production of hardwood machine stress rated lumber

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Abstract

There is considerable interest in using hardwood species in engineered structures. Recently the USDA Forest Products Laboratory (FPL) conducted a series of laboratory and field studies to examine use of mechanical grading procedures to enhance the use of hardwoods for structural lumber. Our first laboratory efforts revealed that for most domestic hardwood species the relationships between bending strength and the strength in tension and compression parallel to the grain is similar to those for softwood species. Thus, the procedures used to assign allowable design properties to machine stress rated (MSR) lumber are also applicable to hardwood species. Further research at the FPL and West Virginia University showed that significantly higher properties could be obtained through mechanical grading of red oak than is currently possible through visual grading. These encouraging results prompted us to conduct a demonstration study of machine stress rating hardwood lumber at the Spencer, W. Va. division of the Burke-Parsons-Bowlby Corp. Using the transverse vibration technique to measure modulus of elasticity (MOE), 800 2 by 8s were graded as 1650f-1 .4E MSR lumber by the Northeastern Lumber. Manufacturer's Association with the assistance of the Southern Pine Inspection Bureau. The lumber was used to construct a 40-foot span timber bridge in Jackson County, W. Va.

Introduction

There is increasing interest in using hardwood lumber in timber bridges, glulam beams, trusses, and other engineered wood structures. Efficient utilization of hardwood species in such structures depends upon utilizing grading systems that can make the most efficient use of the available resource. In the summer of 1992 we received a request from Lew McCreery, Regional Rural Development Coordinator for the Northeastern area of State and" Private Forestry, USDA Forest Service, to assist a mill that wanted to evaluate more efficient grading systems. The objective of this report is to document the results of this work.

In the fall of 1992 we met with representatives of the Burke-Parsons-Bowlby Corp. at their Spencer, W. Va., plant to discuss the objectives of our proposed study and their production situation. The primary products of the Spencer plant are wood members treated with either creosote or CCA preservatives. For several years, they have also supplied oak lumber for timber bridges. They assemble and install the completed bridges. During the initial discussion we learned that they were concerned not only about providing better grading for their current production, but also about grading methods that would be responsive to future changes in the available resource. Because their bridge lumber is cut from untreated switch tie stock, the most of the lumber is nominal 2 by 8 inches (50 by 230 mm) in cross section and of varying lengths. We learned that having a certified grade stamp is usually a requirement for their bridge material. The lumber is typically graded before drying and before surfacing. Because structural lumber is not a primary product, and because the lumber is dried before bridge assembly, the Spencer plant basically runs a "batch" operation rather than continuous production that would be typical of most softwood

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mills. With this background in mind, we decided that mechanical grading provided the best opportunity to improve their grading efficiency in a reasonable time frame. Although previous work has evaluated the potential of several hardwood species for mechanical grading (14,19,20,26), to our knowledge the use of machine grading had never been demonstrated by actually certifying MSR lumber in a commercial operation. Thus, several obstacles needed to be overcome to gain certification of hardwood MSR lumber.

The objectives of this project were to:

- train quality supervisors of the Northeastern Lumber Manufacturer's Association in the mechanical grading process
- use MSR lumber produced from a hardwood species to construct a timber bridge
- demonstrate the production of MSR lumber in a small mill
- learn the potentials and problems of smaller mills trying to use the MSR process.

Background

Visual graded lumber

All current hardwood structural lumber is visually graded. Historically, allowable property values for visually graded lumber have been estimated from clearwood data and adjusted according to procedures in ASTM D 245 (3). 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 percent 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 (23), an attempt was made to "calibrate" properties derived by the clearwood procedure of ASTM D 245 (6) with anticipated results obtained from tests of full-size lumber and derived by ASTM D 1990. This was done by first calculating properties of dry 2 by 4s using the clear-wood procedure. The properties of wider width lumber were then calculated using the size-effect formula of ASTM D 1990.

The ASTM D 2555 (4) 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 weighing 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 (11) (Table 1). A similar problem

Table 1. — *Mean clearwood property values at green MC for red oak and northern red oak.*[a]

Commercial group	Species	MOE	MOR	UCS	Grown in central Wisconsin?
		($\times 10^6$ lb./in.^{2})	(lb./in.^{2})	(lb./in.^{2})	
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 D 2555 (4); 1 lb./in.^{2} = 6.89×10^3 Pa.
[b] Controlling property for the group.

exists for other species groups. Depending upon variation of the clearwood property values of the species in the group and the relative standing timber volume of the species, this procedure could produce very conservative estimates for visually graded 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 percent greater than that used for softwood species.

In 1979, an in-grade testing program was initiated to evaluate the mechanical properties of visually graded, 2-inch- (38-mm-) thick dimension lumber by testing full-size pieces that had previously been graded by commercial graders (21). In this program, it was judged necessary to test approximately 360 pieces of lumber in each of three sizes 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 clearwood procedure (6) for deriving allowable property values for visually graded lumber (1). 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 volume. For such species, it may be desirable to restrict testing to one property and to infer conservative property estimates for other properties. In ASTM D 1990, conservative formulas are provided for data adjusted to nominal 2- by 8-in. (standard 38- by 184-mm) dimensions and 15 percent average moisture content. These formulas, which are based on an "equal rank" assumption (18), 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 D 1990 formulas are:

$$\text{If MOR} \leq 7.2 \text{ ksi } (\leq 49.6 \text{ MPa}),$$
$$\text{UCS/MOR} = 1.55 - (0.32 \times \text{MOR}) + (0.022 \times \text{MOR}^2)$$

or

$$\text{If MOR} > 7.2 \text{ ksi } (> 49.6 \text{ MPa}),$$
$$\text{UCS/MOR} = 0.40$$

and

$$\text{UTS/MOR} = 0.45 \times \text{MOR}$$

Although these relationships are conservative relative to average trends of the data, they do allow estimates to be made of untested properties (Figs. 1 and 2). If the ASTM D 1990 procedures were used to determine new hardwood properties, and we want to minimize the number of pieces that must be tested, we estimate the cost of the lumber alone to be about $0.5 million (Table 2).

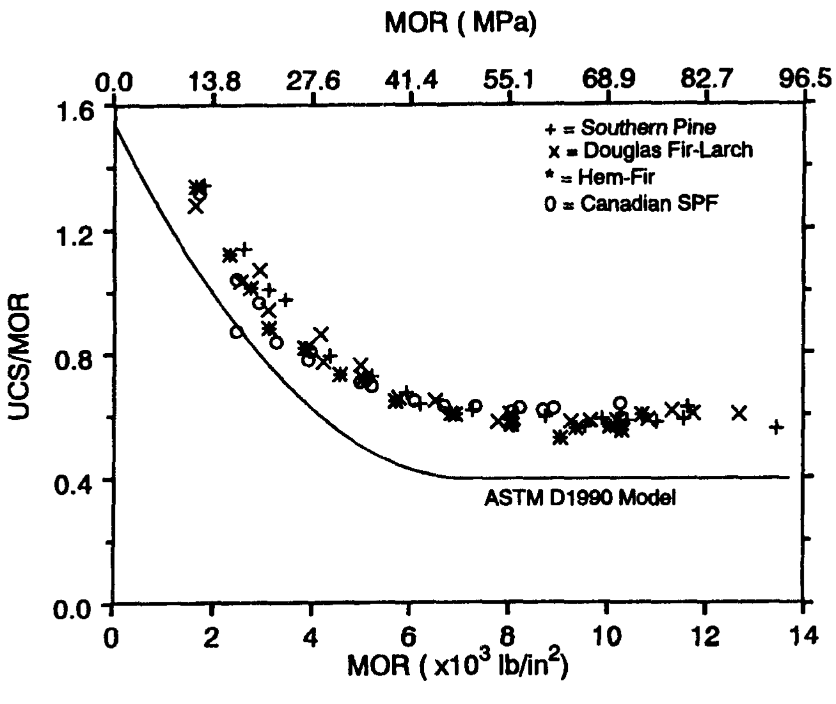

Figure 1. — *Relationships between UCS and MOR assumed in ASTM in-grade standard for 2 by 8 lumber at 15 percent moisture content.*

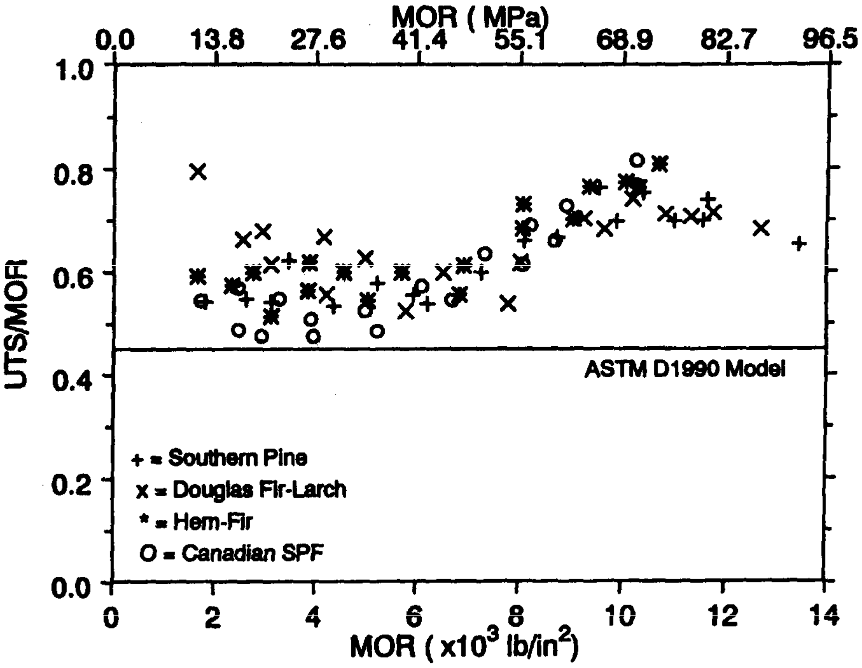

Figure 2. — *Relationships between UTS and MOR assumed* ***in*** *ASTM in-grade standard for 2 by 8 lumber at 15 percent* ***moisture content.***

Table 2. — *Anticipated lumber costs of in-grade testing.*

Species	Sample size	cost
		($)
Sweetgum	800	29,000
Red maple	800	29,000
Mixed maple	1400	50,000
Yellow poplar	800	29,000
Red oak	3240	111,000
White oak	2880	100,000
Beech-Birch-Hickory	3960	136,000
Aspen-Cottonwood	2160	74, 000
		$558,000

Very little hardwood lumber is in continuous production. Thus, it would likely be very difficult to obtain the required three sizes and two grades to do even bending tests. And the resulting design values would still be for a grouping of species in many instances and would thus not necessarily represent the optimal property assignment for the lumber produced at any given mill.

Thus, we see that although visual grading is currently the universally accepted procedure for the structural grading of hardwood species, for our project it has the following limitations:

1. Because of the inability to differentiate between individual oak species and the calculation of properties based on species grouping, assignment of flexural properties are likely to be overly conservative.
2. Testing full-size members using the procedures of ASTM, D 1990 will likely yield higher allowable properties, but the procedure will be very expensive and require several years to complete. The resulting design value will still likely be based on a species grouping.
3. For timber bridge applications where MOE usually controls span, optimal grading efficiency would be achieved by direct measurement of lumber stiffness.

Further, studies on the yield of visually graded lumber cut from logs indicate that most of the lumber will be in the lower grades (Fig. 3).

Machine graded lumber

Several procedures are available for machine grading of lumber. However, the traditional procedure of machine stress rating relies upon the relationship between strength and stiffness to establish grade boundaries. Sorting efficiency for lumber grades is further controlled by visual restrictions on allowable edge knot sizes (15). 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 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 set-

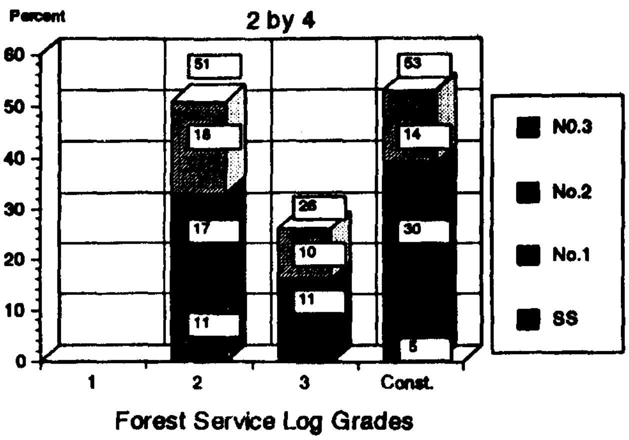

Figure 3. — Log dimension yield.

tings on an MSR machine. Other property values are determined either as a function of MOR (UTS and UCS) or by the clearwood procedure (shear strength parallel to the grain and compression strength perpendicular to the grain) (8). The strength-MOR relationships used to calculate allowable tensile strength (F_t) from UTS and allowable compressive strength (F_c) from UCS were determined from tests of softwood species (18). The following new relationship, based on data adjusted to 15 percent moisture content, was recently adopted by the American Lumber Standards Committee, Board of Review, to assign F_c values to MSR lumber:

$$\text{If } F_b \geq 1350 \text{ psi } (\geq 19.55 \text{ MPa}), \quad F_c = 0.373 \times F_b + 1085$$

or

$$\text{If } F_b < 1350 \text{ psi } (\geq 19.55 \text{ MPa}), \quad F_c = 1588 \text{ psi}$$

In terms of the USC/MOR ratio, these become:

$$\text{If MOR} \geq 2.835 \text{ ksi } (\geq 19.55 \text{ MPa}), \quad \text{UCS/MOR} = 2061 \times (1/\text{MOR}) + 0.3376$$

or

$$\text{If MOR} < 2.835 \text{ ksi } (< 19.55 \text{ MPa}), \quad \text{UCS/MOR} = 1.06$$

Thus, species-independent relationships between MOR, UCS, and UTS are used to assign tension and compression properties to mechanically graded softwood species. It is therefore essential to either verify that these relationships apply to hardwood species, or two establish new relationships for hardwoods.

Table 3. — *Grades of southern pine MSR lumber.*

Grade	Bending (F_b)	MOE (E)	Tension (F_t)	Compression (F_c)
	(psi)	(million psi)	----- (psi) -----	
1200-1.2E	1200	1.2	600	1400
1350f-1.3E	1350	1.3	750	1600
1400f-1.2E	1400	1.2	800	1600
1500f-1.3E	1500	1.3	900	1650
1500f-1.4E		1.4		
1600f-1.4E	1600	1.4	950	1675
1650f-1.4E	1650	1.4	1020	1700
1650f-1.5E		1.5		
1800f-1.5E	1800(2)	1.5	1300	1750
1800f-1.6E	1800	1.6	1175	1750
1950f-1.5E	1950	1.5	1375	1800
1950f-1.7E		1.7		
2000f-1.6E	2000	1.6	1300	1825
2100f-1.8E	2100	1.8	1575	1875
2250f-1.6E	2250	1.6	1750	1925
2250f-1.9E		1.9		
2400f-1.7E	2400	1.7	1925	1975
2400f-1.8E		1.8		
2400f-2.0E		2.0		
2550f-2.1E	2550	2.1	2050	2025
2700f-2.2E	2700	2.2	2150	2100
2850f-2.3E	2850	2.3	2300	2150
3000f-2.4E	3000	2.4	2400	2200
3150f-2.5E	3150	2.5	2500	2250
3300f-2.6E	3300	2.6	2650	2325

Grade names for MSR lumber are given in terms of the allowable bending strength (F_b) and the mean MOE value when tested in an edgewise orientation. For example, a typical grade name for MSR lumber might read "1650f-1.4E." The actual grade names approved for MSR production vary somewhat by grading agency. The grades approved for southern pine are shown in Table 3.

Property relationships for hardwood species

MOE-MOR relationship. — It is not necessary to know the MOE-MOR relationship to grade MSR lumber. However, knowing the relationship makes the process of qualifying an MSR grade more efficient. Hardwoods appear to have a higher MOR value for a given MOE value than do softwood species (Fig. 4). For some hardwood species, the advantage of a higher MOR value may be somewhat offset by a lower correlation between MOE and MOR. For these species, it may be necessary to set the grade limit for MOR lower to compensate for the higher degree of variation in the relationship. The correlation for red maple, based on Kendall's tau (16), is about equal to those of softwood species currently mechanically graded. However, the correlation of red oak appears slightly lower, and that of yellow poplar and aspen cottonwood is much lower. It should be noted that the data sets for the hardwood species are an order of magnitude smaller than those of the softwood species and may not be as reliable. However, lower correlations between MOE and MOR have been observed for yellow poplar and sweetgum by other researchers (14).

UCS/MOR relationship. — Figure 5 shows that the relationship between UCS/MOR and MOR of red oak and red maple has the same shape as that found for visually graded softwood species tested in the in-grade program (18) and would yield a slightly higher UCS value than would the softwood trends. Because the data in these studies came from only a limited number of specimens, we do not recommend using the hardwood data directly to estimate UCS from MOR. However, it appears that the relationships assumed in assigning allowable F_c values to MSR lumber produced from softwood species could be safely applied to MSR lumber produced from hardwood species.

UTS/MOR relationship. — Figure 6 shows the relationship between UTS/MOR and MOR obtained for three hardwood species. The UTS/MOR ratio for hardwoods is generally higher than that of softwood species. Thus, we conclude that any relationship for estimating UTS from MOR deemed applicable to MSR lumber produced from softwood species is also applicable to hardwood species.

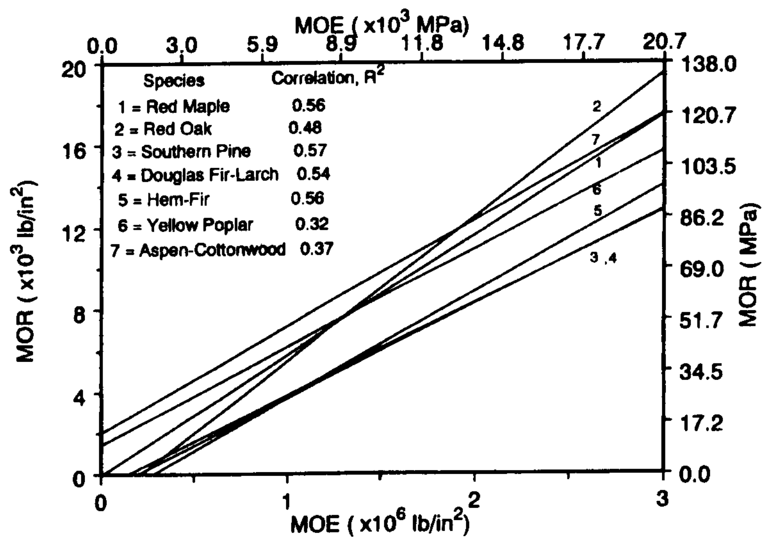

Figure 4. — *MOE-MOR relationship of several hardwood and softwood specimens.*

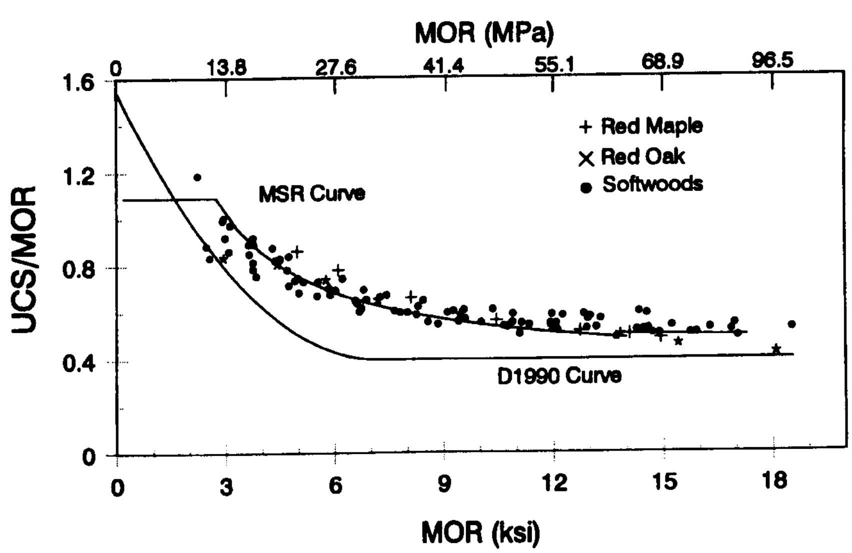

Figure 5. — *Relationships between UCS and MOR for red oak, red maple, and softwood species along with assumed ASTM in-grade standard curve and MSR curve.*

Application to other hardwood species

Relative to the information available for softwood species, little information is available on the relationships between mechanical properties for structural lumber produced from hardwood species. However, from the results of our studies, it appears that procedures used to assign allowable properties to mechanically graded softwood lumber are generally applicable to hardwood species. There is little reason to doubt that a significant MOE-MOR relationship exists for domestic hardwood species and most tropical hardwood species (7,14,25,26).

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 (19), 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 most hardwoods.

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 (9). 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 (Table 4). For these reasons, we urge caution in applying these results to hardwood species known to have special problems similar to those discussed here.

Mill certification

Presorting

As noted earlier, the normal Burke-Parsons-Bowlby operation is a batch operation in which bridge material is first visually graded rough green, and then kiln-dried. Because drying oak lumber may take 30 to 45 days, this presorting helps to eliminate lengthy drying expenses for lumber that would not make the intended grade. Because such a presort would also be desirable in an MSR operation, we measured the MOE of all the green lumber prior to drying using a DynaMOE vibrating grader The E-rating of the green lumber was done in December of 1992. The temperature during the E-rating ranged from 14° to 32°F. The MOE values were adjusted to room temperature using the temperature adjustment procedures used in the in-grade program (21). The in-grade procedure was developed from data on Douglas-fir and southern pine. To see if the procedure was generally applicable to oak, we measured the MOE of five pieces near the end of the day when the wood was at 32°F. We then stickered the lumber overnight in a heated room and measured the MOE again at the end of the next day. We expected a change in MOE of 8.3 percent for the green lumber. The average change for the five MOE readings was 7.8 percent with

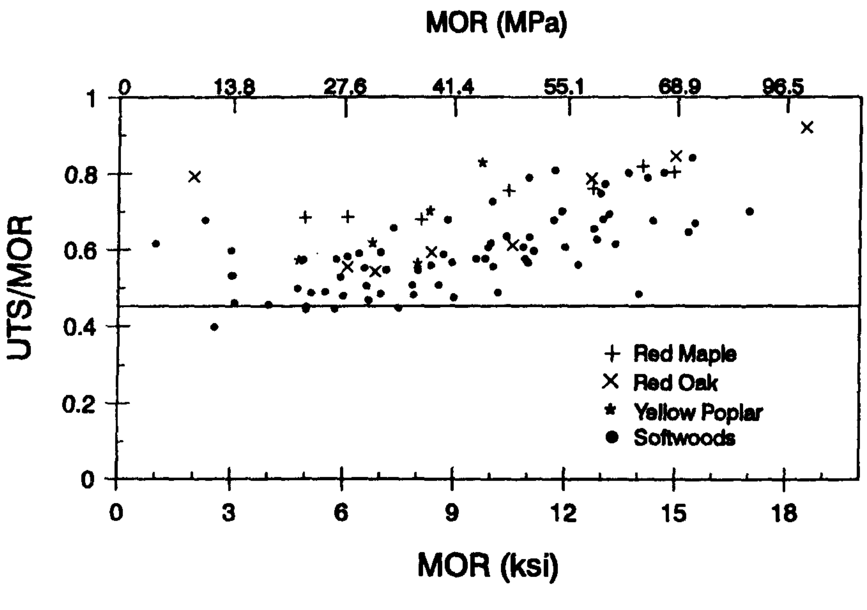

Figure 6. — *Relationships between UTS and MOR for three hardwood species.*

Table 4. — *Occurrence of interlocked grain in domestic hardwoods (10).*

Wood type	Percent of pieces containing interlocked grain
	(%)
Ash	0
Basswood	0
Beech	0
Birch	0
Blackgum	53
Buckeye	10
Chestnut	0
Cottonwood	24
Elm	19
Hackberry	0
Hickory	0
Magnolia	0
Mahogany	10
Maple, hard	0
Maple, soft	0
Oak, chestnut	0
Oak, red	0
Oak, white	0
Pecan	0
Sweetgum	48
Sycamore	45
Tupelo	68
Walnut, black	0
Willow	0
Yellow-poplar	0

individual values changing from 7.6 to 8.1 percent. Given the limited sample size, this close agreement gave us confidence that we could use the adjustment procedure developed in the in-grade program on our oak lumber Since changes in MOE with temperature are much larger for green lumber than for dry, any error due to the adjustment would be even smaller with the dry lumber.

Certification

In January 1993 we went back to Spencer for the actual grading. The first order of business was training. Melvin Travis, Quality Supervisor of the Southern Pine Inspection Bureau (SPIB) conducted a half-day classroom session on the procedures the SPIB uses to mechanically grade lumber. This was followed by additional training in the mill.

Of the 803 pieces of red oak 2 by 8s available for our study, 547 pieces were 10 feet long, 105 pieces were 12 feet long, and 151 pieces were 16 feet long. Prior to drying, the lumber had been graded by the limber Products Service. The lumber was then dried to an average moisture content of 17 percent and surfaced on two faces: 61 percent of the lumber was No. 3 visual grade and 35 percent was No. 2 grade. Only about 3 percent of the lumber made No. 1 grade and only about 1 percent was Select Structural.

The first step was to determine the machine settings for MOE and the visual restrictions on knots and slope of grain needed to produce the MSR lumber. Determining these limitations is called "grade qualification." Grade qualification was done under the supervision of Steve Card, Quality Supervisor of the Northeastern Lumber Manufacturer's Association (NELMA), with assistance from Melvin Travis and the FPL staff. The details of the qualification procedure vary somewhat by grading agency and will be different if the mill intends to produce more than one grade at a time. The qualification procedure we followed can be summarized as:

1. Determine the flatwise MOE of each piece of lumber.
2. Use this information to estimate the MOE if tested on edge (see equation given below).
3. Visually grade the lumber for nonstrength-reducing defects equivalent to No. 2 visual grade or higher.
4. Select a target MSR grade using the MOE data and the possible grades approved for the agency (in this case the grades approved for southern pine).
5. From all the lumber that meets the non-strength-reducing limitations of No. 2 visual grade and the target MOE values, select 60 pieces of lumber at random as the qualification sample.
6. Obtain an edgewise MOE on each of the 60 pieces in the qualification sample. The average MOE of this 60-piece sample must be at least equal to the average MOE of the grade minus 0.04. No more than two of the 60 pieces can have an MOE value less than 0.82 times the average MOE value for the grade proposed for production.
7. Proof-load the lumber to 2.1 times the target F_b value. No more than two pieces can have an MOR less than 2.1 times F_b.
8. Measure and record the maximum strength-reducing defect of each of the 60 pieces (generally the maximum edge knot or the worst slope of grain). This information will be used

to set visual restrictions on knots and slope of grain in subsequent MSR production.

Edgewise MOE was estimated from the flatwise vibration MOE using an equation developed in previous research (19,20).

$$MOE = 0.05 + 0.873 \times E_f$$

where

MOE = static edgewise MOE at a span to depth ratio of 17 to 1

E_f = flatwise vibration MOE determined over the full length

Using the data on the vibration MOE, we chose a target grade of 1650F- 1.4E. Edgewise MOE and MOR was verified on each of the 60 pieces in the qualification sample using a Metriguard model 312 bending proof-loader set for a span-to-depth ratio of 21 to 1. The required average MOE of the sample was (1.4- .04) = 1.36 million psi. The minimum acceptable edge MOE of any piece in the sample was 0.82 x 1.4 million, or 1.15 million psi. Strength values were verified by proof-loading the 60 pieces to 2.1 times the target F_b value, or 3465 psi. A valid qualification sample was obtained (Table 5). From the defect information collected on these pieces, the maximum allowable defect for future production was determined to be a 3.25-inch edge knot. A maximum slope of grain of 1 inch in 8 inches was also required (the same as No. 2 visually graded lumber).

The potential of MSR for improving properties and yield is shown in Table 6. The lumber had already been visually graded prior to our arrival, so we were not able to indicate the yield of structural lumber from the cants. However, of the lumber that made No. 3 or better, only 33 percent was No. 2 and only 4 percent was Select Structural or No. 1. However, 36 percent of this lumber could have been graded as 1650f- 1.4E MSR. For the bridge engineer, the MSR procedure would have let him use the 1.4 million MOE with confidence, instead of the 1.1 million MOE of No. 3 red oak. For the producer, the MSR procedure would have given him a yield of 1.4 million MOE lumber that was much larger than he would claim by visually grading.

Some of the nonstrength-related grade descriptions of MSR lumber were originally set with truss applications in mind. However some of these limitations are less applicable to lumber intended for use in a timber bridge. For example, more bowing could be allowed in the member to be used in bridge decks because the tensioning rods would pull all lumber straight. Also, more wane could be tolerated because an asphalt surface was to be placed over the finished deck. For this reason, we decided to repeat the certification process using just the lumber that was visually graded as No. 3. This information could be useful in the future to develop a special "(bridge grade" of MSR lumber. The limiting parameters for the No. 3 visual lumber were the same as for the standard MSR with a No. 2 visual defect limitation except that the maximum allowable defect was determined to be a 3.5-inch edge knot (Table 6).

This was the first time that the mill had tried to produce MSR lumber and several lessons were learned which could increase yield in future runs. A considerable amount of material was over the maximum allowable moisture content of 19 percent. This was as a result of targeting an average moisture content of 19 percent, rather than an average of about 15 percent. Also, better control of the planer setup would have reduced the amount of material with scant thickness. Finally, turning some of the logs 90 degrees to place the horns of the crook up during sawing would have produced bowed pieces out of about 70 percent

Table 5. — *Summary of qualification test on oak MSR lumber.*

Characteristics	No. 2 Visual	No. 3 Visual
Average sample MOE (million psi)	1.651	1.600
Pieces < $0.82 \times E$	1	0
Pieces < $2.1 \times F_b$	2	2
Maximum defect (in.)	3.25 edge knot	3.5 edge knot

Table 6. — *Results of red oak certification.*

Grades	No. 3 and better	Allowable properties	
		F_b	MOE
	(%)	(psi)	(million psi)
Visual			
Select structural	1	1380	1.4
No. 1	3	990	1.3
No. 2	33	960	1.2
No. 3	63	540	1.1
MSR			
1650f-1.4E			
No. 2 Visual	36	1650	1.4
No. 3 Visual	95	1650	1.4

of the logs rather than the crook. The grade limits on bow are less restrictive than those on crook, and bow is less of a problem in stress-laminated bridge decks.

Conclusions

From the results of this study we conclude that:

1. It has been demonstrated that 1650f-1.4E MSR lumber can be qualified using red oak and standard industry procedures currently used for softwood species.
2. Equipment is commercially available for producing MSR lumber at small mills.
3. Using the MSR process, it is possible to produce grades of lumber not achievable with the visual grading process and to assure the reliability of the assigned properties through direct measurement of critical properties.
4. The yield of the higher grades of lumber can be increased using the MSR process.
5. Now that we have shown it is possible to certify a broad range of allowable properties for hardwood lumber using the MSR process, there is a need to quantify the increase in bridge performance that could be achieved using more precise grading procedures.

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