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Moisture Content and Tensile Strength of Douglas Fir Dimension Lumber

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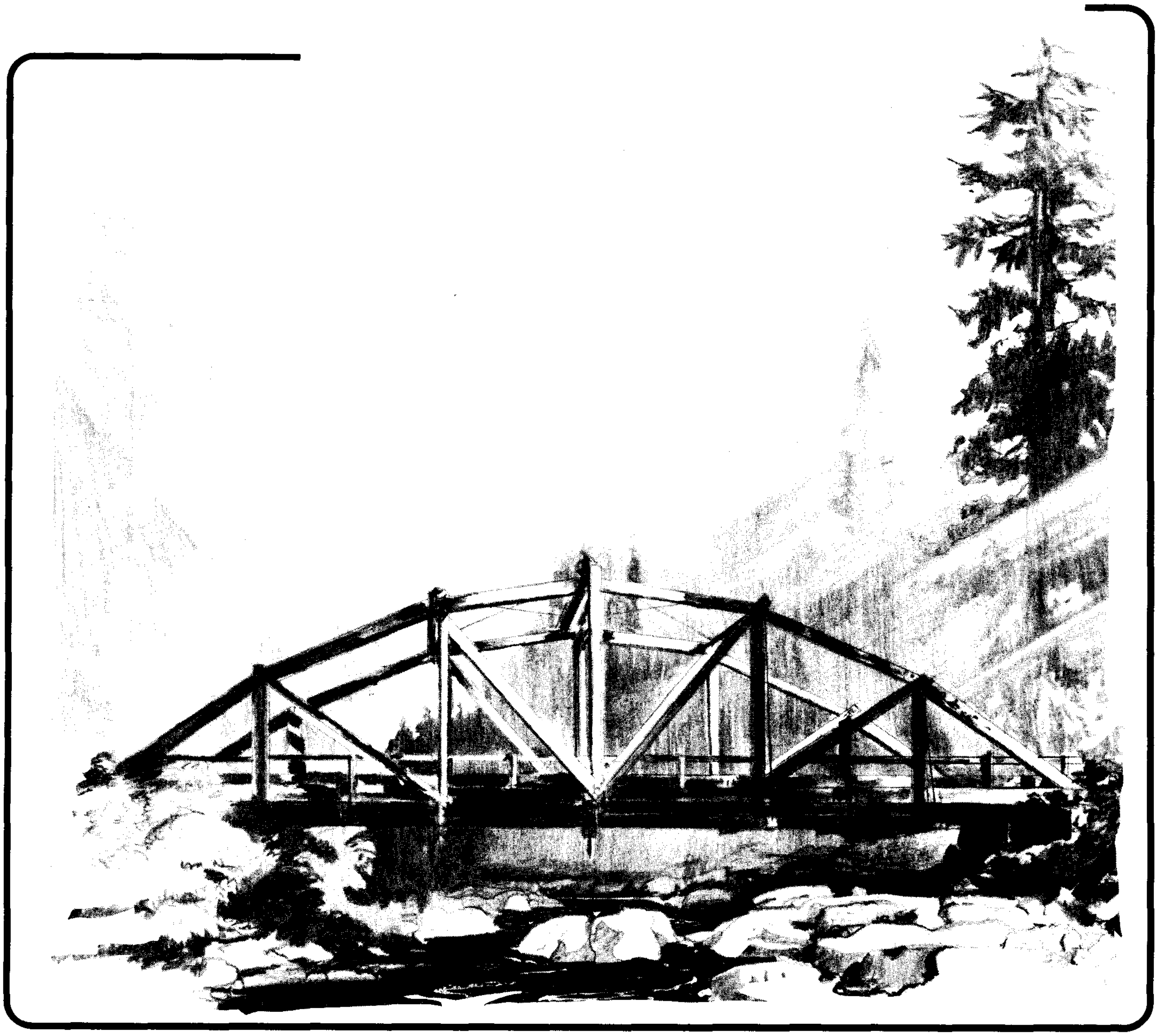

Abstract

Three grades and two sizes of lumber (Select Structural, No. 1, and No. 2; 2 by 4 and 2 by 8) were tested in tension parallel to the grain at various moisture content levels (green, 20, 15, and 10 percent). Results of this study indicate that the current ASTM D 245-88 and ASTM D 2915-88 standards are not valid for adjusting 2-in. dimension lumber for change in moisture content. Lumber was much less sensitive to changes in moisture content than predicted by ASTM D 245-88 and ASTM D 2915-88. Results indicate an optimum value in the relationship between moisture content and tensile strength. The tensile strength at 10 percent moisture content may be less than that at 15 percent moisture content.

Keywords: Tensile strength, moisture content, Douglas Fir, lumber, Weibull distribution

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The terms Douglas Fir and Southern Pine are from the list “Commercial Names for Lumber,” p. 343, in Checklist of United States Trees, Agric. Handb. 541, 1979.

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Contents

Research Highlights

This paper presents the experimental results of a program to evaluate the effect of moisture content on the tensile parallel-to-grain properties of Douglas Fir 2-in. dimension lumber. These studies were initiated because previous research on the effect of moisture content on flexural properties had shown that ASTM D 245-88 procedures did not accurately predict the effect of moisture content on modulus of rupture.

A review of published literature indicated that clear wood tensile strength may show no increase, and may even show a decrease, when the wood is dried to moisture contents below 20 percent. Two previous studies on the effect of moisture content on tensile strength of lumber also indicated the possibility of no increase in strength with drying, especially in the lower end of the cumulative frequency distribution. One of these studies utilized lumber that had previously been kiln dried with a commercial schedule, and the other study used lumber that had been dried slowly.

Lumber of three grades (Select Structural, No. 1, and No. 2) and two sizes (nominal 2 by 4 in. and 2 by 8 in.) were sampled from a sawmill in the Pacific Northwest. For each grade-size combination, the sample was divided into four identical populations based on strength ratio and green modulus of elasticity. Three of the groups were then equilibrated to moisture content levels of 10, 15, and 20 percent prior to testing. Except for testing speed, all samples were tested in tension parallel to the grain following procedures given in ASTM D 198-84. The testing speed was about 10 times faster than the ASTM D 198 recommendation and is comparable to that now given in ASTM D 4761-88.

The results of our study show that moisture content influenced tensile strength throughout the range of properties, from weakest to strongest. The magnitude of the change for a given property was influenced by lumber grade, width, and moisture content level.

From the results of this study, we conclude the following:

1. The changes in ultimate tensile stress with changes in moisture content differ considerably from those observed in previous studies with modulus of rupture. The observed change in ultimate tensile stress values with change in moisture content is also much lower than the values assumed in ASTM D 245-88.

2. Throughout the range of the data, ultimate tensile stress tends to first increase, and then to decrease, as the lumber dries. The ultimate tensile stress at 10 percent moisture content may be considerably lower than that at higher moisture content levels.

3. Ultimate tensile stress may exhibit significant skewness and cannot usually be considered to follow a normal distribution. The three-parameter Weibull distribution was found to provide an adequate fit to tensile strength data at all levels of moisture content.

4. The change in tensile modulus of elasticity with changes in moisture content is less than that previously reported for bending modulus of elasticity and is not very sensitive to percentile level. Tensile modulus of elasticity can usually be considered to follow a normal distribution.

5. Cumulative frequency distributions of ultimate tensile stress for a given grade-size combination at various moisture content levels often intertwine because of the reduction in strength that occurs below an optimum moisture content level. For this reason, sole reliance should not be placed on cumulative frequency distribution plots when evaluating moisture content effects on tensile strength.

6. Results of this study indicate a need for additional data for lumber at moisture contents <8 percent.

Analytical models for adjusting the tensile strength of lumber for changes in moisture content are presented in a separate publication.

Moisture Content and Tensile Strength of Douglas Fir Dimension Lumber

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Introduction

Recent studies on the effect of moisture content (MC) on the mechanical properties of Southern Pine and Douglas Fir nominal 2-in. dimension lumber have shown that the change in modulus of rupture (MOR) depends upon the initial strength of the lumber (Aplin and others 1986, McLain and others 1984). The MOR of strong (high-quality) lumber was more sensitive to changes in MC than predicted by the ASTM D 245-88 method (ASTM 1989), whereas the MOR of low-strength (low-quality) lumber may not be affected by drying. Obvious decreases in MOR were observed for some lumber when dried from 15 to 10 percent MC.

The objective of this study was to investigate the effect of MC on the ultimate tensile stress (UTS) of Douglas Fir dimension lumber. This paper presents the experimental procedure and results. Analytical models for adjusting tensile strength for changes in MC are presented in a separate publication (Green and Evans 1988).

Background

Clear Wood

The parallel-to-the-grain tensile strength of clear wood is much less sensitive to changes in MC than is bending strength. For softwoods, the average increase in MOR is 69 percent when the wood is dried from green to 12 percent (ASTM D 2555-88, ASTM 1989). The average increase in tensile strength is 13 percent (USDA Forest Service 1987).

The effect of MC on the static mechanical properties of small, clear wood specimens was reviewed by Gerhards (1981). Of the 48 papers Gerhards reviewed, only those of Kollmann (1956), Kufner (1978), and Leont'ev (1960) provided data on the effect of MC on tensile strength parallel to the grain. Generally, mean tensile strength was found to increase as MC decreased (Fig. 1). The data of Kollmann (1956) suggest maximum strength at about 6 percent MC. Although not as pronounced as the maximum value obtained by Kollmann, most strength values obtained by Kufner (1978) also suggest a maximum value in this range. This reduction in strength is presumably a result of drying degrade that occurs at low MC levels.

Curry (1952) investigated the effect of MC on the tensile strength of aircraft-quality Sitka spruce. Based on his analysis of 1,600 separate specimens, Curry concluded that no correction is required for MC levels below 20 percent when considering the average tensile strength of a species (Fig. 2). Further analysis by Curry indicated that the magnitude of the correction for individual pieces varied with specific gravity (Fig. 3). Note that these results indicate maximum strength occurred between 15 and 20 percent MC. The room temperature data presented by Östman (1985) also indicate a peak in the UTS-MC curve at MC of about 15 percent.

Only Kufner's study (1978) measured tensile modulus of elasticity (TMOE). Depending on species, Kufner observed a maximum TMOE between 2 and 5 percent MC (as opposed to the maximum MC value between 5 and 8 percent he observed with tensile strength).

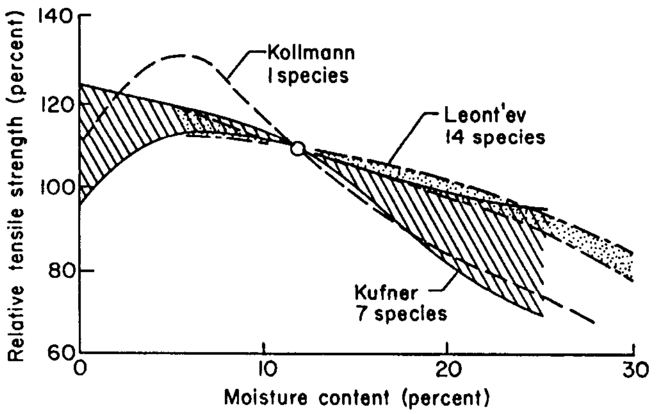

Figure 1—Effect of moisture content on tensile strength of wood parallel to grain relative to strength at 12 percent moisture content at about 20°C (52°F) (Gerhards 1981).

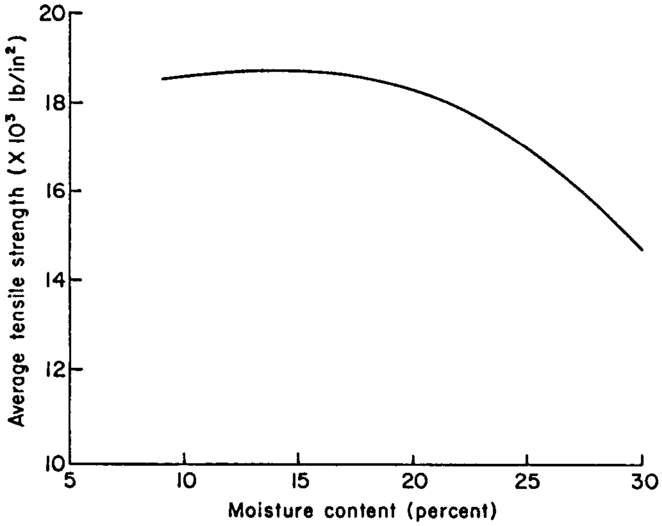

Figure 2—Average tensile strength of Sitka spruce at various moisture contents (Curry 1952).

Lumber

Historically, the procedures used for adjusting the bending strength of lumber for changes in MC have also been used to adjust tensile strength (Green 1982). Although its justification is not apparent, this practice is consistent with the historical practice of relating tensile strength to bending strength (Galligan and others 1979). Thus, the current design procedure (ASTM D 245-88, ASTM 1989) assumes that tensile strength and bending strength increase 25 percent as lumber is dried from green to an average MC of 15 percent.

Hoffmeyer (1978) conducted studies on the relationship of tensile strength to moisture content using low-grade European spruce joists (including a substantial number of “rejects”). The 1.8- by 5.7-in. lumber was tested at equilibrium MCs of approximately 14, 24, and 56 percent. Half the specimens came from Sweden and half from Denmark. As has been observed with bending strength (Green 1982), the effect of MC on tensile strength was found to depend upon strength (Fig. 4). Below about the 50th percentile, drying had little influence on tensile strength. Dry to green ratios for tensile strength at different percentiles were found to be less than those observed for bending. Hoffmeyer cautions, however, that the tensile specimens warped to a certain extent during drying, which may have affected the results.

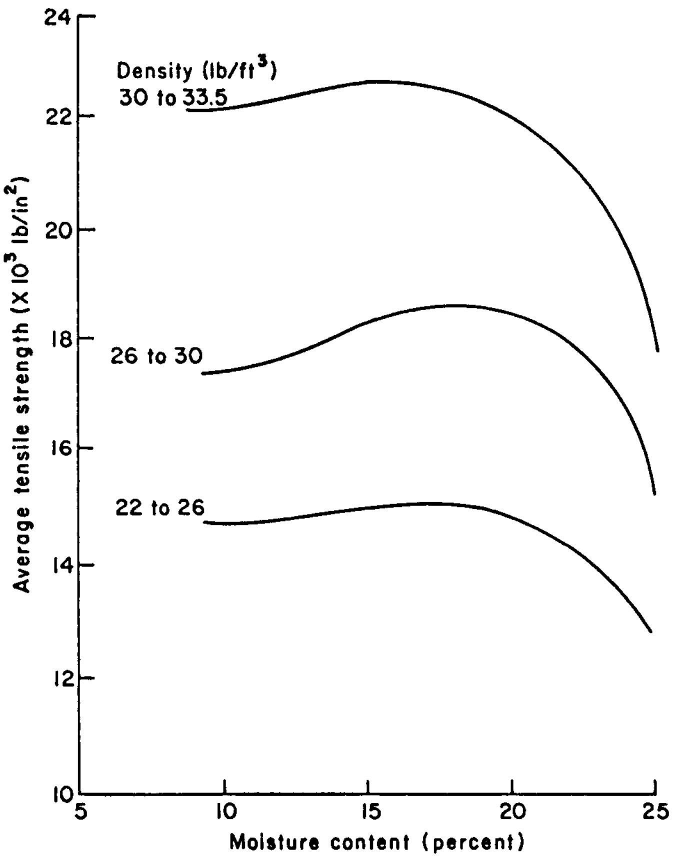

Figure 3—Average tensile strength for three density ranges of Sitka spruce at various moisture contents (Curry 1952).

The Swedish specimens apparently behaved somewhat differently than the Danish specimens. The lower percentiles of the lumber obtained from Sweden showed a decrease in tensile strength with decreasing MC below 24 percent MC (Fig. 5). Note that the green values are plotted at a moisture content of 27 percent to match assumed green value for spruce (USDA 1987). With the Danish specimens, this decrease was only observed at the highest percentile level (Fig. 5). However, because of the small sample size (approximately 47 specimens per location), no definite conclusions were possible.

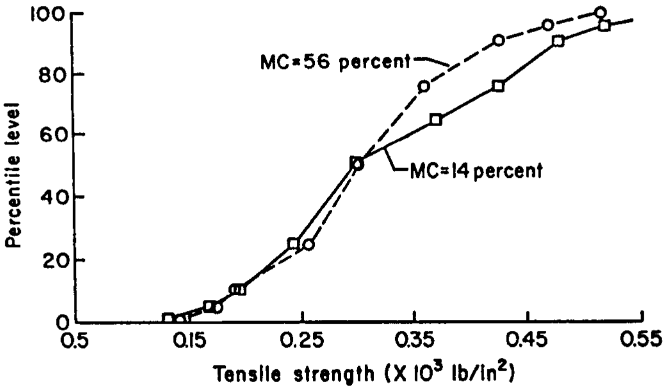

Figure 4—Effect of moisture content on tensile strength of European spruce (adapted from data given in Hoffmeyer 1978).

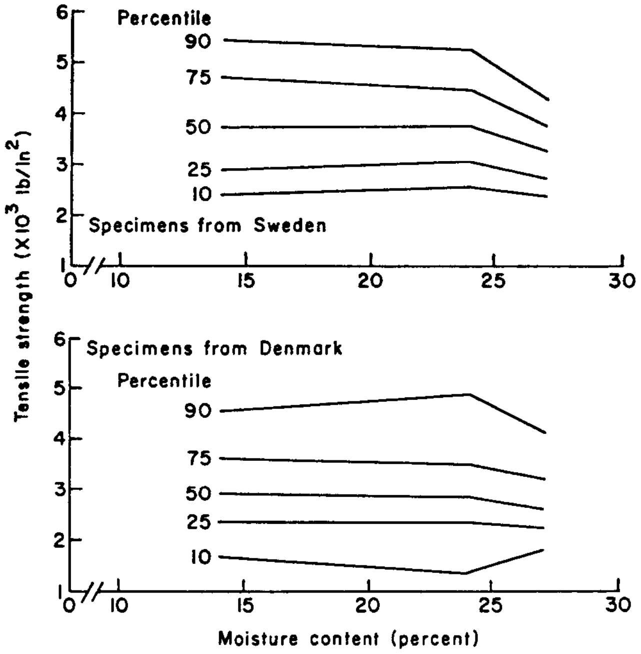

Figure 5—Effect of moisture content on tensile strength of European spruce from Sweden and Denmark (adapted from data given in Hoffmeyer 1978).

Madsen and Neilsen (1981) investigated the effect of MC on the tensile strength of No. 2 and better Hem-Fir nominal 2- by 6-in. lumber at 25 and 10 percent MC. All material used in this study had previously been dried using a commercial kiln schedule. The higher MC level was achieved by placing the lumber in a room maintained at high relative humidity so that the lumber adsorbed water. Below about 3,000 lb/in^2 (the 30th percentile), tensile strength appeared to be independent of MC (Fig. 6). The results may have been influenced by a moisture hysteresis effect not present in the Hoffmeyer (1978) study.

Of the two studies reviewed, only Hoffmeyer (1978) reported TMOE results (Fig. 7). The effect of MC on TMOE was less dependent upon the percentile level than was tensile strength. The dry to green ratio for TMOE was only a little smaller than the ratio Hoffmeyer (1978) obtained for flexural MOE.

Conclusions From Clear Wood and Lumber Studies

Tensile strength parallel to the grain is less sensitive to changes in MC than is bending strength. Clear wood studies indicate no increase in strength, and possibly a decrease in strength, below some MC values. These MC values vary by study from 5 to 20 percent. Lumber studies, including one in which the lumber had previously been dried using a commercial schedule, also indicate no increase in strength with drying for lumber in the lower tail of the cumulative strength distribution. None of these lumber studies, however, contained material of several grade levels that would allow modeling of the relationship between MC and UTS for a wide range of quality levels.

Materials and Methods

Experimental Design and Lumber Selection

The objective of the sampling program was to produce a data set having a broad range of quality for future analytical modeling. Approximately 2,700 pieces of Douglas Fir nominal 2- by 4-in. and 2- by 8-in. dimension lumber (hereafter referred to as 2 by 4 and 2 by 8 lumber) were obtained from one mill in the Pacific Northwest. Each size was represented by three grades: Select Structural, No. 1, and No. 2. The grade was established on the basis of strength-reducing growth characteristics. That is, pieces that normally would be assigned to the No. 1 and No. 2 grades because of wane, splits, shake, and other appearance factors were not selected for the test samples, nor were pieces with decay selected.

The experimental design (Fig. 8) was intended to produce four sample populations of lumber matched in terms of their estimated green strength and stiffness. The target cell size was intended to produce groups of approximately 100 specimens, but 115 boards were placed in each cell to account for expected grade changes caused by drying effects. A two-step procedure was used to assign pieces to the conditioning groups. First, pieces were graded at the mill by a qualified grader, and each board was marked with its green grade. The grade-controlling defect for the piece was noted as well as the maximum strength-reducing defect in the test span. The maximum edge defect in

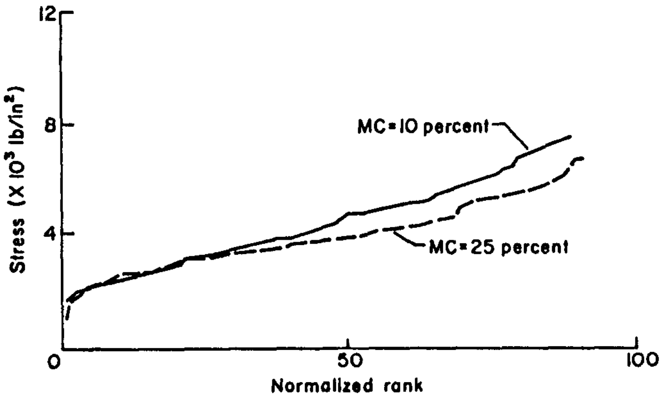

Figure 6—Effect of moisture content (MC) on tensile strength parallel to grain (Madsen and Nielsen 1981).

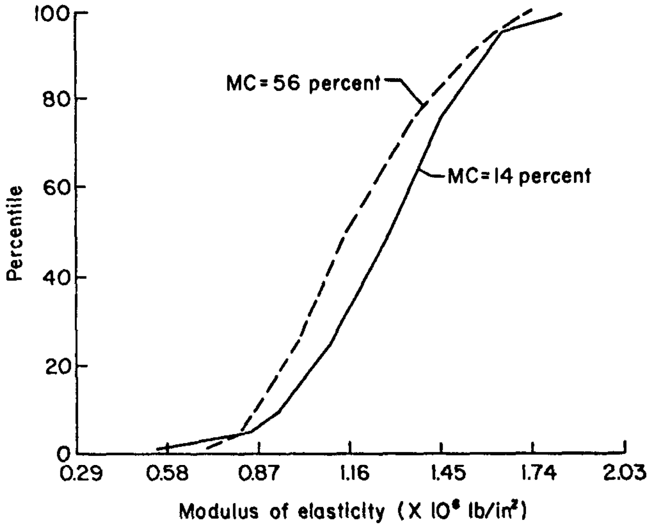

Figure 7—Effect of moisture content (MC) on elastic modulus of European spruce (adapted from data given in Hoffmeyer 1978).

the test span was also recorded. Grade classification was determined on the basis of the entire length of each piece.

Next, the lumber was nondestructively tested to measure MOE of each piece (Table 1). Within each size-grade combination, the lumber was separated into E-classes. The exact number and width of each E-class were determined after examining the distributions of MOE values within a size-grade combination. The material within each E-class was then ranked according to estimated strength ratios.

To assign lumber within a size-grade combination to a particular moisture group, the four pieces with the highest estimated strength ratios within a particular E-class were randomly assigned to one of the four MC categories (10, 15, and 20 percent MC and green).

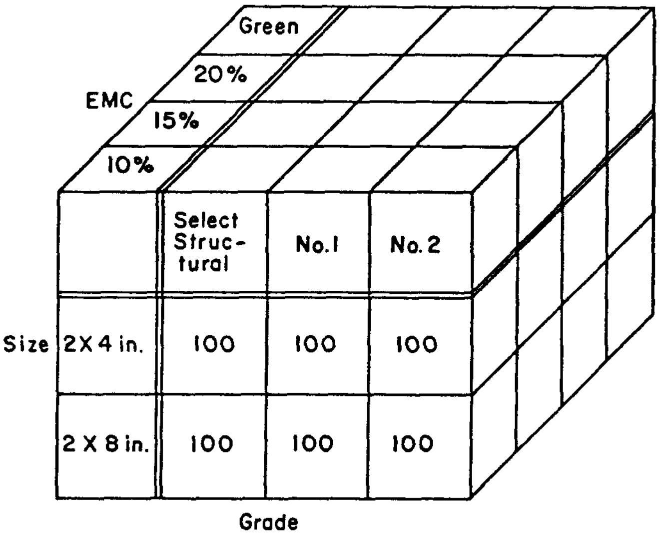

Figure 8—Experimental design for tests on relationship between equilibrium moisture content (EMC) and tensile strength.

The next four pieces were then selected for high strength ratios and the pieces assigned to groups. This procedure was followed until 115 specimens were assigned to each moisture level cell.

Drying and Conditioning

After the specimens were assigned to MC categories, the specimens intended to be conditioned to 20, 15, and 10 percent MC were loaded into conditioning chambers and allowed to come to equilibrium.

The initial setting for all 2 by 4 specimens was for a MC of 20 percent. Upon reaching 20 percent MC, the chambers containing the 15- and 10-percent MC specimens were reset for a MC of 15 percent, and the specimens intended for 20 percent MC were tested. This procedure, which was followed for all MC levels, allowed time for testing while subsequent MC levels were reached.

The 2 by 8 specimens were conditioned to the desired MC levels following similar procedures.

Testing Procedures

Specimens that reached the desired conditions were tested in tension parallel to the grain according to ASTM D 198-84 (ASTM 1989), except that a faster testing speed was used. A constant rate of loading was used such that the average specimen failed in approximately 1.5 min. The test span for tension was the middle 8 ft of each 2 by 4 specimen and the middle

12 ft of each 2 by 8 specimen. The number of growth rings per inch was recorded for each specimen. Both UTS and TMOE values were determined for each specimen using the actual cross-sectional dimensions at time of test. For the calculation of TMOE, a partial load-deflection curve was obtained for each specimen. Ovendry MC and specific gravity values were determined from cross-sectional samples removed from each specimen near the failure point.

Results and Discussion

Sample Selection and Testing Speed

The goal of the sampling program was to obtain a broad range of material quality in the samples to ensure that eventual analytical models would be applicable to a wide range of grades (Table 2). We did not intend that the exact percentage of changes found experimentally for individual grade-size combinations would be directly applicable to results obtained for equivalent grades and sizes of lumber sampled in the In-Grade Testing Program. We expected, for example, that eliminating lumber placed in a grade solely for “cosmetic” reasons could result in a lowering of the 5th-percentile strength relative to that which might be obtained had selection not been restricted to lumber with the required “strength-reducing” growth characteristic.

When this study was initiated, ASTM D 198-84 (ASTM 1989) was the only standard available for testing lumber. However, we know that tensile strength data were being collected in the U.S. and Canadian In-Grade Testing Programs at a faster rate than that specified in ASTM D 198-84. Therefore, the failure rate of approximately 1.5 min was chosen to correspond with the rate used in the In-Grade Programs (Shelley 1989). Since this study was completed, an additional ASTM standard has been approved that allows testing at a faster rate. The procedures used in this standard meet all requirements of ASTM D 4761-88 (ASTM 1989).

Verification of Populations

The green MOE and strength ratio values for any given grade-size combination indicate that distributions were matched effectively (Table 3). A pairwise comparison of the cumulative frequency distributions of green MOE using the Kolmogorov-Smirnov two-sample test statistic (Conover 1980) showed no significant differences between the treatment groups ($p > 0.75$) for virtually all pairwise comparisons. Likewise, analysis of variance by grade and by size showed no significant differences in the mean values for different MC groups. Similarly, no persistent differences in specific gravity with MC groups are evident in Table 3.

Although slightly different from the target values, the mean MC values indicate the effectiveness of the conditioning procedure (Table 4). The minimum and maximum values also show that little overlap occurred in MC values.

Moisture Effects

Mean Ultimate Tensile Stress and Tensile Modulus of Elasticity

The effects of MC on the properties of Douglas Fir dimension lumber are summarized in Table 5. Weibull distribution fit to these data is summarized in Appendix A. Analysis of variance (Table 6) indicated a significant grade by size interaction for both UTS and TMOE. In addition, UTS has a significant size by MC interaction. On average, size, grade, and MC all have a significant effect on UTS and TMOE.

In general, mean UTS first increases and then decreases with drying, whereas mean TMOE consistently increases with drying (Fig. 9). Note that in Figure 9, green values are plotted at 23 percent to correspond with green values found acceptable for Southern Pine and Douglas Fir bending models (Green and Evans 1988). The occurrence of a maxium UTS value is consistent with clear wood results previously discussed, but this value is much more pronounced than the maximum value previously observed with mean MOR (Fig. 10) (Aplin and others 1986). The mean UTS plots are also noticeably flatter than the MOR plots. For many grade-size combinations, the UTS value at 10 percent MC is only slightly different than the value for green specimens (Table 5).

The TMOE of Douglas Fir was less sensitive to changes in moisture content than was bending MOE. In drying from green to 15 percent MC, TMOE increased about 7 percent (Table 7). In a previous study on bending properties, MOE increased about 15 percent in drying from green to 15 percent MC (Aplin and others 1986).

Percentile Estimates of Ultimate Tensile Stress and Tensile Modulus of Elasticity

Trends in the UTS-MC relationship for 5th percentile UTS appear similar to those of mean UTS at equivalent stress levels (Fig. 11). At the lower stress levels, however, UTS appears to increase only slightly between green and 20 percent MC. In general, UTS does not increase nearly as much in drying from green to 15 percent average MC (Table 7) as the 25 percent increase assumed in Table 11 of ASTM D 245-88 (ASTM 1989).

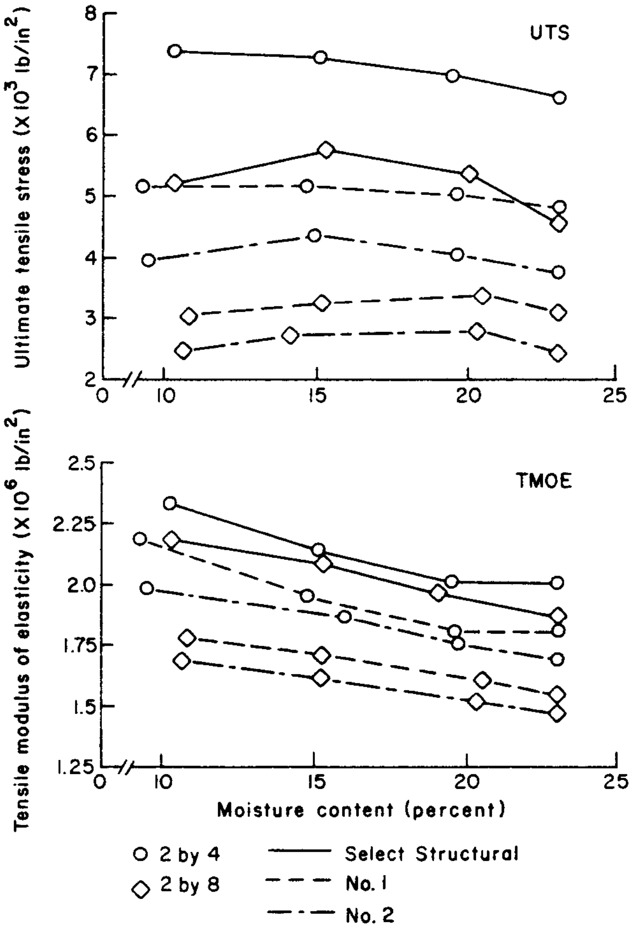

Figure 9—Effect of moisture content on average ultimate tensile stress (UTS) and average tensile modulus of elasticity (TMOE).

As was true with mean properties, 5th percentile TMOE generally improves with drying (Fig. 11). As noted in previous studies, the slope of the TMOE to MC relationship appears to be independent of percentile level. As was true with mean trends, the change in 5th percentile TMOE is only about half that previously observed for bending MOE.

The change in tensile strength between 15 and 10 percent MC is of particular interest as an indication of the potential effect of MC levels lower than 10 percent. As can be seen in Table 8, the lumber in most grade-size combinations generally lost strength between 15 and 10 percent. Even at the 50th percentile, this loss averaged about 8 percent. Thus, we anticipate that further loss could occur at lower MC levels.

Axial load and Axial Stiffness

Lumber design procedures could be simplified by the use of parameters that are not sensitive to changes in MC. Two potential parameters are axial load and axial stiffness.

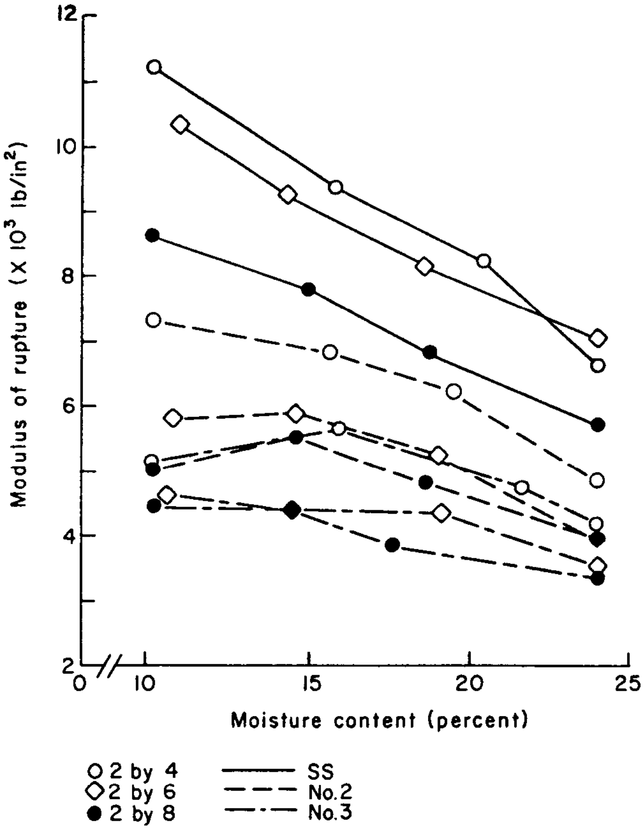

Figure 10—Effect of moisture content on average modulus of rupture (Aplin and others 1986).

Axial load *P* is the product of UTS and cross-sectional area *A:*

$$P = T \times A \tag{1}$$

where

T is ultimate tensile stress (lb/in^2),

A cross-sectional area (in^2), and

P axial load (lb).

For a given member type, length, and load configuration, axial load indicates the ability of the member to resist axial force.

Axial stiffness is the product of TMOE and cross-sectional area. The elongation d of a uniform member pulled in uniaxial tension may be calculated from

$$EA = PL/d \tag{2}$$

where

L is length (in.),

E tensile MOE (1b/in^2), and

EA axial stiffness.

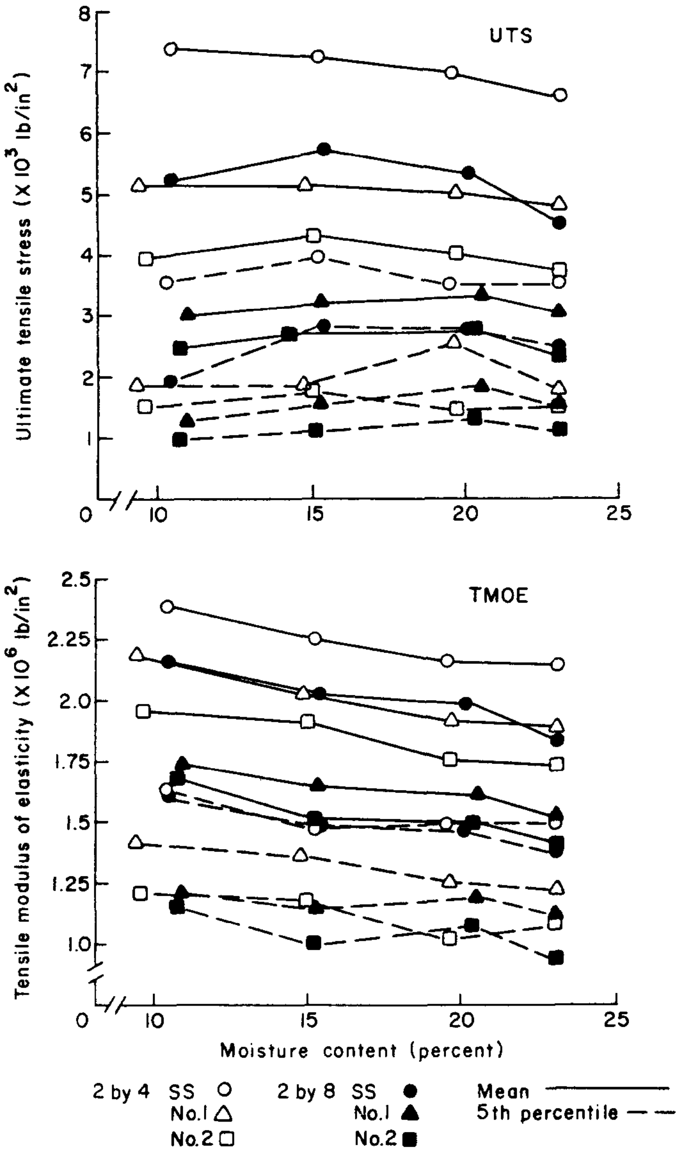

Figure 11—Effect of moisture content on average and 5th-percentile ultimate tensile stress (UTS) and tensile modulus of elasticity (TMOE).

As lumber dries, it shrinks and the cross-sectional area decreases. These decreases might offset any increases in UTS and TMOE.

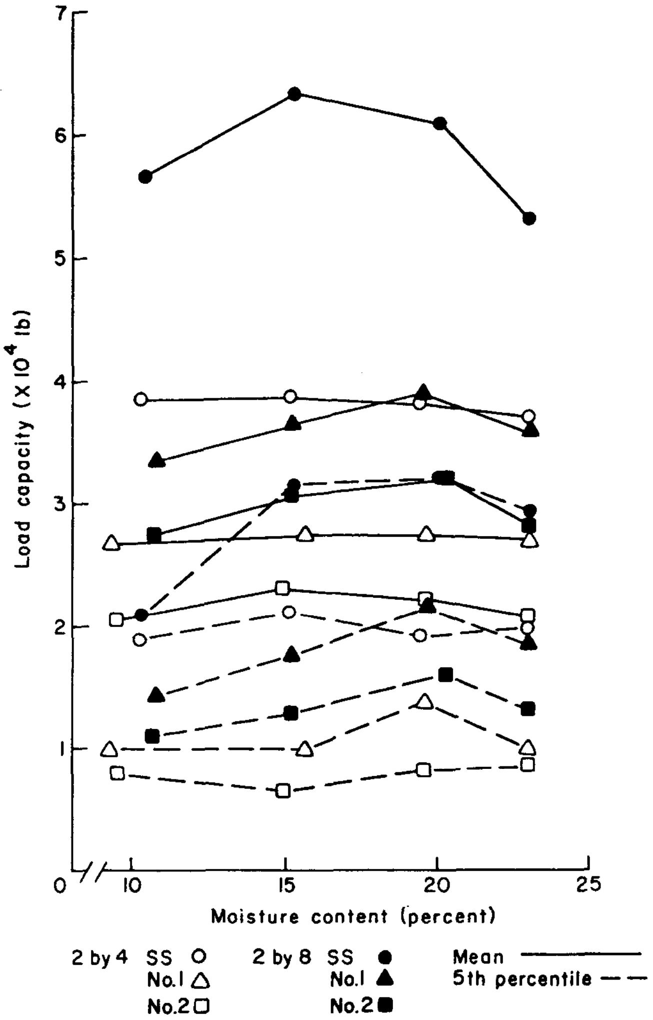

Figure 12—Effect of moisture content on axial load.

Descriptive statistics for the axial load and axial stiffness values obtained in this study are given in Table 9. Trends in axial load (Fig. 12) indicate that 2 by 4 lumber is less sensitive to changes in MC than 2 by 8 lumber. However, decreases in axial load with decreasing MC are still evident. Trends in axial stiffness (Fig. 13) indicate that 2 by 4 lumber is less sensitive to changes in MC than is 2 by 8 lumber. The general trend is that axial stiffness increases with decreasing MC; the response of 2 by 4 lumber is almost nil (Fig. 13).

Property Distributions

The effect of MC can also be discussed in terms of its general effect on lumber property distributions. Changes in the distribution of UTS (or TMOE) can be discussed more conveniently than changes in particular percentiles. To enhance our understanding of the MC effect and to provide basic information needed for future analytical studies, the distributional form of the data is analyzed and described.

Inspection by grade and size of the experimental cumulative frequency distributions (CDFs) of the four MC groups did not indicate a consistency in the relationship between UTS and MC (Appendix B, Fig. B1). However, inspection of the CDFs alone may be misleading. As was seen in Figures 9 and 11, UTS tends to first increase with decreasing MC as the

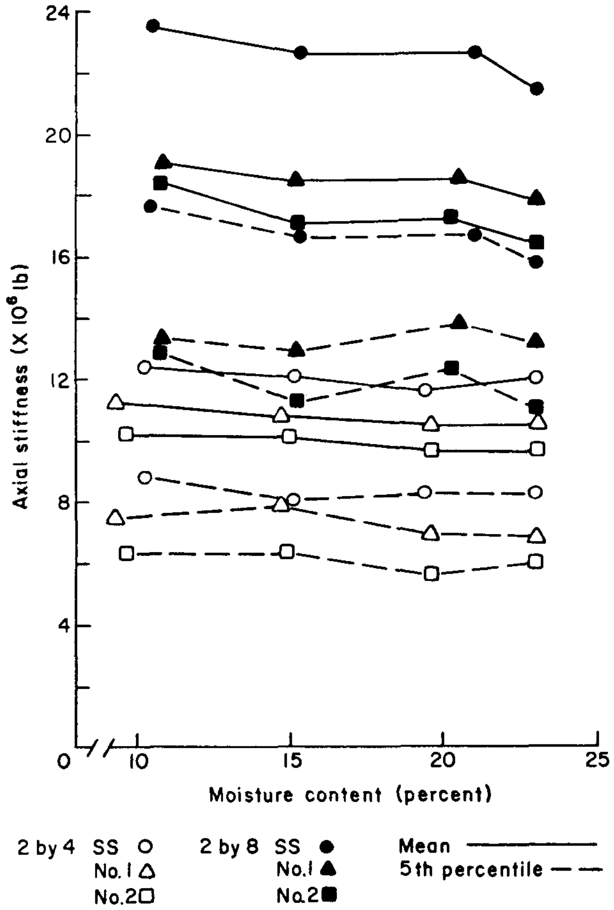

Figure 13—Effect of moisture content on axial stiffness.

lumber dries from green to 15 percent MC and then to decrease with drying below 15 percent MC. Thus, intertwining of the CDFs obscures the real relationships in the data. Relationships between UTS and MC at various percentile levels may be seen in Appendix B (Fig. B3).

With TMOE, there is a definite trend toward increasing TMOE with decreasing MC (Appendix B, Fig. B2). This observation confirms trends seen in Figures 9 and 11.

Comparison of Data Sets

Comparison of Groups

Three tests were used to test the hypothesis that no differences occurred between grade-size-MC groups. First, a Kolmogorov-Smirnov two-sample test statistic (Conover 1980) was used to test the equality of distribution pairs. Mean values of the MC groups were compared within each grade-size combination using an analysis of variance for each variable and then conducting a multiple comparison of the group means, using a series of modified two-sample t-tests (Miller 1981). Finally, a modified chi-square test was used to compare 5th percentile values. With the sample sizes used in this study, the chi-square test lacks power (will tend to indicate equality for dissimilar data groups) when applied to 5th percentiles values. This is because of the scarcity of observations in the tail regions of the distributions.

The results for UTS and TMOE are presented in Table 10. If none of the groups could be considered equal ($p < 0.2$ for each comparison), then the entry is "none equal;" otherwise, the groups are listed. For mean and 5th percentile values, the groups are ordered from low to high with respect to the indicated property. Two groups that share a common underline cannot be considered different ($p > 0.2$). Groups that do not share a common underline are significantly different ($p < 0.2$).

Ultimate Tensile Stress

Tests of the equality of the means and equality of distributions indicated that green UTS values were different from the other MC values for Select Structural specimens (Table 10). For the other grades, no consistent pattern is present. For 5th percentile UTS, no significant differences between the different MC levels were detected for 2 by 4 lumber. For 2 by 8 lumber, distinct differences in 5th percentile UTS values were found for 10 percent MC with Select Structural, for 10 and 20 percent MC with No. 1, and for 20 percent MC with No. 2.

Statistical tests of the means and distributions generally indicated a distinct difference between grades (Table 10). The 5th percentile values, however, sometimes indicated no difference between adjacent grades.

The UTS also appeared to differ significantly by lumber size (Table 10). In all but one case, significant differences between sizes were found for distribution, mean values, and 5th percentile values.

Tensile Modulus of Elasticity

Tests for the equality of means and distributions for TMOE of 2 by 4 lumber indicated that MOE values for green and 20-percent MC lumber were equal (Table 10). Distinct differences may be found at the 15- and 10-percent MC levels. For 2 by 8 lumber, the mean and distributional values were not significantly different at the 15- and 20-percent MC levels.

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Table 1—Flatwise modulus of elasticity values, by grade, for Douglas Fir lumber in the green state

			Modulus of elasticity (× $10^6$1b/in)				
Size[a] (in.)	Grade[b]	Number of specimens	Mean	Standard deviation	5th percentile	50th percentile	95th percentile
2 by 4	SS	456	1.99	0.37	1.37	2.01	2.61
	No. 1	460	1.81	0.36	1.24	1.81	2.43
	No. 2	460	1.71	0.36	1.18	1.66	2.36
2 by 8	SS	456	2.10	0.34	1.59	2.08	2.72
	No. 1	460	1.75	0.31	1.31	1.68	2.33
	No. 2	460	1.65	0.34	1.19	1.59	2.29

[a] Nominal dimensions.

[b] SS is Select Structural.

Table 2—Estimated strength ratios for the test span of each specimen, by grade, for Douglas Fir lumber in the green state

			Estimated strength ratio (percent)				
Size[a] (in.)	Grade[b]	Number of specimens	Mean	Standard deviation	5th percentile	50th percentile	95th percentile
2 by 4	SS	456	89.4	10.0	69.9	91.0	100
	No. 1	460	72.9	14.6	49.0	75.0	96
	No. 2	460	63.5	18.7	34.0	62.5	100
2 by 8	SS	456	79.9	9.8	63.0	81.0	94
	No. 1	460	11.7	11.7	50.0	69.0	88
	No. 2	460	58.1	17.9	24.0	59.0	84

[a] Nominal dimensions.

[b] SS is Select Structural.

Table 3—Effectiveness of sorting procedure used with green lumber

Size[a] (in.)	Grade[b]	Moisture content group (percent)	Green flexural MOE[c]		Mean strength ratio (percent)	Mean specific gravity[d]
			Mean	Standard deviation		
2 by 4	SS	10	1.990	0.371	88.5	0.531
		15	1.996	0.378	89.8	0.531
		20	1.991	0.376	89.4	0.524
		(green)	1.995	0.370	89.4	0.525
	No. 1	10	1.809	0.360	71.8	0.509
		15	1.810	0.355	71.0	0.502
		20	1.813	0.365	73.2	0.501
		(green)	1.809	0.364	73.3	0.493
	No. 2	10	1.710	0.365	61.5	0.500
		15	1.711	0.372	64.5	0.492
		20	1.710	0.365	63.3	0.496
		(green)	1.704	0.363	63.0	0.487
2 by 8	SS	10	2.096	0.340	79.8	0.495
		15	2.099	0.340	80.1	0.493
		20	2.100	0.340	80.1	0.489
		(green)	2.103	0.350	79.8	0.487
	No. 1	10	1.745	0.320	68.8	0.461
		15	1.749	0.320	69.1	0.464
		20	1.749	0.320	68.8	0.463
		(green)	1.749	0.310	69.0	0.458
	No. 2	10	1.651	0.330	57.6	0.460
		15	1.656	0.350	58.2	0.461
		20	1.655	0.340	57.9	0.457
		(green)	1.644	0.330	58.0	0.456

[a] Nominal dimensions.
[b] SS is Select Structural.
[c] Modulus of elasticity.
[d] Specific gravity based on ovendry weight and ovendry volume.

Table 4—Effectiveness of conditioning process

Size[a] (in.)	Grade[b]	Moisture content group (percent)	Moisture content (percent) Mean	Standard deviation	Minimum	Maximum
2 by 4	SS	10	10.2	1.1	8	12
		15	15.1	1.1	13	17
		20	19.4	0.9	18	21
		(green)	36.6	16.9	23	119
	No. 1	10	9.3	0.4	8	10
		15	14.7	1.1	13	18
		20	19.6	1.2	17	22
		(green)	41.5	22.3	22	162
	No. 2	10	9.6	0.4	9	11
		15	14.9	1.0	13	17
		20	19.6	1.2	17	22
		(green)	42.7	22.6	24	159
2 by 8	SS	10	10.4	1.1	9	12
		15	15.3	0.5	14	17
		20	21.0	0.9	18	23
		(green)	40.3	18.5	24	122
	No. 1	10	10.8	0.9	9	12
		15	15.2	0.5	14	16
		20	20.5	0.8	19	23
		(green)	40.2	22.6	24	157
	No. 2	10	10.7	1.0	8	12
		15	15.2	0.5	13	17
		20	20.3	0.9	18	23
		(green)	36.8	15.6	23	127

[a] Nominal dimensions.
[b] SS is Select Structural.

Table 5—Descriptive statistics for tensile modulus of elasticity and ultimate tensile stress of Douglas Fir[a]

Size[b] (in.)	Grade	MC group (percent)	Sample size	TMOE ($\times 10^6$ lb/in^2)			TMOE COV (percent)	UTS ($\times 10^3$ lb/in^2)			UTS COV (percent)
				Mean	SD	5th percentile[c]		Mean	SD	5th percentile[c]	
2 by 4	SS	10	102	2.389	0.466	1.633	19.501	7.385	2.034	3.577	27.537
		15	113	2.252	0.443	1.470	19.652	7.242	1.947	3.973	26.882
		20	106	2.165	0.415	1.498	29.159	6.982	1.944	3.512	27.838
		(green)	111	2.160	0.392	1.500	18.143	6.618	1.740	3.536	26.287
	No. 1	10	96	2.188	0.474	1.416	21.670	5.156	2.127	1.867	41.252
		15	105	2.032	0.427	1.363	21.036	5.157	2.106	1.862	40.825
		20	110	1.921	0.311	1.260	21.950	5.036	1.873	2.526	37.186
		(green)	114	1.898	0.442	1.232	23.266	4.826	1.878	1.790	38.907
	No. 2	10	96	1.961	0.521	1.210	26.590	3.940	2.331	1.524	59.166
		15	102	1.915	0.480	1.179	25.079	4.392	2.279	1.741	51.890
		20	108	1.769	0.465	1.024	26.267	4.069	2.087	1.459	51.289
		(green)	111	1.737	0.451	1.086	25.946	3.743	1.614	1.536	43.134
2 by 8	SS	10	109	2.169	0.363	1.615	16.740	5.216	2.361	1.919	45.272
		15	113	2.036	0.346	1.488	17.014	5.755	2.176	2.818	37.811
		20	114	1.994	0.351	1.475	17.597	5.349	2.173	2.792	40.616
		(green)	113	1.835	0.324	1.380	17.670	4.551	1.599	2.470	35.133
	No. 1	10	113	1.744	0.335	1.211	19.211	3.041	1.505	1.293	49.499
		15	114	1.649	0.316	1.145	19.165	3.258	1.391	1.572	42.682
		20	115	1.618	0.805	1.198	18.853	3.394	1.472	1.862	43.370
		(green)	115	1.527	0.286	1.128	18.701	3.063	1.194	1.551	38.971
	No. 2	10	113	1.671	0.364	1.157	21.782	2.494	1.259	0.993	50.480
		15	114	1.516	0.353	0.998	23.270	2.720	1.257	1.118	46.214
		20	114	1.503	0.332	1.080	22.095	2.783	1.305	1.320	46.881
		(green)	113	1.409	0.320	0.940	22.716	2.419	0.975	1.108	40.321

[a] SS is Select Structural; MC, moisture content; TMOE, tensile modulus of elasticity; SD, standard deviation; COV, coefficient of variation; UTS, ultimate tensile stress.

[b] Nominal dimensions.

[c] Nonparametric estimate of 5th percentile value (ASTM D 2915-88; ASTM 1989).

Table 6—Partial analysis of variance for ultimate tensile stress and tensile modulus of elasticity

Effect	Degrees of freedom	Ultimate tensile stress[a]		Tensile modulus of elasticity[a]	
		F-statistic	$p > F$	F-statistic	$p > F$
Size	1	600.55	0.0000	227.62	0.0000
Grade	2	564.41	0.0000	262.44	0.0000
Moisture content	3	11.09	0.0001	84.47	0.0000
Grade by size	2	3.75	0.0237	15.51	0.0001
Size by moisture content	3	1.29	0.2749	3.89	0.0087
Grade by moisture content	6	1.79	0.0972	0.58	0.7461
Size by grade by moisture content	6	0.88	0.5116	0.64	0.7011

[a] The null hypothesis is that the factor or interaction had no effect on ultimate tensile stress or tensile modulus of elasticity; p is the probability of rejecting this hypothesis when it is true.

Table 7—Percentage of change in mean and 5th percentile ultimate tensile stress and tensile modulus of elasticity of lumber during drying from the green condition

Property	Grade[a]	Moisture content of lumber[b] (percent)					
		2 by 4 in.			2 by 8 in.		
		20	15	10	20	15	10
MEAN VALUES							
Ultimate tensile stress	SS	5.5	9.4	11.6	17.5	26.5	15.6
	1	4.3	6.8	6.8	10.8	6.4	-0.7
	2	9.2	17.8	5.7	13.0	14.9	1.3
Tensile modulus of elasticity	SS	0.2	4.7	11.0	8.7	11.0	18.3
	1	1.4	6.2	15.3	5.9	8.0	16.2
	2	2.9	10.4	13.0	6.7	8.5	18.6
5TH PERCENTILE VALUES							
Ultimate tensile stress	SS	-0.7	12.4	1.2	13.0	14.1	-22.3
	1	41.1	4.0	4.3	20.1	1.4	16.6
	2	-5.0	13.3	-0.8	19.1	0.9	-10.4
Tensile modulus of elasticity	SS	8.9	-2.0	8.9	6.9	7.8	17.0
	1	2.3	10.6	14.9	6.2	1.5	7.4
	2	-5.7	8.6	11.4	14.9	6.2	23.1

[a] SS is Select Structural.

[b] Nominal dimensions.

Table 8—Percentage of change in ultimate tensile stress from 15 to 10 percent moisture content for Douglas Fir lumber

	Change in ultimate tensile stress (percent)						
	Select Structural		No. 1		No. 2		
Percentile	2 by 4	2 by 8	2 by 4	2 by 8	2 by 4	2 by 8	Mean
5	-10.0	-31.9	0.3	-17.7	-12.5	-6.1	-13.0
10	-7.1	-29.1	-3.3	-14.3	-20.1	-14.1	-14.7
25	-1.4	-15.1	-5.7	-7.6	-12.4	-15.4	-9.6
50	1.8	-11.8	-3.1	-11.8	-11.9	-9.6	-7.7
75	4.3	-1.2	1.9	-11.9	-9.2	-3.9	-3.3
90	2.8	-4.6	6.2	6.4	-4.3	-10.1	-0.6
95	2.9	-4.0	-8.3	10.1	-9.6	-9.0	-2.0

Table 9—Axial stiffness and load of Douglas Fir at various moisture contents[a]

				Axial stiffness (× 10^6 lb)				Load (× 10^4 lb)			
Size[b] (in.)	Grade	MC group (percent)	Sample size	Mean	SD	5th percentile[c]	COV (percent)	Mean	SD	5th percentile[c]	Load COV (percent)
2 by4	SS	10	102	12.411	2.249	8.801	18.125	3.841	1.042	1.881	27.117
		15	113	12.051	2.279	8.009	18.911	3.881	1.038	2.122	26.742
		20	106	11.826	2.206	8.336	18.651	3.815	1.052	1.920	27.568
		(green)	111	12.074	2.190	8.347	18.141	3.700	9.734	1.979	26.310
	No. 1	10	96	11.341	2.340	7.524	20.638	2.672	1.093	0.991	40.911
		15	105	10.815	2.174	7.911	20.106	2.744	1.100	0.996	40.075
		20	110	10.491	2.237	6.994	21.323	2.748	1.009	1.388	36.707
		(green)	114	10.592	2.449	6.915	23.122	2.693	1.046	0.998	38.832
	No. 2	10	96	10.228	2.603	6.365	25.446	2.053	1.201	0.794	58.511
		15	102	10.179	2.476	6.397	24.321	2.331	1.188	0.641	50.969
		20	108	9.665	2.486	5.676	25.728	2.222	1.135	0.801	51.088
		(green)	111	9.689	2.501	6.093	25.808	2.087	0.895	0.847	42.909
2 by 8	SS	10	109	23.547	3.806	17.654	16.164	5.658	2.540	2.080	44.897
		15	113	22.621	3.767	16.695	16.653	6.393	2.398	3.148	37.501
		20	114	22.717	3.930	16.890	17.300	6.099	2.477	3.190	40.610
		(green)	113	21.438	3.761	15.848	17.544	5.316	1.853	2.926	34.856
	No. 1	10	113	19.146	3.597	13.395	18.788	3.337	1.634	1.429	48.955
		15	114	18.497	3.428	12.925	18.532	3.651	1.537	1.755	42.090
		20	115	18.589	3.394	13.819	18.257	3.896	1.658	2.168	42.563
		(green)	115	17.899	3.344	13.210	18.682	3.590	1.395	1.846	38.877
	No. 2	10	113	18.410	3.861	12.928	20.973	2.745	1.369	1.087	49.887
		15	114	17.044	3.917	11.286	22.981	3.057	1.408	1.278	46.058
		20	114	17.305	3.795	12.358	21.930	3.203	1.500	1.510	46.829
		(green)	113	16.455	3.692	11.077	22.437	2.826	1.136	1.327	40.192

[a] SS is Select Structural; MC, moisture content; SD, standard deviation; COV, coefficient of variation.
[b] Nominal dimensions.
[c] Nonparametric estimate of the 5th percentile value (ASTM D 2915-88, ASTM 1989).

Table 10—Test of equality of experimental parameters for tensile modulus of elasticity and ultimate tensile stress[a,b,c]

Size[d] (in.)	Grade[e]	Moisture content group (percent)	Tensile modulus of elasticity		Ultimate tensile stress		
			Distribution	Mean	Distribution	Mean	5th percentile
			MOISTURE CONTENT[f]				
2 by 4	SS		G 20 15 10	G 20 15 10	G 20 15 10	G 20 15 10	20 G 10 15
	No. 1		G 20 15 10	G 20 15 10	G 20 15 10	G 20 10 15	G 15 10 20
	No. 2		G 20 15 10	G 20 15 10	10 G 20 15	G 10 20 15	20 10 G 15
2 by 8	SS		G 20 15 10	G 20 15 10	G 10 20 15	G 10 20 15	10 G 20 15
	No. 1		G 20 15 10	G 20 15 10	10 G 15 20	10 G 15 20	10 G 15 20
	No. 2		G 20 15 10	G 20 15 10	10 G 20 15	10 G 20 15	10 G 15 20
			GRADE[g]				
2 by 4		10	None equal	None equal	None equal	None equal	None equal
2 by 8			None equal	None equal	None equal	None equal	None equal
2 by 4		15	2 1 SS	None equal	None equal	None equal	2 1 SS
2 by 8			None equal	None equal	None equal	None equal	None equal
2 by 4		20	None equal	None equal	None equal	None equal	2 1 SS
2 by 8			None equal	None equal	None equal	None equal	2 1 SS
2 by 4		(green)	None equal	None equal	None equal	None equal	2 1 SS
2 by 8			None equal	None equal	None equal	None equal	None equal

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Table 10—Test of equality of experimental parameters for tensile modulus of elasticity and ultimate tensile stress[a,b,c]—con.

Size[d] (in.)	Grade[e]	Moisture content group (percent)	Tensile modulus of elasticity: Distribution	Tensile modulus of elasticity: Mean	Ultimate tensile stress: Distribution	Ultimate tensile stress: Mean	Ultimate tensile stress: 5th percentile
				SIZE[h]			
	SS	10	Not equal	Not equal	Not equal	Not equal	Not equal
		15	Not equal	Not equal	Not equal	Not equal	Not equal
		20	Not equal	Not equal	Not equal	Not equal	Not equal
		(green)	Not equal	Not equal	Not equal	Not equal	Not equal
	No. 1	10	Not equal	Not equal	Not equal	Not equal	Not equal
		15	Not equal	Not equal	Not equal	Not equal	8 4
		20	Not equal	Not equal	Not equal	Not equal	Not equal
		(green)	Not equal	Not equal	Not equal	Not equal	Not equal
	No. 2	10	Not equal	Not equal	Not equal	Not equal	Not equal
		15	Not equal	Not equal	Not equal	Not equal	Not equal
		20	Not equal	Not equal	Not equal	Not equal	Not equal
		(green)	Not equal	Not equal	Not equal		

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[a] Equality of groups not rejected at $p = 0.2$.

[b] Tests of distribution based on Kolmogorov-Smirnov tests of means based on analysis of variance and modified multiple comparison t-test. Tests of 5th percentiles based on a modified chi-square test.

[c] Groups sharing a common underline cannot be considered different ($p \geq 0.2$). Groups that do not share a common underline can be considered different ($p < 0.2$). For distributions, order of groups does not represent order of distribution. For means and 5th percentiles, groups are ranked from low to high.

[d] Nominal dimensions.

[e] SS is Select Structural.

[f] Moisture content groups: G, green; 10, 15, and 20 percent.

[g] Grades: 2 is No. 2; 3 is No. 3.

[h] Nominal size: 4 is 2 by 4; 8 is 2 by 8.

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Appendix A—Distributional Form of Tensile Data

Normal Distribution

The data were tested for normality using the Kolmogorov-Smirnov (KS), the Anderson-Darling (AD), and the Shapiro-Francia (SF) tests. Details of these goodness-of-fit tests can be found in D'Agostino and Stephens (1986). Skewness (lack of symmetry) and kurtosis (degree of flatness) were also examined. Because the sample sizes used in this study were smaller than required to assure that the coefficients of skewness and kurtosis were normally distributed, critical values for these coefficients were obtained from Table A6 of Snedecor and Cochran (1967).

All three normality tests indicated a lack of normality for ultimate tensile stress (UTS), especially the more sensitive Anderson-Darling (AD) test for goodness-of-fit (D'Agostino and Stephens 1986). In 19 of 24 grade-size combinations (Table Al), the UTS data exhibited significant skewness. Only the two higher grades of nominal 2- by 4-in. lumber tended not to be significantly skewed. Kurtosis was significant only 10 of 24 times, mostly in No. 2 grade nominal 2- by 8-in. lumber. Distributions that exhibited significant kurtosis tended to be flatter than would be expected for a normal distribution.

Tensile modulus of elasticity (TMOE) tended to be normally distributed for 2 by 4 lumber and Select Structural 2 by 8 lumber, but not for No. 1 and No. 2 grade 2 by 8 lumber. With TMOE, skewness was also the primary reason to reject normality. Normality was rejected 10 of 24 times, mostly with No. 2 grade lumber. Kurtosis was significant only 2 of 24 times. These results are similar to those obtained with bending MOE in previous studies (Aplin and others 1986; McLain and others 1984).

Results of normality tests for axial stiffness and axial load are not presented because they were virtually identical to those for TMOE and UTS, respectively.

Weibull Distribution

Tables A2 through A5 present the estimated parameters for the three-parameter Weibull distribution fit to the data using a maximum-likelihood estimation procedure. Tables A6 through A9 present the estimates for the two-parameter Weibull distribution. The Weibull distribution was selected because of its flexibility in fitting both right-skewed[1] (shape parameters less than about 3.6) and left-skewed[2] (shape parameters greater than about 3.6) distributions.

As noted previously for bending (Aplin and others 1986; McLain and others 1984), the UTS distribution of 2 by 4 Select Structural lumber tends to be normal or skewed to the left (Table A2). Unlike MOR, UTS of 2 by 8 Select Structural lumber is right skewed. The UTS of the lower grades also tends to be right skewed for both widths. As with bending MOE, tensile MOE tends to range from normal to skewed slightly to the right for all grades and sizes. As noted, the skewness of axial stiffness and load parallels that of MOE and UTS.

The goodness-of-fit of the two- and three-parameter Weibull distribution was evaluated using the KS test, AD test, and a Shapiro-Wilk-type correlation test (CT) (Evans and others 1989). For complete data sets, all the tests have good power against a number of distributional alternatives. The three-parameter distribution appears to provide a satisfactory fit to both UTS and TMOE (Table A10). The two-parameter Weibull distribution does not usually provide an adequate fit to the data, especially for lower grade and wider lumber (Table All). For two-parameter and three-parameter distributions, percentage differences between Weibull and nonparameteric point estimates are shown for comparison.

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[1] A right-skewed distribution has a relatively long "tail" toward increasing values of the property.

[2] Warren, W.G. 1978. Program for maximum-likelihood estimation of Weibull parameters. Personal communication to Forest Products Laboratory, Madison, WI.

Table A1—Assessment of normality for ultimate tensile stress and tensile modulus of elasticity[a, b]

Size[c] (in.)	Grade[d]	Moisture content group (percent)	Ultimate tensile stress					Tensile modulus of elasticity				
			KS	AD	SF	Skewness[e]	Kurtosis[f]	KS	AD	SF	Skewness	Kurtosis
2 by 4	SS	10	–	*	–	–	**	–	–	–	–	–
		15	**	**	**	**	–	–	–	–	–	–
		20	–	*	*	*	–	–	–	–	–	–
		(green)	–	*	–	–	**	–	–	–	–	–
	No. 1	10	–	**	*	–	**	–	–	–	–	–
		15	–	–	–	*	–	–	–	–	–	–
		20	–	*	–	–	–	–	–	–	–	–
		(green)	–	–	–	–	*	–	–	–	–	*
	No. 2	10	**	**	**	**	–	–	*	*	**	–
		15	**	**	**	**	–	–	–	–	–	–
		20	**	**	**	**	–	–	–	–	–	*
		(green	–	*	**	**	–	*	*	–	*	–
2 by 8	SS	10	–	**	**	**	–	–	–	–	–	–
		15	**	**	**	**	–	–	–	–	–	–
		20	**	**	**	**	–	–	–	–	*	–
		(green)	**	**	**	**	–	–	–	–	–	–
	No. 1	10	**	**	**	**	**	*	–	–	–	–
		15	**	**	**	**	**	**	–	–	**	–
		20	**	**	**	**	**	**	**	**	**	–
		(green)	**	**	**	**	**	–	*	*	*	–
	No. 2	10	**	**	**	**	**	**	**	**	**	–
		15	**	**	**	**	**	**	**	**	**	–
		20	**	**	**	**	–	**	**	**	**	–
		(green)	**	**	**	**	–	**	**	*	*	–

[a] Dash (–), no reason to reject normality with $p > 0.05$.
* reason to reject normality with $0.01 < p \leq 0.05$.
** reason to reject normality with $p \leq 0.01$.

[b] KS is Kolmogorov-Smirnov goodness-of-fit test; AS, Anderson-Darling test; SF, Shapiro–Francia test.

[c] Nominal dimensions.

[d] SS is Select Structural.

[e] Lack of symmetry.

[f] Degree of flatness.

Table A2—Three-parameter Weibull distribution for ultimate tensile stress of Douglas Fir lumber at various moisture contents

			Ultimate tensile stress (× 10^3 lb/in^2)							
			Estimated Weibull parameters			Weibull S-percent point			50 percent tolerance limit; 95 percent CI	
Size[a] (in.)	Grade[b]	Moisture content group (percent)	Shape	Scale	Location	Estimate	95 percent lower CI[c]	95 percent upper CI	Weibull	Non-parametric[d]
2 by 4	SS	10	4.284	8.139	0	4.069	3.438	4.700	3.540	3.190
		15	4.453	7.943	0	4.077	3.581	4.573	3.661	1.510
		20	4.274	7.692	0	3.839	3.316	4.363	3.400	2.670
		(green)	4.274	7.055	0.214	3.735	3.171	4.300	3.262	3.000
	No. 1	10	2.069	4.703	0.990	2.109	1.760	2.459	1.816	1.530
		15	2.615	5.799	0	1.863	1.468	2.257	1.532	1.410
		20	2.725	5.208	0.317	2.101	1.733	2.470	1.792	1.710
		(green)	2.370	4.669	0.691	2.024	1.687	2.361	1.741	1.510
	No. 2	10	1.349	3.319	0.901	1.269	1.115	1.422	1.139	0.970
		15	1.425	3.466	1.247	1.678	1.511	1.845	1.538	1.460
		20	1.597	3.614	0.832	1.394	1.202	1.587	1.233	1.25
		(green)	1.977	3.431	0.702	1.465	1.250	1.681	1.284	0.890
2 by 8	SS	10	1.722	4.450	1.243	2.036	1.771	2.300	1.814	1.460
		15	1.833	4.298	1.938	2.788	2.538	3.039	2.578	2.446
		20	2.083	4.817	1.092	2.249	1.956	2.542	2.003	2.347
		(green)	1.985	3.395	1.546	2.306	2.103	2.510	2.136	2.333
	No. 1	10	1.658	2.622	0.705	1.143	1.008	1.277	1.030	1.033
		15	1.560	2.324	1.169	1.516	1.399	1.632	1.418	1.305
		20	1.480	2.235	1.382	1.682	1.580	1.784	1.597	1.598
		(green)	1.505	1.946	1.305	1.576	1.481	1.671	1.496	1.362
	No. 2	10	1.492	1.995	0.696	0.969	0.874	1.064	0.889	0.901
		15	1.531	2.047	0.878	1.172	1.072	1.272	1.088	0.977
		20	1.678	2.320	0.719	1.114	0.992	1.236	1.011	1.057
		(green)	2.204	2.290	0.393	0.988	0.842	1.134	0.865	0.735

[a] Nominal dimensions.
[b] SS is Select Structural.
[c] CI is confidence interval.
[d] Nonparametric estimate of 5th percentile value (ASTM D 2915-88, 1989).

Table A3—Three-parameter Weibull distribution for tensile modulus of elasticity of Douglas Fir lumber at various moisture contents

			Tensile modulus of elasticity (× 10^6 lb/in^2)							
		Moisture content	Estimated Weibull parameters			Weibull 5-percent point			50 percent tolerance limit; 95 percent CI	
Size[a] (in.)	Grade[b]	group (percent)	Shape	Scale	Location	Estimate	95 percent lower CI[c]	95 percent upper CI	Weibull	Non-parametric[d]
2 by 4	SS	10	3.263	1.518	1.030	2.386	2.285	2.487	2.301	2.330
		15	3.316	1.466	0.938	2.250	2.158	2.342	2.173	2.150
		20	3.368	1.393	0.916	2.164	2.077	2.252	2.091	2.130
		(green)	3.103	1.237	1.053	2.153	2.105	2.200	2.125	2.100
	No. 1	10	3.113	1.503	0.842	2.179	2.074	2.284	2.091	2.060
		15	2.812	1.231	0.937	2.017	1.926	2.108	1.941	1.920
		20	2.458	1.089	0.955	1.893	1.804	1.982	1.819	1.810
		(green)	2.605	1.192	0.840	1.876	1.785	1.966	1.799	1.810
	No. 2	10	1.979	1.110	0.977	1.899	1.787	2.012	1.805	1.770
		15	2.961	1.471	0.601	1.901	1.799	2.004	1.815	1.780
		20	2.439	1.184	0.720	1.739	1.640	1.838	1.656	1.630
		(green)	2.350	1.120	0.745	1.703	1.612	1.794	1.627	1.570
2 by 8	SS	10	3.306	1.232	1.062	2.165	2.089	2.240	2.102	2.090
		15	3.234	1.145	1.009	2.031	1.960	2.101	1.972	1.950
		20	3.095	1.132	0.979	1.985	1.913	2.056	1.925	1.890
		(green)	2.909	0.980	0.960	1.824	1.758	1.890	1.769	1.750
	No. 1	10	2.235	1.107	0.752	1.740	1.672	1.808	1.683	1.620
		15	2.267	0.764	0.972	1.622	1.558	1.686	1.568	1.550
		20	1.892	0.623	1.065	1.578	1.518	1.638	1.528	1.520
		(green)	2.129	0.650	0.951	1.498	1.441	1.556	1.450	1.460
	No. 2	10	2.145	0.833	0.934	1.636	1.564	1.708	1.575	1.530
		15	2.284	0.858	0.755	1.487	1.417	1.557	1.428	1.410
		20	1.707	0.613	0.957	1.451	1.387	1.515	1.398	1.390
		(green)	2.732	0.917	0.593	1.395	1.330	1.459	1.341	1.310

[a] Nominal dimensions.

[b] SS is Select Structural.

[c] CI is confidence interval.

[d] Nonparametric estimate of 5th percentile value (ASTM D 2915-88, 1989).

Table A4—Three-parameter Weibull distribution for axial load of Douglas Fir lumber at various moisture contents

			Axial load (× 10^4 lb)							
			Estimated Weibull parameters			Weibull 5-percent point			50 percent tolerance limit; 95 percent CI	
Size[a] (in.)	Grade[b]	Moisture content group (percent)	Shape	Scale	Location	Estimate	95 percent lower CI[c]	95 percent upper CI	Weibull	Non-parametric[d]
2 by 4	SS	10	4.357	4.229	0	2.139	1.813	2.464	1.866	1.698
		15	4.491	4.254	0	2.196	1.931	2.461	1.973	0.837
		20	4.333	4.200	0	2.116	1.832	2.400	1.878	1.462
		(green)	4.252	3.929	0.135	2.088	1.773	2.404	1.824	1.660
	No. 1	10	2.067	2.416	0.532	1.107	0.928	1.285	0.957	0.790
		15	2.673	3.083	0	1.015	0.805	1.225	0.839	0.780
		20	2.768	2.899	0.169	1.161	0.959	1.362	0.991	0.951
		(green)	2.374	2.604	0.387	1.132	0.944	1.319	0.974	0.849
	No. 2	10	1.354	1.719	0.479	0.671	0.591	0.751	0.604	0.502
		15	1.500	1.900	0.619	0.881	0.785	0.978	0.800	0.802
		20	1.599	1.967	0.460	0.767	0.662	0.872	0.679	0.698
		(green)	1.984	1.909	0.395	0.822	0.701	0.942	0.721	0.502
2 by 8	SS	10	1.744	4.844	1.338	2.220	1.930	2.511	1.976	1.600
		15	1.846	4.769	2.159	3.113	2.833	3.393	2.878	2.720
		20	2.091	5.511	1.228	2.559	2.223	2.895	2.277	2.720
		(green)	2.019	4.000	1.776	2.695	2.453	2.937	2.492	2.730
	No. 1	10	1.670	2.873	0.778	1.263	1.115	1.412	1.139	1.140
		15	1.582	2.604	1.314	1.712	1.580	1.844	1.601	1.450
		20	1.518	2.597	1.565	1.932	1.811	2.053	1.830	1.799
		(green)	1.494	2.257	1.549	1.858	1.748	1.967	1.766	1.600
	No. 2	10	1.503	2.185	0.776	1.079	0.974	1.184	0.991	1.010
		15	1.530	2.292	0.995	1.323	1.211	1.435	1.229	1.100
		20	1.678	2.666	0.831	1.285	1.145	1.425	1.167	1.230
		(green)	2.209	2.672	0.461	1.157	0.987	1.328	1.014	0.840

[a] Nominal dimensions.
[b] SS is Select Structural.
[c] CI is confidence interval.
[d] Nonparametric estimate of 5th percentile value (ASTM D 2915-88, 1989).

Table A5—Three-parameter Weibull distribution for axial stiffness of Douglas Fir lumber at various moisture contents

			Axial stiffness (× 10^6 lb)							
			Estimated Weibull parameters			Weibull 5-percent point			50 percent tolerance limit; 95 percent CI	
Size[a] (in.)	Grade[b]	Moisture content group (percent)	Shape	Scale	Location	Estimate	95 percent lower CI[c]	95 percent upper CI	Weibull	Non-parametric[d]
2 by 4	SS	10	3.743	8.235	4.982	12.449	11.962	12.935	12.040	12.133
		15	3.431	7.758	5.084	12.056	11.582	12.529	11.658	11.522
		20	3.386	7.442	5.146	11.825	11.358	12.291	11.433	11.542
		(green)	3.148	6.997	5.811	12.039	11.585	12.493	11.658	11.611
	No. 1	10	3.346	7.911	4.234	11.325	10.808	11.841	10.891	10.706
		15	2.874	6.366	5.147	10.751	10.288	11.214	10.363	10.265
		20	2.555	5.979	5.180	10.360	9.890	10.829	9.966	9.920
		(green)	2.575	6.545	4.783	10.460	9.957	10.964	10.038	9.984
	No. 2	10	2.022	5.654	5.216	9.933	9.361	10.504	9.453	9.174
		15	3.045	7.736	3.265	10.123	9.595	10.651	9.680	9.541
		20	2.546	6.562	3.845	9.527	8.996	10.058	9.081	8.893
		(green)	2.328	6.160	4.232	9.495	8.989	10.002	9.070	8.800
2 by 8	SS	10	3.305	12.947	11.909	23.497	22.707	24.287	22.834	22.645
		15	3.284	12.608	11.305	22.582	21.816	23.347	21.939	21.850
		20	3.066	12.555	11.470	22.611	21.810	23.411	21.939	21.534
		(green)	2.929	11.443	11.223	21.320	20.558	22.083	20.680	20.351
	No. 1	10	3.335	12.196	8.197	19.123	18.393	19.854	18.510	17.897
		15	2.267	8.282	11.156	18.201	17.508	18.895	17.619	17.588
		20	1.894	6.946	12.422	18.145	17.477	18.814	17.584	17.573
		(green)	2.055	7.372	11.366	17.534	16.866	18.203	16.973	16.861
	No. 2	10	2.205	9.065	10.385	18.063	17.292	18.833	17.416	16.778
		15	2.342	9.770	8.384	16.739	15.960	17.518	16.085	15.655
		20	1.729	7.097	10.983	16.724	15.993	17.455	16.111	15.879
		(green)	2.780	10.746	6.883	16.302	15.557	17.048	15.677	15.233

[a] Nominal dimensions.
[b] SS is Select Structural.
[c] CI is confidence interval.
[d] Nonparametric estimate of 5th percentile value (ASTM D 2915-88, 1989).

Table A6.—Two-parameter Weibull distribution for ultimate tensile stress of Douglas Fir lumber at various moisture contents

			Ultimate tensile stress (× 10^3 lb/in^2)						
			Estimated Weibull parameters[c]		Weibull 5-percent point			50 percent tolerance limit; 95 percent CI	
Size[a] (in.)	Grade[b]	Moisture content group (percent)	Shape	Scale	Estimate	95 percent lower CI[d]	95 percent upper CI	Weibull	Non-parametric[e]
2 by 4	SS	10	4.284	8.139	4.069	3.531	4.607	3.617	3.190
		15	4.453	7.943	4.077	3.582	4.572	3.661	1.510
		20	4.274	7.692	3.839	3.338	4.341	3.418	2.670
		(green)	4.423	7.276	3.718	3.265	4.171	3.338	3.000
	No. 1	10	2.661	5.817	1.905	1.495	2.316	1.561	1.530
		15	2.615	5.799	1.863	1.482	2.243	1.543	1.410
		20	2.923	5.651	2.046	1.678	2.414	1.737	1.710
		(green)	2.824	5.429	1.897	1.545	2.249	1.601	1.510
	No. 2	10	1.837	4.467	0.887	0.622	1.152	0.664	0.970
		15	2.079	4.987	1.195	0.889	1.501	0.939	1.460
		20	2.099	4.617	1.122	0.840	1.404	0.885	1.250
		(green)	2.489	4.228	1.282	1.016	1.547	1.058	0.890
2 by 8	SS	10	2.381	5.902	1.695	1.321	2.070	1.381	1.460
		15	2.817	6.469	2.525	1.850	2.657	1.915	2.446
		20	2.637	6.034	1.957	1.581	2.332	1.641	2.347
		(green)	3.002	5.096	1.895	1.578	2.211	1.629	2.333
	No. 1	10	2.148	3.446	0.865	0.668	1.061	0.700	1.033
		15	2.445	3.676	1.091	0.875	1.306	0.910	1.305
		20	2.387	3.831	1.104	0.885	1.323	0.920	1.598
		(green)	2.675	3.446	1.135	0.929	1.342	0.962	1.302
	No. 2	10	2.122	2.829	0.698	0.534	0.862	0.561	0.901
		15	2.294	3.079	0.844	0.663	1.024	0.692	0.977
		20	2.283	3.155	0.859	0.671	1.047	0.701	1.057
		(green)	2.660	2.727	0.893	0.721	1.064	0.749	0.735

“Nominal dimensions.

[b] SS is Select Structural.

[c] Location for each parameter was zero.

[d] CI is confidence interval.

[e] Nonparametric estimate of 5th percentile value (ASTM D 2915-88, 1989).

Table A7—Two-parameter Weibull distribution for tensile modulus of elasticity of Douglas Fir lumber at various moisture contents

			Tensile modulus of elasticity (× 10^6 lb/in^2)						
			Estimated Weibull parameters[c]		Weibull 5-percent point			50 percent tolerance limit; 95 percent CI	
Size[a] (in.)	Grade[b]	Moisture content group (percent)	Shape	Scale	Estimate	95 percent lower CI[d]	95 percent upper CI	Weibull	Non-parametric[e]
2 by 4	SS	10	5.751	2.580	2.420	2.324	2.517	2.339	2.330
		15	5.696	2.433	2.281	2.194	2.369	2.208	2.150
		20	5.839	2.335	2.193	2.109	2.278	2.123	2.130
		(green)	6.006	2.323	2.186	2.106	2.265	2.119	2.070
	No. 1	10	5.027	2.377	2.210	2.107	2.313	2.123	2.060
		15	5.238	2.205	2.056	1.967	2.145	1.981	1.920
		20	4.872	2.090	1.939	1.851	2.027	1.865	1.810
		(green)	4.435	2.073	1.919	1.831	2.006	1.845	1.810
	No. 2	10	3.969	2.161	1.970	1.853	2.087	1.872	1.770
		15	4.299	2.101	1.929	1.827	2.032	1.843	1.780
		20	4.203	1.947	1.784	1.690	1.879	1.705	1.630
		(green)	4.100	1.910	1.747	1.654	1.841	1.669	1.570
2 by 8	SS	10	6.296	2.323	2.192	2.115	2.269	2.127	2.090
		15	6.281	2.182	2.058	1.987	2.129	1.999	1.950
		20	5.877	2.142	2.012	1.938	2.086	1.950	1.890
		(green)	5.932	1.971	1.853	1.786	1.921	1.796	1.750
	No. 1	10	5.628	1.883	1.764	1.696	1.833	1.707	1.620
		15	5.347	1.781	1.663	1.596	1.730	1.607	1.550
		20	5.291	1.747	1.630	1.563	1.696	1.574	1.520
		(green)	5.553	1.647	1.541	1.482	1.601	1.491	1.460
	No. 2	10	4.738	1.819	1.684	1.607	1.761	1.619	1.530
		15	4.440	1.657	1.525	1.452	1.599	1.463	1.410
		20	4.602	1.638	1.513	1.442	1.584	1.453	1.390
		(green)	4.647	1.537	1.421	1.354	1.487	1.365	1.310

[a] Nominal dimensions.

[b] SS is Select Structural.

[c] Location for each parameter was zero.

[d] CI is confidence interval.

[e] Nonparametric estimate of 5th percentile value (ASTM D 2915-88, 1989).

Table A8—Two-parameter Weibull distribution for axial load of Douglas Fir lumber at various moisture contents

Size[a] (in.)	Grade[b]	Moisture content group (percent)	Axial load ($\times 10^4$ lb)						
			Estimated Weibull parameters[c]		Weibull 5-percent point			50 percent tolerance limit; 95 percent CI	
			Shape	Scale	Estimate	95 percent lower CI[d]	95 percent upper CI	Weibull	Non-parametric[e]
2 by 4	SS	10	4.357	4.229	2.139	1.861	2.417	1.905	1.698
		15	4.491	4.254	2.196	1.931	2.461	1.974	0.837
		20	4.333	4.200	2.116	1.843	2.389	1.887	1.462
		(green)	4.420	4.068	2.077	1.824	2.331	1.865	1.660
	No. 1	10	2.682	3.014	0.996	0.783	1.208	0.818	0.790
		15	2.673	3.083	1.015	0.811	1.219	0.844	0.780
		20	2.964	3.082	1.132	0.931	1.333	0.963	0.951
		(green)	2.829	3.029	1.060	0.864	1.256	0.895	0.849
	No. 2	10	1.856	2.328	0.470	0.331	0.609	0.353	0.502
		15	2.115	2.646	0.650	0.486	0.814	0.512	0.802
		20	2.107	2.521	0.616	0.462	0.770	0.486	0.698
		(green)	2.503	2.357	0.719	0.571	0.868	0.595	0.502
2 by 8	SS	10	2.402	6.402	1.859	1.452	2.266	1.517	1.600
		15	2.841	7.184	2.526	2.077	2.975	2.149	2.720
		20	2.638	6.880	2.231	1.803	2.660	1.872	2.720
		(green)	3.029	5.951	2.232	1.863	2.602	1.922	2.730
	No. 1	10	2.170	3.781	0.962	0.745	1.179	0.780	1.140
		15	2.472	4.117	1.238	0.997	1.480	1.035	1.450
		20	2.428	4.395	1.293	1.041	1.546	1.082	1.799
		(green)	2.680	4.037	1.333	1.091	1.575	1.130	1.600
	No. 2	10	2.146	3.113	0.780	0.599	0.961	0.628	1.010
		15	2.301	3.461	0.952	0.749	1.155	0.781	1.100
		20	2.285	3.631	0.990	0.773	1.206	0.808	1.230
		(green)	2.668	3.184	1.046	0.846	1.247	0.878	0.840

[a] Nominal dimensions.

[b] SS is Select Structural.

[c] Location for each parameter was zero.

[d] CI is confidence interval.

[e] Nonparametric estimate of 5th percentile value (ASTM D 2915-88, 1989).

Table A9—Two-parameter Weibull distribution for axial stiffness of Douglas Fir lumber at various moisture contents

			Axial stiffness (× 10^6 lb)						
			Estimated Weibull parameters[c]		Weibull 5-percent point			50 percent tolerance limit; 95 percent CI	
Size[a] (in.)	Grade[b]	Moisture content group (percent)	Shape	Scale	Estimate	95 percent lower CI[d]	95 percent upper CI	Weibull	Non-parametric[e]
2 by 4	SS	10	6.251	13.341	12.581	12.119	13.044	12.193	12.133
		15	5.948	12.989	12.213	11.764	12.661	11.837	11.522
		20	5.988	12.737	11.981	11.532	12.429	11.604	11.542
		(green)	6.015	12.986	12.218	11.774	12.663	11.845	11.611
	No. 1	10	5.296	12.285	11.463	10.955	11.972	11.036	10.706
		15	5.511	11.705	10.952	10.502	11.402	10.574	10.265
		20	5.005	11.393	10.589	10.122	11.055	10.197	9.920
		(green)	4.754	11.563	10.705	10.218	11.192	10.296	9.984
	No. 2	10	4.177	11.238	10.294	9.713	10.875	9.806	9.174
		15	4.475	11.144	10.268	9.743	10.792	9.828	9.541
		20	4.318	10.621	9.756	9.252	10.261	9.333	8.893
		(green)	4.119	10.654	9.747	9.228	10.265	9.311	8.800
2 by 8	SS	10	6.452	25.168	23.778	22.966	24.589	23.097	22.645
		15	6.428	24.220	22.877	22.105	23.649	22.230	21.850
		20	5.975	24.378	22.928	22.101	23.755	22.234	21.534
		(green)	5.977	23.030	21.661	20.874	22.447	21.001	20.351
	No. 1	10	5.780	20.642	19.374	18.645	20.103	18.763	17.897
		15	5.540	19.939	18.663	17.935	19.391	18.052	17.588
		20	5.495	20.030	18.737	18.004	19.470	18.122	17.573
		(green)	5.527	19.304	18.065	17.362	18.768	17.476	16.861
	No. 2	10	4.934	19.994	18.563	17.746	19.380	17.877	16.778
		15	4.476	18.610	17.147	16.323	17.970	16.455	15.655
		20	4.661	18.851	17.426	16.617	18.235	18.747	15.879
		(green)	4.711	17.938	16.595	15.833	17.357	15.956	15.233

[a] Nominal dimensions.
[b] SS is Select Structural.
[c] Location for each parameter was zero.
[d] CI is confidence interval.
[e] Nonparametric estimate of 5th percentile value (ASTM D 2915-88, 1989).

Table A10—Evaluation of fit of three-parameter Weibull distribution to ultimate tensile stress and tensile modulus of elasticity data”

			Indicators of fit									
			Ultimate tensile stress					Tensile modulus of elasticity				
			Goodness-of-fit test[d]			Difference in estimate (percent)[e]		Goodness-of-fit test			Difference in estimate (percent)	
Size[b] (in.)	Grade[c]	Moisture content group	KS	AD	CT	Median	5th percentile	KS	AD	CT	Median	5th percentile
2 by 4	SS	10	–	–	–	−7.4	13.8	–	–	–	−1.2	−1.1
		15	–	–	–	−2.5	2.6	–	–	–	−0.4	3.3
		20	–	–	–	−2.1	9.3	–	–	–	−0.4	0.8
		(green)	–	–	–	−0.6	5.6	–	–	–	0.0	2.3
	No. 1	10	–	–	–	1.1	13.0	–	–	–	−1.0	0.1
		15	–	–	–	0.2	0.1	–	–	–	1.3	1.2
		20	–	–	–	4.9	−16.8	–	–	–	−1.4	3.2
		(green)	–	–	–	0.7	13.1	–	–	–	−0.7	−0.8
	No. 2	10	–	–	–	8.2	−16.7	–	–	–	−0.7	1.6
		15	–	–	–	9.1	−3.6	–	–	–	1.0	0.1
		20	–	–	–	3.3	−4.5	–	–	–	0.6	−0.2
		(green)	–	–	–	0.1	−4.6	–	–	–	0.1	4.1
2 by 8	SS	10	–	–	–	0.2	6.1	–	–	–	−0.0	0.8
		15	–	–	–	−0.4	−1.1	–	–	–	0.5	−3.0
		20	–	–	–	8.0	−19.4	–	–	–	0.3	−1.2
		(green)	–	–	–	1.6	−6.6	–	–	–	0.9	−2.8
	No. 1	10	–	–	*	1.2	−11.6	–	–	–	2.0	−3.7
		15	–	–	–	−4.4	−3.6	–	–	–	0.3	−1.3
		20	–	–	*	3.5	−9.7	–	–	–	1.4	−5.4
		(green)	–	–	–	−0.2	1.6	–	–	–	0.9	−1.1
	No. 2	10	–	–	–	5.2	−2.4	–	–	–	1.2	0.7
		15	–	–	–	4.8	4.8	–	–	–	2.4	−1.5
		20	–	–	*	6.5	−15.6	–	–	–	1.8	−3.4
		(green)	–	–	–	5.8	−10.8	–	*	–	2.7	−1.2

[a] Dasll (–), no reason to reject normality with $p > 0.05$.
 * reason to reject normality with $0.01 < p < 0.05$.

[b] Nominal dimensions.

[c] SS is Select Structural.

[d] KS is Kolomogorov-Smirnov test; AD, Anderson-Darling test; CT, Shapiro-Wilk-type correlation test.

[e] Percentage of difference = 100[(Weibull estimate – Nonparametric estimate)]/(Nonparametric estimate).

Table A11—Evaluation of fit of two-parameter Weibull distribution to ultimate tensile stress and tensile modulus of elasticity data[a]

			Indicators of fit									
			Ultimate tensile stress					Tensile modulus of elasticity				
		Moisture content	Goodness-of-fit test[d]			Difference in estimate (percent)[e]		Goodness-of-fit test			Difference in estimate (percent)	
Size[b] (in.)	Grade[c]	group	KS	AD	CT	Median	5th percentile	KS	AD	CT	Median	5th percentile
2 by 4	SS	10	–	–	–	–2.1	13.8	–	–	–	–1.0	–11.9
		15	**	**	*	–2.5	2.6	–	–	–	0.8	–2.1
		20	–	*	–	–2.1	9.3	–	–	–	0.7	–4.5
		(green)	–	*	–	–0.5	5.1	–	–	–	1.0	–2.2
	No. 1	10	–	–	–	4.0	2.0	–	–	–	1.1	–8.9
		15	–	–	–	0.2	0.1	–	–	–	2.8	–6.8
		20	–	–	–	5.5	–19.0	–	–	–	1.3	–7.5
		(green)	–	–	–	2.3	6.0	–	–	–	0.6	–7.1
	No. 2	10	**	**	**	15.4	–41.8	*	**	*	3.4	–17.8
		15	**	**	*	16.1	–31.4	–	–	–	3.9	–15.9
		20	*	*	**	8.1	–23.1	–	–	–	3.8	–16.8
		(green)	–	–	–	2.8	–16.5	*	**	*	3.3	–10.9
2 by 8	SS	10	–	–	–	4.7	–11.7	*	*	–	1.8	–8.7
		15	*	**	*	3.7	–20.0	**	*	–	1.9	–11.7
		20	**	**	*	10.5	–29.9	*	**	–	1.9	–9.9
		(green)	*	–	*	4.9	–23.3	**	**	*	2.7	–11.8
	No. 1	10	**	**	*	4.7	–33.1	**	**	–	3.4	–10.1
		15	**	**	*	0.5	–30.6	**	**	*	2.9	–17.6
		20	**	**	**	8.8	–40.7	**	**	**	3.8	–20.8
		(green)	**	**	**	6.0	–26.8	**	*	*	3.2	–14.2
	No. 2	10	**	**	*	11.0	–29.7	**	**	**	4.9	–15.0
		15	**	**	**	10.5	–24.5	**	**	*	5.1	–13.8
		20	**	**	**	10.8	–34.9	**	**	**	4.9	–17.8
		(green)	*	**	–	7.8	–19.4	**	**	*	5.5	–13.7

[a] Dash (–), no reason to reject normality with $p > 0.05$.
* reason to reject normality with $0.01 < p \leq 0.05$.
** reason to reject normality with $p \leq 0.01$.

[b] Nominal dimensions.

[c] SS is Select Structural.

[d] KS is Kolomogorov–Smirnov test; AD, Anderson–Darling test; CT, Shapiro-Wilk-type correlation test.

[e] Percentage of difference = 100[(Weibull estimate – Nonparametric estimate)]/(Nonparametric estimate).

Appendix B— Supplementary Figures

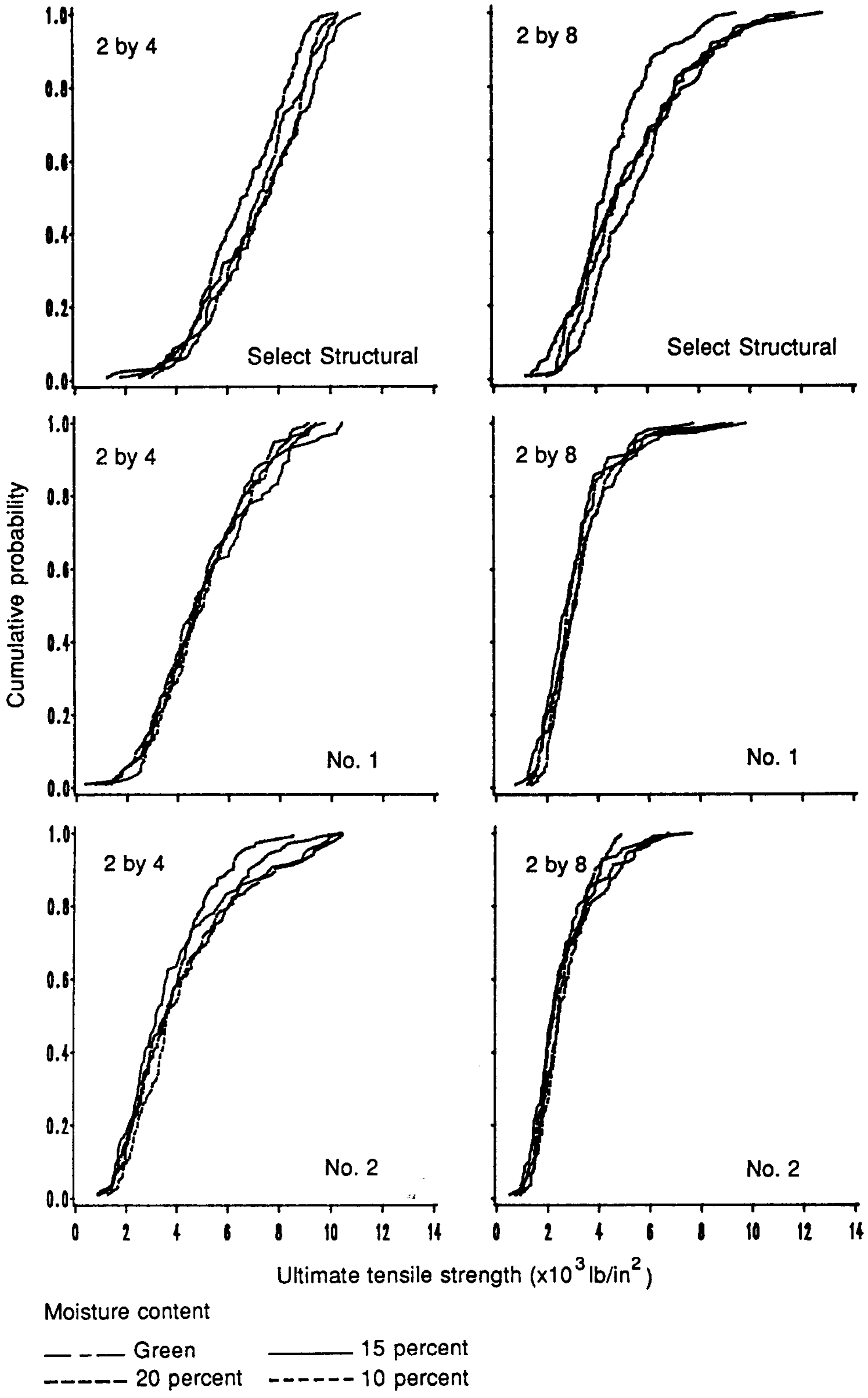

Figure B1—Cumulative frequency distribution of ultimate tensile stress for nominal 2 by 4 and 2 by 8 lumber at various *moisture content levels.*

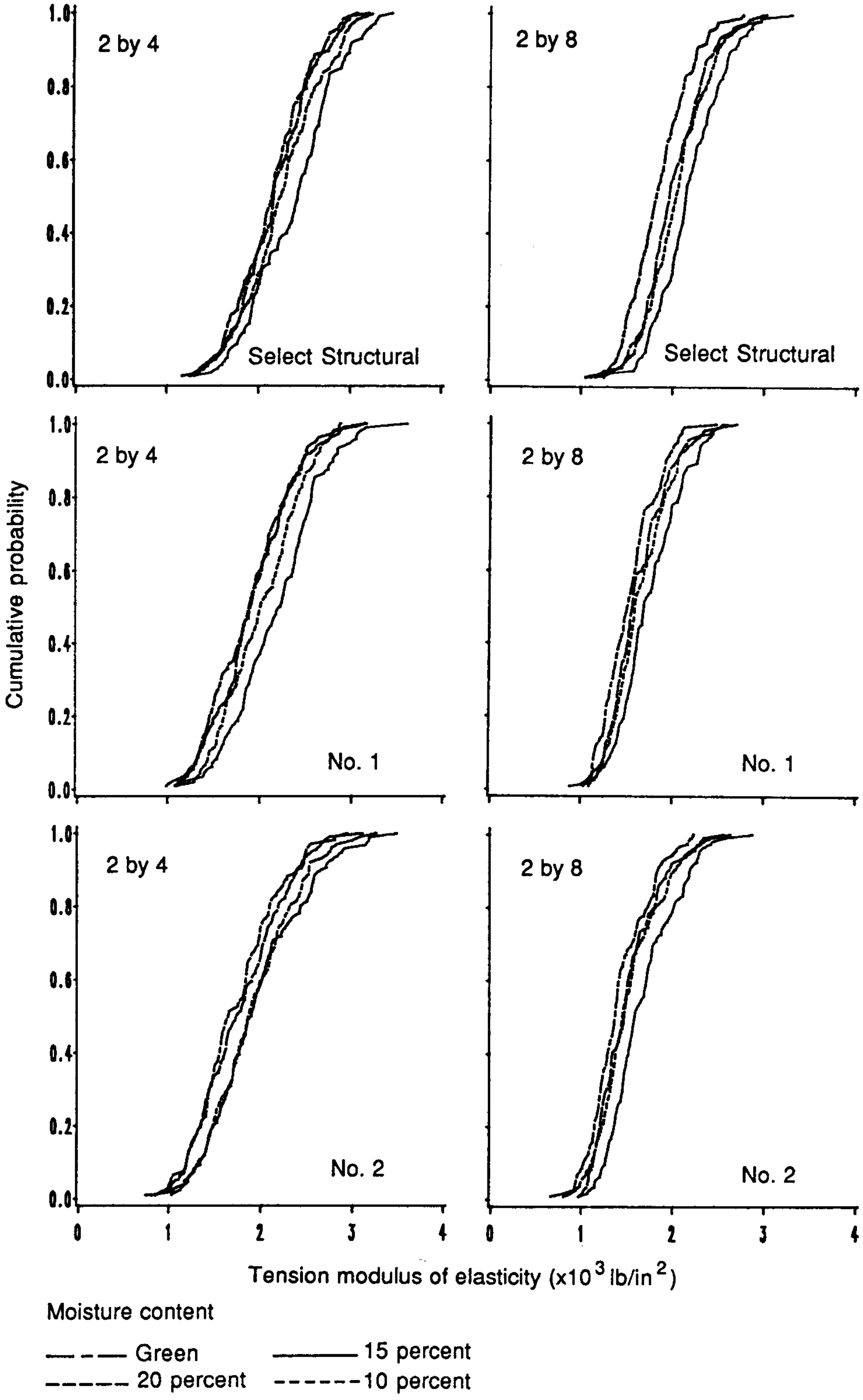

Figure B2—Cumulative frequency distribution of tensile modulus of elasticity for nominal 2 by 4 and 2 by 8 lumber at various moisture content levels.

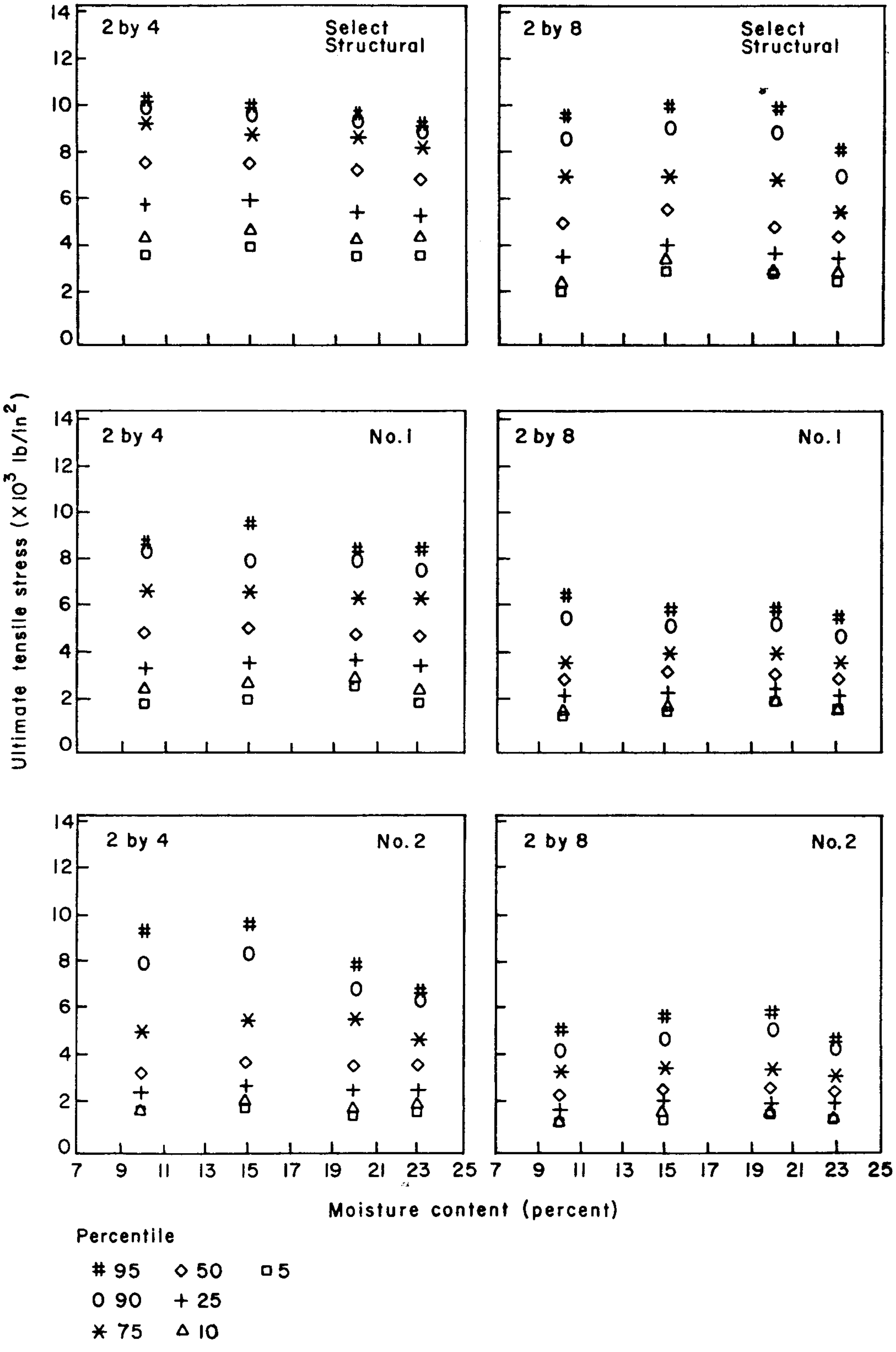

Figure B3—Effect of moisture content on ultimate tensile stress of nominal 2 by 4 and 2 by 8 lumber at various percentile levels.

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