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

Relationship between Grain Angle and Energy Loss

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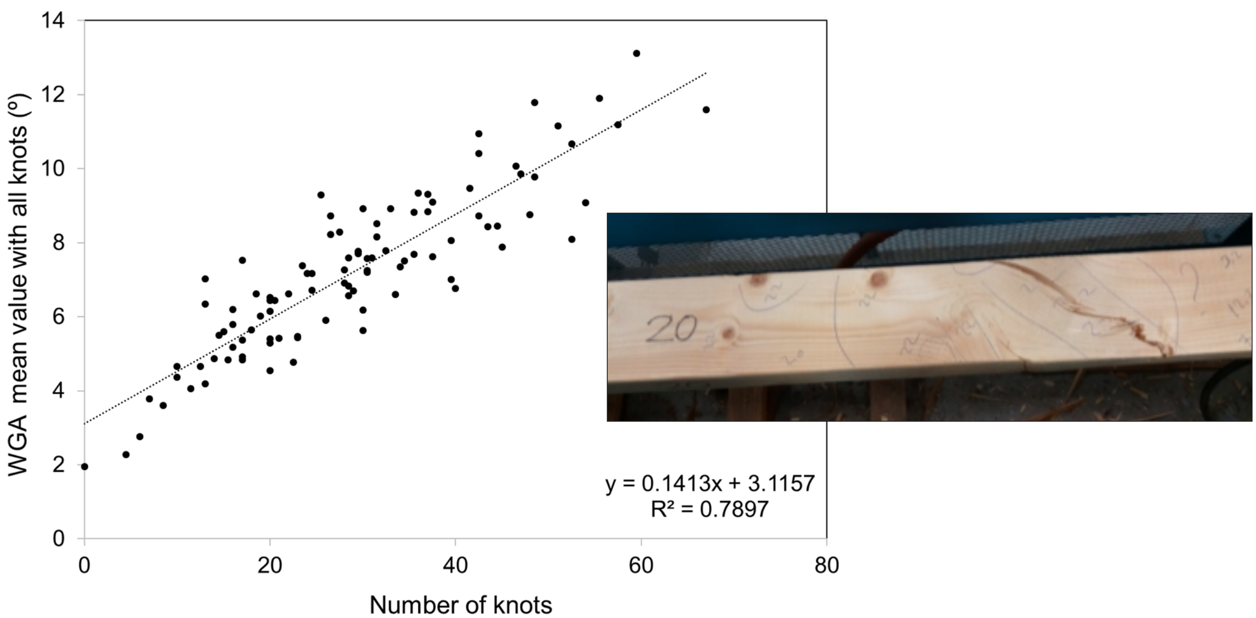

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Abstract

This study was undertaken to examine the relationship between lumber grain angle and the energy loss characteristics of structural lumber. A random sample of 100 spruce–pine–fir lumber specimens was obtained from a local lumber yard. Grain angle was measured at numerous locations for each specimen with equipment that uses a dielectric nondestructive testing technique. A commonly used free transverse vibration test, in which the specimens were simply supported in a flatwise bending mode, was used to determine the energy loss characteristics of the specimens. Increases in grain angle resulted in greater energy loss. A statisically significant positive correlative relationship was found between grain angle and energy loss. More importantly, based on results from this study, energy loss measurements may be useful for detecting lumber with low strength values.

Keywords: transverse vibration, lumber, grain angle, nondestructive evaluation

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Contents

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Introduction

The tensile strength of wood products is important in the design of engineered components and systems. For example, the bottom chord of a wood truss is commonly 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 (with fibers generally aligned with the long axis of the wood) than in the radial or tangential directions in softwood species used for structural dimension lumber. The grain direction (also called grain orientation or slope of grain) is the angle made by wood fibers and the edges of a piece of wood. Variations in grain direction are especially great around knots and are a major factor in the ultimate strength of a piece of lumber in tension.

Energy storage and loss characteristics, as measured using free vibration nondestructive techniques, have received considerable examination as potential predictors of wood strength. Logarithmic decrement obtained from free vibration measurements is a measure of energy loss. It is hypothesized that logarithmic decrement is sensitive to wood product characteristics such as slope-of-grain and the presence of large strength-reducing defects.

Literature Review

A search of the literature (USDA Forest Products Laboratory's library collection, Web of Science, Engineering Index, Ross 2015, and Proceedings from the International Nondestructive Testing and Evaluation of Wood Symposium) yielded several technical papers that investigated the use of common nondestructive test parameters to predict the tensile strength of structural lumber.

Hoyle (1968) summarized early research efforts from a variety of laboratories that resulted in the technology 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 flat-wise orientation, using a center-span dead load) and the corresponding strength of softwood structural lumber. He reported that the statistical models relating static MOE and tensile strength yielded correlation coefficients ranging from 0.74 to 0.82.

Orosz (1977) and Green and McDonald (1993a, 1993b) used transverse vibration nondestructive testing techniques to measure the dynamic MOE of structural lumber. Green and McDonald reported correlation coefficients ranging from 0.46 to 0.60 for the models relating dynamic MOE to tensile strength.

Kaiserlik and Pellerin (1977) examined the use of a longitudinal vibration nondestructive test method to evaluate the tensile strength of softwood lumber. They reported a correlation coefficient of 0.84 when dynamic MOE was compared with tensile strength values. In addition to measuring the longitudinal MOE, they measured the attenuation rate of the wave as it travelled through the lumber specimens. When incorporating this additional parameter in their prediction equation, they reported a correlation coefficient of 0.90.

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 tensile strength 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.

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.

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.

Researchers have investigated a nondestructive method for measuring grain direction that is based on the difference in dielectric constants (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 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 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 (Viguier 2015). It has been reported that knots, spiral grain, and other defects can be detected by measuring dielectric properties (Martin and others 1987).

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

Objective

The USDA Forest Service, Forest Products Laboratory (FPL) has initiated a program to develop technologies to nondestructively evaluate the tensile properties of structural lumber. The overarching objective of the program is to systematically evaluate the relationships between several nondestructive testing parameters and the tensile properties of softwood structural lumber. The first phase of the overall program is to examine relationships between nondestructive testing parameters and physical properties of wood. The specific objective of the research described in this report was to examine the relationship between grain angle and the energy loss characteristics of structural lumber.

Figure 1. Lumber specimens in conditioning room.

Materials and Methods

One hundred lumber specimens were used in this study (Fig. 1). The lumber was obtained from a local lumber yard and was visually graded as No. 2 from the spruce–pine–fir lumber grouping. The lumber was nominally 2 by 4 in. in cross section (mean actual dimensions were 38 by 88 mm) and 12 ft (mean length 0.367 m) long. The lumber specimens were conditioned to a moisture content level of approximately 12%.

Grain Angle Measurement

A Metriguard Model 511 grain angle meter (Metriguard, Pullman, Washington, USA) was used to measure grain angle of the specimens (Fig. 2). Functional and operational details of this equipment are described in Metriguard Technologies, Inc. (2020). This meter is capable of measuring a maximum grain angle of 23°. Measurements were performed on both wide faces of each specimen, and grain angle values were recorded on the wide face of each specimen (Fig. 3).

A total of 200 grain angle measurements were recorded on each of the two wide faces of each piece of lumber. The maximum, minimum, number of grain angle values, and measured values around knots that had grain angle values <23° on both wide faces were recorded. The mean grain angle values were calculated separately for three groups of measurements: the middle (along the center of the wide surface), the edge (close to the edge of the wide surface), and around knots with grain angles <23°. The mean values were calculated for both faces for a total of six means per specimen (3 means × 2 surfaces). As previously stated, the grain angle meter was capable of measuring up to 23°; therefore, all grain angles greater than or equal to 23° would

Figure 2. Device for measurement of grain angle.

Figure 3. Lumber specimens with grain angle measurements on surface.

be reported as 23°. Finally, three different mean grain angle values were calculated depending on knots.

Weighted grain angle mean value with all knots ($WGA_{\text{with knots}}$) of each lumber specimen was calculated using the formula in Equation (1):

$$\mathrm{WGA}_{\text{with knots}} = \left(\frac{n_{<23}}{100}\bar{x}_{<23}\right) + \left(\frac{n_{\geq 23}}{100}\bar{x}_{\geq 23}\right) + \left(\frac{(100 - n_{\text{knots}})/2}{100}\bar{x}_{\text{middle}}\right) + \left(\frac{(100 - n_{\text{knots}})/2}{100}\bar{x}_{\text{edge}}\right) \tag{1}$$

Weighted grain angle mean value with <23° knots ($WGA_{\text{with <23 knots}}$) of each lumber specimen was calculated using the formula in Equation (2):

$$\mathrm{WGA}_{\text{with <23 knots}} = \left(\frac{n_{<23}}{100}\bar{x}_{<23}\right) + \left(\frac{(100 - n_{<23})/2}{100}\bar{x}_{\text{middle}}\right) + \left(\frac{(100 - n_{<23})/2}{100}\bar{x}_{\text{edge}}\right) \tag{2}$$

Grain angle mean value except knots ($GAMV_{\text{except knots}}$) was calculated using the formula in Equation (3):

$$\mathrm{GAMV}_{\text{except knots}} = \left(\frac{(\bar{x}_{\text{middle}} + \bar{x}_{\text{edge}})}{2}\right) \tag{3}$$

where

$WGA_{\text{with knots}}$ is weighted grain angle (WGA) mean value with all knots,

$n_{<23}$ is number of knots (<23°),

$x_{<23}$ is grain angle mean value of knots for <23°,

$n_{\geq 23}$ is number of knots (≥23°),

$x_{\geq 23}$ is grain angle mean value of knots for ≥23° (accepted 23),

n_{knots} is total number of knots (<23°+ ≥23°),

x_{middle} is grain angle mean value (for middle part of surface of lumber), and

x_{edge} is grain angle mean value (for edge part of lumber surface).

Weighted grain angle mean value includes measurements obtained from lumber surface (edge and middle) and knots that have <23° and ≥23° grain angles. Additionally, weighted grain angle mean value without ≥23° knots includes measurements obtained from lumber surface (edge and middle) and knots that have only <23° grain angles. And finally, grain angle mean value excluding knots includes measurements obtained from lumber surface (edge and middle) without knots. Table 1 provides a summary of data obtained from the lumber samples used. Measured values are given in Table 2, and grain angle mean values found are given in Table 3. Grain angle mean values with or without knots were used to investigate the relationship between grain angle and attenuation obtained with transverse vibration.

Logarithmic Decrement (Decay of Free Vibration)

The following briefly describes the test setup that was used for measurement of logarithmic decrement (a measurement of energy loss) (Ross 2015).

Figure 4 illustrates the free transverse vibration test setup used. The specimen was simply supported at both ends. A span length of 11.5 ft (3.5 m) was used.

A slight deflection was introduced at the midspan by mechanically tapping the specimen. The specimen was then allowed to freely oscillate in the vertical (transverse) direction, and the load at one support was continuously monitored and recorded (Fig. 5).

Table 1—Basic statistical information—average values, standard deviation values, maximum and minimum values, coefficient of variation

Values	Mean number of knots	WGA[a] mean value with all knots (deg)	WGA mean value with <23° knots (deg)	Grain angle mean value without knots (deg)	Logarithmic decrement	Oscillation frequency of transverse vibration (Hz)
Mean	28.88	7.23	3.43	2.77	0.028	6.47
Standard deviation	13.57	2.18	1.03	0.90	0.007	0.66
Minimum value	0	1.95	1.71	1.27	0.017	4.95
Maximum value	67	13.12	7.39	6.97	0.086	7.71
Coefficient of variation (%)	48.38	30.26	30.00	32.58	27.434	10.22

[a]WGA, weighted grain angle.

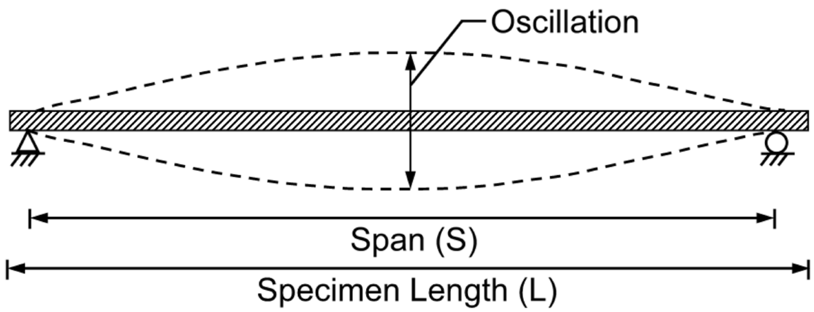

Figure 4. Free transverse vibration test setup.

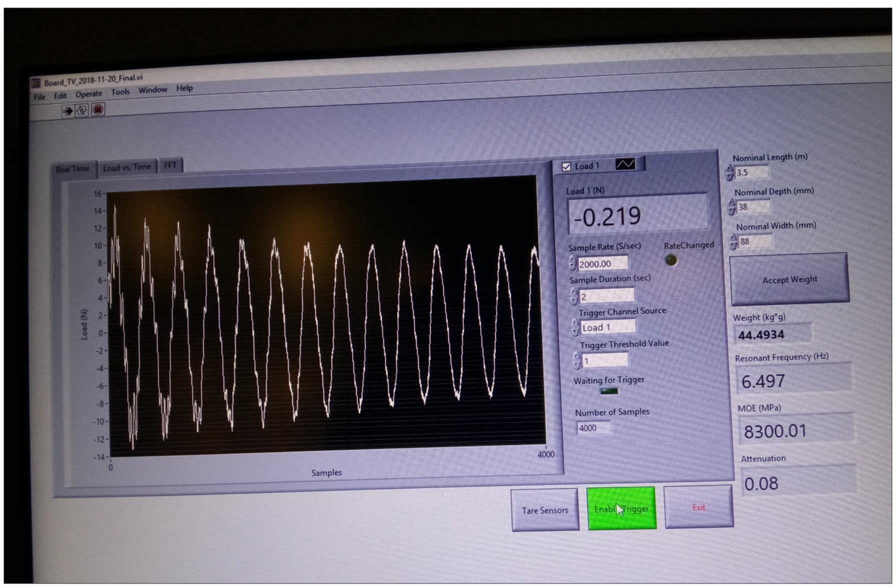

Figure 5. Recorded signal from freely oscillating specimen.

Table 2—Measured grain angle values

	Numbered face of lumber												Other side face of lumber											
	Grain angle around knots						Grain angle of lumber (deg)						Grain angle around knots						Grain angle of lumber (deg)					
	≤22°				≥23°		Middle of lumber			Side of lumber			≤22°				≥23°		Middle of lumber			Side of lumber		
Specimen No.	Number of knots	Min. (deg)	Max. (deg)	Mean (deg)	Number of knots	Mean (deg)	Min.	Max.	Mean	Min.	Max.	Mean	Number of knots	Min. (deg)	Max. (deg)	Mean (deg)	Number of knots	Mean (deg)	Min.	Max.	Mean	Min.	Max.	Mean
1	9	8	13	11.44	23	23	2.2	10.1	4.72	0.1	5.5	0.952	18	5	15	11.271	12	23	1.8	7.1	4.415	0.1	4	1.683
2	0	0	0	0	17	23	1.8	5.4	3.02	0.1	4.4	0.765	1	13	13	13	18	23	1.8	7.1	3.48	0.1	1.8	0.31
3	2	10	14	12	23	23	1.6	5	2.975	0.1	2.1	0.384	4	12	15	12.75	28	23	1.5	5.1	3.373	0.1	2.8	0.865
4	8	7	15	11.75	21	23	4.3	9.1	5.583	0.1	5.5	2.815	17	6	15	8.47	28	23	1.8	5.1	3.025	0.1	3.3	0.771
5	20	6	15	10.19	19	23	1.8	4.1	3.044	0.1	2.6	0.879	15	8	15	10	21	23	2.1	5	3.478	0.1	4	0.596
6	5	6	8	7.6	18	23	2.1	5.2	3.308	0.1	3.7	0.588	2	9	15	12	24	23	2.1	5.1	3.575	0.1	3.1	0.852
7	19	7	15	11.23	33	23	4.4	10.2	7.55	0.2	8	3.489	22	7	15	10.86	45	23	4.1	9.2	6.167	0.1	2	0.679
8	4	8	13	10.5	22	23	4.1	22	6.509	0.1	22	2.661	1	12	12	12	24	23	2.5	22	6.68	0.1	22	4.2
9	12	6	15	9.41	11	23	1.5	7	4.5	0.1	3	0.362	13	5	15	8.15	25	23	1.6	22	4.92	0.1	1.9	1.694
10	22	6	15	10.63	23	23	1.4	12.4	4.389	0.1	4.8	1.295	21	5	14	10.07	31	23	1.8	7	3.617	0.1	3	1.1
11	3	10	15	13.33	10	23	2	10.1	5.555	0.1	4	2.016	2	10	15	12.5	14	23	2	5.2	3.28	0.1	1.7	0.353
12	30	5	15	9.73	22	23	1.8	5.1	2.59	0.1	2.5	0.659	19	5	14	7.5	19	23	1.5	5.1	3.027	0.1	2.5	0.882
13	3	14	15	14.66	14	23	2.2	19	8.136	0.1	4.1	1.671	0	0	0	0	17	23	2.8	9.2	6.28	0.1	5.5	1.962
14	24	5	15	9.49	24	23	3.1	8.1	4.763	0.1	3.4	1.953	9	5	14	10.32	36	23	1.8	5.2	3.338	0.4	3.5	1.726
15	8	6	10	8.125	25	23	2.2	7.2	3.52	0.1	2.5	0.369	9	8	15	12	19	23	1.8	7.2	3.131	0.1	2.5	0.628
16	9	6	13	10.45	25	23	2.7	22	7.354	1.2	5.5	3.411	22	6	15	9.36	41	23	2.8	22	6.525	0.1	22	3.447
17	11	5	11	6.63	21	23	1.4	3.3	2.255	0.1	1.7	0.318	9	5	14	7.44	16	23	2.3	5.8	4.027	0.1	10	2.263
18	17	5	10	8.05	15	23	2.5	4.2	3.5	0.1	2.7	0.944	19	5	15	11.89	34	23	1.6	6.8	3.667	0.1	4.5	0.738
19	2	7	8	7.5	4	23	2.1	5.1	3.383	0.1	3.2	1.626	2	5	7	6	4	23	1.2	3.3	2.1	0.1	0.8	0.159
20	10	8	15	11.59	25	23	7.1	22	11.5	0.6	22	4.688	8	9	14	12.12	18	23	2.8	22	8.113	0.1	22	3.588
21	1	12	12	12	14	23	2.3	5.1	3.55	0.1	2.5	1.075	1	12	12	12	9	23	1.7	5.1	3.142	0.1	2.8	0.867
22	0	0	0	0	13	23	2.2	22	5.291	0.1	22	2.225	0	0	0	0	13	23	3.2	22	7.014	0.1	22	4.026
23	8	5	11	8.75	18	23	1.6	3.2	2.544	0.1	2.5	0.486	5	5	12	7.6	15	23	1.5	2.9	2.4	0.1	1.2	0.336
24	9	8	15	10.33	20	23	3.3	13.1	6.992	0.2	7.1	2.627	14	6	15	11.42	29	23	3.1	6.1	4.563	0.1	2.8	0.6
25	2	10	10	10	7	23	1.2	5.4	3.11	0.1	2.5	0.721	2	6	8	7	6	23	2.4	8.4	3.725	0.1	3.2	0.906
26	4	15	15	15	13	23	1.1	7.1	2.436	0.1	7.1	0.984	5	13	15	14.6	4	23	1.1	5.1	2.87	0.1	3.1	0.894
27	11	6	15	9.92	32	23	1.8	8.1	4.529	0.1	4.5	1.64	31	7	15	9.93	31	23	1.2	6.1	3.786	0.1	2.8	1.021
28	4	5	8	6	0	0	2.2	5.5	3.425	0.1	6	1.464	4	6	15	10.25	1	23	1.4	3.9	2.523	0.1	1	0.257
29	1	14	14	14	7	23	2.2	6.6	4	0.1	2.8	1.163	0	0	0	0	12	23	2.2	9.8	4.555	0.1	4	0.993
30	0	0	0	0	13	23	1.1	22	5.571	0.1	10.2	1.205	2	9	10	9.5	11	23	2.7	15.2	6.575	0.1	14.1	2.688
31	10	6	12	8.7	8	23	4.1	6.2	5.117	0.8	4.3	2.424	18	6	14	8.66	22	23	1.3	4.4	2.945	0.1	1.6	0.315
32	5	5	11	7.2	21	23	3.1	10.1	5.715	0.1	4.8	1.922	5	8	11	9	24	23	1.5	9.1	5.363	0.1	6.5	1.941
33	19	5	13	7.99	20	23	1.5	5.1	2.973	0.1	1.3	0.545	24	7	14	9.68	16	23	4.6	8.4	6.545	1.9	6.4	3.2
34	0	0	0	0	0	0	1.1	4.4	2.877	0.1	2.8	0.427	0	0	0	0	0	0	1.6	5.1	3.169	0.1	4.1	1.362
35	7	9	15	12.57	22	23	2.5	5.1	3.48	0.1	1.7	0.647	0	0	0	0	24	23	2.2	17	7.656	0.1	22	4.268
36	4	5.8	15	11.7	17	23	2	4.2	3.109	0.1	1.5	0.524	4	8.8	12	10.2	15	23	4	8.1	6.208	0.1	3.5	2.088
37	3	15	15	15	24	23	2	7.1	4.24	0.1	5.3	1.337	4	12	15	13.5	22	23	3.3	8	5.9	0.1	5.3	1.756
38	0	0	0	0	15	23	2.2	6.5	4.18	0.2	5.6	2.061	0	0	0	0	17	23	2.1	5.1	3.127	0.1	2	0.62
39	9	7	12	9.33	24	23	3.2	8.1	5.208	0.1	5	2.389	14	6	16	9.28	18	23	1.5	6	3.12	0.1	2	0.506
40	3	10	12	10.66	20	23	1.5	6.2	4.073	0.1	3.5	1.179	11	6	15	8.545	22	23	1.3	3.2	2.386	0.1	1	0.229
41	32	5	10	7.021	15	23	2.6	4.8	3.775	0.1	5.5	1.88	35	5	15	8.448	23	23	1.1	3.8	2.925	0.1	2.6	0.627
42	12	8	15	12.71	27	23	2.7	5.3	4.033	0.1	5.1	1.459	7	6	15	10.271	28	23	2	6.7	4.97	0.1	4.4	1.321
43	12	6	12	8.5	32	23	3.1	8.1	4.458	0.1	9	1.535	12	6	15	10.157	15	23	2.2	10.1	6.27	0.1	5	1.745
44	9	6	15	9.42	34	23	1.7	8.2	4.11	0.1	5.1	1.31	18	7.7	11.8	9.12	22	23	4	6.1	4.522	0.4	3.8	2.24
45	1	9.1	9.1	9.1	5	23	1	6	2.855	0.1	4.5	1	2	6.2	8.2	7.2	6	23	2.8	5.4	4.218	0.5	4.4	2.3
46	7	10	13	10.71	19	23	3.1	7.2	5.378	0.1	3.7	1.68	0	0	0	0	22	23	1.5	5.7	3.2	0.1	2.7	0.795
47	25	5	14	7.68	14	23	1.5	4.4	2.356	0.1	1.5	0.294	13	7	12	9.53	8	23	3	5.2	4.089	0.3	2.7	1.528
48	1	5.8	5.8	5.8	7	23	2	7.1	4.038	0.1	4	1.507	5	6	8.5	7.16	10	23	1.1	4.4	2.4	0.1	2.8	0.522
49	2	8.5	12	10.25	17	23	1.6	5.2	3.286	0.1	1.4	0.45	2	11	12	11.5	13	23	1.3	4.4	3.189	0.1	9.8	1.269

Table 2—Measured grain angle values—con.

	Numbered face of lumber														Other side face of lumber													
	Grain angle around knots						Grain angle of lumber (deg)								Grain angle around knots						Grain angle of lumber (deg)							
	≤22°				≥23°		Middle of lumber			Side of lumber					≤22°				≥23°		Middle of lumber			Side of lumber				
Specimen No.	Number of knots	Min. (deg)	Max. (deg)	Mean (deg)	Number of knots	Mean (deg)	Min.	Max.	Mean	Min.	Max.	Mean			Number of knots	Min. (deg)	Max. (deg)	Mean (deg)	Number of knots	Mean (deg)	Min.	Max.	Mean	Min.	Max.	Mean		

Specimen No.	Number of knots	Min. (deg)	Max. (deg)	Mean (deg)	Number of knots	Mean (deg)	Min.	Max.	Mean	Min.	Max.	Mean	Number of knots	Min. (deg)	Max. (deg)	Mean (deg)	Number of knots	Mean (deg)	Min.	Max.	Mean	Min.	Max.	Mean
50	23	7	15	10.13	44	23	3.9	7.1	5.038	1.1	4.4	2.957	27	6	15	8.637	21	23	1.6	8.1	4.167	0.1	5.4	1.435
51	25	5	12	7.408	27	23	2.2	6.2	4.055	0.1	4.7	1.224	36	5	12	7.394	20	23	2.8	9.8	5.1	0.1	5.7	2.05
52	3	6.5	14	10.2	18	23	2.8	8.3	5.255	0.1	3.6	1.214	16	4.5	14	7.831	24	23	2.3	6.2	4.167	0.1	1.6	0.453
53	11	6	12	9.69	22	23	1.6	8.1	3.845	0.1	2.2	0.667	9	6	14	9.744	17	23	4.2	7.7	5.775	0.2	4.7	2.3
54	11	7	14	9.454	11	23	4	6.7	5.21	0.1	5.2	1.56	17	5	15	10.629	18	23	1.9	7.1	4.013	0.1	3	0.63
55	3	8	11	10.5	12	23	1.7	6.7	3.19	0.1	1.1	0.305	6	10	15	12.75	13	23	1.4	4.2	2.791	0.1	2.6	0.532
56	4	6	7	6.3	18	23	0.8	6.6	2.736	0.1	3.2	0.614	4	10	13	11.2	14	23	3	12	6.355	0.1	5.8	2.209
57	8	8.8	15	11.6	28	23	5.1	8.1	6.41	0.3	4	2.5	16	5.5	12.8	9.437	33	23	2.3	7.2	4.856	0.1	3	1.075
58	0	0	0	0	26	23	2.5	8.2	5.37	0.1	3.1	1.195	0	0	0	0	34	23	1.8	7.1	4.189	0.1	2.5	0.694
59	14	8.9	15	13.992	29	23	5	8.2	6.409	0.4	4.2	2.573	25	6	13	8.212	43	23	2.5	5.6	3.64	0.1	2.2	0.45
60	0	0	0	0	19	23	1.6	5.2	3.64	0.1	11	1.485	1	13	13	13	21	23	1.2	6.1	3.38	0.1	2.2	0.43
61	7	5	14	9.257	34	23	1.8	9.9	4.85	0.1	5	2.071	11	5	14	9.145	33	23	1	10	7.283	0.1	5	2.628
62	0	0	0	0	15	23	2.3	6.2	3.963	0.1	4	0.547	2	8.8	12.6	10.7	23	23	2	6.5	3.173	0.1	1.8	0.626
63	2	9	12	10.5	14	23	2.1	14	5.283	0.1	4	0.96	1	14	14	14	15	23	1.2	8	4.831	0.1	5.1	1.748
64	2	14	18	16	17	23	1	7.5	3.673	0.1	4	0.819	2	7.8	12	9.9	23	23	1.8	7.2	4.15	0.1	2	0.409
65	5	6	15	10.2	14	23	1.8	7	3.614	0.1	2	0.744	25	5	13	7.148	23	23	0.7	5	2.225	0.1	0.8	0.259
66	29	5	15	7.81	22	23	0.8	5	2.809	0.1	2	0.545	18	6	14	7.655	10	23	2.7	5.5	4.245	0.1	3.3	1.8
67	10	4	12	8.62	15	23	3.6	7.2	5.275	0.1	3.2	1.296	21	5	12	7.747	22	23	1.8	6	3.673	0.1	4.9	0.667
68	0	0	0	0	10	23	1.1	5.3	2.767	0.1	1.5	0.313	3	5.8	12	9.5	15	23	2.6	7.8	4.314	0.1	3.5	1.3
69	23	7	16	10.7	19	23	2.5	10.1	4.608	0.1	4.2	1.213	9	7.1	14	10.544	51	23	2.5	6.7	4.18	0.1	3.2	1.385
70	26	6	13	9.696	7	23	2.7	17	6.2	0.2	5.5	2.572	13	5.5	12	8.669	25	23	0.9	7.1	3.771	0.1	3.1	0.854
71	6	7	11	9.083	27	23	2.5	7.8	4.708	0.1	2.7	1.108	11	7	14	9.563	12	23	2.3	9	4.255	0.1	4.1	0.964
72	5	5	11	9.22	14	23	1.2	8.5	3.223	0.1	2.5	0.481	5	6	12	8.88	18	23	0.8	4	2.283	0.1	1.8	0.479
73	12	9	14	11.5	24	23	2	10.5	4.5	0.1	6.3	1.391	10	8	15	10.99	17	23	2.5	10.7	5.209	0.2	4	1.709
74	5	5	10	8.1	10	23	1.2	3.7	2.117	0.1	2	0.408	9	6	9.3	7.433	16	23	1.1	4	2.254	0.1	0.8	0.308
75	4	10	14	11.625	13	23	2.2	5.4	3.2	0.1	1.8	0.546	3	7.3	10	9.1	12	23	2.5	6.3	4.2	0.1	3	1.2
76	10	6	15	8.7	20	23	0.8	3.4	1.986	0.1	4	1.168	9	7	17	8.6	13	23	0.6	6	2.34	0.1	4.8	1.461
77	2	15	19	17	17	23	2.5	6	4.35	0.2	6	1.664	1	6.3	6.3	6.3	18	23	0.7	4	2.28	0.1	2.4	0.588
78	33	5	15	7.354	36	23	1.5	6.5	3.582	0.1	8.2	2.242	30	5.5	14	8.636	35	23	0.7	5.5	3.6	0.1	5.2	1.657
79	2	7	9.8	8.4	25	23	0.6	3.5	2.007	0.1	2.1	0.573	17	6	14	8.782	25	23	0.9	4	2.442	0.2	3.2	0.7
80	21	7	18	10.2	23	23	0.2	8	2.393	0.1	2.8	0.949	29	6	18	8.78	7	23	0.5	4.7	2.157	0.1	3.2	0.952
81	6	4	11	7.516	9	23	0.2	9.9	3.053	0.2	5.1	1.569	6	6.4	15	10.433	19	23	0.6	3.7	2.094	0.2	3.5	1.409
82	18	6	16	9.27	16	23	2	6.4	3.882	0.8	5.4	3.052	29	6	21	9.068	26	23	0.7	3.3	1.77	0.1	4.3	1.192
83	16	4.5	17	8.85	3	23	2.2	5.2	3.308	0.1	7.4	1.9	13	5.8	12	9.838	13	23	0.3	2.8	1.614	0.1	3.1	1.253
84	12	8	10	7.783	26	23	2	11	4.707	0.1	3.5	1.288	7	6.5	14.6	9.271	14	23	2.5	8	4.306	0.1	8.6	3.029
85	1	9	9	9	22	23	1.9	7.1	3.885	0.6	4.2	2.081	1	8.9	8.9	8.9	23	23	1.5	5.5	3.592	0.2	4	1.52
86	16	10	15	11.03	24	23	1	5.5	3.282	0.2	3.8	1.729	17	5.3	14.2	8.341	3	23	0.8	3.6	2.353	0.1	4.2	1.3
87	19	10	15	10.863	29	23	2.3	11.1	5.396	0.5	8.2	3.105	26	5	13	9.946	20	23	1.3	8.9	4.324	0.2	3.9	1.535
88	28	10	15	10.403	29	23	1.4	8.6	3.281	0.2	5	1.639	17	4	13.5	7.182	13	23	1.4	5.5	3.529	0.6	5.7	2.214
89	1	13	13	13	10	23	1	6.3	2.978	0.1	3	0.865	3	5.5	9.8	8.1	6	23	2.2	5.5	4.094	0.2	7.7	2.407
90	2	9.1	13	11.05	18	23	2	3.4	2.782	0.3	10.1	2.364	14	6.7	10	7.428	6	23	1.7	6.7	3.182	0.2	4.4	1.142
91	1	5.3	5.3	5.3	14	23	1.2	9	3.638	0.2	11.2	1.968	0	0	0	0	22	23	1.1	12.3	4.642	0.3	7	1.837
92	6	4	7.5	6.85	7	23	2.2	6.6	4.039	0.4	3.8	1.869	10	5	6.2	5.82	11	23	1.4	6.8	3.72	0.2	8.1	1.645
93	8	6	10.8	8.1	15	23	2.5	18	5.362	0.2	5	1.871	12	6.4	12.2	11.725	14	23	1	8.2	4.422	0.3	7	3.207
94	10	7.4	20	11.514	1	23	1.4	6.7	3.94	0.2	3	1.457	8	8.2	15	12.587	12	23	1.8	6.3	3.665	0.1	4.3	1.621
95	8	7	11	8.775	11	23	1.5	10.5	4.3	0.2	3.3	1.258	15	4.3	13.2	9.573	12	23	1.9	5.3	2.967	0.1	1.2	0.481
96	33	6.1	15	10.99	22	23	1	8	2.328	0.1	2.8	1.138	24	7.1	12	9.483	17	23	2.4	6.8	4.583	0.2	3.7	1.736
97	5	7	11	8.52	32	23	1.8	11.8	4.174	0.5	3.5	1.647	5	5.8	15	10.48	24	23	1.1	9.5	4.02	0.1	6.2	2.083
98	13	5.5	15.2	7.984	19	23	2	16	6.548	0.6	6	3.513	9	5.5	12	9.033	22	23	1.5	12.3	4.646	0.5	4	2.054
99	9	5	7.3	4.744	32	23	1.5	7.4	4.84	0.2	4.5	2.06	12	5.3	13	8.833	22	23	2	15	4.96	0.2	4.1	1.866
100	2	12.4	13	12.95	15	23	0.4	13.2	3.869	0.1	7.7	1.9	1	5.6	5.6	5.6	12	23	0.3	7.2	2.756	0.1	5.4	2.449

Table 3—Grain angle mean values (with and without knots) and logarithmic decrement values

Specimen No.	Mean number of knots	WGA[a] mean value with all knots (deg)	WGA mean value with <23° knots (deg)	Grain angle mean value without knots (deg)	Logarithmic decrement	Oscillation frequency of transverse vibration (Hz)
1	31	7.59	4.07	2.94	0.0265	6.34
2	18	5.64	1.95	1.89	0.024	7.021
3	28.5	7.59	2.22	1.90	0.0273	6.18
4	37	8.84	3.91	3.05	0.0271	6.99
5	37.5	7.62	3.42	2.00	0.0264	6.7
6	24.5	6.71	2.32	2.08	0.0248	6.616
7	59.5	13.1	5.83	4.47	0.0326	5.941
8	25.5	9.30	5.16	5.01	0.0363	5.019
9	30.5	7.20	3.60	2.87	0.0209	7.557
10	48.5	9.78	4.27	2.60	0.0263	6.843
11	14.5	5.50	3.05	2.80	0.0274	6.169
12	45	7.88	3.53	1.79	0.0245	6.717
13	17	7.53	4.66	4.51	0.0387	4.955
14	46.5	10.1	4.03	2.95	0.0346	6.371
15	30.5	7.25	2.62	1.91	0.0258	6.311
16	48.5	11.8	5.89	5.18	0.0322	6.078
17	28.5	6.57	2.70	2.22	0.0217	7.062
18	42.5	8.72	3.63	2.21	0.0245	7.07
19	6	2.76	1.92	1.82	0.023	7.7
20	30.5	10.8	7.40	6.97	0.086	5.192
21	12.5	4.65	2.26	2.16	0.0242	6.536
22	13	7.03	4.64	4.64	0.0309	5.748
23	23	5.44	1.89	1.44	0.0202	6.884
24	36	9.34	4.56	3.70	0.0291	6.509
25	8.5	3.60	2.24	2.12	0.0237	7.286
26	13	4.19	2.38	1.80	0.02	7.399
27	52.5	10.7	4.29	2.74	0.0279	6.554
28	4.5	2.27	2.17	1.92	0.0189	7.373
29	10	4.66	2.74	2.68	0.0218	7.258
30	13	6.34	4.06	4.01	0.0305	5.938
31	29	6.70	3.58	2.70	0.0232	7.297
32	27.5	8.29	3.95	3.74	0.0312	6.366
33	39.5	8.06	4.49	3.32	0.0356	6.5
34	0	1.96	1.96	1.96	0.0175	7.671
35	26.5	8.73	4.38	4.01	0.0331	5.212
36	20	6.52	3.30	2.98	0.0345	5.482
37	26.5	8.22	3.69	3.31	0.0334	5.567
38	16	5.78	2.50	2.50	0.0364	5.52
39	32.5	7.79	3.58	2.81	0.0297	6.652
40	28	6.91	2.49	1.97	0.0224	6.433
41	52.5	8.09	4.14	2.30	0.0244	6.97
42	37	9.31	3.79	2.95	0.0325	5.549
43	35.5	8.83	4.20	3.50	0.0324	5.908
44	41.5	9.47	3.86	3.05	0.0353	6.407
45	7	3.79	2.67	2.59	0.0202	7.077
46	24	7.18	3.02	2.76	0.0296	5.83
47	30	5.62	3.30	2.07	0.0209	7.404
48	11.5	4.06	2.27	2.12	0.0248	6.669
49	17	5.37	2.23	2.05	0.0299	5.866
50	57.5	11.2	4.89	3.40	0.0325	6.382
51	54	9.08	4.39	3.12	0.0339	6.324
52	30.5	7.58	3.32	2.77	0.0412	6.233
53	29.5	7.71	3.81	3.15	0.0299	6.657
54	28.5	6.83	3.89	2.85	0.0293	6.666
55	17	4.83	2.17	1.71	0.0281	5.905
56	20	6.44	3.21	3.00	0.0297	6.729
57	42.5	10.4	4.51	3.71	0.0331	6.464
58	30	8.92	2.86	2.86	0.037	5.176

Table 3—Grain angle mean values (with and without knots) and logarithmic decrement values—con.

Specimen No.	Mean number of knots	WGA[a] mean value with all knots (deg)	WGA mean value with <23° knots (deg)	Grain angle mean value without knots (deg)	Logarithmic decrement	Oscillation frequency of transverse vibration (Hz)
59	55.5	11.9	4.70	3.27	0.0313	6.157
60	20.5	6.45	2.29	2.23	0.0319	5.961
61	42.5	10.9	4.64	4.21	0.0407	5.434
62	20	6.15	2.17	2.08	0.0288	6.203
63	16	6.20	3.33	3.21	0.0347	5.252
64	22	6.62	2.48	2.27	0.0317	5.671
65	33.5	6.61	2.65	1.71	0.0288	7.516
66	39.5	7.00	3.66	2.35	0.0224	7.409
67	34	7.35	3.58	2.73	0.0239	7.237
68	14	4.86	2.27	2.17	0.0217	6.898
69	51	11.2	4.09	2.85	0.0271	6.779
70	35.5	7.69	4.45	3.35	0.0373	6.175
71	28	7.26	3.33	2.76	0.0267	6.128
72	21	5.41	1.99	1.62	0.0212	6.903
73	31.5	8.16	4.09	3.20	0.0371	5.665
74	20	4.54	1.72	1.27	0.0196	7.713
75	16	5.17	2.58	2.29	0.026	7.059
76	26	5.91	2.49	1.74	0.0272	6.971
77	19	6.03	2.39	2.22	0.0274	6.34
78	67	11.6	4.40	2.77	0.0368	5.863
79	34.5	7.51	2.12	1.43	0.0258	6.874
80	40	6.76	3.56	1.61	0.028	6.156
81	20	5.40	2.45	2.03	0.0233	6.881
82	44.5	8.46	4.20	2.47	0.0264	6.966
83	22.5	4.77	3.07	2.02	0.0209	7.598
84	29.5	7.77	3.82	3.33	0.0248	6.896
85	23.5	7.38	2.83	2.77	0.0296	5.93
86	30	6.18	3.40	2.17	0.0245	7.218
87	47	9.86	5.13	3.59	0.0363	6.059
88	43.5	8.43	4.14	2.67	0.0251	6.018
89	10	4.36	2.71	2.59	0.0224	6.904
90	20	5.29	2.82	2.37	0.0282	6.176
91	18.5	6.62	3.03	3.02	0.0232	6.953
92	17	4.91	3.09	2.82	0.0248	7.184
93	24.5	7.17	4.37	3.72	0.0373	5.689
94	15.5	4.83	3.51	2.67	0.0229	6.678
95	23	5.49	3.08	2.26	0.0267	6.599
96	48	8.76	4.73	2.45	0.0266	7.166
97	33	8.92	3.31	2.98	0.0278	6.127
98	31.5	8.51	4.64	4.19	0.0275	6.518
99	37.5	9.10	3.82	3.43	0.0338	5.76
100	15	5.59	2.86	2.74	0.0247	6.928

[a]WGA, weighted grain angle.

Logarithmic decrement of vibrational decay, δ, a measure of internal friction, was calculated using this formula (for free vibrations):

$$\text{Logarithmic decrement, } \delta = \left(\frac{1}{n-1}\right)\ln\left(\frac{A_1}{A_n}\right) \tag{4}$$

where A_1 and A_n are the amplitudes of two oscillations $n - 1$ cycles apart.

This approach follows classic vibration theory for a simply supported homogenous beam. A more detailed analysis, as proposed by Cai and others (1996), may yield a more representative value for logarithmic decrement.

Results and Discussion

Table 1 provides a summary of data obtained from the lumber samples used.

Figure 6 shows a plot of weighted grain angle mean values versus corresponding logarithmic decrement values for all of the specimens. For most of the specimens, log decrement appears to be related to grain angle. However, data obtained from one specimen deviated significantly from this trend. Closer investigation of this specimen revealed that it had a large defect near its midlength. This defect, which consisted of a large knot and associated grain distortions, made up approximately 90% of the specimen's cross section, as shown in Figure 7. A defect of this magnitude would dissipate a significant amount of energy.

Knots and the area surrounding them in lumber have several characteristics that significantly affect strength. First, a knot is the tissue from a branch or limb of a tree. Its fibers are aligned parallel to its axis; hence, its fibers do not align with the major axis of a piece of lumber. Rather, knots in lumber are an anomalous interruption to otherwise straight grain. Second, the fibers surrounding a knot in a piece of lumber are formed in the tree in a manner in which they flow around the branch or stem. Consequently, they also do not align with the major axis of a piece of lumber. Third, the cell wall structure of the fibers surrounding a knot are significantly different from that of the fibers in clear wood areas of a piece of lumber. Lastly, a distinct boundary zone exists between a knot and the surrounding woody material. Because of this significant anomaly, we did not include it in the following analysis.

Figure 8 illustrates the relationship between grain angle measurements with all knots and logarithmic decrement. Figure 9 illustrates the relationship between grain angle measurements with knots <23º and logarithmic decrement. Note that a linear relationship exists, with an increase in logarithmic decrement readings corresponding to increase in grain angle. Figure 10 shows that a strong relationship exists between grain angle and the number of knots found in a specimen.

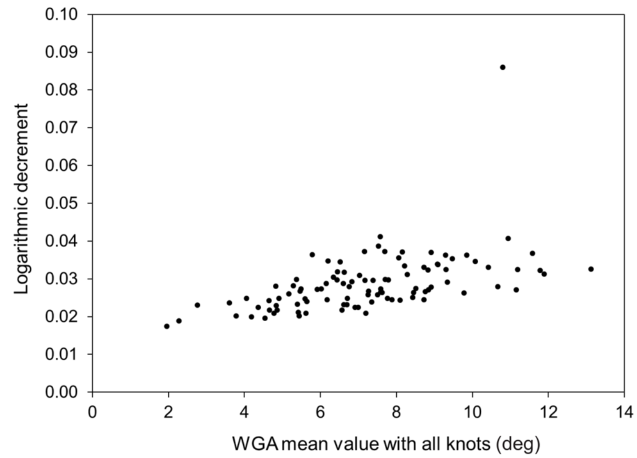

Figure 6. Relationship between weighted grain angle (WGA) mean value with all knots and logarithmic decrement.

Figure 7. Large knot and associated grain distortions made up approximately 90% of the cross section of the deviant specimen.

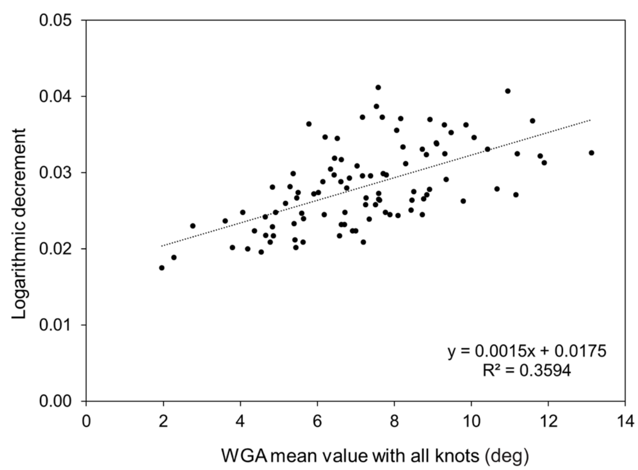

Figure 8. Relationship between weighted grain angle (WGA) mean value with all knots and logarithmic decrement.

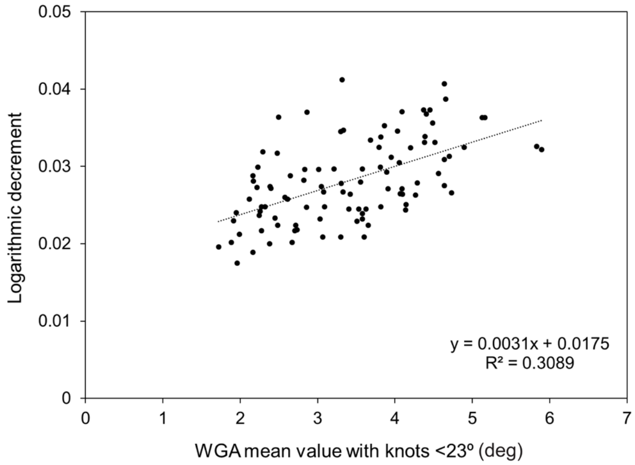

Figure 9. Relationship between weighted grain angle (WGA) mean value with knots that are <23º and logarithmic decrement.

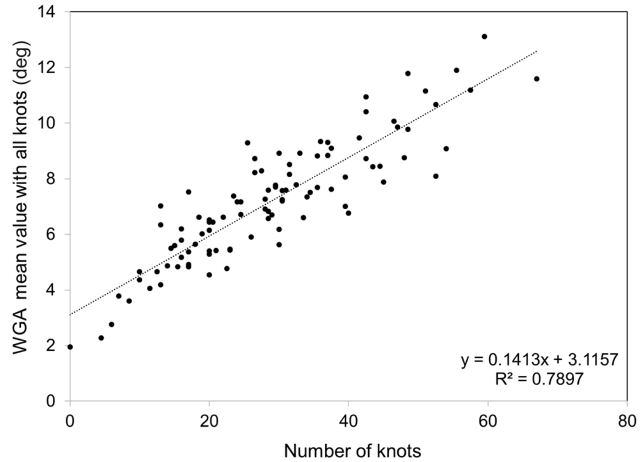

Figure 10. Relationship between weighted grain angle (WGA) mean value with all knots and number of knots.

Concluding Comments

The presence of knots in a piece of lumber significantly affects its value. For lumber that will be used in applications where the appearance of the final product is of primary importance, knots and associated grain distortions (identified as grain angle) are considered significant defects and are often removed during the manufacturing process. Also, they are considered a significant strength-reducing characteristic for structural lumber.

The results of this study indicate that as grain angle increases, energy loss characteristics of structural lumber increase. This is of significance to users of commercial nondestructive evaluation equipment for grading structural lumber. Based on these results, it may be possible to refine their equipment to provide a more accurate means of identifying lower strength pieces of lumber.

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