimen's corresponding deflection was measured. The flatwise bending modulus of elasticity ($MOE_B$) of a specimen was calculated using the formula shown in the following equation:

$$MOE_B = \frac{PL^3}{48I\delta} \quad (1)$$

where

$MOE_B$ is the flatwise bending modulus of elasticity (Pa),

$P$ is applied load (N),

$L$ is span (m),

$I$ is moment of inertia ($m^4$), and

$\delta$ is midspan deflection (m).

(a)
(b)
(c)


**Figure 2. Flatwise bending test setup: (a) schematic diagram of test setup; (b) specimen being tested; (c) load being applied and corresponding deflection measurement.**

### *Transverse Vibration*

Figure 3 illustrates the free transverse vibration test setup that was used. A specimen was simply supported at both ends, and a slight deflection was introduced at the midspan of the specimen. The specimen was then allowed to freely oscillate in the vertical (transverse) direction. Frequency of oscillation was measured, coupled with the weight and dimensions of the specimen, and was used to compute MOE. Transverse vibration dynamic modulus of elasticity ($MOE_V$) was calculated using the formula shown in the following equation:

$$\mathrm{MOE_V} = \frac{F_r^2 W L^3}{2.46 I g} \quad (2)$$

where

$MOE_V$ is transverse vibration dynamic modulus of elasticity (Pa),

$F_r$ is resonant frequency (Hz),

$W$ is beam weight (kg),

$L$ is beam span (m),

$I$ is beam moment of inertia ($m^4$), and

$g$ is acceleration due to gravity (9.8 $m/s^2$).

### *Longitudinal Vibration*

Figure 4 illustrates the pulse echo test setup used in this study. An impact or “pulse” on one end of the specimen induced a wave that flowed along its length. The pulse “echoed” from the opposite end of the specimen. A Model HM 200 Hitman NDT tool (fibre-gen limited, Christchurch, New Zealand) was used for conducting the tests. Frequency of oscillation and the weight and dimensions of the specimens were determined and were then used to compute MOE.

The longitudinal vibration dynamic modulus of elasticity ($MOE_D$) was calculated using the formula shown in the following equation:

$$\mathrm{MOE_D} = c^2 \rho \quad (3)$$

where

$MOE_D$ is the longitudinal vibration dynamic modulus of elasticity (Pa),

$c$ is the speed of sound of transmission (m/s), and

ρ is the density of the lumber specimen ($kg/m^3$).

### Static Tension Tests

Testing was performed on a 422 Tension Proof Loader (Metriguard Technologies, Inc., Pullman, Washington, USA) at Mississippi State University in April of 2019. The equipment holds each end of the specimen using metal grips and with time pulls the sample in tension until failure. If failure occurs within the grips, the sample must be omitted from the data set.

The span of testing in the loader was 1.85 m, allowing each 3.66-m specimen to be fully gripped with 50 mm of overhang beyond the end of each grip. All boards were placed in the same orientation for testing. The loading speed was set so that the ultimate failure would occur within 2 to 5 min after the start of testing. During testing, both tension load and displacement were measured. The tension load was used to calculate tension stress by using the formula shown in Equation (4). The displacement was converted to strain using the formula shown in Equation (5). Linear regression was used to find the slope for the line relating tension stress to tension strain; the slope of the line is the tension modulus of elasticity ($MOE_T$). The steps in developing $MOE_T$ are described in Figure 5.

$$\sigma = \frac{P}{wt} \quad (4)$$

where

σ is tension stress (Pa),

$P$ is tension load (N),

$w$ is actual wide-face width of the specimen (m), and

$t$ is thickness or narrow-face width of the specimen (m).

$$\varepsilon = \frac{\Delta L}{L} \quad (5)$$

where

ε is tension strain (m/m),

$\Delta L$ is change in length of the gauge length (m), and

$L$ is the gauge length (m),

After testing, maximum load was recorded and moisture content samples were cut from each sample near the point of failure. Moisture content samples were cut and weighed within minutes of failure. After testing, the moisture content samples were oven-dried and reweighed to determine the moisture content of the specimen at the time of testing.

### Statistical Analysis

Linear regression analysis techniques were used to examine the relationships among the MOE estimates calculated using the three different methods, as well as the different MOE estimates and the tension strength of the specimens.

## Results and Discussion

Data collected in the study are summarized in Table A1 in the Appendix. A summary of results obtained is included in Table 1. Note that the sample had a moisture content of 10.7% (oven-dry basis). Flatwise static bending $MOE_B$ values ranged from 4,612 to 13,431 MPa, with an average value of 8,793 MPa. Transverse vibration $MOE_V$ values

(a)

(b)

(c)

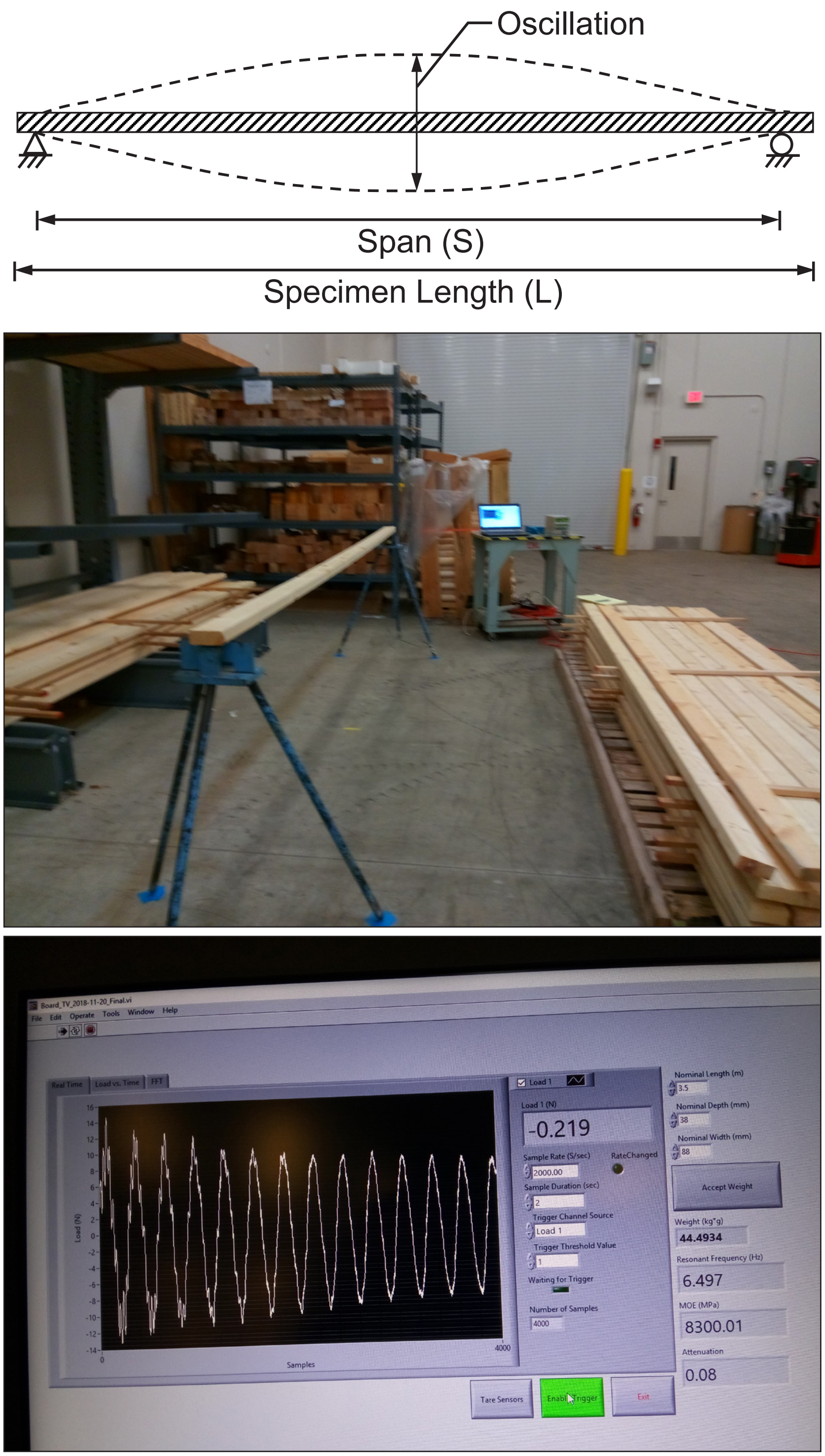


**Figure 3. Transverse vibration test used in this study: (a) transverse vibration test setup; (b) specimen being tested; (c) typical signal observed in response to transverse vibration.**

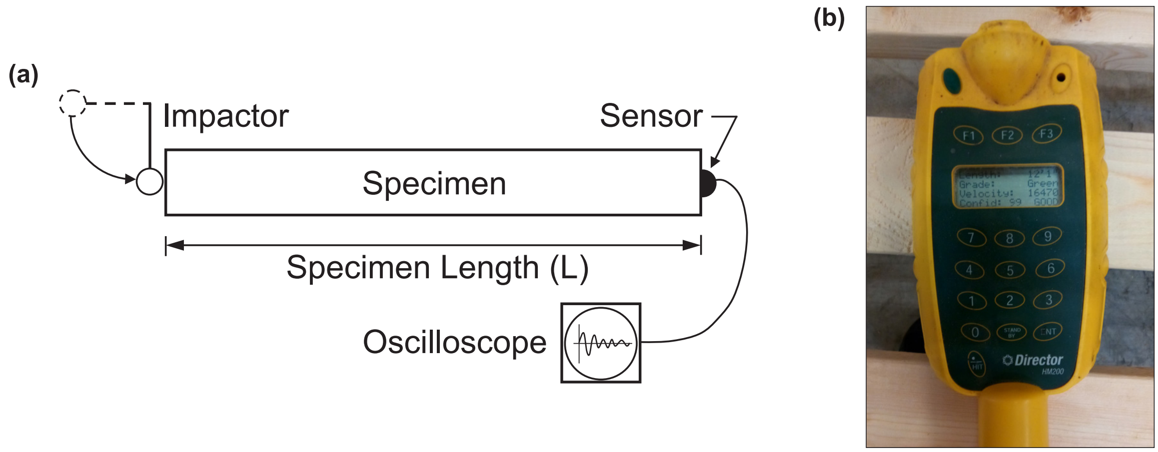


**Figure 4. Longitudinal vibration test used in this study: (a) test setup; (b) Fibre-gen model HM 200 Hitman equipment used to conduct longitudinal vibration tests.**

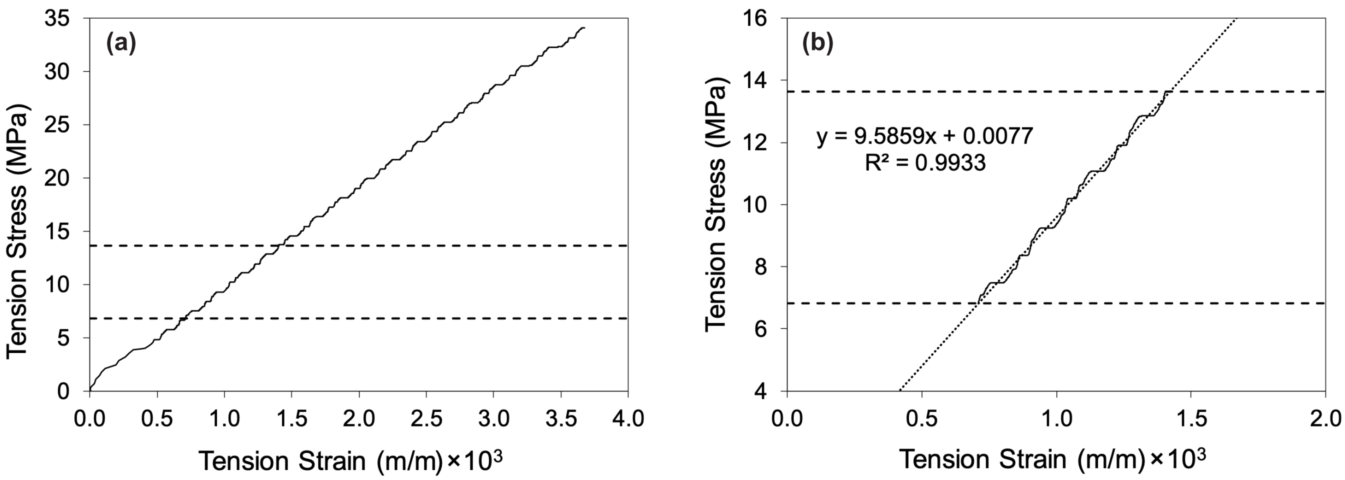


**Figure 5. Tension stress versus tension strain plots used to calculate tension modulus of elasticity ($MOE_T$): (a) a linear range as close to zero as possible while avoiding any disruptions to measurements caused by initial loading (here, the range chosen was 20% to 40% ultimate tensile stress and is bounded by the dashed lines); (b) linear regression was used to find the slope of the line through the chosen region, which is $MOE_T$. In the example, the dashed lines represent the same boundaries as in 5a and the $MOE_T$ in the region is 9.59 GPa.**

ranged from 9,913 to 15,455 MPa, and longitudinal vibration $MOE_D$ values ranged from 5,199 to 15,347 MPa.

Figure 6 shows the plot relating $MOE_D$ to $MOE_B$ and is provided as an example of how the parameters were related to each other. A strong correlative relationship is observed among all the MOE parameters. The coefficient of determination values (commonly known as $r^2$) relating $MOE_B$, $MOE_V$, and $MOE_D$ are between 0.92 and 0.96. The values relating those parameters to $MOE_T$ are between 0.82 and 0.83. The correlative relationships between the MOE parameters and UTS are between 0.47 and 0.50. The coefficients of determination are shown in Table 2.

The slopes relating each parameter and the UTS are given in Table 3. The parameters listed on the left hand column of Table 3 are the abscissa (x coordinate), and the parameters listed along the top of the table are the ordinate (y coordinate). The slopes given are for a linear regression relating the left-hand side, abscissa, values to the top, ordinate, values. The value changes for any two parameters depending upon which parameter is chosen as the abscissa; for example, the slope of the curve relating $MOE_B$ as the abscissa to $MOE_D$ as the ordinate is not the same slope as a curve with $MOE_D$ as the abscissa and $MOE_B$ as the ordinate. It is important that both transverse and longitudinal vibration MOE values were found to be greater than corresponding flatwise bending MOE values. This phenomenon has been observed in similar studies conducted with other lumber from different species of wood.

**Table 1—Summary of physical and mechanical properties of lumber specimens**

| Statistics | MC[a] (%) | Density ($kg/m^3$) | $MOE_B$[b] (MPa) | $MOE_V$[c] (MPa) | $MOE_D$[d] (MPa) | $MOE_T$[e] (MPa) | UTS[f] (MPa) |
|---|---|---|---|---|---|---|---|
| Mean | 10.7 | 0.43 | 8,793 | 9,913 | 9,235 | 8,978 | 22.0 |
| Std. Dev. | 0.37 | 0.043 | 1,951 | 2,099 | 2,067 | 2,372 | 10.5 |
| Max. | 11.8 | 0.58 | 13,431 | 15,465 | 15,347 | 15,026 | 61.8 |
| Min. | 9.7 | 0.34 | 4,612 | 5,598 | 5,199 | 4,330 | 3.42 |
| COV[g] (%) | 3.5 | 10.0 | 22.2 | 21.2 | 22.4 | 26.4 | 47.7 |

[a]MC, moisture content.
[b]$MOE_B$, flatwise bending modulus of elasticity.
[c]$MOE_V$, transverse vibration MOE.
[d]$MOE_D$, longitudinal vibration MOE.
[e]$MOE_T$, tension MOE.
[f]UTS, ultimate tension stress.
[g]COV, coefficient of variation.

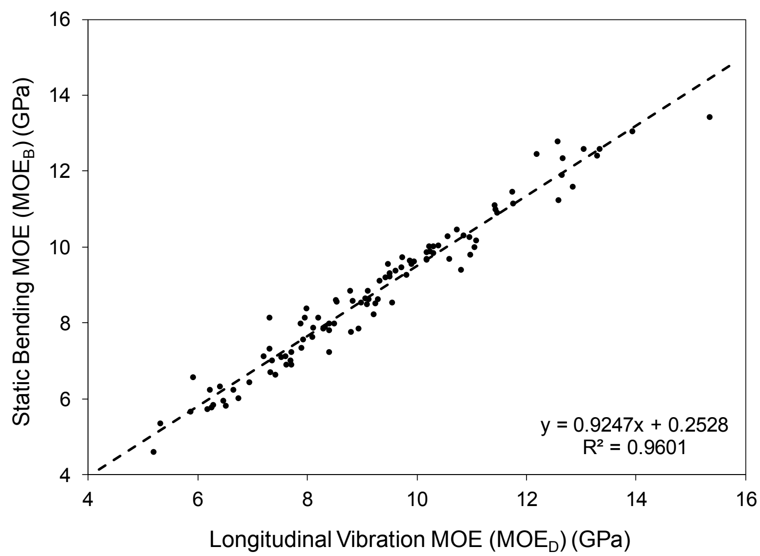


**Figure 6. Longitudinal vibration modulus of elasticity ($MOE_D$) and static bending modulus of elasticity ($MOE_B$).**

# Summary

This study was a systematic investigation on the use of different NDT techniques to evaluate the tensile strength of spruce–pine–fir structural lumber. This research conducted by Mississippi State University, Istanbul University, and the USDA Forest Service, Forest Products Laboratory, examined the use of longitudinal vibration, transverse vibration, and dielectric permittivity. The objective was to derive a robust methodology for estimating the tensile strength of structural lumber and to study the relationship between flatwise bending and vibration moduli for spruce–pine–fir lumber specimens.

By a random selection process, samples for this study were procured from local lumber yards and were conditioned to 10% equilibrium moisture content. Different MOE calculations were made using a series of three separate nondestructive tests; flatwise bending, transverse vibrations, and longitudinal vibration. These nondestructive tests were conducted on each specimen to evaluate the relationship between the three methods.

Static testing was performed using a Metriguard 412 tension proof tester to compare the relationships between static and dynamic modulus values. Statistical regression analysis techniques were used to create empirical models, which revealed a high correlative relationship between the MOE values.

Coefficients of determination obtained were 0.92, 0.96, and 0.93 for MOE of static transverse vibration, MOE of static longitudinal vibration, and MOE of longitudinal transverse vibration, respectively.

Correlative relationships were also observed between nondestructive evaluation parameters and UTS. The values obtained were 0.8261, 0.8242, and 0.8248 for MOE in tension compared with MOE of static, MOE in tension compared with transverse vibration, and MOE in tension compared with longitudinal vibration, respectively.

**Table 2—Coefficients of determination between modulus of elasticity (MOE) parameters and ultimate tension stress (UTS)**

| Abscissa \ Ordinate | $MOE_B$[a] (MPa) | $MOE_V$[b] (MPa) | $MOE_D$[c] (MPa) | $MOE_T$[d] (MPa) | UTS (MPa) |
|---|---|---|---|---|---|
| $MOE_B$ (MPa) | 1 | 0.9264 | 0.9601 | 0.8261 | 0.4946 |
| $MOE_V$ (MPa) | 0.9264 | 1 | 0.9385 | 0.8242 | 0.4903 |
| $MOE_D$ (MPa) | 0.9601 | 0.9385 | 1 | 0.8248 | 0.4799 |
| $MOE_T$ (MPa) | 0.8261 | 0.8242 | 0.8248 | 1 | 0.4849 |
| UTS (MPa) | 0.4946 | 0.4903 | 0.4799 | 0.4849 | 1 |

[a]$MOE_B$, flatwise bending modulus of elasticity.
[b]$MOE_V$, transverse vibration MOE.
[c]$MOE_D$, longitudinal vibration MOE.
[d]$MOE_T$, tension MOE.

**Table 3—Slope of linear regression curves relating modulus of elasticity (MOE) parameters and ultimate tension stress (UTS)**

| Abscissa \ Ordinate | $MOE_B$[a] (MPa) | $MOE_V$[b] (MPa) | $MOE_D$[c] (MPa) | $MOE_T$[d] (MPa) | UTS (MPa) |
|---|---|---|---|---|---|
| $MOE_B$ (MPa) | 1 | 1.036 | 1.038 | 1.111 | 3.781 |
| $MOE_V$ (MPa) | 0.8944 | 1 | 0.9539 | 1.029 | 3.498 |
| $MOE_D$ (MPa) | 0.9247 | 0.9839 | 1 | 1.044 | 3.515 |
| $MOE_T$ (MPa) | 0.7436 | 0.8012 | 0.7898 | 1 | 3.036 |
| UTS (MPa) | 0.1308 | 0.1402 | 0.1365 | 0.1597 | 1 |

[a]$MOE_B$, flatwise bending modulus of elasticity.
[b]$MOE_V$, transverse vibration MOE.
[c]$MOE_D$, longitudinal vibration MOE.
[d]$MOE_T$, tension MOE.

## Acknowledgments

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# Appendix—Test Data of Spruce–Pine–Fir Lumber

**Table A1—Test data of spruce–pine–fir lumber**

| | | | Modulus of elasticity (MOE) | | | | |
|---|---|---|---|---|---|---|---|
| Specimen No. | Moisture content (%) | Density $\rho$ ($g/cm^3$) | Static bending $MOE_B$ (MPa) | Tension $MOE_T$ (MPa) | Longitudinal vibration $MOE_D$ (MPa) | Transverse vibration $MOE_V$ (MPa) | Ultimate tension stress (MPa) |
| 1 | 10.6 | 0.37 | 6,913 | 7,588 | 7,621 | 8,311 | 21.5 |
| 2 | 10.5 | 0.52 | 12,443 | 11,970 | 12,183 | 13,708 | 20.0 |
| 3 | 10.4 | 0.45 | 8,375 | 8,325 | 7,985 | 9,127 | 19.0 |
| 4 | 10.6 | 0.37 | 8,512 | 8,908 | 9,241 | 10,053 | 17.1 |
| 5 | 11.8 | 0.39 | 7,991 | 8,724 | 8,492 | 9,315 | 32.8 |
| 6 | 10.9 | 0.47 | 9,660 | 10,424 | 10,172 | 11,019 | 27.3 |
| 7 | 10.6 | 0.41 | 7,013 | 6,673 | 7,700 | 7,614 | 22.7 |
| 8 | 9.9 | 0.44 | 5,357 | 6,192 | 5,320 | 6,186 | 9.3 |
| 9 | 9.7 | 0.37 | 10,283 | 10,699 | 10,558 | 11,938 | 22.0 |
| 10 | 11.4 | 0.44 | 9,376 | 8,762 | 9,610 | 11,060 | 26.7 |
| 11 | 10.4 | 0.48 | 8,542 | 8,442 | 9,541 | 9,401 | 18.1 |
| 12 | 10.6 | 0.39 | 8,847 | 9,459 | 8,774 | 9,325 | 34.1 |
| 13 | 10.6 | 0.41 | 4,612 | 7,474 | 5,199 | 5,598 | 4.5 |
| 14 | 10.6 | 0.4 | 7,883 | 7,411 | 8,106 | 8,752 | 18.2 |
| 15 | 10.8 | 0.38 | 7,120 | 7,199 | 7,195 | 8,110 | 14.2 |
| 16 | 10.3 | 0.44 | 7,980 | 7,160 | 7,873 | 8,316 | 14.4 |
| 17 | 11 | 0.4 | 9,465 | 9,862 | 9,717 | 10,439 | 26.6 |
| 18 | 10.6 | 0.47 | 11,906 | 12,374 | 12,640 | 12,212 | 26.9 |
| 19 | 10.6 | 0.36 | 10,465 | 10,862 | 10,723 | 11,699 | 38.0 |
| 20 | 10.8 | 0.44 | 6,561 | 4,491 | 5,919 | 6,358 | 3.4 |
| 21 | 10.1 | 0.49 | 10,016 | 10,749 | 10,293 | 11,514 | 18.3 |
| 22 | 11.3 | 0.38 | 6,330 | 5,151 | 6,399 | 6,737 | 3.9 |
| 23 | 11.6 | 0.39 | 8,841 | 9,161 | 9,108 | 9,901 | 28.6 |
| 24 | 11.3 | 0.47 | 9,611 | 9,073 | 9,951 | 10,879 | 17.3 |
| 25 | 10.7 | 0.38 | 9,560 | 10,381 | 9,895 | 10,728 | 24.9 |
| 26 | 10.6 | 0.49 | 13,047 | 13,467 | 13,928 | 14,517 | 25.2 |
| 27 | 10.6 | 0.41 | 8,634 | 8,077 | 9,114 | 9,017 | 26.4 |
| 28 | 10.9 | 0.48 | 11,583 | 13,104 | 12,846 | 14,507 | 61.8 |
| 29 | 10.7 | 0.5 | 12,594 | 12,958 | 13,327 | 14,455 | 25.9 |
| 30 | 10.6 | 0.44 | 7,342 | 6,090 | 7,892 | 8,616 | 8.3 |
| 31 | 10.6 | 0.43 | 11,453 | 12,443 | 11,740 | 12,111 | 37.6 |
| 32 | 10.7 | 0.44 | 8,654 | 10,566 | 9,056 | 9,085 | 19.1 |
| 33 | 10.5 | 0.47 | 10,310 | 10,127 | 10,852 | 10,291 | 28.4 |
| 34 | 10.8 | 0.38 | 10,987 | 11,783 | 11,440 | 12,020 | 54.0 |
| 35 | 10.6 | 0.47 | 5,737 | 4,473 | 6,182 | 7,133 | 10.8 |
| 36 | 10.7 | 0.49 | 6,904 | 6,244 | 7,702 | 7,838 | 10.5 |
| 37 | 10.8 | 0.48 | 7,126 | 6,686 | 7,602 | 8,140 | 10.1 |
| 38 | 10.8 | 0.45 | 6,435 | 5,666 | 6,934 | 7,402 | 11.6 |
| 39 | 10.7 | 0.44 | 9,876 | 10,662 | 10,240 | 10,406 | 14.7 |

**Table A1—Test data of spruce–pine–fir lumber—con.**

| Specimen No. | Moisture content (%) | Density ρ (g/cm$^3$) | Modulus of elasticity (MOE) Static bending $MOE_B$ (MPa) | Tension $MOE_T$ (MPa) | Longitudinal vibration $MOE_D$ (MPa) | Transverse vibration $MOE_V$ (MPa) | Ultimate tension stress (MPa) |
|---|---|---|---|---|---|---|---|
| 40 | 10.6 | 0.39 | 7,637 | 7,470 | 8,091 | 9,035 | 24.1 |
| 41 | 10.6 | 0.45 | 11,099 | 10,593 | 11,421 | 11,628 | 26.8 |
| 42 | 10.5 | 0.48 | 7,004 | 7,230 | 7,349 | 7,991 | 17.9 |
| 43 | 10.8 | 0.46 | 7,571 | 6,250 | 7,919 | 8,712 | 13.5 |
| 44 | 10.8 | 0.42 | 8,535 | 9,412 | 8,985 | 9,255 | 26.6 |
| 45 | 10.8 | 0.41 | 9,728 | 10,035 | 9,734 | 10,791 | 20.5 |
| 46 | 10.9 | 0.46 | 7,235 | 6,041 | 8,393 | 8,332 | 17.5 |
| 47 | 10.7 | 0.45 | 12,346 | 12,975 | 12,662 | 13,181 | 43.6 |
| 48 | 10.9 | 0.37 | 7,767 | 6,835 | 8,796 | 8,747 | 13.6 |
| 49 | 10.3 | 0.45 | 6,647 | — | 7,424 | 8,519 | 7.8 |
| 50 | 10.6 | 0.4 | 8,138 | 9,140 | 8,195 | 8,638 | 23.9 |
| 51 | 10.6 | 0.45 | 9,231 | 9,393 | 9,500 | 9,707 | 20.0 |
| 52 | 10.6 | 0.51 | 9,406 | 10,057 | 10,800 | 10,469 | 29.0 |
| 53 | 10.6 | 0.44 | 9,695 | 9,822 | 10,180 | 10,333 | 20.8 |
| 54 | 10.9 | 0.43 | 9,109 | 9,859 | 9,321 | 9,937 | 19.0 |
| 55 | 10.7 | 0.34 | 5,833 | 4,991 | 6,287 | 6,237 | 10.9 |
| 56 | 10.3 | 0.43 | 9,835 | 12,781 | 10,305 | 10,458 | 22.0 |
| 57 | 10.5 | 0.4 | 8,146 | 7,271 | 7,953 | 8,660 | 17.6 |
| 58 | 10.9 | 0.47 | 5,811 | 4,654 | 6,514 | 6,737 | 14.5 |
| 59 | 10.8 | 0.47 | 8,495 | 9,025 | 9,094 | 9,538 | 24.8 |
| 60 | 10.5 | 0.44 | 7,330 | 4,834 | 7,308 | 8,800 | 7.5 |
| 61 | 10.3 | 0.4 | 5,654 | 7,824 | 5,866 | 6,415 | 7.2 |
| 62 | 10.5 | 0.41 | 7,100 | 8,656 | 7,521 | 8,672 | 14.0 |
| 63 | 10.8 | 0.49 | 5,766 | 6,063 | 6,247 | 7,312 | 10.7 |
| 64 | 10.8 | 0.42 | 5,958 | 5,873 | 6,466 | 7,352 | 13.4 |
| 65 | 11.5 | 0.38 | 9,688 | 10,498 | 10,593 | 12,179 | 37.1 |
| 66 | 10.8 | 0.41 | 11,144 | 10,993 | 11,757 | 12,209 | 36.7 |
| 67 | 10.6 | 0.41 | 10,272 | 10,467 | 10,951 | 11,724 | 28.3 |
| 68 | 10.7 | 0.45 | 9,990 | 9,952 | 11,045 | 11,391 | 21.1 |
| 69 | 10.5 | 0.45 | 9,556 | 10,288 | 9,464 | 11,595 | 17.0 |
| 70 | 10.6 | 0.42 | 7,244 | 9,704 | 7,702 | 8,904 | 20.0 |
| 71 | 10.7 | 0.52 | 9,270 | 11,400 | 9,803 | 10,783 | 20.9 |
| 72 | 10.1 | 0.38 | 8,605 | 9,245 | 8,514 | 10,257 | 24.8 |
| 73 | 10.8 | 0.39 | 6,016 | 4,330 | 6,743 | 7,082 | 10.6 |
| 74 | 10.8 | 0.43 | 12,584 | 13,021 | 13,036 | 13,706 | 32.8 |
| 75 | 10.5 | 0.34 | 8,555 | 8,155 | 8,528 | 9,163 | 24.6 |
| 76 | 10.8 | 0.39 | 9,645 | 9,733 | 9,872 | 10,335 | 31.8 |
| 77 | 10.9 | 0.46 | 8,631 | 9,576 | 9,287 | 10,108 | 19.4 |
| 78 | 10.7 | 0.42 | 8,139 | 5,572 | 7,307 | 7,813 | 14.5 |
| 79 | 11.6 | 0.39 | 7,851 | 9,171 | 8,933 | 10,359 | 22.1 |

**Table A1—Test data of spruce–pine–fir lumber—con.**

| | | | Modulus of elasticity (MOE) | | | | |
|---|---|---|---|---|---|---|---|
| Specimen No. | Moisture content (%) | Density ρ ($g/cm^3$) | Static bending $MOE_B$ (MPa) | Tension $MOE_T$ (MPa) | Longitudinal vibration $MOE_D$ (MPa) | Transverse vibration $MOE_V$ (MPa) | Ultimate tension stress (MPa) |
| 80 | 10.6 | 0.45 | 7,842 | 8,554 | 8,296 | 9,847 | 30.4 |
| 81 | 10.7 | 0.49 | 11,234 | 11,353 | 12,580 | 12,704 | 29.8 |
| 82 | 10.6 | 0.42 | 10,049 | 10,859 | 10,386 | 11,083 | 31.1 |
| 83 | 10.5 | 0.42 | 12,773 | 13,003 | 12,560 | 13,226 | 52.6 |
| 84 | 10.5 | 0.44 | 10,009 | 9,561 | 10,229 | 11,240 | 22.1 |
| 85 | 10.9 | 0.51 | 8,592 | 7,739 | 8,820 | 9,983 | 14.0 |
| 86 | 11.3 | 0.44 | 10,896 | 11,206 | 11,457 | 12,508 | 43.3 |
| 87 | 10.5 | 0.44 | 7,890 | 7,662 | 8,314 | 8,662 | 17.7 |
| 88 | 10.6 | 0.41 | 6,711 | 6,410 | 7,317 | 7,807 | 17.1 |
| 89 | 10.5 | 0.44 | 9,800 | 9,250 | 10,967 | 11,557 | 16.0 |
| 90 | 11 | 0.43 | 7,819 | 7,240 | 8,402 | 9,124 | 22.1 |
| 91 | 10.2 | 0.58 | 13,431 | 15,026 | 15,347 | 15,465 | 20.9 |
| 92 | 11.8 | 0.48 | 12,404 | 12,291 | 13,292 | 13,187 | 29.0 |
| 93 | 10.6 | 0.4 | 6,230 | — | 6,653 | 6,914 | 4.6 |
| 94 | 10.6 | 0.43 | 9,318 | 8,907 | 9,498 | 10,161 | 24.9 |
| 95 | 11 | 0.45 | 9,868 | 9,834 | 10,168 | 10,596 | 33.9 |
| 96 | 11.8 | 0.44 | 10,181 | 11,738 | 11,075 | 12,982 | 25.3 |
| 97 | 11 | 0.5 | 9,203 | 8,267 | 9,425 | 10,193 | 26.3 |
| 98 | 10.6 | 0.4 | 7,993 | 8,105 | 8,394 | 9,137 | 22.2 |
| 99 | 10.1 | 0.42 | 6,234 | 6,471 | 6,215 | 8,132 | 13.6 |
| 100 | 9.9 | 0.37 | 8,230 | 7,391 | 9,216 | 9,845 | 18.7 |