INVESTIGATION OF THE MECHANICAL PROPERTIES OF RED OAK 2 BY 4'S

David W. Green
Research Engineer

and

Kent A. McDonald
Wood Scientist

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

(Received March 1992)

ABSTRACT

Efficient utilization of the U.S. hardwood supply depends upon developing better methods of grading lumber and assigning allowable property values to structural lumber produced from hardwood species. This study evaluated the properties of lumber cut from logs of the northern red oak species group and tested in bending, and in tension and compression parallel to the grain. Compared to published values derived by ASTM D245 clear-wood procedures, the results of this study indicate that significant increases in allowable properties could be obtained using procedures based on tests of full-size lumber given in ASTM D1990. The relationships between hardwood lumber strength in compression parallel to the grain and bending strength and between tension parallel to the grain and bending strength were found to be similar to those for softwood species. Thus, procedures used to assign properties to machine-graded softwood species should be applicable to northern red oak.

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

INTRODUCTION

To utilize the U.S. hardwood timber supply efficiently, better methods are needed for grading lumber and assigning allowable property values to structural lumber produced from hardwood species. Allowable property values of softwood lumber are assigned by the "clear-wood" procedures in ASTM D245-D2555 (ASTM 1991). These procedures are also used to assign allowable property values to hardwood structural lumber (NFPA 1991; DeBonis and Bendtsen 1988). Historically, structural lumber produced from softwood species has been graded by visual means. However, machine grading (Galligan et al. 1978) and recent assignment of property values based on full-size testing of visually graded lumber (D1990, ASTM 1991) are also used to obtain a representative estimate of softwood property values. Currently, the technical basis does not exist for assigning allowable property values to hardwood lumber graded by machine. Further, full-size testing of hardwood structural lumber that follows procedures used for softwood species (Green et al. 1989) would be prohibitively expensive.

The primary objective of this study was to show that relationships between mechanical

Wood and Fiber Science, 25(1), 1993, pp. 35–45

TABLE 1. *Mean clear-wood property values at green moisture content for red oak and northern red oak.*[a]

Commercial group	Species	MOE (×10⁶ lb/in.²)	MOR (lb/in.²)	UCS (lb/in.²)	Grown in central Wisconsin
Red oak	Black oak	1.182	8,820	3,470	yes
	Cherrybark oak	1.790	10,850	4,620	no
	Laurel oak	1.393	7,940	3,170	no
	Northern red oak	1.353	8,300	3,440	yes
	Pin oak	1.318	8,330	3,680	no
	Scarlet oak	1.476	10,420	4,690	no
	Southern red oak	1.141[b]	6,920[b]	3,030	no
	Water oak	1.552	8,910	3,740	no
	Willow oak	1.286	7,400	3,000[b]	no
Northern red oak	Black oak	1.182[b]	8,220[b]	3,470	yes
	Northern red oak	1.353	8,300	3,440[b]	yes
	Pin oak	1.318	8,330	3,680	no
	Scarlet oak	1.476	10,420	4,690	no

[a] ASTM D2555 (ASTM 1990); 1 lb/in.² = 6.89 × 10³ Pa.
[b] Controlling property for the group.

property values for structural lumber produced from northern red oak are similar to those found for 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) red oak lumber that might result from basing allowable property values for visually graded lumber on tests of full-size lumber.

Results of this study will begin to provide a technical basis for the machine grading of hardwood lumber. Further, this study will help justify the estimates of tensile and compression strengths parallel to the grain from bending strength for hardwood species, making possible the use of ASTM D1990 procedures. Use of the D1990 procedures for visually graded lumber could cut the cost of conducting a full-size lumber testing program for hardwood species by at least two-thirds.

BACKGROUND INFORMATION

Clear-wood tests

Allowable property values for visually graded lumber can be estimated from clear-wood data and adjusted according to procedures in ASTM standard D245 (ASTM 1991). In this procedure, tests are conducted on green, clear, straight-grain specimens to establish distributions of strength property values for individual species. A normal distribution is then fit to these data and, for strength estimates, the 5th percentile level or "5% exclusion limit" is calculated. The estimate is then multiplied by factors to account for defects (strength ratio), moisture content, and size of the specimen. A combined adjustment factor is then applied for duration of load and safety. For the 1991 edition of the National Design Specifications, an attempt was made to "calibrate" properties derived by the clear-wood procedure of D245 with anticipated results obtained from tests of full-size lumber and derived by D1990. This was done by first calculating properties of dry 2 by 4's using the clear-wood procedure. The properties of greater width lumber were then calculated using the size-effect formula of D1990.

The ASTM D2555 standard also provides procedures for estimating the property values of species grouped together for marketing purposes. To calculate allowable group property values, estimates of standing timber volume for the individual species are used as weighting factors to ensure that the strength and stiffness values for all species are appropriately represented in the group. However, standing timber volumes for the oaks are classified only as "red oak" or "white oak" and are not published for individual species. Thus, the resulting allowable property value is based on the lowest property value of any species in the group (DeBonis and Bendtsen 1988) (Table 1). Depending upon variation of the clear-wood property values of the species in the group and the relative standing timber volume of the species, this procedure could produce conservative estimates for oak lumber. The degree of conservativeness could be further increased for the strength properties, because the reduction taken for the general adjustment factor for hardwood strength properties is 10% greater than that used for softwood species. Thus, for visually graded oak dimension lumber, we anticipate an increase in allowable property values through testing of full-size members.

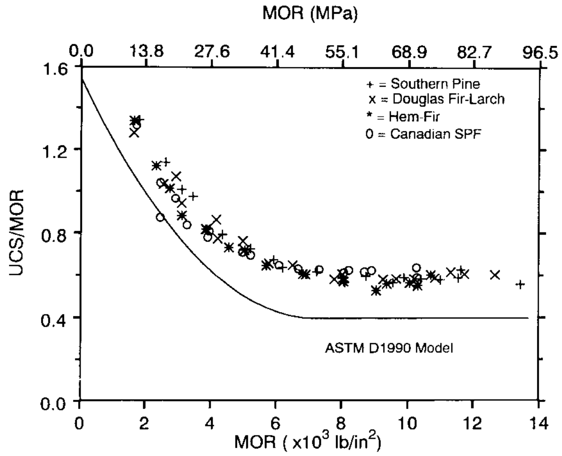

FIG. 1. UCS/MOR relationships assumed in ASTM In-Grade standard for 2 by 8's at 15% moisture content.

Full-size lumber tests

In 1979, an In-Grade Testing Program was initiated to evaluate the mechanical properties of visually graded, 2-in.- (38-mm-)-thick dimension lumber by testing full-size pieces that had previously been graded by commercial graders (Green et al. 1989). In this program, it was judged necessary to test approximately 360 pieces of lumber in each size and two grades to obtain a representative property estimate for each of the three test modes that were evaluated (bending, tension parallel, and compression parallel to the grain). The In-Grade Program led to the development of an alternative to the clear-wood procedure (ASTM D1990) for deriving allowable property values for visually graded lumber (ASTM 1991). Testing a minimum of 6,500 pieces of lumber for each species or species group would be extremely expensive for hardwood species. This standard recognizes that the expense of an in-grade testing program may be hard to justify for some species having little commercial value. For such species, it may be desirable to restrict testing to one property and to infer conservative property estimates for other properties. In ASTM D1990, conservative formulas are provided for data adjusted to nominal 2- by 8-in. (standard 38- by 184-mm) dimensions and 15% average moisture content. These formulas, which are based on an "equal rank" assumption (Green and Kretschmann 1991), can be used to estimate ultimate tensile stress parallel to the grain (UTS) and ultimate compressive stress parallel to the grain (UCS) based on test data for modulus of rupture (MOR) (or to estimate MOR and UCS based on test data for UTS). The ASTM D1990 formulas are

$$USC/MOR = 1.55 - (0.32 \times MOR) + (0.022 \times MOR^2) \quad (1)$$

if MOR $\leq$ 7.2 ksi ($\leq$49.6 MPa)

or $$USC/MOR = 0.40 \quad (2)$$

if MOR $>$ 7.2 ksi ($>$49.6 MPa)

and $$UTS/MOR = 0.45 \quad (3)$$

Although conservative, relative to average trends of the data, these relationships do allow estimates to be made of untested properties (Figs. 1 and 2).

Machine-graded lumber

Several procedures are available for machine grading of lumber. However, the traditional procedure of machine stress rating (MSR) relies upon the relationship between strength and stiffness to establish grade boundaries. Sorting efficiency for lumber grades is further

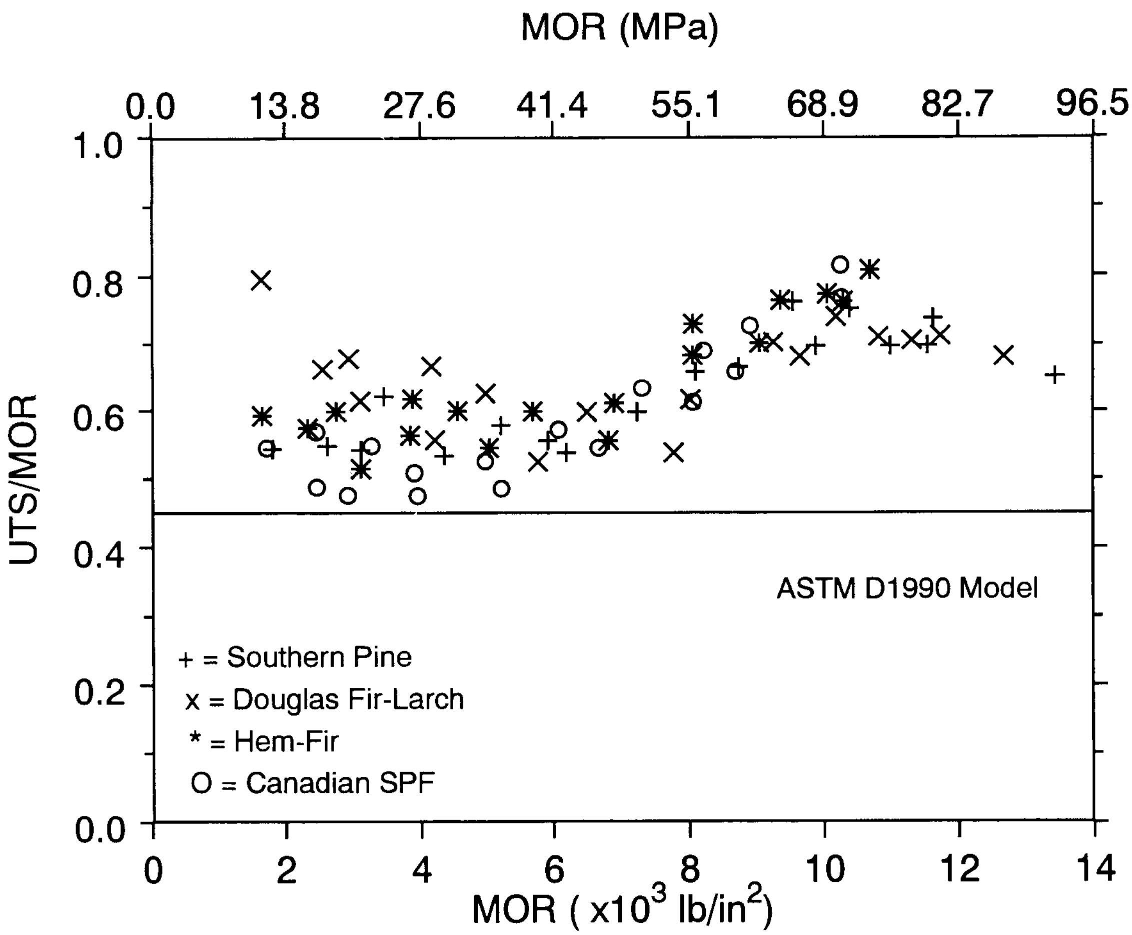

FIG. 2. UTS/MOR relationships assumed in ASTM In-Grade standard for 2 by 8's at 15% moisture content.

controlled by visual restrictions on allowable edge knot sizes (Galligan et al. 1978). Qualifying lumber for an MSR grade is an iterative procedure in which deflection limits are set for individual grades, and the resulting output is tested for conformance to claimed properties. Thus, it is not necessary to know the relationship between modulus of elasticity (MOE) and MOR to qualify an MSR machine. Also, the relationship need not be linear, but a significant relationship must exist between MOE and MOR. Traditionally, MOE and MOR values are used to establish the grade cut-off settings on an MSR machine. Other property values are determined either as a function of MOR (UTS and UCS) or by the clear-wood procedure (shear strength parallel to the grain and compression strength perpendicular to the grain) (Bendtsen and Youngs 1981). The strength-MOR relationships used to calculate allowable tensile strength (Ft) from UTS and allowable compressive strength (Fc) from UCS were determined from tests of softwood species (Green and Kretschmann 1991). The following new relationship, based on data adjusted to 15% moisture content, was recently adopted by the American Lumber Standards Committee, Board of Review, to assign UCS values to MSR lumber:

$$\text{UCS/MOR} = 2.061 \times (1/\text{MOR}) + + 0.338 \quad (4)$$

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

$$\text{UCS/MOR} = 1.06 \quad (5)$$

if MOR $<$ 2.835 ksi ($<$19.55 MPa)

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.

From the discussion previously given, we see that both visually graded and MSR lumber 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 previously noted, the relationship between UCS/MOR and UTS/MOR varies slightly with lumber width. The relationship for 2 by 4's is slightly more conservative than that for wider width lumber. Also, the UCS/MOR relationship used with MSR lumber is based on tests of 2 by 4's. For these reasons, 2 by 4's were selected for this study.

The 2 by 4's used were cut from 12-ft- (3.6-m-)-long red oak logs obtained from a mill in central Wisconsin. The logs were determined to be a mixture of black oak (*Quercus velutina*) and northern red oak (*Quercus rubra*). Thus, this lumber was in the northern red oak commercial grouping. Other species in this grouping do not grow in central Wisconsin (Table 1). Details of log and lumber processing and grade yield are given in McDonald and Whipple (1992). The lumber was dried to approximately 15% moisture content using a mild kiln schedule and then planed to 1.5 by 3.5 in. (38.1 by 88.9 mm). The lumber was graded following procedures given in the National Grading Rule (NELMA 1992) by a quality supervisor of the Southern Pine Inspection Bureau. The grade-controlling defect in each piece was marked by the quality supervisor for later measurement by laboratory personnel. To provide optimum yield of graded material, 12-ft- (3.6-m-)-long 2 by 4's that did not meet at least the No. 2 grade were also graded in 10-ft (3-m) and 8-ft (2.4-m) lengths, and respective pieces were cut to these sizes. Lumber failing to meet at least the No. 3 grade description was not tested in this study. The lumber was equilibrated in a humidity room maintained at 20 C and 75% relative humidity (nominal 12% moisture content).

A full-span dynamic modulus of elasticity, MOE_d, was obtained on each piece using vibration techniques (Metriguard E-Computer,[1] Pullman, Washington) with the lumber oriented flatwise. This information was used to sort the lumber into three groups of equivalent estimated strength values based on stiffness for testing in bending, and in tension and compression parallel to the grain. The 12- and 10-ft- (3.6- and 3-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. Because the 8-ft (2.4-m) lumber was considered too short for testing in tension parallel to the grain, these pieces ranked by MOE were assigned only to two groups. Because of the small number of specimens, the No. 1 grade specimens were included with the Select Structural (SS) lumber for ranking purposes.

Testing was conducted following procedures in ASTM D4761 (ASTM 1991). Edgewise bending tests were conducted using third-point loading and a span-to-depth ratio of 17:1. The grade-controlling defect was placed between the load heads and randomly located with respect to the edge to be stressed in tension. A static MOE was obtained on each piece. The clear span between grips for the tensile tests was 7 ft (2.1 m) for the 12-ft- (3.6-m-)-long specimens and 5 ft (1.5 m) for the 10-ft- (3-m-)-long specimens. Compression testing was conducted on full-length specimens supported

[1] 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 2. *Strength and MOE of red oak 2 by 4's obtained from central Wisconsin.*

Property	Grade	Sample size	Average moisture content	Average specific gravity[a]	Values at indicated property level[b]					
					Mean	COV	5th	10th	25th	50th
MOE (static)	SS	40	11.6	0.623	1.82	16.4	1.29	1.35	1.64	1.82
	No. 1	15	11.7	0.630	1.77	17.2	1.26	1.34	1.41	1.80
	No. 2	91	11.6	0.625	1.57	17.0	1.15	1.24	1.36	1.57
	No. 3	68	11.7	0.625	1.48	21.0	0.90	1.05	1.30	1.47
MOE_{adj}	SS	94	11.6	0.622	1.77	16.0	1.28	1.34	1.64	1.85
	No. 1	52	11.6	0.628	1.72	16.1	1.18	1.33	1.47	1.78
	No. 2	241	11.5	0.621	1.57	17.1	1.16	1.24	1.36	1.53
	No. 3	193	11.6	0.629	1.52	21.5	0.96	1.04	1.32	1.57
MOR	SS	40	11.6	0.623	13.27	20.4	8.97	10.16	10.84	13.14
	No. 1	15	11.7	0.630	11.51	21.4	—[c]	7.34	9.38	11.61
	No. 2	91	11.6	0.625	9.36	28.0	4.62	6.23	7.21	9.33
	No. 3	68	11.7	0.625	7.66	32.9	3.67	4.41	5.91	7.57
UTS	SS	19	11.6	0.622	11.62	30.7	—[c]	6.73	9.08	11.44
	No. 1	8	11.6	0.644	8.49	37.1	—[c]	—[c]	5.57	7.01
	No. 2	39	11.5	0.620	5.69	38.2	3.35	3.40	4.55	5.07
	No. 3	41	11.6	0.640	4.70	47.0	2.47	2.78	3.24	4.09
UCS	SS	31	11.7	0.616	6.24	17.3	3.54	4.69	5.70	6.46
	No. 1	21	11.5	0.626	6.11	11.8	4.51	5.04	5.53	6.28
	No. 2	93	11.5	0.619	5.54	15.7	4.25	4.42	4.80	5.56
	No. 3	69	11.6	0.627	4.92	22.4	3.20	3.47	4.31	4.79

[a] Specific gravity based on ovendry weight and volume at 12% moisture content. 1 lb/in.^{2} = 6.89 × 10^3 Pa.
[b] MOR, UTS, and UCS property values are given in × 10^3 lb/in.^{2}. MOE and MOE_{adj} values are given in × 10^6 lb/in.^{2}. MOE_{adj} determined from vibration MOE measured on 214 samples, adjusted to static MOE by $MOE_{adj} = 0.0477 + 0.873\ MOE_d$.
[c] Sample size insufficient to estimate indicated percentile.

according to provisions in ASTM D198 (ASTM 1991). For all specimens, failure occurred between 30 sec and 5 min.

RESULTS AND DISCUSSION

Potential increases in allowable properties

Mechanical property values of the visually graded red oak tested in this study are summarized in Table 2. For this analysis, the lumber of various 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, a consistent significant difference was not found between the UCS values of the pieces of various lengths tested in compression parallel to the grain. For the pieces tested in tension parallel to the grain, the median UTS value for the material tested using a 5-ft (1.5-m) clear span was about 3% to 4% greater than that tested using a 7-ft (2.1-m) clear span. Because of the small sample sizes of the individual grades when separated by test length, it was not possible to establish if this difference was significant when compared to the 2% difference predicted by ASTM D1990. The MOE values obtained by vibration methods on all specimens were combined to obtain the overall MOE estimates. The vibration values (MOE_d) were converted to static MOE values (MOE_{adj}) using

$$MOE_{adj} = 0.0477 + 0.873\ MOE_d \qquad (6)$$

where both MOE values are given in pounds per square inch. This equation was determined from data taken on the specimens tested in bending where both static and vibration MOE values were measured.

When adjusted to an equivalent basis (Appendix), the mean MOE values obtained in this study were at least 15% greater than those published for the northern red oak species group (Table 3). However, the published MOE

TABLE 3. *Ratio of allowable properties developed from test results for 2 by 4's to property values derived by clear-wood procedures at 12% moisture.*

Grade	Species or grouping	Ratio to clear-wood estimates[a]			
		MOE	MOR	UTS	UCS
Select Structural	Northern red oak[b]	1.22	1.54	—[c]	1.18
	Douglas fir-larch[d]	1.04	1.31	1.25	1.30
	Hem-fir[d]	1.03	1.58	1.43	1.38
	Southern pine[d]	1.08	1.58	1.25	1.39
No. 2	Northern red oak[b]	1.16	1.17	1.31	2.21
	Douglas fir-larch	0.92	1.15	1.10	1.59
	Hem-fir	0.95	1.21	1.21	1.69
	Southern pine	0.98	1.18	0.94	1.59
No. 3	Northern red oak[b]	1.22	1.74	1.71	2.85

[a] Values are calculated using allowable properties at 15% moisture content, given in NFPA (1991) for E, Fb, Ft, and Fc (see Appendix).
[b] Values from nonparametric 5th percentile estimates from Table 2.
[c] Sample size insufficient to estimate 5th percentile.
[d] Values from Green and Evans (1987) at 12% moisture content. Mean values used for MOE; nonparametric 5th percentiles for MOR, UTS, and UCS.

value of the northern red oak group is controlled by the MOE of black oak. The MOE of clear northern red oak is almost 15% greater than that of black oak (Table 1). If most lumber in this study was from the northern red oak species, the measured MOE values for No. 2 grade are in general agreement with the NDS, and about a 6% increase would be expected for SS and No. 3 grade lumber. This potential increase is much greater than the ratio of experimental to published MOE values found in the In-Grade Testing Program for softwoods (Table 3). Such increases in MOE for red oak could significantly increase spans of deflection-controlled structures, such as light-frame floors and bridge decks. This also illustrates the potential benefit of using mechanical sorting, where lumber is assigned from the actual MOE measured on the piece rather than from some conservative group number.

A comparison of oak experimental strength property values with published values is less reliable than comparisons involving MOE because of the smaller sample sizes tested for strength. However, strength test results were consistently greater than the published values for all properties tested (Table 3).

The MOR ratios in Table 3 indicate that the 5th percentile estimates are at least 17% greater than those given in the NDS, and the potential increase is much greater for SS and No. 3. Little of this difference would be expected as a result of the differences between the strength of black and northern red oak (Table 1). Although our sample may not be representative of red oak in general, these increases are typical of increases found with softwood results from the In-Grade Program (Table 3).

Experimental UTS values for the No. 2 oak were about 30% greater than the published values (Table 3). However, given the small number of pieces tested in tension for any given lumber grade, it was not possible to accurately estimate potential increases in allowable tensile strength. Using the softwood increases as a guide, some increase in the UTS estimates could be expected for No. 2 northern red oak if allowable properties were based on in-grade testing of full-size lumber. An even larger increase might be found for No. 3 oak.

For UCS, the values obtained in this study were at least 18% greater than the published values (Table 3). Again, little difference was found between the clear-wood UCS values of black and northern red oak (Table 1). Values also generally increased for softwoods (Table 3). Thus, it seems reasonable to expect that significant increases in UCS of northern red oak could be obtained using in-grade testing.

The results obtained from one mill in central Wisconsin indicate that substantial increases in the allowable properties of visually graded

TABLE 4. *MOE and strength relationships for 2 by 4's at 12% moisture content.*

Property relationship	Species/group	Sample size	Strength = A + B(MOE)[a] (× 10³ lb/in.²) A	B	Coefficient of determination R^2	Standard error (× 10³ lb/in.²)
MOR-MOE[b]	Northern red oak	215	−1.52	7.009	0.46	2.42
	Southern pine[c]	575	0.14	4.444	0.46	2.01
	Southern pine[d]	2,161	−0.66	4.490	0.52	2.00
	Douglas fir-larch[d]	2,781	−0.91	4.593	0.56	1.63
	Hem-fir[d]	903	−1.46	5.166	0.53	1.65
UTS-MOE_{adj}	Northern red oak	107	−7.26	6.766	0.29	3.04
	Southern pine[e]	384	−1.95	3.170	0.43	1.65
USC-MOE	Northern red oak	214	1.51	2.501	0.49	0.77
	Southern pine[c]	297	1.90	1.770	0.43	0.76
MOE-MOE_d	Northern red oak	215	0.05	0.873	0.85	0.12
MOR-MOE_d	Northern red oak	215	−0.45	5.705	0.34	2.67
UTS-MOE_d	Northern red oak	107	−4.03	5.907	0.29	3.04
UCS-MOE_d	Northern red oak	259	1.63	2.183	0.49	0.77

[a] 1 lb/in.² = 6.89 × 10³ Pa.
[b] Units for MOE are × 10⁶ lb/in.².
[c] FPL-64 (Doyle and Markwardt 1966).
[d] Data summarized in Green and Evans (1987).
[e] FPL 84 (Doyle and Markwardt 1967).

northern red oak by 2 by 4's might be obtained if allowable properties were based on tests of full-sized structural lumber (ASTM D1990) instead of on clear-wood calculation procedures (ASTM D245). 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.

Relationships between lumber properties

MOE-strength.—As previously explained, the grading of MSR lumber does not require a knowledge of the MOE-MOR relationship. However, knowing the relationship in advance makes the process of qualifying an MSR machine more efficient. Regression statistics for strength-MOE relations are given in Table 4. Although the coefficients of determination were not large, they are significant and generally comparable to those found in southern pine studies (Doyle and Markwardt 1966). The MOE-UTS relationship found in the oak lumber was nonlinear. This is probably a result of the nonuniform distribution in lumber quality because of the small sample size. Evaluation of the association between MOE and UTS using the Kendall correlation coefficient (a nonparametric correlation coefficient not dependent upon assumptions of linearity) yielded 0.48. This value is the same as that obtained using data from Doyle and Markwardt (1966, 1967) and only slightly less than about 0.53 to 0.56 obtained from the In-Grade Testing Program data.

UCS/MOR.—Figure 3 shows that the relationship between UCS/MOR and MOR followed a relationship similar to that found for softwood species (Green and Kretschmann 1991). For a direct comparison between the results obtained with softwood species in the In-Grade Testing Program and those obtained in this study, it was necessary to drop the results for the No. 3 grade material. This is because No. 3 grade material was not tested in the In-Grade Testing Program in the United States. From this comparison, it appears that the relationships assumed in assigning allowable UCS values to softwood species either for ASTM D1990 or for MSR lumber should be

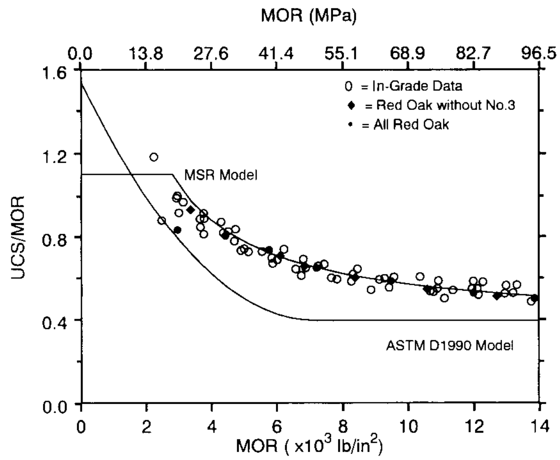

FIG. 3. UCS/MOR relationships for red oak 2 by 4's at 12% moisture content.

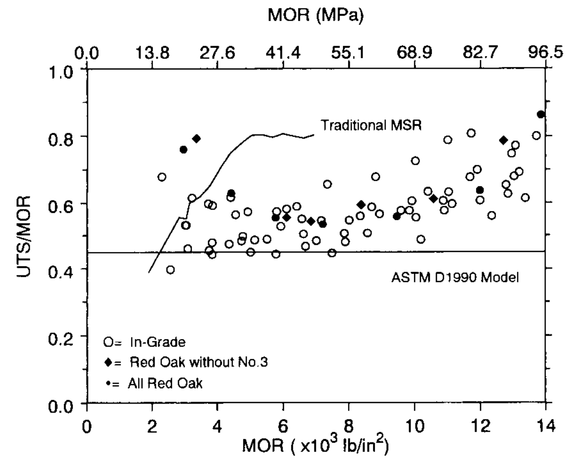

FIG. 4. UTS/MOR relationships for red oak 2 by 4's at 12% moisture content.

applicable to structural lumber cut from the northern red oak group.

UTS/MOR.—Figure 4 shows the relationship between UTS/MOR and MOR obtained for the northern red oak group. This was similar to the relationship obtained with softwood species. Thus, we concluded that property relationships used in ASTM D1990 to estimate UTS from MOR may be used with the northern red oak group. We also concluded that any relationship used to estimate UTS from MOR that is deemed applicable to MSR lumber produced from softwoods is also applicable to the northern red oak.

From these results, it would appear that procedures used to assign allowable properties to mechanically graded softwood lumber are applicable to northern red oak. 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, avoids the need for extensive testing that would be required for visually graded lumber by ASTM D1990. Also, mechanical grading allows properties to be assigned based on the resource at hand, rather than basing properties on the weakest species in a group of species, which is common with visually graded lumber. However, the flexibility of the mechanical grading system makes it possible to produce an infinity of grades. 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.

CONCLUSIONS

From the results of this study on the properties of 2 by 4's cut from the northern red oak group, we conclude the following:

1. Substantial increases in allowable property values over current assignments might be obtained if design values were obtained using procedures in ASTM D1990 from tests of full-size structural 2 by 4's.
2. Property relationships given in ASTM D1990 to derive one property estimate from another could be used to derive allowable properties in tension and compression parallel to the grain from bending strength. Property estimates derived in this manner appear to be conservative.
3. A significant relationship exists between modulus of elasticity and modulus of rupture. Thus, there appears to be no obstacle to machine sorting of lumber cut from the northern red oak group.

4. Property relationships obtained for the northern red oak group are similar in form to those obtained for softwood species using the In-Grade Testing Program data. It appears that property relationships used to derive allowable compressive and tensile strengths for softwood MSR lumber should be applicable to the northern red oak group.

ACKNOWLEDGMENTS

This study was funded as part of the Timber Bridge initiative of the USDA Forest Service. Additional support was provided by the Kersten Lumber Company, Birnamwood, Wisconsin. We wish to acknowledge the assistance of James W. Whipple, Wisconsin Department of Natural Resources, and Arne Olson, Southern Pine Inspection Bureau.

REFERENCES

ASTM. 1991. American Society for Testing and Materials, annual book of standards, vol. 04.08, Wood. Philadelphia, PA.

Standard test methods of static tests of timbers in structural sizes. ASTM D198.

Standard methods for establishing structural grades and related allowable properties for visually graded lumber. ASTM D245.

Standard methods for establishing clear wood strength values. ASTM D2555.

Standard test methods for mechanical properties of lumber and wood based structural material. ASTM D4761.

Standard practice for establishing allowable properties for visually graded dimension lumber from in-grade tests of full size specimens. ASTM D1990.

BENDTSEN, B. A., AND R. L. YOUNGS. 1981. Machine stress rating of wood: An overview. Pages 21–34 *in* Proceedings of XVII IUFRO World Congress, Division 5, September 8, 1981, Kyoto, Japan.

DEBONIS, A. L., AND B. A. BENDTSEN. 1988. Design stresses for hardwood structural grades create new opportunities. Pages 48–50 *in* Executive Summaries, 43rd annual meeting, Forest Products Research Society, 25–29 June, 1988, Reno, NV. Forest Products Research Society, Madison, WI.

DOYLE, D. V., AND L. J. MARKWARDT. 1966. Properties of southern pine in relation to strength grading of dimension lumber. Res. Pap. FPL-64. USDA Forest Service, Forest Products Laboratory, Madison, WI.

———, AND ———. 1967. Tension parallel-to-grain properties of southern pine dimension lumber. Res. Pap. FPL-84. USDA Forest Service, Forest Products Laboratory, Madison, WI.

GALLIGAN, W. L., D. SNODGRASS, AND G. CROW. 1978. Machine stress rated lumber: Practical concerns and theoretical restraints. Gen. Tech. Rep. FPL-7. USDA Forest Service, Forest Products Laboratory, Madison, WI.

GREEN, D. W., AND J. W. EVANS. 1987. Mechanical properties of visually graded lumber, vol. 1, A summary. Publication PB-88-159-389. USDA National Technical Information Service, Springfield, VA.

———, AND D. E. KRETSCHMANN. 1991. Lumber property relationships for use in engineering design codes. Wood Fiber Sci. 23(3):436–456.

———, B. E. SHELLEY, AND H. P. VOKEY. 1989. In-grade testing of structural lumber. Proceedings 47363. April 1988, Forest Products Research Society, Madison, WI.

MCDONALD, K. A., AND J. W. WHIPPLE. 1992. Yield of 2 by 4 red oak stress-graded dimension lumber from factory-grade logs. Forest Prod. J. 42(6):5–10.

NELMA. 1992. Standard grading rules for northeastern lumber. Northeastern Lumber Manufacturer's Association, Cumberland, ME.

NFPA. 1991. Design values for wood construction: A supplement to the national design specifications. National Forest Products Association, Washington, DC.

APPENDIX

To compare allowable properties derived by clear-wood procedures, it was necessary to convert the results in the National Design Specification (NDS) for northern red oak to the same basis as our experimental results. For most species, strength properties of dimension lumber in the 1991 edition of the NDS are tabulated at a nominal 12-in. (0.3-m) width and 240-in. (6.1-m) length for grades SS, No. 1, No. 2, and No. 3. The assumed average moisture content is 15%. For hardwoods, these strength values were obtained by first calculating values for 2 by 4's by the clear-wood procedures of ASTM D245 at 15% moisture content. Then, D1990 procedures were used to tabulate the values of nominal 2 by 12's (standard 38- by 286-mm).

$$MOR = Fb \times 1.5 \times 2.3 \times fbl \times fbmc \qquad (7)$$

where

- 1.5 converts from 2 by 12 at a length of 240 in. to 2 by 4 at a length of 144 in.,
- 2.3 is the general adjustment factor for hardwoods in bending and tension,
- fbl is the length adjustment for MOR from 144- to 60-in. length by D1990, $(144/60)^{0.14}$, and
- fbmc is the adjustment from 15% to 12% moisture content of MOR by the formula given in the Annex of D1990.

$$UTS = Ft \times 1.5 \times 2.3 \times ftl \times ftmc \qquad (8)$$

where

ftl is the length adjustment for UTS from 240- to 120-in. length by D1990, $(240/120)^{0.14}$ and

ftmc is the adjustment for UTS from 15% to 12% moisture content by the formula given in the Annex of D1990.

$$\text{UCS} = \text{Fc} \times 1.15 \times 2.1 \times \text{fcmc} \qquad (9)$$

where

1.15 converts from 2 by 12 to 2 by 4,

2.1 is the general adjustment factor for hardwoods in compression, and

fcmc is the adjustment from 15% to 12% moisture content by the formula given in the Annex of D1990.

The MOE values for most species in the NDS are given for a uniformly distributed load on a beam having a span-to-depth ratio of 21:1 and an average moisture content of 15%.

$$\text{MOE} = \text{E} \times 0.990 \times \text{femc} \qquad (10)$$

where

0.990 converts MOE from a uniform load at a span to depth ratio of 21:1 to third-point loading at 17:1 and

femc is the adjustment of MOE from 15% to 12% moisture content by the formula given in the Annex of D1990.

Comparison values for softwood species were calculated from clear-wood properties given in the 1986 edition of the NDS, not the D1990 values given in the 1991 edition of the NDS.