LOCALIZED TENSILE STRENGTH AND MODULUS OF ELASTICITY OF E-RELATED LAMINATING GRADES OF LUMBER

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ABSTRACT

Localized modulus of elasticity (MOE) and tensile strength (T) of six E-rated grades and two visual grades of 2 by 6 Douglas-fir laminating lumber were measured over a test span of 2 ft. The E-rated laminating grades studied were C14, 2.3E-1/6, 2.3E-1/3, 2.0E-1/6, 2.0E-1/3, and 1.7E-1/4. The visual laminating grades were L2 and L3, which consisted of lumber not qualifying for the E-rated grades. Multivariate statistical parameters and probability distributions were fit to the localized MOE and T data. These parameters can be used to simulate lumber properties needed to predict the reliability of glued-laminated timber beams. Localized MOE and T data were simulated using a multivariate approach to determine whether the statistical properties of the original MOE and T data were preserved in the simulated data. The original statistical properties (i.e., probability distributions and correlations) were preserved in the simulated data for all lumber grades studied.

Keywords: MOE (modulus of elasticity), tensile strength, lumber, glulam, simulation, reliability.

INTRODUCTION

Monte Carlo simulation models are available for predicting the strength and stiffness of glued-laminated (glulam) timber beams (e.g., Foschi and Barrett 1980; Ehlbeck et al. 1985a, b; Hernandez et al. 1991). These models require accurate input data on the localized material properties of the constituent laminating lumber. Tensile strength (T) and modulus of elasticity (MOE) are the most critical material properties, since glulam beam failures usually initiate in the tension zone of the beams.

To date, most MOE and T data on laminating lumber have been collected using long-span tests. However, most glulam beam models require input on the localized material properties of the lumber, as well as the correlations among these properties. In response to this need, Taylor and Bender (1991) developed a multivariate statistical approach for generating localized MOE and T properties of visually graded laminating lumber. They validated the multivariate approach using independent sets of long-span T data. The approach is based on a multivariate Normal model, along with a transformation scheme to accommodate random variables that are non-Normal. The research reported here extends the work by Taylor and Bender (1991) to include E-rated grades of laminating lumber.

The objectives of this research were:

1. to characterize localized (2-ft segment) MOE

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TABLE 1. *Summary of test results for localized (2-foot) MOE and T data.*

Grade	Lumber modulus of elasticity			Lumber tensile strength		
	Sample size	Mean (10^6 psi)	COV (%)	Sample size	Mean (10^3 psi)	COV (%)
C14	994	2.849	14.6	398	9.468	27.1
2.3E-⅙	974	2.510	10.9	396	8.110	26.7
2.3E-⅓	185	2.611	11.9	77	6.438	28.1
2.0E-⅙	998	2.217	9.9	399	6.354	28.2
2.0E-⅓	977	2.203	11.7	392	5.374	33.6
1.7E-¼	970	1.900	12.8	400	5.482	29.1
L2	970	1.534	15.7	396	3.930	31.0
L3	1000	1.596	20.8	395	3.226	33.5

and T properties for six E-rated and two visual grades of 2 by 6 Douglas-fir laminating lumber;

2. to model the localized MOE and T data using the method developed by Taylor and Bender (1991). This model is needed as input to Monte Carlo models that predict structural reliability of glulam timber beams.

PROCEDURE

This study included six E-rated and two visual laminating grades of 2 by 6 Douglas-fir lumber. The E-rated grades (listed in descending order of quality) were: C14, 2.3E-⅙, 2.3E-⅓, 2.0E-⅙, 2.0E-⅓, and 1.7E-¼. The visual grades were L2 and L3. Detailed descriptions of the laminating grades are published by the American Institute of Timber Construction (AITC 1984, 1988). One mill located in the Northwestern United States supplied a random sample of lumber for each grade. The visually graded L2 and L3 lumber consisted of lumber that did not qualify for any of the E-rated grades. Of the 1,437 lumber specimens tested, 1,328 were 16 feet long and 109 specimens were 14 feet long.

Laboratory test procedures followed ASTM Standards D198 and D4761 (ASTM 1990a, b) and are summarized as follows:

1. The lumber was conditioned to a moisture content of approximately 12% (dry-weight basis). Locations and sizes of knots, as well as dimensions, moisture content, and weight were recorded for each specimen.
2. Localized flatwise bending MOE was measured on five contiguous 2-foot segments for the 16-foot lumber (and 4 segments for the 14-foot lumber) using third-point loading. The total span was 6 feet and deflection was measured relative to the load head to minimize effects of shear deformation. The 2-foot segment size was chosen to match that of Taylor and Bender (1991).
3. Segments 1 and 4 of each lumber specimen were destructively tested in tension (at a test span of 2 feet). Tensile strength could not be measured for all segments because of allowances for the tension tester grips. Each specimen was cut (between Segments 2 and 3) prior to testing, to avoid problems with wood splitting. The load rate was approximately 4,000 psi/min for all specimens, resulting in failure times of approximately 1 to 2 minutes.

LABORATORY TEST RESULTS

Summary statistics of 2-foot segment MOE and T for each grade are given in Table 1. It should be emphasized that the MOE and T statistics in Table 1 are from localized data, whereas most published lumber property statistics are based on long-span measurements. Hence, comparisons between these localized data and long-span data may be misleading. For example, part of the variability in the segment MOE data is due to within-piece variation, and the other part is due to variation between pieces of lumber. As another example, the segment tensile strength values tend to be

TABLE 2. *Summary of localized (2-foot) MOE and T data collected on 2 by 6 Douglas-fir finger-jointed lumber (Hooper and Bender 1988).*

	Lumber modulus of elasticity			Finger joint tensile strength		
Grade	Sample size*	Mean (10^6 psi)	COV (%)	Sample size	Mean (10^3 psi)	COV (%)
C14	70	2.658	9.0	35	6.066	21.2
2.3E-⅙	64	2.545	9.6	32	6.855	15.7
2.3E-⅓	50	2.612	10.4	25	6.647	16.7
2.0E-⅙	70	2.207	12.6	35	5.702	17.2
2.0E-⅓	66	2.275	11.1	33	5.167	22.0
L2	62	1.874	17.1	31	4.398	20.3
L3	60	1.751	18.6	30	3.676	25.0

* Lumber MOE measured on both sides of finger joint, resulting doubled sample sizes.

higher than long-span values due to the effect of lumber length on tensile strength (Showalter et al. 1987; Lam and Varoglu 1990; Zhao and Woeste 1991; Taylor et al. 1991).

The segment MOE values shown in Table 1 were higher than the nominal grade MOEs. This is to be expected since E-rated grades have to meet tensile strength and MOE criteria (as well as visual criteria). Since the tensile strength criterion usually controls, the actual MOEs are typically higher than the nominal grade MOE.

The data in Table 2 were excerpted from a finger-jointed lumber study by Hooper and Bender (1988) for purposes of comparison with the data reported here. Hooper and Bender tested the same grades of 2 by 6 Douglas-fir lumber except for the 1.7E-¼ grade. The average MOEs of the E-rated grades in Table 2 are in good agreement with those in Table 1, considering the sample sizes involved. The differences between the L2 and L3 MOEs in Tables 1 and 2 can be explained by the fact that the 1.7E-¼ grade was not included in both studies (recall that visual grades L2 and L3 consisted of lumber that did not qualify for any of the E-rated grades). As expected, the tensile strengths of the finger-jointed lumber (Table 2) generally were lower than those of the solid lumber (Table 1) for the E-rated grades. The tensile strengths of the L2 and L3 grades of finger-jointed lumber were higher than those of the solid lumber because the lumber that would have qualified for the 1.7E-¼ grade was not pulled (removed by grading).

Serial and cross-correlation coefficients of the localized MOE and T data are shown in Table 3. Lag-1, lag-2, and lag-3 serial correlations in MOE were estimated directly from the data since there were at least four observations of localized MOE per specimen. As previously mentioned, the lumber specimens were comprised of 4 or 5 specimens, depending on their lengths. All segment MOE data were used to fit probability distributions; however, only the first 4 segment values from each specimen were used to estimate serial correlations (to simplify statistical estimation procedures). Only lag-3 serial correlation in T was estimated from the data since Segments 1 and 4 were tested. Lag-1 and lag-2 serial correlations in T were calculated from the lag-3 correlation by assuming a first-order autoregressive model (Showalter et al. 1987; Taylor and Bender 1991). Details on the statistical estimation methods can be found in Richburg (1989) and Taylor and Bender (1991).

The amount of serial and cross-correlations calculated from the MOE and T data varied significantly between grades as shown in Table 3. One reason for the variability between grades is that the range of MOE is restricted within grades. When the data were combined across all lumber grades, correlations were significantly higher than for individual grades. There are no published data on serial correlations of MOE and T for the E-rated laminating grades studied here. However, the correlations are similar to those reported by Taylor (1988) for visual laminating grades 302-24 and L1.

SIMULATION RESULTS AND DISCUSSION

Modeling localized MOE and T

A multivariate statistical method, developed by Taylor and Bender (1991), was used to model localized MOE and T. The method was first used to model 8-foot lumber specimens consisting of four contiguous 2-foot segments. The 8-foot specimens contained four values of localized MOE and four values of T, denoted as X_1, X_2, X_3, X_4 and X_5, X_6, X_7, X_8, respectively. $X_1, X_2, \ldots, X_8$ were then treated as a vector of correlated random variables. Each specimen was represented by a single vector containing four values of MOE and four values of T. The first step of the procedure was to estimate parameters for best fitting probability distribution functions for both segment MOE and T. The segment values of MOE were assumed to be identically distributed; hence, all segment MOE values were combined to estimate the parameters of the probability density functions for each grade. Similarly, segment T values were combined to estimate the parameters of the distributions for each grade. One disadvantage of combining segment values for both MOE and T stems from the issue of statistical independence. For example, maximum likelihood estimation (MLE) of distribution parameters is based on the assumption of independent observations. However, the benefits gained by using much larger sample sizes for distribution fitting were judged to outweigh the value of independent data (by using only one segment value per lumber specimen). The estimated parameters for the MOE and T distributions are summarized in Tables 4 and 5. The Chi-square goodness-of-fit test failed to reject any of the hypothesized distributions at a significance level of at least 5% (significance exceeded 5% due to correlation in the data).

The next step in the modeling process was to estimate the correlation matrix, $\boldsymbol{\Sigma}$, for the variables $X_1, X_2, \ldots, X_8$. The values for lag-0, lag-1, lag-2, and lag-3 serial correlations in MOE and T, and MOE-T cross-correlations must be calculated to complete this step. These values were then substituted into the 8 × 8

TABLE 3. *Serial and cross-correlation coefficients estimated from the 2-foot test data for each lumber grade.*

Correlation	C14	2.3E-1/6	2.3E-1/3	2.0E-1/6	2.0E-1/3	1.7E-1/4	L2	L3	All grades
Serial MOE lag-0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Serial MOE lag-1	0.7885	0.7363	0.6006	0.6299	0.4840	0.7184	0.7337	0.6781	0.9138
Serial MOE lag-2	0.6291	0.6083	0.6596	0.5112	0.4666	0.6349	0.6755	0.6949	0.8839
Serial MOE lag-3	0.4858	0.4519	0.6110	0.5321	0.5406	0.6013	0.6399	0.7078	0.8511
Cross MOE-T lag-0	0.2305	0.2263	0.2297	0.3061	0.4193	0.2578	0.3115	0.4844	0.6951
Cross MOE-T lag-1	0.1825	0.0750	0.0401	0.2132	0.1509	0.1554	0.1921	0.2508	0.6616
Cross MOE-T lag-2	0.1489	0.0387	−0.0149	0.1487	0.1126	0.1035	0.1709	0.2408	0.6484
Cross MOE-T lag-3	0.1024	0.0289	0.0639	0.0455	0.1171	0.0897	0.1151	0.2598	0.6256
Serial T lag-0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Serial T lag-1	0.7767	0.7267	0.5351	0.6590	0.5705	0.7274	0.7651	0.6410	0.8945
Serial T lag-2	0.6033	0.5282	0.2863	0.4343	0.3254	0.5291	0.5853	0.4108	0.8002
Serial T lag-3	0.4686	0.3838	0.1532	0.2862	0.1857	0.3848	0.4478	0.2633	0.7158

TABLE 4. *Parameters for the best fitting probability density functions of 2-foot MOE (in million psi).*

Grade	Sample size	Distribution type	Parameters		
			Location	Scale	Shape
C14	994	3-P Lognormal	1.872	−0.103	0.398
2.3E-⅙	974	3-P Lognormal	1.505	−0.028	0.252
2.3E-⅓	185	3-P Weibull	1.236	1.495	4.968
2.0E-⅙	998	3-P Lognormal	1.100	0.092	0.192
2.0E-⅓	977	3-P Lognormal	0.935	0.217	0.199
1.7E-¼	970	3-P Lognormal	0.403	0.391	0.160
L2	970	3-P Lognormal	0.775	−0.324	0.313
L3	1000	2-P Lognormal	NA	0.446	0.206

correlation matrix, Σ. Once these two steps were completed, values of MOE and T were simulated using the algorithm presented in Taylor and Bender (1991). Two hundred random vectors were generated for each grade, representing 200 simulated pieces of 8-foot lumber with 4 localized MOEs and 4 Ts each. The simulation procedure was repeated 10 times so confidence intervals could be calculated on the simulated values.

Validation of the simulation procedure

The two criteria used to judge the simulation procedure were how well 1) the original probability distributions and 2) the original correlations of localized MOE and T were preserved in the simulated data.

Probability Distributions.—By its mathematical formulation, the multivariate approach exactly preserves the distributions of the individual lumber properties. As an additional check, the Kolmogorov-Smirnov (KS) goodness-of-fit test was performed to test the hypothesis that the simulated data could have been a sample from the original probability distributions (the KS test was chosen because the distribution parameters were known, i.e., not estimated from the simulated data). The KS test failed to reject any of the hypothesized distributions at a significance level of 10%, indicating that the original distributions were preserved in the simulated data.

Correlations.—Even though the multivariate approach exactly preserves the univariate distributions of MOE and T, it is possible that the nonlinear transformation may alter the original correlation matrix. Ninety-nine percent confidence intervals were calculated for each term in the MOE-T correlation matrix to check if the original correlations were preserved in the simulated data. For all grades, the confidence intervals for the simulated correlations covered the original correlation values.

Han et al. (1991) used Monte Carlo simulation to test the multivariate approach over

TABLE 5. *Parameters for the best fitting probability density functions of 2-foot T (in thousand psi).*

Grade	Sample size	Distribution type	Parameters		
			Location	Scale	Shape
C14	398	3-P Weibull	3.430	6.806	2.539
2.3E-⅙	396	2-P Lognormal	NA	2.057	0.272
2.3E-⅓	77	3-P Weibull	3.768	2.946	1.482
2.0E-⅙	399	2-P Lognormal	NA	1.810	0.279
2.0E-⅓	392	3-P Lognormal	0.450	1.533	0.348
1.7E-¼	400	2-P Lognormal	NA	1.661	0.286
L2	396	2-P Lognormal	NA	1.324	0.298
L3	395	2-P Lognormal	NA	1.119	0.324

TABLE 6. *Estimated serial and cross-correlation coefficients for 20-foot lumber.*

Lag correlation	C14	2.3E-⅙	2.3E-⅓	2.0E-⅙	2.0E-⅓	1.7E-¼	L2	L3
Serial MOE lag-0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Serial MOE lag-1	0.7885	0.7363	0.6006	0.6299	0.4840	0.7184	0.7337	0.6781
Serial MOE lag-2	0.6291	0.6083	0.6596	0.5112	0.4666	0.6349	0.6755	0.6949
Serial MOE lag-3	0.4858	0.4519	0.6110	0.5321	0.5406	0.6013	0.6399	0.7078
Serial MOE lag-4	0.3755	0.3483	0.5286	0.4385	0.3792	0.5220	0.5648	0.6083
Serial MOE lag-5	0.2894	0.2617	0.5065	0.3655	0.3494	0.4627	0.5124	0.5942
Serial MOE lag-6	0.2230	0.1988	0.4581	0.3321	0.3371	0.4153	0.4664	0.5646
Serial MOE lag-7	0.1718	0.1501	0.4197	0.2881	0.2738	0.3688	0.4211	0.5200
Serial MOE lag-8	0.1324	0.1136	0.3875	0.2469	0.2465	0.3280	0.3814	0.4956
Serial MOE lag-9	0.1020	0.0859	0.3542	0.2167	0.2240	0.2923	0.3455	0.4662
Cross MOE-T lag-0	0.2305	0.2263	0.2297	0.3061	0.4193	0.2578	0.3115	0.4844
Cross MOE-T lag-1	0.1817	0.1666	0.1379	0.1928	0.2029	0.1852	0.2285	0.3285
Cross MOE-T lag-2	0.1450	0.1377	0.1515	0.1565	0.1956	0.1637	0.2104	0.3366
Cross MOE-T lag-3	0.1120	0.1023	0.1403	0.1629	0.2266	0.1550	0.1993	0.3428
Cross MOE-T lag-4	0.0865	0.0788	0.1214	0.1342	0.1590	0.1346	0.1759	0.2946
Cross MOE-T lag-5	0.0667	0.0592	0.1163	0.1119	0.1465	0.1193	0.1596	0.2878
Cross MOE-T lag-6	0.0514	0.0450	0.1052	0.1016	0.1414	0.1071	0.1453	0.2735
Cross MOE-T lag-7	0.0396	0.0340	0.0964	0.0882	0.1148	0.0951	0.1312	0.2519
Cross MOE-T lag-8	0.0305	0.0257	0.0890	0.0756	0.1034	0.0845	0.1188	0.2401
Cross MOE-T lag-9	0.0235	0.0194	0.0813	0.0663	0.0939	0.0753	0.1076	0.2258
Serial T lag-0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Serial T lag-1	0.7767	0.7267	0.5351	0.6590	0.5705	0.7274	0.7651	0.6410
Serial T lag-2	0.6033	0.5282	0.2863	0.4343	0.3254	0.5291	0.5853	0.4108
Serial T lag-3	0.4686	0.3838	0.1532	0.2862	0.1857	0.3848	0.4478	0.2633
Serial T lag-4	0.3640	0.2790	0.0820	0.1886	0.1059	0.2799	0.3426	0.1688
Serial T lag-5	0.2827	0.2027	0.0439	0.1243	0.0604	0.2036	0.2621	0.1082
Serial T lag-6	0.2196	0.1473	0.0235	0.0819	0.0345	0.1481	0.2005	0.0693
Serial T lag-7	0.1706	0.1071	0.0126	0.0540	0.0197	0.1077	0.1534	0.0444
Serial T lag-8	0.1325	0.0778	0.0067	0.0356	0.0112	0.0783	0.1174	0.0285
Serial T lag-9	0.1029	0.0566	0.0036	0.0234	0.0064	0.0570	0.0898	0.0183

a wide range of distribution skewnesses and correlations. They found that the multivariate method preserved the correlation between variables with excellent accuracy except for cases involving mixtures of extreme positively and negatively skewed distributions in conjunction with high correlations.

EXTENSION OF THE MODEL TO SIMULATE LONGER LUMBER

The multivariate approach can be used to simulate lumber of any length. Simulating longer lumber simply requires extrapolating the MOE-T correlation matrix. For example, 20-ft lumber (comprised of 10 2-ft segments) would require a 20 × 20 correlation matrix, where X_1 through X_{10} are localized MOEs and X_{11} through X_{20} are localized Ts. Extrapolation is based on the assumptions of third-order and first-order autoregressive models for serial correlations in MOE and T, respectively. Taylor and Bender (1991) describe procedures for extrapolating MOE-T correlation matrices.

The correlation values needed to simulate 20-ft lumber are summarized in Table 6. The multivariate approach for 20-ft lumber was checked in the same manner as for the 8-foot lumber. The distributions of MOE and T, as well as the correlation matrices were preserved in the simulated data. Additional details on the extended multivariate model can be found in Richburg (1989).

SUMMARY AND CONCLUSIONS

The objectives of this study were to characterize localized modulus of elasticity (MOE) and tensile strength (T) for E-rated grades of laminating lumber and to model the data using a multivariate statistical approach developed by Taylor and Bender (1991). The multivariate model is needed as input for Monte Carlo simulation models of glued-laminated (glulam) timber beams.

Six E-rated and two visual laminating grades of 2 by 6 Douglas-fir lumber were studied. The E-rated grades were C14, 2.3E-⅙, 2.3E-⅓, 2.0E-⅙, 2.0E-⅓, and 1.7E-¼, and the visual grades were L2 and L3. The visual grades were comprised of lumber that did not qualify for any of the E-rated grades. MOE and T were measured using a test span of 2 ft.

The localized MOE data for the lumber studied here were similar to those reported for finger-jointed lumber (Hooper and Bender 1988). As expected, localized T values of the lumber were generally higher than those of similar grades of finger-jointed lumber. Significant correlations were observed among localized (2-ft) segment values of MOE and T within individual pieces of lumber. When all grades were combined, the lag-1 correlations for MOE and T were 0.9138 and 0.8945, respectively. Lag-1 correlation represents the correlation between adjoining lumber segments. Lag-0 correlations, i.e., correlations between MOE and T within the same segment, was 0.6951 when all grades were combined.

Multivariate statistical parameters were estimated from the MOE and T data and these parameters were incorporated into a multivariate algorithm to simulate correlated segment values of MOE and T. The original probability distributions of MOE and T, as well as the original correlations, were preserved in the simulated MOE and T data for all grades studied. Statistical parameters were extrapolated for 20-ft lumber to illustrate how the model can be used to simulate longer lumber. The multivariate model of E-rated lumber will provide valuable input to Monte Carlo models that simulate reliability of glulam timber beams. Similar research is needed for other lumber sizes, species and grades.

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