MECHANICAL PROPERTIES OF RED MAPLE STRUCTURAL LUMBER

David W. Green
Research Engineer

and

Kent A. McDonald
Wood Scientist

USDA Forest Service
Forest Products Laboratory[1]
One Gifford Pinchot Drive
Madison, WI 53705-2398

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ABSTRACT

Efficient utilization of hardwood structural lumber depends on developing better procedures of grading and property assignment. In this study, we evaluated the properties of red maple 2- by 4-in. (standard 38- by 89-mm) lumber tested in bending and in tension and compression parallel to the grain and compared the results to published values derived by ASTM D 245 clear wood procedures. The results indicate that significant increases in allowable properties could be obtained using procedures based on tests of full-size lumber. The results also demonstrate that the relationships between lumber strength in compression parallel to grain and bending strength and between tension parallel to grain and bending strength are similar to those for softwood species. Thus, procedures used to assign properties to mechanically graded softwood species should be applicable to red maple.

Keywords: Red maple, mechanical properties, bending, tension parallel to grain, compression parallel to grain, mechanical grading.

INTRODUCTION

The increase in the number of bridges built in the past few years shows an increasing interest in using lumber produced from hardwood species in structural applications. There is also considerable interest in using hardwoods in glulam beams. Increasing the use of hardwood lumber in metal plate wood trusses and in post-frame construction is also being discussed. However, allowable mechanical properties for hardwood species are based only on visual grading, with property assignment based on tests derived from small, clear specimens. To utilize the supply of hardwood in the United States efficiently in engineered structures, better methods are needed for grading and property assignment of structural lumber produced from hardwood species.

Structural lumber produced from softwood species has historically been graded by visual means. Allowable mechanical properties have been assigned to softwood lumber using clear wood procedures of American Society for Testing and Materials (ASTM) D 245 and D 2555 (ASTM 1991b, c). These procedures are also used to assign allowable properties to hardwood structural lumber (NFPA 1991; DeBonis and Bendtsen 1988). However, machine grading (Galligan et al. 1978) and more recent assignment of properties based on full-size testing of visually graded lumber (ASTM

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1991e) are used to obtain a more representative estimate of softwood properties. Currently, the technical basis does not exist for assigning allowable properties to hardwood lumber graded by machine. Further, full-size testing of hardwood structural lumber following procedures used for softwood species (Green et al. 1989) would involve testing in three modes; bending, tension, and compression parallel to grain. Thus, an in-grade testing program might be prohibitively expensive. These obstacles must be overcome to encourage more efficient grading and property assignment procedures for hardwood structural lumber.

The primary objective of this study was to show that relationships between mechanical properties for structural lumber produced from red maple are similar to those found for lumber from softwood species. A secondary objective was to evaluate potential increases in allowable property values of nominal 2- by 4-in. (standard 38- by 89-mm) (2 by 4) red maple lumber that might result from basing allowable properties for visually graded lumber on tests of full-size lumber rather than on those assigned by ASTM D 245 procedures.

Results of this study will begin to provide a technical basis for the machine grading of hardwood lumber. Further, this study will help to justify the estimates of tensile and compression strength parallel to the grain from bending strengths for hardwood species, making possible the use of ASTM D 1990 (ASTM 1991e) procedures. Using the ASTM D 1990 procedures for visually graded lumber could cut the cost of conducting a full-size lumber test program for hardwood species by at least two-thirds.

BACKGROUND

Historically, allowable properties for visually graded lumber have been estimated from clear wood data adjusted according to procedures given in ASTM Standard D 245 (Bendtsen and Galligan 1978). In this procedure, tests are first conducted on green, clear, straight-grained specimens to establish a distribution of strength properties for individual species. A normal distribution is then fit to these data, and for strength estimates, the 5th percentile, or 5-percent exclusion limit, is calculated. Specific factors are then multiplied by the 5th percentile to account for defects, moisture content (MC), and size of the member. A general adjustment factor is applied for duration of load and factor of safety. For the 1991 National Design Specifications (NDS), an attempt was made to "calibrate" hardwood property assignment by the clear wood procedure with results obtained from tests of full-size lumber. This was done by first calculating properties of 2 by 4 lumber using the clear wood procedure. The properties of wider lumber were calculated by using the size effect formula of ASTM D 1990.

In 1979, a program was initiated to evaluate the mechanical properties of visually graded, nominal 2-in.- (standard 38-mm-) thick softwood dimension lumber by testing full-size pieces that were previously graded by commercial graders (Green et al. 1989). In this program, testing approximately 360 pieces of lumber in each of three sizes and two grades was necessary to get representative property estimates for each test mode evaluated (bending, tension parallel to grain, and compression parallel to grain). Obviously, testing a minimum of 6,500 pieces of lumber for each hardwood species, or species group, would be expensive. This in-grade testing program led to the development of an alternative to the clear wood procedure for deriving allowable properties for lumber: ASTM D 1990. This standard recognizes that the expense of a full in-grade testing program may be hard to justify for species that currently have a small commercial market. For such species, it may be desirable to restrict testing to one property and to infer conservative property estimates for other properties. The ASTM Standard D 1990 uses the relationships for 2- by 8-in. (standard 38- by 184-mm) lumber (2 by 8) at 15-percent MC as a basis for setting allowable properties. Conservative formulas are provided for data adjusted to 2 by 8 dimensions that can be used

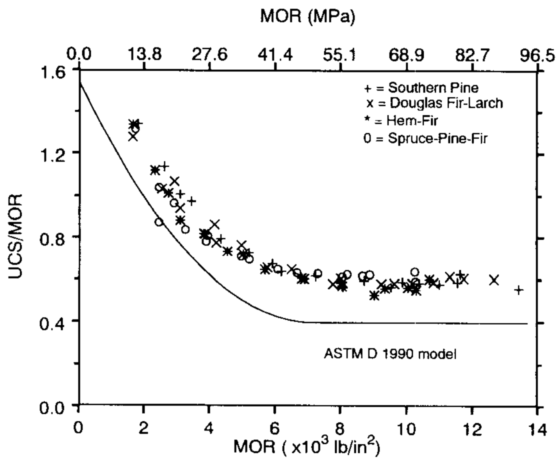

FIG. 1. Relationships between UCS and MOR assumed in ASTM in-grade standard for 2 by 8 lumber at 15-percent moisture content.

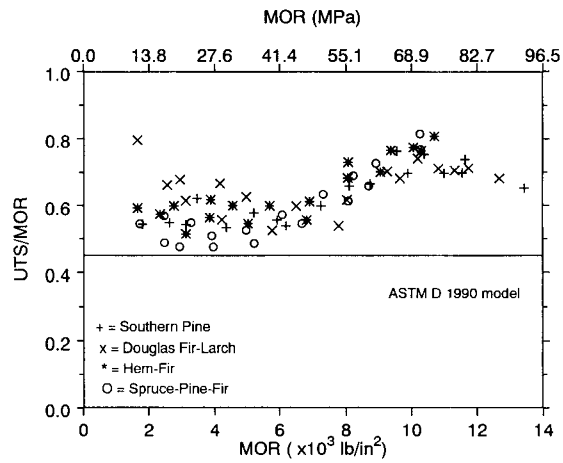

FIG. 2. Relationships between UTS and MOR assumed in ASTM in-grade standard for 2 by 8 lumber at 15-percent moisture content.

to estimate ultimate tensile stress parallel to grain (UTS) and ultimate compression stress parallel to grain (UCS) based on test data for modulus of rupture (MOR) (or to estimate MOR and UCS based on test data for UTS). Based on data from four softwood species, the relationship between UCS and MOR and between UTS and MOR varied somewhat with lumber width, MC, and species (Green and Kretschmann 1991). The ASTM D 1990 equation is

$$\begin{aligned} \text{UCS/MOR} &= \\ &= 1.55 - (0.32\ \text{MOR}) + \\ &\quad + [0.022 \times (\text{MOR}^2)] \\ &\quad \text{MOR} \leq 7.2\ \text{ksi} \\ &= 1.55 - (0.046\ \text{MOR}) + \\ &\quad + [0.00047 \times (\text{MOR}^2)] \\ &\quad \text{MOR} \leq 49.6\ \text{MPa} \end{aligned} \tag{1}$$

or

$$\text{UCS/MOR} = 0.40 \text{ if MOR} > 7.2\ \text{ksi}\ (49.6\ \text{MPa}) \tag{2}$$

and

$$\text{UTS/MOR} = 0.45\ \text{MOR} \tag{3}$$

Although fairly conservative, these relationships do allow estimates to be made of untested properties (Figs. 1 and 2).

A number of alternative procedures are currently available for the automated grading of lumber. However, the traditional procedure, machine stress rating (MSR), relies on the relationship between bending strength and bending stiffness to establish grade boundaries. Sorting efficiency for individual grades is further controlled by visual restrictions on allowable edge knot sizes (Galligan et al. 1978). Qualification of lumber for an MSR grade is an iterative procedure in which load-deflection limits are set for individual grades and the resulting output is tested for conformance to claimed properties. Thus, for an output-controlled grading system such as MSR, knowing the relationship of modulus of elasticity (MOE) to MOR is not really necessary to qualify a grade. Also, the relationship does not have to be linear, but it must be significantly different from zero. Traditionally, MOE and MOR have been used in qualifying a grade with other properties set either as a function of MOR (UTS and UCS) (Green and Kretschmann 1991) or by the ASTM D 245 clear wood procedure (shear strength and compression strength perpendicular to grain). The strength-MOR relationships used to calculate UTS and UCS were determined from tests on softwood species. A new relationship was recently adopted by the American Lumber Standards Committee to assign UCS values to MSR lumber:

if MOR $\geq$ 2.835 ksi (19.55 MPa)

$$UCS/MOR = 2.278 \times (1/MOR) + 0.338 \quad (4)$$

or

if MOR < 2.835 ksi (19.55 MPa)

$$UCS/MOR = 1.07 \times (1/MOR) \quad (5)$$

The traditional relationship between UTS and MOR for MSR lumber is a discontinuous function (Green and Kretschmann 1991). Other relationships may be used with appropriate quality control. The UCS/MOR relationship is virtually identical to that identified by Green and Kretschmann if the data are adjusted to 2 by 4 lumber at 15-percent MC.

For lumber to be used in engineered structures, mechanical grading is an attractive alternative for more efficient assignment of allowable properties. Mechanical grading, using grading machines appropriate for smaller mills, eliminates the need for extensive testing that would be required for visually graded lumber by ASTM D 1990. Also, mechanical grading allows for properties to be assigned based on the resource at hand, rather than on the weakest species in the group, which is common with visually graded lumber. However, the flexibility of the mechanical grading system makes producing an unlimited number of grades possible. This flexibility places increased emphasis on understanding the marketing and technical implications of grade selection and encourages producers to identify specific users interested in buying mechanically graded lumber prior to production.

From this discussion, we see that both visual grading and MSR systems use assumed relationships between UCS, UTS, and MOR to assign properties to structural grades. However, these relationships were established from data on softwood species, and few data exist to justify the use of these relationships with hardwood species.

MATERIALS AND METHODS

As noted earlier, the relationship between UCS and MOR varies slightly by width of the lumber. The relationship for 2 by 4 lumber is slightly more conservative than that for wider lumber. Also, the UCS/MOR relationship used with MSR lumber is based on tests of 2 by 4 lumber. For these reasons, 2 by 4 lumber was selected for this study. The 2 by 4 lumber used in this study was cut from 12- to 16-ft- (3.6- to 4.9-m-) long red maple (*Acer rubra*) logs obtained from a mill in central Vermont. Details of log and lumber processing and grade yield information were given by McDonald et al. (in process). The lumber was dried to approximately 13-percent MC using a mild kiln schedule and then planed to 1.5 by 3.5 in. (38 by 89 mm). The lumber was graded following procedures given in the Standard Grading Rules (NELMA 1991) by a quality supervisor of the Southern Pine Inspection Bureau. The grade-controlling defect in each piece was marked by the grader for later measurement by our laboratory personnel. To provide optimum yield of graded material, 2 by 4 lumber that did not meet at least a No. 3 grade description when graded full-length was also graded in 8- to 14-ft (2.4- to 4.3-m) lengths. Following grading, the lumber was trimmed to the length on which the grade was made. Lumber failing to meet at least the No. 3 grade description was not tested in this study. Prior to sorting and testing, the lumber was equilibrated in a humidity room maintained at 68 F (20 C) and 65-percent relative humidity (nominal 12-percent MC).

A full-span dynamic modulus of elasticity (MOE_d) value was obtained on each piece using vibration techniques (Metriguard E-Computer[2]) with the lumber oriented flatwise. This information was used to sort the lumber into three groups of equivalent esti-

[2] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

TABLE 1. *Strength and modulus of elasticity of red maple 2 by 4 lumber obtained from central Vermont.*[a]

Property	Grade	Sample size	Avg MC	Avg SG[b]	Mean	COV (%)	Percentile[c] 5th	10th	25th	50th
MOE	SS	46	11.4	0.57	1.89	17.1	1.20	1.40	1.66	1.90
(static)	No. 2	128	11.2	0.57	1.78	15.4	1.38	1.45	1.58	1.77
($\times 10^6$ lb/in.^{2})	No. 3	83	11.3	0.57	1.72	16.1	1.30	1.40	1.53	1.69
MOE_{adj}	SS	114	11.3	0.57	1.89	14.8	1.45	1.54	1.70	1.89
($\times 10^6$ lb/in.^{2})	No. 1	6	11.3	0.57	1.91	—[d]	—	—	—	—
	No. 2	305	11.3	0.56	1.79	14.3	1.42	1.49	1.63	1.80
	No. 3	197	11.3	0.57	1.72	14.8	1.35	1.43	1.58	1.73
MOR	SS	46	11.4	0.57	11.80	26.8	4.79	7.37	9.92	12.28
($\times 10^3$ lb/in.^{2})	No. 2	128	11.2	0.57	10.60	26.7	5.27	6.75	8.50	10.73
	No. 3	83	11.3	0.57	9.18	31.6	4.32	5.07	6.80	9.09
UTS	SS	20	11.3	0.57	9.12	27.9	4.65	5.52	6.88	9.25
($\times 10^3$ lb/in.^{2})	No. 2	49	11.3	0.56	7.19	34.3	3.34	3.79	5.18	7.63
	No. 3	32	11.3	0.56	6.01	39.4	2.63	3.09	3.97	5.78
UCS	SS	48	11.3	0.56	6.39	12.7	4.79	5.38	5.88	6.46
($\times 10^3$ lb/in.^{2})	No. 2	128	11.1	0.56	5.92	14.2	4.55	4.90	5.38	5.97
	No. 3	82	11.2	0.56	5.49	15.8	3.98	4.30	4.92	5.57

[a] MC is moisture content, SG specific gravity, COV coefficient of variation, MOE modulus of elasticity, MOR modulus of rupture, UTS ultimate tensile stress, UCS ultimate compression stress, SS Select Structural. 1 lb/in.^{2} = 6.89 × 10^3 Pa.
[b] SG based on oven-dry weight and volume at 12-percent moisture content.
[c] MOE_{adj} determined from vibration MOE measured on 21 samples. Adjusted to static MOE by $E_{adj} = 0.0477 + 0.873E_{vib}$.
[d] Sample sizes insufficient to estimate indicated percentile.

mated strength based on stiffness. The 10- to 16-ft- (3- to 4.9-m-) long lumber within each grade was ranked by MOE. Each of three ordered specimens was then randomly assigned to one of three groups for testing in bending, or in tension or compression parallel to grain. Because the 8-ft (2.4-m) lumber was considered too short for testing in tension parallel to grain, these pieces ranked by MOE were assigned to only two groups. Because of the small number of specimens, the No. 1 grade was included with the Select Structural (SS) lumber for ranking purposes.

Testing was conducted following procedures given in ASTM D 4761 (ASTM 1991d). Edgewise bending tests were conducted using third-point loading and a span-to-depth ratio of 17:1. To avoid a possible nonconservative bias in the results because of the small sample size, the grade-controlling defect was placed between the load heads and randomly located with respect to the edge to be stressed in tension. The clear span between grips for the tensile tests was 5 ft (1.5 m) less than the length of the specimen. Compression testing was conducted on full-length specimens supported according to provisions given in ASTM D 198 (ASTM 1991a). For all specimens, a constant rate of cross-head movement was used to provide failure within the range of 30 sec to 5 min.

RESULTS AND DISCUSSION

Potential increases in allowable properties

The primary focus of this study was to evaluate the relationships between lumber properties. Evaluation of lumber property relationships can be accomplished using a relatively small number of specimens, sampled from one geographic location, if the specimens have a broad range of lumber quality. Evaluation of the potential increases for individual grades of visually graded lumber was a secondary objective. Evaluation of absolute properties of individual grades of lumber would require a much larger sample collected over a broad geographic range (ASTM D 1990).

The mechanical properties of the red maple tested in this study are summarized in Table 1. For this analysis, the lumber of various

TABLE 2. *Ratio of test results for 2 by 4 lumber to property values derived by clear wood procedures at 12-percent moisture content.*

Grade	Species or group	Ratio of test results to clear wood estimates			
		MOE	MOR	UTS	UCS
SS	Red maple	1.07	0.89	1.63	1.68
	Northern red oak	1.22	1.54	—	1.18
	Douglas fir-larch	1.04	1.31	1.25	1.30
	Southern pine	1.08	1.58	1.25	1.39
	Hem-fir	1.03	1.58	1.43	1.38
	Yellow-poplar	1.03	1.67	1.09	—
No. 2	Red maple	1.14	1.45	2.62	1.67
	Northern red oak	1.16	1.17	1.31	2.12
	Douglas fir-larch	0.92	1.15	1.10	1.59
	Southern pine	0.98	1.18	0.94	1.59
	Hem-fir	0.95	1.21	1.21	1.69
	Yellow-poplar	1.13	1.33	1.35	—
No. 3	Red maple	1.27	2.16	2.31	4.12
	Northern red oak	1.22	1.78	1.71	2.85

lengths was combined by grade. No length effect was expected, or observed, for the MOR of bending specimens because all lumber was tested using a 60-in. (1.5-m) span. Also, no consistent significant difference was found between the UCS values of the pieces of various lengths tested in tension or compression parallel to grain. The MOE values obtained by vibration measurements on all specimens were combined to obtain the overall MOE_d estimates. To obtain MOE estimates based on all specimens, a regression equation was obtained between MOE and MOE_d using the pieces tested in bending. This MOE value, MOE_{adj}, is estimated from

$$MOE_{adj} = 0.156 + 0.848 \times MOE_d \qquad R^2 = 0.95 \tag{6}$$

When adjusted to an equivalent basis, the mean MOE values of red maple obtained in this study were 7 to 27% higher than those published in the NDS (Table 2). The lower grades showed a potentially larger increase than did the higher grades if evaluated on the basis of full-size lumber tests. However, such increases in MOE might significantly increase spans of deflection-controlled structures such as light frame floors and stress laminated bridge decks. The difference between MOE estimates based on clear wood tests and those based on full-size lumber tests is believed to be a function of the representativeness of the sample, rather than a lack of accuracy of ASTM D 245 adjustment procedures. For softwood species, the MOE values obtained from the in-grade testing program were much closer to the expected results from clear wood tests. However, the estimates from clear wood tests on softwoods were based on test specimens cut from many trees per species, while those for red maple were based on only 14 trees. Thus, we suggest that clear-wood-based test results can give reasonable estimates of MOE if a sufficiently representative sample is obtained.

Comparison of experimental strength properties for red maple with published values was less reliable than comparisons involving MOE because of the smaller sample sizes for strength tests. Except for the MOR of SS grade, increases in strength values from 45% to more than 300% were found (Table 2). Although the larger increases for some properties were probably unrealistic because of the relatively small samples sizes used in this study, they do indicate that substantial increases in allowable strength properties can be obtained for red maple 2 by 4 lumber by using full-size test procedures. As Table 2 shows, an increase was generally obtained when softwood species were tested with full-size 2 by 4 specimens, rather than deriving properties from tests of small clear specimens.

The low value for the MOR of SS red maple was believed to be an anomalous result of having a small sample size. Examining the data indicated that two specimens had MOR values significantly below the other values in the distribution. This caused the difference between the 5th and 10th percentiles to be much larger for the MOR of SS grade than the difference between the same percentiles for other strength properties (Table 1). Also, all other species had a test-to-clear wood ratio greater than 1 for MOR (Table 2).

The results obtained from a mill in Vermont indicate that substantial increases in the allowable properties of visually graded red maple 2 by 4 lumber might be obtained if allowable properties were based on tests of full-size structural lumber (ASTM D 1990) instead of on clear wood calculation procedures (ASTM D 245). Obviously, the results from lumber sampled at only one mill are not sufficient to justify an increase in allowable properties. An extensive and expensive sampling program would be required to justify such increases. The experimental design of such a program and the technical and economic justification for carrying it out should be carefully considered before any in-grade testing program is undertaken.

Projected properties of wider specimens

In-grade tests of full-size specimens of softwood species confirmed historical assumptions that MOE does not vary with lumber width (Green and Evans 1987). Thus, MOE measured on 2 by 4 lumber should provide reasonable estimates of the MOE of wider lumber. However, in-grade tests showed that width affected strength properties much more than had previously been determined in ASTM D 245. The ASTM D 1990 Standard provides a formula for estimating the effect of specimen size on lumber strength properties. This formula was used to adjust design values for width of red maple in the 1991 NDS version. Thus, except for the MOR of SS, the change in properties shown in Table 2 could be assumed to apply to values listed for nominal 2- by 12-in. (standard 38- by 286-mm) lumber (2 by 12).

Relationships between lumber properties

MOE properties.—As was noted, knowing the MOE-MOR relationship is not necessary to grade MSR lumber. However, knowing the relationship in advance makes the process of qualifying an MSR grade more efficient. It is also not necessary for the relationship to be linear. The relationships between strength and MOE shown in Table 3 illustrate how erroneous conclusions may be reached regarding the potential for mechanical grading with standard measures of correlation. The usual R^2 value for the MOR-MOE relationship of red maple is only 0.31. This is significantly less than the values of 0.52, 0.56, and 0.53 found for southern pine, Douglas fir-larch, and hem-fir in the in-grade program. With this information, one might conclude that the MOR of red maple is less correlated with MOE than is the softwood species. The Kendall Tau correlation coefficient is a nonparametric correlation coefficient not dependent upon assumptions of linearity (Gibbons 1976). For red maple, the value of the Kendall Tau (0.56) is the same as those of the three softwood species (0.57, 0.54, 0.56) tested in the in-grade program. Thus, there is no reason to believe that red maple could not be sorted as efficiently as the softwoods in a mechanical grading operation. Other examples are provided in Table 3.

UCS/MOR relationship.—Figure 3 shows that the relationship between UCS/MOR and MOR has the same shape as those found for visually graded softwood species tested in the in-grade program (Green and Kretschmann 1991) and would yield a slightly higher UCS value than would the softwood trends. Because no No. 3 grade lumber was tested in the in-grade testing program in the United States, the red maple results are shown both with all grades included and with the No. 3 grade lumber removed. Because the data in this study came from only a limited number of specimens collected in one location, we do not recommend using the red maple curves directly to estimate UCS from MOR. However, it appears that the relationships assumed in assigning allowable UCS values to softwood species, either in ASTM D 1990 or those used with MSR lumber, could be safely applied to structural lumber produced from red maple.

UTS/MOR relationship.—Figure 4 shows the relationship between UTS/MOR and MOR obtained for red maple. This is similar in form to the relationship obtained with softwood species in the in-grade testing program. It is also similar to the in-grade results for yellow-poplar (Fig. 4). Thus, we conclude that property relationships used in ASTM D 1990 to estimate UTS from MOR for softwood species

TABLE 3. *Modulus of elasticity and strength relationships for 2 by 4 lumber at 12-percent moisture content.*

Property relationship	Species/group	Sample size	Strength A + B(MOE) (× 10³ lb/in.²)[a]		Coefficient of determination R^2 (%)	Kendall Tau coefficient (%)
			A	B		
MOR–MOE	Red maple	260	−0.06	5.840	0.31	0.56
	Northern red oak	215	−1.52	7.009	0.46	0.48
	Southern pine[b]	575	0.14	4.444	0.46	0.48
	Southern pine[c]	2,161	−0.66	4.490	0.52	0.57
	Douglas fir-larch[c]	2,781	−0.91	4.593	0.56	0.54
	Hem-fir[c]	903	−1.46	5.166	0.53	0.56
	Yellow-poplar[c]	126	1.42	4.763	0.25	0.32
	Aspen-cottonwood	85	2.02	5.164	0.30	0.37
UTS–MOE_{adj}	Red maple	102	−2.00	5.082	0.21	0.33
	Northern red oak[d]	107	−4.03	6.563	0.29	0.34
	Southern pine[e]	384	−1.95	3.170	0.43	0.48
	Yellow-poplar	100	−1.39	5.046	0.14	0.27
UCS–MOE_{adj}	Red maple	260	1.94	2.200	0.36	0.46
	Northern red oak[d]	214	1.63	2.426	0.49	0.53
	Southern pine[b]	297	1.90	1.770	0.43	0.49
MOE–MOE_d	Red maple	260	0.16	0.848	0.72	0.65
	Northern red oak	215	0.05	0.873	0.85	0.77
MOR–MOE_d	Red maple	260	1.84	4.432	0.18	0.40
	Northern red oak[d]	215	−2.96	5.622	0.33	0.39
UTS–MOE_d	Red maple	102	−1.21	4.309	0.21	0.33
	Northern red oak	107	−4.03	5.907	0.29	0.34
UCS–MOE_d	Red maple	260	2.28	1.866	0.36	0.46
	Northern red oak[d]	214	1.63	2.180	0.49	0.53

[a] 1 lb/in.² = 6.89 × 10³ Pa.
[b] Doyle and Markwardt (1966).
[c] Green and Evans (1987).
[d] Coefficients A and B are corrections of typographical errors in Green and McDonald (1993).
[e] Doyle and Markwardt (1967).

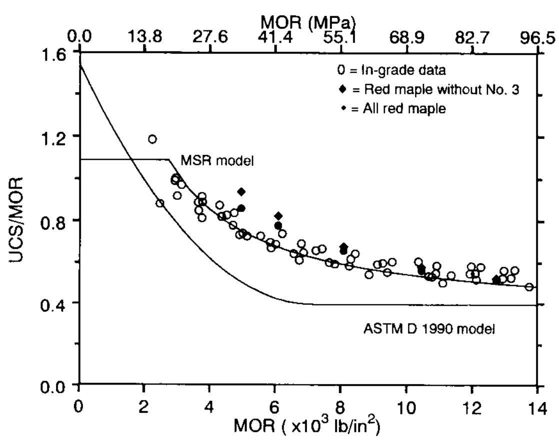

FIG. 3. Relationships between UCS and MOR for red maple 2 by 4 lumber at 12-percent moisture content.

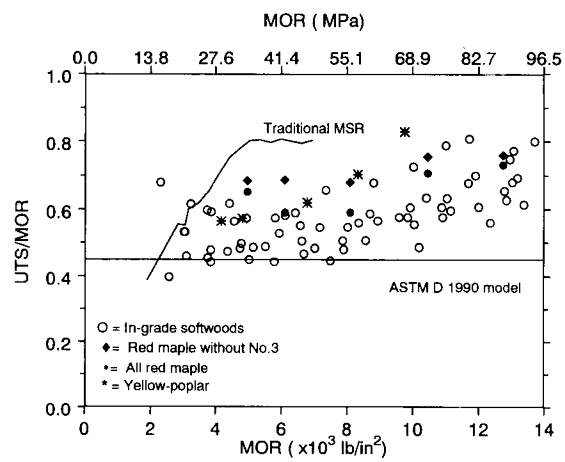

FIG. 4. Relationships between UTS and MOR for red maple 2 by 4 lumber at 12-percent moisture content.

may be used with red maple. We also conclude that any relationship for estimating UTS from MOR deemed applicable to MSR lumber produced from softwood species is also applicable to red maple lumber.

Application to other hardwood species

Little information is available on the relationships between mechanical properties for structural lumber produced from hardwood species relative to the information available for softwood species. However, from the results of this study, it appears that procedures used to assign allowable properties to mechanically graded softwood lumber are applicable to red maple. There is little reason to doubt that a significant MOE-MOR relationship exists for domestic hardwood species and most tropical hardwood species (Appiah 1984; Roos et al. 1990; Faust et al. 1991; Senft and Lucia 1979). In-grade data indicate significant MOE-strength relationships for yellow-poplar and aspen-cottonwood.

The general form of the relationship between UCS and MOR can be predicted from MOE for softwood species (Green and Kretschmann 1991). Further, the UCS/MOR relationship follows this same trend using data on clear wood of both hardwood and softwood species. The UCS/MOR relationship also applies to a high-density hardwood, northern red oak (Green and McDonald 1993), and to a medium-density hardwood, red maple. Further, the relationships between UTS and MOR obtained in the in-grade testing program could be used to obtain a conservative estimate of UTS for northern red oak and red maple. Data collected in the in-grade testing program also indicate that the UTS/MOR relationships found for softwoods could also be used with yellow-poplar (Fig. 4). Thus, the authors conclude that the property relationships given in ASTM D 1990, and those used to estimate the properties of softwood MSR lumber, are also applicable to most domestic hardwood species.

Special problems with certain species could make the property relationships discussed in this paper unreliable. For example, tropical species prone to brittle heart cannot be reliably graded on the basis of an MOE-MOR relationship (Collins and Amin 1990). We speculate that the MOE-MOR relationship and the relationships between MOR, UCS, and UTS could also be affected by factors such as severe growth stresses and interlocked grain. For these reasons, we urge caution in applying these results to hardwood species known to have special problems similar to those discussed here.

CONCLUDING REMARKS

From the results of this study on the properties of 2 by 4 lumber produced from red maple, we conclude the following:

1. Substantial increases in allowable properties could generally be expected if design values were obtained using procedures outlined in ASTM D 1990 based on tests of full-size structural lumber.
2. If only bending test results of full-size lumber are available, property relationships given in ASTM D 1990 could be used to derive allowable properties in tension parallel to grain and compression parallel to grain. Property estimates derived in this manner are expected to be conservative.
3. There is a significant relationship between modulus of elasticity and modulus of rupture. Thus, there would appear to be no obstacle to the mechanical sorting of lumber produced from red maple.
4. Property relationships obtained for red maple lumber are similar in form to those obtained for softwood lumber using the in-grade testing program data. Thus, property relationships used to derive allowable compressive and tensile strengths for softwood MSR lumber should be applicable to red maple lumber.
5. With smaller data sets, the Kendall correlation coefficient is a more reliable indicator of the suitability of MOE-strength relationships for species to be mechanically graded than is the standard coefficient of determination R^2.

The authors conclude that property relationships used to assign properties to softwood lumber in ASTM D 1990, and those used to assign properties to MSR lumber, are applicable to lumber produced from most domestic hardwood species.

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