Tensile strength of laminating grades of lumber

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Abstract

Knowledge of the distributional characteristics of tensile strength for laminating grades of lumber in the United States is necessary for the reliability-based design of glued-laminated (glulam) timbers. The work reported here provides tensile strength distributional characteristics, including three-parameter Weibull distributional estimates, for four Douglas-Fir/Larch and three Southern Pine laminating grades. A total of 1,345 "on-grade" 2 by 6's, 12 feet long, were tested in tension parallel to grain. Included were 916 L1, L2D, L2, or L3 Douglas-Fir/Larch specimens and 429 No. 1D, No. 2D, or No. 2M Southern Pine specimens. No end joints were included. Testing followed standard ASTM D procedures, with the exception that the specimens were tested to failure at a faster rate than provided in the standard. These data can be used as input for reliability-based analysis models and as baseline criteria for alternative grades.

Current deterministic design procedures for glued-laminated (glulam) timbers require only the characterization of near-minimum properties for strength in tension parallel to grain and bending. However, this information will not be sufficient for new reliability-based design procedures, which will require distributional data for the strength properties of glulam timbers.

Computer simulation models are the most promising method of predicting distributional properties for a large number of laminating combinations. Several computer models for predicting the strength and stiffness distributions of glulam timbers have already been developed, including one by Foschi and Barrett (5). Accurate and reliable data on the tensile strength distributional characteristics for laminating grades of lumber are needed to provide input into these models, and to provide a baseline for determining the acceptance of alternative laminating grades.

Only small samples of tensile strength data from several studies are available for U.S. laminating grades of lumber, or lumber grades having similar visual-grading criteria (4,8,9,11-14). Although the database from those studies was useful in planning the work reported here, it was inadequate to meet the present need for accurate characterization of tensile strength distributions. Thus, it was important to evaluate large samples of visually graded laminating lumber.

The purpose of this study was to collect and evaluate tensile strength distributional properties for L1, L2D, L2, and L3 Douglas-Fir/Larch and No. 1D, No. 2D, and No. 2M Southern Pine laminating grades of lumber. The West Coast Lumber Inspection Bureau (16) and the Western Wood Products Association (17) give the basic requirements for the Douglas-Fir/Larch grades, and the Southern Pine Inspection Bureau (15) gives the basic requirements for the Southern Pine grades. The American Institute of Timber Construction (AITC) (1) gives additional requirements for all laminating grades. The basic slope-of-grain requirements for the Southern Pine grades were 1:10 for No. 1D and 1:8 for No. 2D and No. 2M.

Experimental design

The specimen collection program provided representative samples of Douglas-fir/Larch and Southern Pine lumber meeting the grade requirements for the laminating grades chosen. In other words, the samples collected were "on-grade."

Specimens were collected from more than 25 laminating plants represented by AITC, which account for nearly all of the glulam timber production in the United States. Douglas-fir/Larch was sampled more exten-

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TABLE 1. – *Summary of physical properties.*

Grade	Sample size[a]	Moisture content[b] Mean	Moisture content[b] Standard deviation	Mean width	Mean thickness	Specific gravity Mean	Specific gravity Standard deviation
		----------(%) ----------		----------(in.)----------			
Douglas-Fir/Larch							
L1	357	10.7	1.8	5.49	1.50	0.54	0.05
L2D	222	10.5	1.4	5.50	1.50	.53	.05
L2	222	10.3	1.3	5.51	1.50	.48	.04
L3	118	10.2	1.5	5.50	1.50	.50	.05
Southern Pine							
No. 1D	194	11.7	1.6	5.53	1.40	.61	.06
No. 2D	117	11.5	1.8	5.55	1.38	.59	.06
No. 2M	118	11.1	1.8	5.55	1.38	.54	.06

[a] These sample sizes also apply to Tables 2, 3, 4, and 6.
[b] Based on ovendry method.
[c] Based on calculated dry weight and on test volume.

sively because of a greater number of manufacturing plants and because this species group accounts for the majority of the total glulam production. The number of specimens chosen for each grade was based on a number of considerations, including their assumed relative importance when used in a computer simulation model to predict beam strength and stiffness. L1 Douglas-Fir/Larch and No. 1D Southern Pine are the most important of the visually graded laminating grades, whereas L2D and L2 Douglas-Fir/Larch and No. 2D and No. 2M Southern Pine are of secondary importance, and L3 Douglas-Fir/Larch is of least importance.

The number of specimens per grade collected from each plant's inventory was based on the plant's relative production. The smaller plants were visited once and the larger plants were visited twice. The number of specimens from each plant visit varied from 1 to 28.

In general, the test specimens were selected systematically from each laminating plant's inventory. For most of the plants, specimens were selected from different bundles based on their placement into inventory (early, middle, or late placement). The selection of different bundles minimized the chance of bias that a time-of-production effect might have on tensile strength. Actual sample sizes for each of the grades evaluated are given in Table 1.

Nominal 2 by 6 lumber, 12 feet long, was sampled. To reflect actual production practices, the selected Southern Pine specimens were resurfaced at each plant to a thickness of 1-3/8 inches, but the Douglas-Fir/Larch specimens were left at their original 1-1/2-inch thickness. The specimens were collected between December 1981 and September 1982.

Research methods

Except as specifically noted in this section, the research methods reported here are the same as we reported earlier (10).

Test procedures

With the exception of the rate of loading, testing followed ASTM D 198 (3) tension parallel-to-grain procedures. Based on the results of Gerhards et al. (7), we chose a rate of loading such that the specimens failed in an average time of 2 minutes. That rate of loading is faster than the standard ASTM rate, which states "the load may be applied at constant rate of grip motion so that maximum load is achieved in about 10 minutes, but not less than 5 nor more than 20 minutes.''

We tested the specimens in the tension machine at the Forest Products Laboratory, Madison, Wis. The grips for that machine each take up about 2.5 feet. Thus, when 12-foot lumber is tested, the result is a 7-foot test span. Rotation at the grips was prevented to partially simulate the restraint the lumber would experience as part of a glulam timber.

Data obtained

The data collected included moisture content (MC), using a resistance meter and/or the ovendry method; specific gravity (SG), based on dry weight and test volume; and modulus of elasticity (MOE), determined flatwise with an E computer that uses a vibration technique.

Statistical analysis

We performed an analysis of variance for tensile strength, MOE, and SG to test for the significance of plant-to-plant variation, visit-to-visit variation within a plant, and possible size-of-plant variation.

The analysis of these results also included the determination of lower tail properties, such as fifth percentile point estimates, confidence intervals, and tolerance limits. We used several procedures for estimating lower tail properties, including nonparametric estimates and estimates based on the normal, two-parameter lognormal, and three-parameter Weibull distributions. All methods used are consistent with those used in the U.S. In-Grade Testing Program (6).

For each species and grade, the three distributional forms used to get estimates were checked extensively for goodness-of-fit. A Kolmogorov-Smirnov (KS) goodness-of-fit test was used to test, in each case, whether each of the distributions provided an adequate fit for the data. Because the KS test is known to have particularly small power in testing Weibull fits, we also used a test incorporating the Anderson-Darling statistic.

Results and discussion

The test results and statistical analyses are presented in this section, followed by comparisons between grades and between the test values and corresponding values now used in industry specifications (1).

Test results

Physical properties. — Table 1 summarizes the mean physical properties of MC, width and thickness dimensions, and SG. The mean MC values ranged from 10 to 12 percent, and no adjustments for MC were made to the test data. Sample sizes are also listed in Table 1. The same sample sizes apply to Tables 2, 3, 4, and 6.

Tensile strength and MOE values. — Mean tensile strength and MOE values for the four Douglas-Fir/Larch and three Southern Pine grades decrease as the grade levels decrease, which was expected (Table 2). Most of these differences are statistically significant and this will be discussed later. The tensile strength coefficients of variation (COVs) range from 31 to 44 percent, and the MOE COVs range from 17 to 20 percent.

TABLE 2. — ***Summary of tensile strength and nodulus of elasticity values.***

Grade	Tensile strength Mean	SD[b]	COV[c]	Modulus of elasticity[a] Mean	SD	COV
	-------- (psi) --------		(%)	---- (million psi) ----		(%)
Douglas-Fir/Larch						
L1	4,970	1,560	31.4	2.14	0.36	17.0
L2D	3,690	1,300	35.2	1.97	.34	17.4
L2	3,230	990	30.7	1.73	.29	17.0
L3	2,480	1,080	43.6	1.67	.33	19.9
Southern Pine						
No. 1D	6,450	2,220	34.4	2.15	.36	16.7
No. 2D	3,220	1,310	40.7	1.84	.31	16.9
No. 2M	2,630	970	36.7	1.58	.27	17.2

[a] Dynamic modulus of elasticity from E computer.
[b] Standard deviation.
[c] Coefficient of variation.

Statistical analyses

Analysis of variance. — The analysis-of-variance results often showed a visit effect, which indicates the material tested was more consistent for a given visit than between visits. In addition, there were occasional plant effects, but those effects showed no consistent patterns across grades. Conversely, there were no size-of-plant effects. Therefore, it would be a good idea to continue using several plants and several visits per plant for the collection of samples in future studies.

Distributional and nonparametric estimates. — Table 3 summarizes the estimates of the tensile strength and MOE data using the three-parameter Weibull, two-parameter lognormal, and normal statistical distributions, as well as the nonparametric estimates. The 5th percentile for strength and the 50th percentile for MOE are currently the bases for developing design properties of many wood products.

Table 4 gives parameter estimates for the three-parameter Weibull fits on the tensile strength and MOE data. Also given in Table 4 are the asymptotic standard deviations of the parameter estimates. Results of three

TABLE 3. — ***Summary of distribution estimates of tensile strength and modulus of elasticity values.***

Grade	Statistical distribution	Tensile strength 50th percentile	5th percentile	75-percent tolerance limit, 5th percentile	95-percent confidence interval, 5th percentile Lower	Upper	Modulus of elasticity 50th percentile	95-percent confidence interval, 50th percentile Lower	Upper
		----------(psi)----------					----------(million psi)----------		
Douglas-Fir/Larch									
L1	Weibull	4,890	2,470	2,420	2,310	2,640	2.15	2.11	2.20
L1	Nonparametric	4,810	2,680	2,610	2,340	2,890	2.14	2.11	2.18
L1	Lognormal	4,730	2,770	2,720	2,630	2,920	2.11	2.07	2.15
L1	Normal	4,970	2,400	2,310	2,150	2,660	2.14	2.10	2.18
L2D	Weibull	3,500	1,960	1,930	1,860	2,070	1.95	1.90	2.01
L2D	Nonparametric	3,390	2,110	2,090	1,670	2,240	1.93	1.87	1.99
L2D	Lognormal	3,490	2,030	1,980	1,900	2,180	1.94	1.89	1.98
L2D	Normal	3,690	1,550	1,460	1,290	1,830	1.97	1.92	2.01
L2	Weibull	3,160	1,720	1,680	1,600	1,850	1.71	1.66	1.76
L2	Nonparametric	3,200	1,770	1,580	1,400	1,900	1.71	1.66	1.76
L2	Lognormal	3,080	1,810	1,770	1,700	1,940	1.70	1.66	1.75
L2	Normal	3,230	1,600	1,530	1,400	1,810	1.73	1.69	1.77
L3	Weibull	2,320	1,050	1,010	940	1,170	1.61	1.54	1.68
L3	Nonparametric	2,320	990	950	720	1,360	1.65	1.55	1.72
L3	Lognormal	2,280	1,160	1,110	1,030	1,310	1.64	1.58	1.70
L3	Normal	2,480	700	600	400	1,010	1.67	1.60	1.75
Southern Pine									
No. 1D	Weibull	6,180	3,330	3,250	3,100	3,560	2.14	2.08	2.21
No. 1D	Nonparametric	6,190	3,370	3,240	2,880	3,470	2.14	2.07	2.19
No. 1D	Lognormal	6,080	3,420	3,330	3,170	3,700	2.12	2.06	2.17
No. 1D	Normal	6,450	2,810	2,640	2,330	3,290	2.15	2.09	2.20
No. 2D	Weibull	2,990	1,520	1,480	1,410	1,650	1.84	1.78	1.91
No. 2D	Nonparametric	2,980	1,490	1,430	1,210	1,650	1.86	1.80	1.92
No. 2D	Lognormal	2,980	1,540	1,480	1,380	1,730	1.81	1.75	1.87
No. 2D	Normal	3,220	1,050	930	700	1,440	1.84	1.78	1.90
No. 2M	Weibull	2,530	1,230	1,190	1,100	1,370	1.58	1.52	1.64
No. 2M	Nonparametric	2,560	1,330	1,260	780	1,400	1.56	1.49	1.66
No. 2M	Lognormal	2,470	1,360	1,310	1,230	1,510	1.55	1.50	1.61
No. 2M	Normal	2,630	1,040	950	780	1,320	1.58	1.52	1.63

TABLE 4. — *Three-parameter Weibull estimates of mechanical properties.*

Property	Species	Grade	Sample size	Parameter estimates[a] Shape	Scale	Location	Asymptotic standard deviations Shape	Scale	Location
Tensile strength	DF	L1	355	2.695	4,471	991	0.135	156	114
		L2D	221	1.754	2,444	1,517	0.107	119	52
		L2	222	2.390	2,518	997	0.203	163	129
		L3	118	1.751	2,024	683	0.139	132	53
	SP	No. 1D	194	1.953	4,670	2,310	0.152	269	164
		No. 2D	117	1.603	2,283	1,170	0.140	162	61
		No. 2M	118	2.080	2,161	718	0.171	133	74
Modulus of elasticity	DF	L1	355	4.180	1.504	0.775	0.490	.154	.147
		L2D	221	2.723	0.978	1.098	0.266	.061	.051
		L2	222	2.532	0.785	1.032	0.232	.056	.046
		L3	118	1.671	0.610	1.123	0.182	.051	.027
	SP	No. 1D	194	3.453	1.258	1.014	0.398	.119	.109
		No. 2D	117	3.832	1.174	0.777	0.798	.212	.201
		No. 2M	118	3.802	1.017	0.657	0.678	.152	.143

[a]Parameters for tensile strength will yield results in psi; parameters for MOE will yield results in million psi.

TABLE 5. — *Correlation of tensile strength with modulus of elasticity (MOE) and/or specific gravity (SG).*

Species[a]	Regression model[b] A	B	C	r^2
Modulus of elasticity				
Douglas-Fir/Larch	−2,130	3,411	0	0.40
Southern Pine	−5,002	5,528	0	.48
Specific gravity				
Douglas-Fir/Larch	−5,542	0	19,733	.23
Southern Pine	−12,835	0	31,785	.37
Modulus of elasticity and specific gravity				
Douglas-Fir/Larch	−3,108	3,151	2,850	.40
Southern Pine	−10,139	4,152	13,170	.51

[a] Correlation based on 1,277 Douglas-Fir/Larch 302-24, L1, L2D, L2, or L3 specimens and 646 Southern Pine 302-24, No. 1D, No. 2D, and No. 2M specimens. The 302-24 data were reported in a previous study (10).
[b] Regression model: tensile strength =A + B(MOE) + C(SG) with tensile strength in psi and MOE in million psi.

TABLE 6. — *Comparison with AITC values.*

Grade	Tensile strength Test value[a]	AITC value[b]	Test ÷ AITC	Modulus of elasticity Test value[c]	AITC value[d]	Test ÷ AITC
	------- (psi) -------			--- (million psi) ---		
Douglas-Fir/Larch						
L1	2,420	2,470	0.98	2.14	2.1	1.02
L2D	1,930	2,260	.85	1.97	1.9	1.04
L2	1,680	1,930	.87	1.73	1.8	.96
L3	1,010	1,070	.94	1.67	1.6	1.04
Southern Pine						
No. 1D	3,250	2,620	1.24	2.15	2.0	1.08
No. 2D	1,480	1,680	.88	1.84	1.8	1.02
No. 2M	1.190	1,420	.84	1.58	1.5	1.05

[a] 75-percent tolerance limit of 5th percentile test values calculated assuming a three-parameter Weibull distribution.
[b]75-percent tolerance limit of 5th percentile values in AITC 200 (2).
[c]50th percentile.
[d]Value in AITC 117 (1) and in AITC 200 (2).

statistical goodnewof-fit tests showed no significant lack of fit on any test for any data set. Similar goodness-of-fit tests were performed for the normal and lognormal distributional fits with several cases of lack of fit occurring. Thus, the Weibull distribution was the only distributional form to fit all of the tensile strength and MOE distributions. Visually, the Weibull distributional fits can be seen in Figures 1 through 4.

The Weibull distribution also provides information on the whole distribution. The nonparametric estimates provide a set of estimates that do not depend upon a particular distribution and, as such, do not provide any distributional information. Estimates based on the normal or lognormal distributions are probably not as good as the Weibull and nonparametric estimates. For these reasons, only Weibull parameter estimates for the tensile strength and MOE distributions are given in Table 4. These estimates should prove useful to future research.

Regression analysis. — We examined correlations between tensile strength and MOE, tensile strength and SG, and tensile strength and both MOE and SG, for each grade separately. In general, those single-grade correlations were low, with r^2 values ranging from 0.03 to 0.30. MOE was a better predictor of tensile strength than was SG. In fact, the addition of SG to MOE as a predictor did not significantly increase most of the r^2 values. MOE was a better predictor for Southern Pine (r^2 values from 0.23 to 0.30) than for Douglas-Fir/Larch (r^2 values from 0.15 to 0.24). SG was also a better predictor for Southern Pine (r^2 values from 0.07 to 0.21) than for Douglas-Fir/Larch (r^2 values from 0.02 to 0.14).

Combining all of the grades per species from this study, plus the 302-24 grade from a previous study (10), increased the r^2 values. That was expected because of the increased sample size, as well as the increased range of tensile strength, MOE, and SG values. The combined grade r^2 values were lowest again for SG, and ranged from the Douglas-Fir/Larch SG value of 0.23 to the Southern Pine combined MOE and SG value of 0.51 (Table 5). The addition of SG did not change the Douglas-Fir/Larch MOE r^2 value, and only slightly increased the Southern Pine MOE r^2 value. The r^2 values found with these data are in the range reported in the literature and are discussed in more detail in Gerhards et al. (7).

Comparisons

We make two comparisons in this section: 1) among

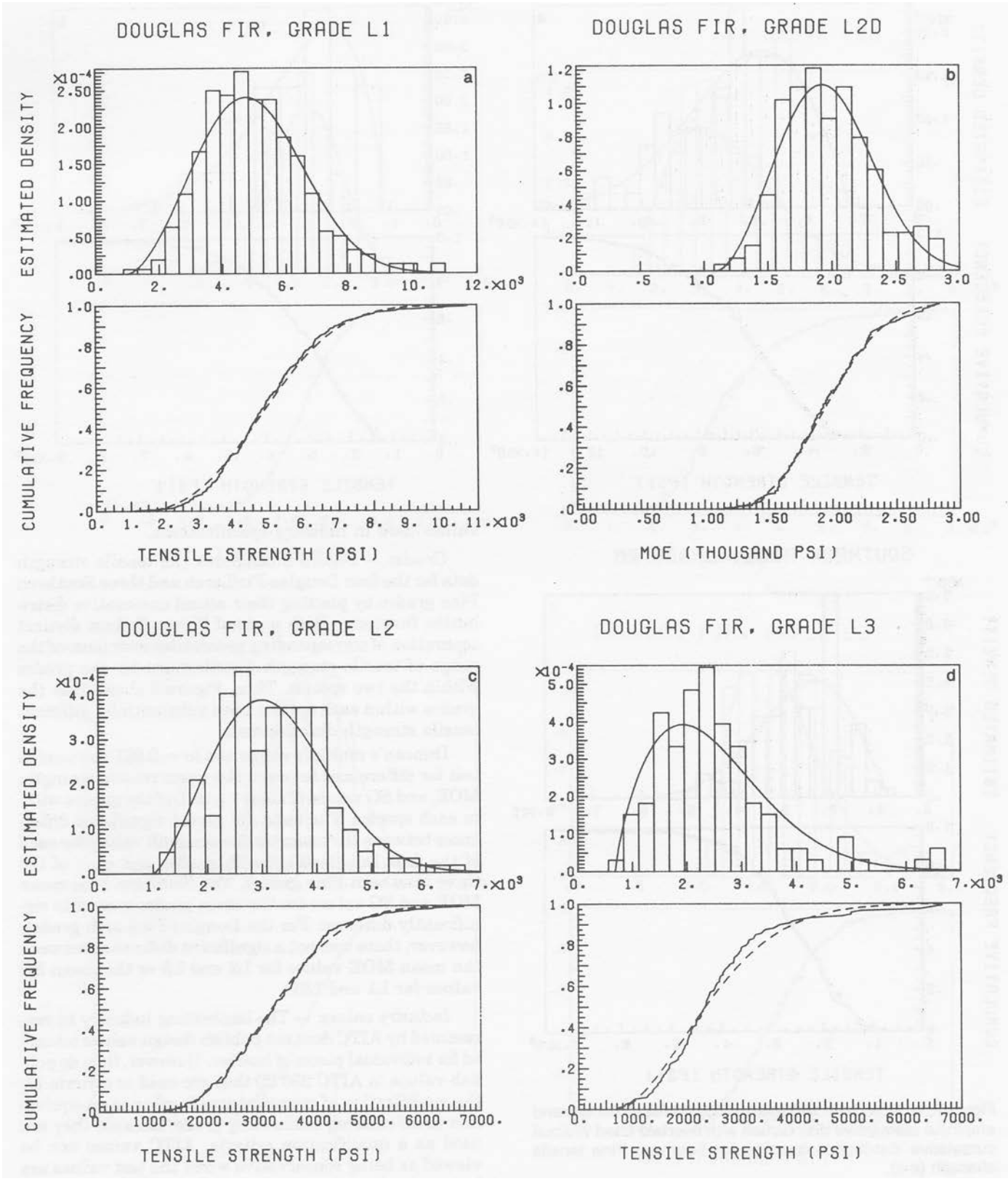
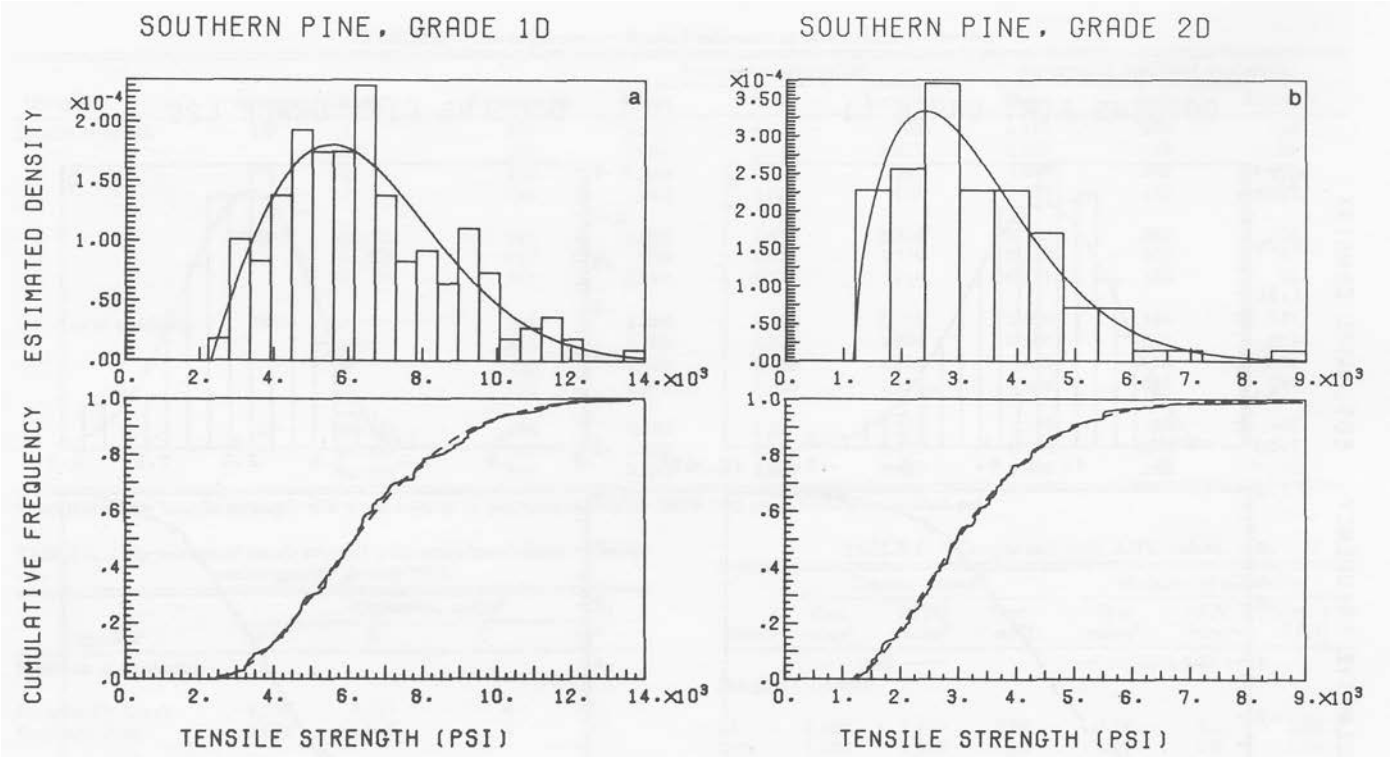


Figure 1. - Histogram with overlaid fitted Weibull density and empirical cumulative distribution with overlaid fitted Weibull cumulative distribution function for Douglas-Fir/Larch tensile strength (a-d).



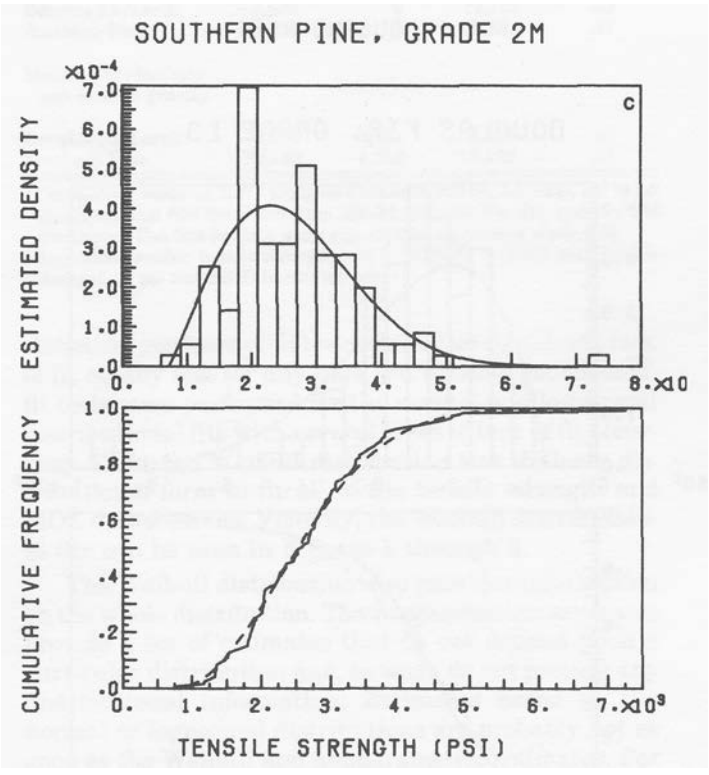


Figure 2. - Histogram with overlaid fitted Weibull density and empirical cumulative distribution with overlaid fitted Weibull cumulative distribution function for Southern Pine tensile strength (a-c).

the four Douglas-Fir/Larch and three Southern Pine grades within each species; and 2) between the tensile strength and MOE test data and the corresponding values used in industry specifications.

Grades. - Figure 5 compares the tensile strength data for the four Douglas-Fir/Larch and three Southern Pine grades by plotting their actual cumulative distribution functions. Both parts of Figure 5 show distinct separation of corresponding percentiles over most of the range of tensile strength distributions for the grades within the two species. Thus, Figure 5 shows that the grades within each species have substantially different tensile strength distributions.

Duncan's multiple range test (α = 0.05) was used to test for differences between the mean tensile strength, MOE, and SG values (Tables 1 and 2) of the grades within each species. The tests did reveal significant differences between the mean tensile strength values for each of the four Douglas-Fir/Larch grades and each of the three Southern Pine grades. The Southern Pine mean MOE and SG values for the three grades were also significantly different. For the Douglas-Fir/Larch grades, however, there was not a significant difference between the mean MOE values for L2 and L3 or the mean SG values for L1 and L2D.

Industry values. - The laminating industry as represented by AITC does not publish design values intended for individual pieces of lumber. However, they do publish values in AITC 200 (2) that are used as criteria for the qualification of manufactured lumber as an equivalent to an existing laminating grade. Because they are used as a qualification criteria, AITC values can be viewed as being conservative when the test values are lower than the AITC values. Table 6 compares the tensile strength and MOE results with the corresponding AITC values.

For tensile strength, the 75 percent tolerance limit of the 5th percentile is the important level to consider

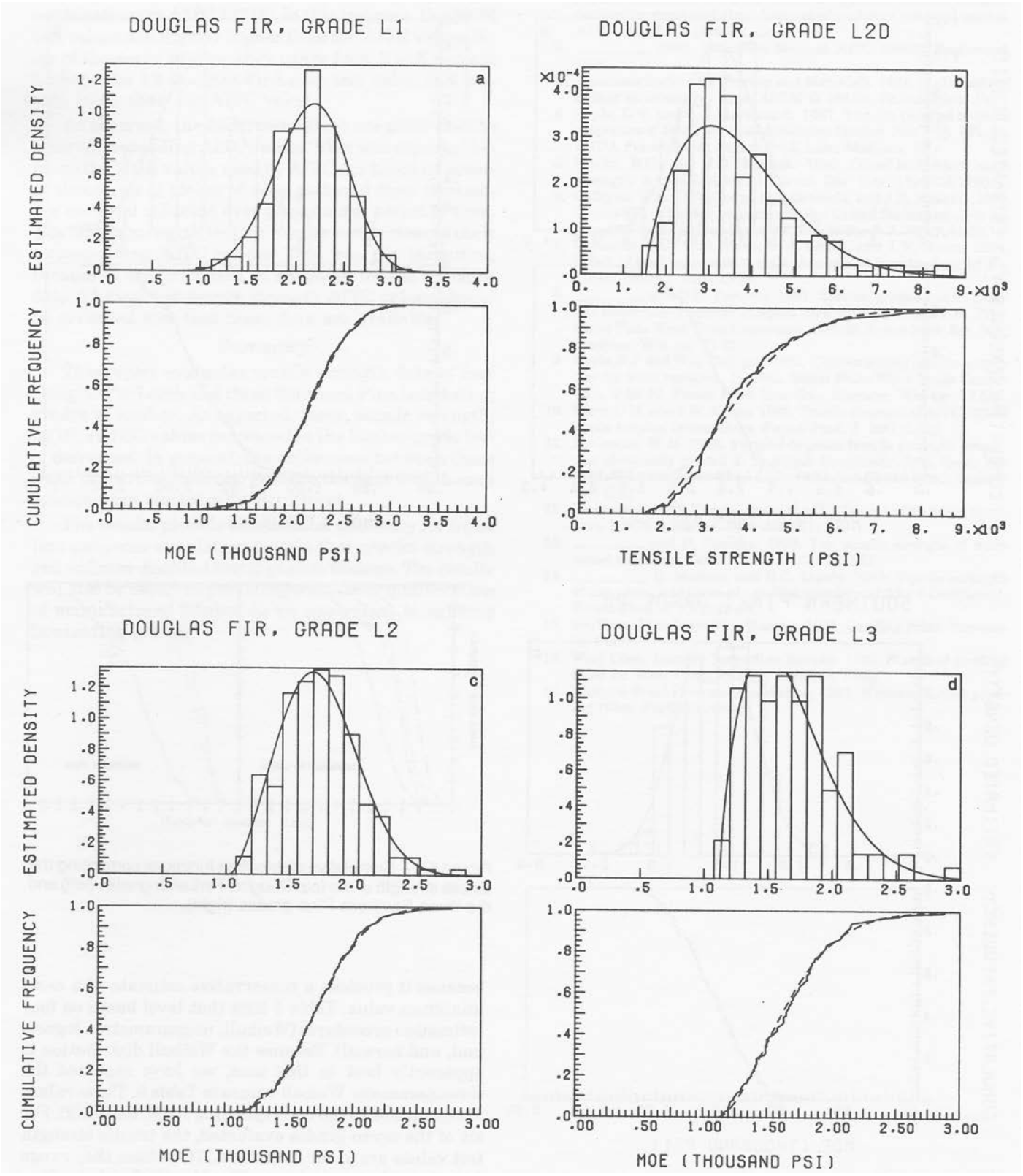


Figure 3. - Histogram with overlaid fitted Weibull density and empirical cumulative distribution with overlaid fitted Weibull cumulative distribution function for Douglas-Fir/Larch modulus of elasticity (a-d).

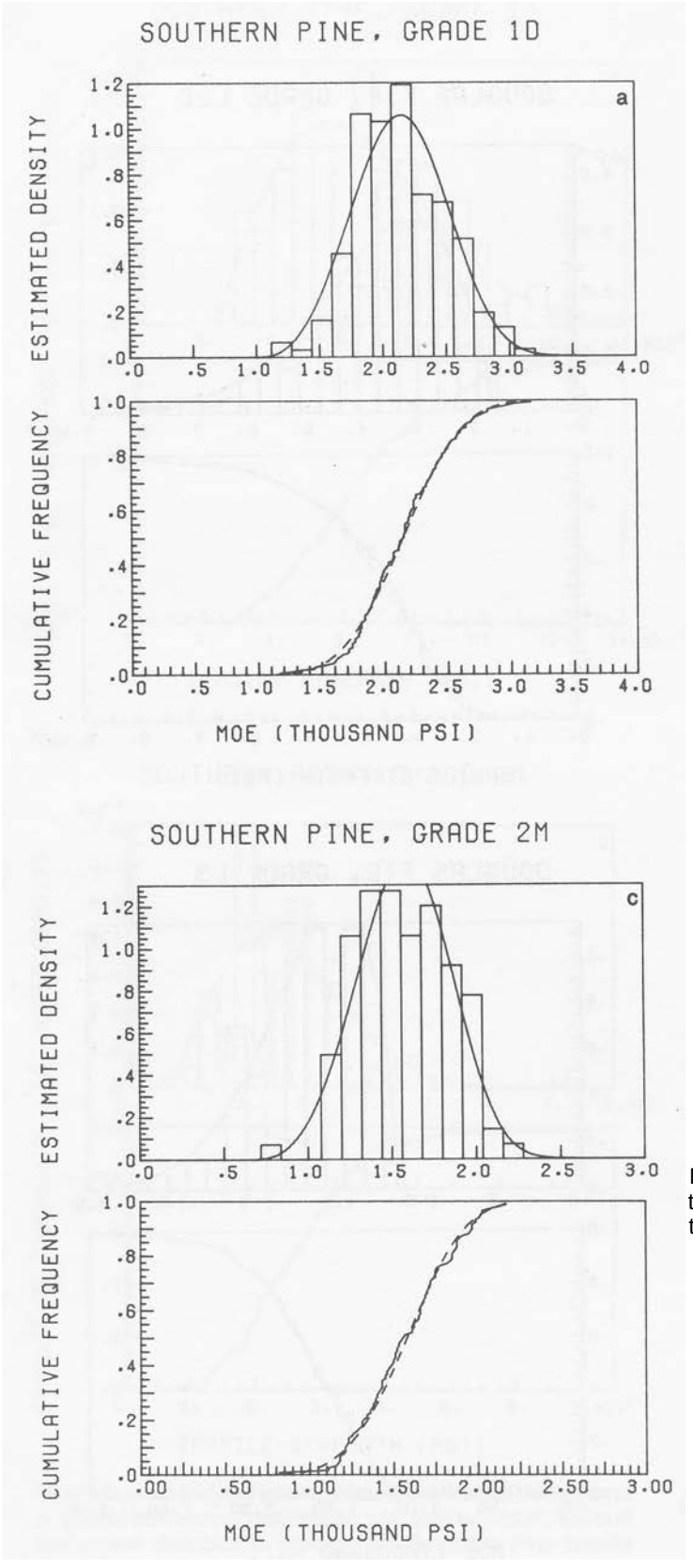


Figure 4. - Histogram with overlaid fitted Weibull density and empirical cumulative distribution with overlaid fitted Weibull cumulative distribution function for Southern Pine modulus of elasticity (a-c).

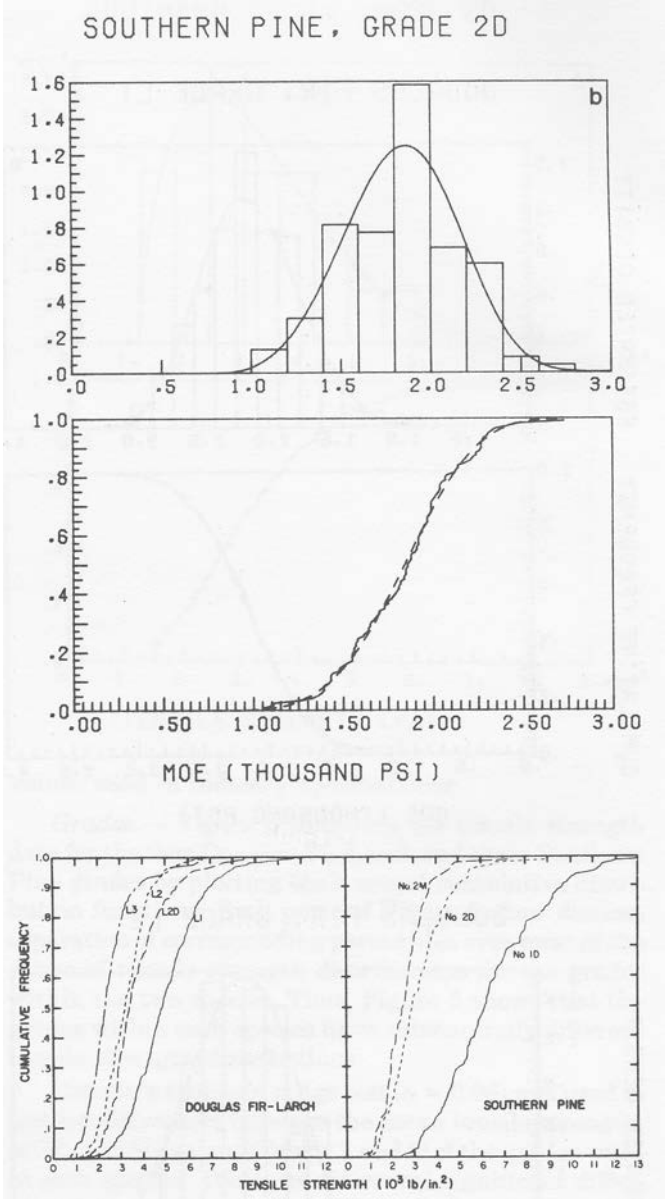


Figure 5. - Cumulative distribution functions comparing the tensile strength of the four Douglas-Fir/Larch grades (left) and the three Southern Pine grades (right).

because it provides a conservative estimate of a near-minimum value. Table 3 lists that level based on four estimation procedures (Weibull, nonparametric, lognormal, and normal). Because the Weibull distribution is apparently best in this case, we have repeated the three-parameter Weibull values in Table 6. Those values are compared to the corresponding AITC values (2). For six of the seven grades evaluated, the tensile strength test values are lower than the AITC values; they range from 2 to 16 percent lower. The No. 1D Southern Pine test value, on the other hand, is 24 percent higher than the AITC value.

For MOE, the 50th percentile is the important level to consider because it is the value commonly used in design. The mean test values given in Table 2 are repeat-

ed in Table 6. Those values then can be compared to the mean AITC values (2) as well as used to develop design combinations in AITC 117 (1). In this instance, the MOE test values are slightly higher than the AITC values for six of the seven grades; they range from 2 to 8 percent higher. The L2 Douglas-Fir/Larch test value is 4 percent lower than the AITC value.

As observed, the MOE test values are quite close to their corresponding AITC values. This was expected because the MOE values used by AITC are based on several thousands of pieces of data gathered from laminating material collected over an extended period of time. The tensile strength test values are not as close to their corresponding AITC values. This was not surprising because of the prior lack of adequate tensile strength data. The current tensile strength AITC values should be reviewed now that these data are available.

Summary

This report evaluates tensile strength data of four Douglas-Fir/Larch and three Southern Pine laminating grades of lumber. As expected, mean tensile strength, MOE, and SG values decreased as the lumber grade level decreased. In general, the differences between those three properties from one grade to the next within each species were statistically significant.

The results provide information necessary for input into computer simulation models that predict strength and stiffness distributions of glulam timbers. The results will also be useful in providing criteria for qualification of manufactured lumber as an equivalent to existing laminating grades.

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