MECHANICAL GRADING OF OAK TIMBERS

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ABSTRAT: For many wood species, the grading of timbers [>76 mm (>4-in.) thick] has not changed in decades. Most timbers are still visually graded by methods that originated in the 1930s. Mechanical grading procedures used to accurately grade 38-mm (2-in. nominal) dimension lumber have not been adapted for use with timbers. Furthermore, the only reliable timber test data available for most softwood species were obtained near the turn of the 20th century, and no test data are available for hardwood timber. The lack of better grading procedures and test data makes it likely that current property assignments for timbers are wasteful. Given that the reduced availability of lumber is expected to continue well into the 21st century, the structural engineer must have the widest possible options for structural timbers. Therefore, a study was conducted by the USDA Forest Service, Forest Products Laboratory, to examine use of a pulse echo stress wave technique along the length of timbers to estimate modulus of elasticity (MOE) of green timbers and the development of a machine stress rated grade for oak timbers. Two hundred and ninety-five untreated 178- by 229-mm (7- by 9-in.) mixed oak timbers, 4.9 m (16 ft) in length, were measured weighted, and nondestructively evaluated to determine their pulse echo MOE. Two hundred twenty were destructively tested in bending; 75 were tested to failure in compression parallel to the grain. The results of these tests determined relationships between pulse echo MOE and static bending MOE and between bending and compressive strength. These tests suggests a clear potential of establishing a machine stress rated grade for oak timbers. This article discusses the implication of these results, potential commercial grades, and a follow-up study to qualify the suggested grades.

INTRODUCTION

For the first time in its history, the United States does not have a large, unreserved volume of softwood sawtimber. This is reflected in the volatility of sawtimber prices during the past 5 years. An increasing demand for lumber, coupled with anticipated shifts in sawtimber availability between regions of the country, makes extension of the supply through improved utilization critical. (Lumber in this paper is defined as the solid-wood product of a sawmill that is usually not further manufactured.) Advances in the past two decades in engineered wood products, such as I-beams, glulam, structural composite lumber, and trusses, have greatly improved utilization of the nation's sawtimber.

Mechanical graded lumber is that which results from a process using a mechanical device for identification and appraisal of one or more physical or mechanical characteristics and a visual quality evalutation to sort lumber into categories for assignment of design properties. For 38-mm (2-in. nominal) thick "dimension" lumber, mechanical grading alternatives improve wood utilization by offering more precise property assignments than available by traditional visual grading methods. At this time, however, mechanical grading is not available for thicker structural members in the United States. Structural timbers are still visually graded by methods that originated in the 1930s. Furthermore, the only reliable timber test data available for most softwood species were obtained near the turn of the 20th century. There is no comprehensive test data available for hardwood timbers.

The lack of precise grading procedures and test data makes it likely that current property assignments for timbers are wasteful. Establishment of mechanical grading procedures for timbers will expand the possibilities for regrading old timbers recovered from salvage operations and the in-place evaluation of timbers in existing structures.

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Note. Associate Editor: J. J. Beaudoin. Discussion open until October 1, 1999. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on January 27, 1997. This paper is part of the ***Journal of Materials in Civil Engineering,*** Vol. 11, No. 2, May, 1999. ©ASCE, ISSN 0899-1561/99/0002-0091-0097/$8.00 + $.50 per page. Paper No. 15021.

The work reported here is just part of a research program to remove the technical barriers for mechanical grading of timbers. Companion studies are investigating Southern pine (Green and Kretschmann 1997), Eastern hemlock and red maple (Green et al. 1996), and salvage timbers (Falk et al. 1995). The objective of the study reported here is to confirm the use of established machine stress rated (MSR) relationships and procedures for use with structural oak timbers and to evaluate the properties of proposed grades.

BACKGROUND

Lumber Supply

In 1990, total U.S. consumption of lumber was estimated at 13.3 X 10^7 m^3, (4.7 X 10^9 ft^3) (Haynes et al. 1993). This was about 40% more than the average consumption in the 1950s and 1960s but down slightly from the historic highs reached in 1988. Lumber from softwood species comprises nearly 82% of all lumber consumption, and the volume is expected to increase about 30%.

The availability of lumber is expected to vary greatly between different regions of the United States. By 2010, lumber production in the West is expected to decrease about 36% from 1990 levels. From 2010 to 2040, western lumber production is expected to increase as timber available from private inventories increases, but production in 2040 is projected to remain about 11% below 1990 levels.

Compared with 1990 levels, softwood lumber production in the South is expected to more than double by 2040. This is due to increased prices resulting from tighter timber management restrictions and timber acreage set asides, which reduced the available timber supply in the West. Trees not previously harvested for pulpwood production because of poor pulp prices are also reaching sawtimber sizes and will contribute additional resources to the South. Softwood production in the Northeast and the Midwest is expected to increase by 2010, then remain relatively constant until 2040. For the United States as a whole, available softwood stocks are not expected to increase significantly until after 2010, when the supply from the West begins to recover.

Unlike the situation with softwood species, significant increases in the volume of growing stock of hardwoods are expeted. Currently, the volume of hardwood growing stocks exceeds demand for a number of species (Table 1). This is

TABLE 1. Inventory Percentages of Selected Species of All U.S. Hardwood Sawtimber (Bones 1990)

Species (1)	Inventory (%) (2)	Increase from 1957–1987 (%) (3)
Oaks	38.9	83
Hickory	5.1	65
Yellow birth	1.1	41
Soft maple	6.0	383
Tupelo, B. gum	3.9	58
Yellow poplar	6.6	178
Red alder	3.3	34
Aspen/cottonwood	6.5	101

especially true for lower quality material that might be suitable for structural lumber if better ways could be found for structural grading. The greatest increase in growth stock is expected to shift from the Northeast and Midwest to the South as a result of the maturation of the forest in the former two areas.

Timber Production

Although ASTM defines timbers as having a thickness > 89 mm (4 in. nominal), most production statistics on timbers are for lumber that is 89 mm (4 in.) and thicker. It is generally understood in the engineering community that the production of heavy timbers is being replaced by engineered wood products, such as I-beams, glulam, structural composite lumber, and trusses. Although large-scale replacement of timbers with other products may occur in the long run, timbers still represent a significant proportion of total lumber production today. In the West, the production of timbers for 1993 was 2.33 X $10^6 m^3$ (989 X 10^6 board ft) (data supplied by Western Wood Products Association, personal communication, February 1994). This was down from the 1989 value of 3.07 X $10^6 m^3$ (1.3 X 10^9 board ft) but still represented 5.6% of total production. Timber production for 1992 in the South was 1.9 X $10^6 m^3$ (806 X 10^6 board ft), which was an increase from the 1990 levels (data supplied by Southern Forest Products Association, personal communication, October 1993). That was 3.6% of the total Southern pine production. Although accurate data are not available for Northeastern softwood timbers or hardwood timbers, it is evident that timbers still represent a significant volume of structural lumber.

Timber Grading and Properties

Visual Grading

The most comprehensive data set available for U.S. timbers is that given by Cline and Heim (1912). This was the data set used to establish the visual grading system used in the United States. However, only softwood species were included in these data. Growth characteristic data are sufficient to regrade this data set by current visual grading rules.

For lumber 89 mm (4 in. nominal) and less in thickness, dimension lumber grading rules are standardized across species. The grade descriptions for a given grade are the same whether it is Southern pine, Douglas fir-larch, or yellow poplar. However, grading rules for timbers are not standardized across the United States but are standardized regionally. Thus, select structural Southern pine timbers have a different allowable knot size than select structural white pine. Further, all agencies except the Southern Pine Inspection Bureau, separate timber into "use" categories of beams and stringers or posts and timbers. Beams and stringers are intended for use as bending members, and posts and timbers are primarily used as columns in compression. Except for Southern pine, timbers graded as beams and stringers have a more restrictive grade description for the middle third of the member than they do for the outer two-thirds of the length. This differs from the grading of dimension lumber and Southern pine timbers, where the same grade description is used for the entire length of the member.

Properties for visually graded timbers are calculated from the properties of clear, straight-grained wood according to ASTM D 245 and ASTM D 2555 ("Standard" 1994e,f). For groupings with multiple species, the property assignment may be inefficient for individual species, because the properties assigned for the group are based on the lowest properties in the group. For example, the commercial grouping red oak is composed of nine species (Table 2), each with a different clear wood strength and stiffness value. Individual oak species cannot be identified by visual inspection of the sawn timbers. One species, Southern red oak, has mechanical properties significantly less than those of the other species. As a result of ASTM D 245 procedures, Southern red oak properties limit some properties of the red oak group.

Other inefficiencies exist in assignment of properties to timbers. For examples, we know that the testing of full-size dimension lumber in the In-Grade Testing Program (Green et al. 1989) resulted in many significant changes in property assignment for visually graded dimension lumber. Further, the data of Cline and Heim (1912) suggest that bending size effects for timbers may be less severe than specified in ASTM D 1990 ("Standard" 1994b) for dimension lumber. Mechanical grading affords the opportunity for more efficient assignment of properties to 5l-mm-(2-in.-nominal) thick lumber of hardwood species (Table 3) as well as softwood species (Green et al. 1993). All this information suggests considerable potential for improving the allowable property assignments of timbers by mechanical grading techniques. Further, the establishment of mechanical grading procedures for timbers provides a basis for mechanical grading of recycled timbers and grading old timbers in place.

TABLE 2. Mean, Clear Wood Properties of Species in Red Oak Group (Wood 1987)

Species (1)	MOR [MPa ($\times 10^3$ lb/in.^{2})] (2)	MOE [MPa ($\times 10^6$ lb/in.^{2})] (3)
Black oak	95.8 (13.9)	11,300 (1.64)
Cherrybark oak	124.8 (18.1)	15,700 (2.28)
Laurel oak	86.9 (12.6)	11,600 (1.69)
Northern red oak	98.6 (14.3)	12,500 (1.82)
Pin oak	96.5 (14.0)	11,900 (1.73)
Scarlet oak	120.0 (17.4)	13,200 (1.91)
Water oak	106.2 (15.4)	13,900 (2.02)
Willow oak	100.0 (14.5)	13,100 (1.90)
Southern red oak	75.2 (10.9)	10,300 (1.49)

TABLE 3. Comparison of Mechanical and Visual Grading of Red Oak Dimension Lumber

Grade (1)	Red oak (2)	Yield from No. 3 and better (%) (3)
Mechanical	1650-1.4E (No. 2 visual override)	36
	1550f-1.4E (No. 3 visual override)	95
Visual		
SS	1380f-1.4E	1
No. 1	990f-1.3E	3
No. 2	960f-1.2E	33
No. 3	570f-1.1E	63

Note: SS = select structural.

Machine Grading

Currently, no procedures are available to mechanically grade timbers. The easiest alternative for mechanically grading timbers is to develop a system parallel to that used to grade MSR dimension lumber. To establish a technical basis for the mechanical grading of mixed oak timbers, we must establish a relationship between static modulus of rupture (MOR) and modulus of elasticity (MOE). This relationship will be used to sort the timber into grades. We must also establish a method of predicting ultimate compressive stress (UCS) and tension strength parallel to the grain. Traditionally, these properties are estimated from bending strength. Methods are available for estimating shear strength and compression strength perpendicular to grain (ASTM D 245).

Historically, flatwise deflection has been used as a predictor of static MOR and MOE for mechanically graded lumber. It may not be practical to sort timbers by deflection; therefore, an alternative prediction variable is needed. Schad et al. (1995) applied the pulse echo (PE) stress wave technique to measure MOE in railroad switch ties. To obtain the PE stress wave measurement of MOE (PE MOE), an accelerometer was attached to one end of each member, and pulse energy was introduced to the member through a hammer impact on the opposite end. Echo waves were recorded to obtain a time between peaks on an oscilloscope. The PE MOE was calculated using the speed of the sound wave c and density ρ of each tie using the following:

$$\text{PE MOE} = c^2 \times \rho \tag{1}$$

This PE MOE equation was used in the study reported herein to nondestructively assess the MOE of the large timbers.

MATERIALS AND METHODS

Our study, reported herein, was conducted in two phases. In the first phase, we tested a sample of oak timbers to establish the property relationships needed to assign allowable properties by mechanical grading. From the result of these initial tests, we proposed grade boundaries (minimum MOE levels for a grade plus visual restrictions in overall wood quality). In the second phase, we took an additional qualification sample that was graded using our proposed boundaries. These members were then tested to failure to verify the assumed properties and to refine the initial grade description.

Initial Sample

A PE MOE sample of 168 untreated oak timbers [178 mm by 229 mm by 4.9 m (7 by 9 in. by 16 ft)], hereafter called 7 by 9s, was obtained from a mill in central West Virginia. The timbers were green (>30% moisture content). From the 168-piece PE MOE sample, 100 timbers were selected that contained the largest PE MOE range possible for testing. An additional 50 pieces of mixed oak 7 by 9 timbers were obtained from a mill in central Pennsylvania. For each mill, the material was from within a 150-mi radius. The timbers were graded after purchase by a quality supervisor of the Southern Pine Inspection Bureau (“Standard 1994a). The timbers were graded only for characteristics that directly affect strength properties, such as knots, slope of grain, checks, and splits. Measurements of the overall dimensions and weight, to the nearest pound (0.453 kg), were taken for each timber.

Sorting

The 150 green timbers were ranked based on PE MOE and sorted, based on groups of three, into bending and compression test groups. The first timber group went to bending, the second to compression, and the third to bending. This process was continued until all timbers were assigned a test group.

Bending

One hundred green 7 by 9 timbers were tested in third-point loading at a span-to-depth ratio of 17:1 according to ASTM D 198 (“Standard” 1994d). The test span was 3.88 m (153 in.), with a cross-head speed of 4.6 mm/min (0.183 in./min). This testing setup resulted in an average time to failure of 21 min. After testing, a 25.4-mm-(1-in-.) thick section of each 7 by 9 was removed from an area close to the location of failure to determine moisture content and specific gravity according to ASTM D 2395 (“Standard” 1994g) and ASTM D 4442 (“Direct” 1994).

Compression

The 50 compression 7 by 9s were cut to a 2.8-m (11l-in.) length. Each specimen was tested in a restraining cage to prevent lateral buckling, which had five supports on each side at intervals of 0.71 m (28 in.) (ASTM D 198). Two linear variable displacement transformers (LVDTs), with a gauge length of 1.83 m (72 in.), were placed on opposing sides. The loading rate was 2.8 mm/min (0.11 in./minute), which produced an average time to failure of 13 min.

Grade Qualification Sample

The second sample of material was obtained solely from the mill in West Virginia. Before obtaining the qualification samples, a PE MOE was taken on 404 of the 7 by 9 pregraded, untreated, red and white oak timbers, which had been graded by mill employees to have characteristics equivalent to those of No. 2 visual grade (“Standard” 1991). Test results of the initial 100-piece bending sample were used to establish a 95% lower confidence limit on the MOE-MOR relationship and the relationship between static MOE and PE MOE. Two, somewhat arbitrary, target grades were selected for sampling: 1500f-1.5E and 1950f-1.7E. The grades are designated by the recommended allowable extreme fiber stress in bending F_b and the allowable modulus of eksticity E. For example, 1950f-1.7E designates an MSR grade with an allowable F_b of 13.4 MPa (1,950 lb/in.^{2}) and an E of 11.7 GPa (1.7 X 10^6 lb/in.^{2}). The first grade is comparable in properties to the select structural Southern pine timbers; the second is comparable to the dense select structural Douglas fir beams and stringers. Traditionally, for mechanically graded lumber, the fifth percentile nonpanmetric point estimate must equal 82% of the target average MOE value. This limits the variability of the lower half of the MOE distribution of the grade to a coefficient of variation of 11%. Thus, the minimum acceptable edgewise MOEs were 8.48 and 9.58 GPa [1.23 (0.82 X 1.5) and 1.39 (0.82 X 1.7) X 10^6 lb/in.^{2}] for the two proposed grades. A value for longitudinal stress wave speed, which was equivalent to these edgewise MOE values, was back-calculated using the experimental edgewise MOE and PE MOE relationship.

Selection

Using the appropriate longitudinal stress wave speed limits just determined, 145 specimens were selected from the 404-piece sample. From the 145 specimens, two 60-piece qualification samples, one for each grade, were selected for bending testing and 25 pieces were selected for compression testing. The initial compression sample tested had a limited range of MOE. The 25-piece compression specimens were meant to supplement the initial compression tests by filling in the high and low stiffness extremes.

Testing

The test methods were the same as those used in the initial sample testing.

RESULTS AND DISCUSSION

Initial Sample

Data Summary by Visual Grade

Test data for the visually graded timbers are summarized in Table 4. The average specific gravity value given in the National Design Specifications (NDS) for mixed oak is 0.68 (*National* 1992). This is the same as the average of all material that we tested. All timbers tested were well above the fiber saturation point with art average moisture content ranging from 61 to 77%.

A comparison of properties obtained in this study, with those published in the NDS, requires that the values be adjusted to an equivalent basis. The allowable MOE values given in the NDS are for a span-to-depth ratio of 21:1 and a uniformly distributed load. Our timbers were tested in third-point bending and a span-to-depth ratio of 17:1, The adjustments in MOE for loading configuration used results in a correction of only 1.003 according to ASTM D 2915 ("Standard" 1994c). To compare bending strength values, we divided the fifth percentile bending strength by the general adjustment factor of 2.1 (ASTM D 245). The average adjusted MOE for all grades of the initial test material is greater than published values of either mixed oak or Northern red oak (Table 5). The allowable bending value, for the only cell with enough data to calculate a nonparametric fifth percentile (select structural), of the oak timbers is well above the NDS value for both mixed and red oak grades (Table 5).

TABLE 5. Allowable Properties for Visual Graded Timbers

Species (1)	MOE [MPa (×10[6] lb/in.[2])] SS (2)	No. 1 (3)	No. 2 (4)	F_b SS [MPa (×10[6] lb/in.[2])] (5)
Initial sample[a]	10,700 (1.55)	9,900 (1.44)	8,700 (1.26)	14.0 (2,033)
Mixed oak[b]	6,900 (1.0)	6,900 (1.0)	5,500 (0.8)	9.3 (1,350)
Northern red oak[b]	9,000 (1.3)	9,000 (1.3)	6,900 (1.0)	11.0 (1,600)

Note: SS = select structural.
[a]MOE is mean × 1.003 and F_b is 5th percentile MOR/2.1.
[b]Values from *National* (1992).

Property Relationships

Regression relationships between PE MOE, static MOE, MOR, and UCS are given in Table 6. Of particular interest is the relationship between static MOE and MOR. This relationship is our basis for setting mechanical properties for mechanically graded lumber. The strength-stiffness relationship and the lower 95% confidence boundary for the visual timbers tested in the initial sample is shown in Fig. 1. The coefficient of determination r^2 of 0.51 is typical of that expected for lumber (Green et al. 1996).

TABLE 4. Strength and MOE of Green Mixed Oak 7 by 9 Timbers from West Virginia and Pennsylvania

Property (1)	Grade (2)	Sample size (3)	Average MC (%) (4)	Average specific gravity[a] (5)	Mean[b] (6)	COV (7)	5th percentile[b] (8)	25th percentile[b] (9)	50th percentile[b] (10)	75th percentile[b] (11)
					(*a*) Bending test					
PE MOE	SS	32	68.3	0.70	11,784 (1,709)	15.4	8,750 (1,269)	10,673 (1,548)	11,756 (1,705)	12,811 (1,858)
	No. 1	11	65.6	0.73	11,604 (1,683)	15.1	—	9,722 (1,410)	11,446 (1,660)	13,101 (1,900)
	No. 2	15	77.5	0.67	10,418 (1,511)	13.0	—	9,239 (1,340)	10,205 (1,480)	11,790 (1,710)
	Below grade	42	76.7	0.66	11,308 (1,640)	14.4	8,646 (1,254)	10,205 (1,480)	11,377 (1,650)	12,259 (1,778)
	All	100	72.9	0.68	11,356 (1,647)	15.0	8,826 (1,280)	10,101 (1,465)	11,377 (1,650)	12,411 (1,800)
Static MOE	SS	32	68.3	0.70	10,694 (1,551)	19.1	7,578 (1,099)	9,543 (1,384)	10,177 (1,476)	12,135 (1,760)
	No. 1	11	65.6	0.73	9,949 (1,443)	18.5	—	8,764 (1,271)	9,612 (1,394)	10,405 (1,509)
	No. 2	15	77.5	0.67	8,660 (1,256)	18.8	—	7,026 (1,019)	8,481 (1,230)	10,418 (1,511)
	Below grade	42	76.7	0.66	9,563 (1,387)	18.3	7,040 (1,021)	8,074 (1,171)	9,460 (1,372)	10,991 (1,594)
	All	100	72.9	0.68	9,832 (1,426)	19.7	7,026 (1,019)	8,288 (1,202)	9,812 (1,423)	11,066 (1,605)
MOR	SS	32	68.3	0.70	45.1 (6.538)	18.9	29.4 (4.269)	39.8 (5.777)	43.9 (6.362)	51.4 (7.451)
	No. 1	11	65.6	0.73	42.0 (6.091)	13.1	—	38.2 (5.538)	43.8 (6.347)	46.4 (6.735)
	No. 2	15	77.5	0.67	33.2 (4.822)	20.2	—	28.5 (4.130)	34.1 (4.942)	37.7 (5.462)
	Below grade	42	76.7	0.66	38.1 (5.530)	21.1	27.1 (3.931)	31.9 (4.632)	38.5 (5.578)	42.9 (6.217)
	All	100	72.9	0.68	40.0 (5.808)	21.7	27.1 (3.930)	34.1 (4.951)	40.0 (5.807)	45.9 (6.661)
					(*b*) Compression test					
PE MOE	SS	14	60.9	0.70	11,549 (1,675)	15.3	—	10,742 (1,558)	11,377 (1,650)	12,618 (1,830)
	No. 1	11	36.8	0.70	12,308 (1,785)	18.0	—	11,032 (1,600)	12,135 (1,760)	12,756 (1,850)
	No. 2	7	65.9	0.71	11,921 (1,729)	11.4	—	11,584 (1,680)	12,273 (1,780)	12,618 (1,830)
	Below grade	18	70.7	0.67	10,763 (1,561)	11.9	—	9,157 (1,328)	10,998 (1,595)	11,597 (1,682)
	All	50	65.7	0.69	11,487 (1,666	15.1	8,729 (1,266)	10,687 (1,550)	11,584 (1,680)	12,480 (1,810)
Static MOE	SS	14	60.9	0.70	10,956 (1,589)	23.9	—	9,294 (1,348)	10,549 (1,530)	12,011 (1,742)
	No. 1	11	36.8	0.70	10,529 (1,527)	19.2	—	8,619 (1,250)	10,549 (1,530)	11,446 (1,660)
	No. 2	7	65.9	0.71	11,604 (1,683)	20.6	—	10,205 (1,480)	12,480 (1,810)	13,238 (1,920)
	Below grade	18	70.7	0.67	10,156 (1,473)	19.0	—	8,398 (1,218)	10,032 (1,455)	12,080 (1,752)
	All	50	65.7	0.69	10,667 (1,547)	20.7	7,288 (1,057)	9,012 (1,307)	10,377 (1,505)	12,080 (1,752)
UCS	SS	14	60.9	0.70	22.7 (3.285)	22.6	—	19.6 (2.840)	23.0 (3.337)	25.0 (3.620)
	No. 1	11	36.8	0.70	22.1 (3.210)	18.5	—	19.8 (2.872)	22.6 (3.283)	23.7 (3.440)
	No. 2	7	65.9	0.71	20.4 (2.964)	15.1	—	17.0 (2.465)	21.1 (3.065)	22.0 (3.196)
	Below grade	18	70.7	0.67	19.3 (2.802)	16.9	—	17.1 (2.483)	18.0 (2.607)	22.0 (3.191)
	All	50	65.7	0.69	21.0 (3.050)	17.9	15.8 (2.286)	17.7 (2.561)	21.2 (3.073)	23.7 (3.431)

Note: MC = moisture content; COV = coefficient of variation; Static MOE = static edgewise modulus of elasticity; MOR = modulus of rupture; SS = select structural; UCS = ultimate compressive stress.
[a]Specific gravity is based on ovendry weight and ovendry volume.
[b]Value of property level in MPa (×10[3] lb/in.[2]).

TABLE 6. Bending Strength-MOE Relationships for Red Oak Timbers [$D = A + B*(I)$]

Dependent variable D (1)	Independent variable I (2)	n (3)	A (4)	B (5)	r^2 (6)	Root-mean-square error (7)
(a) Initial sample						
MOR	STATMOE	100	8.72 (1,264)	3.187	0.51	6.14 (890)
95% MOR	STATMOE	100	−3.45 (−500)	3.173	—	—
MOR	PE MOE	100	7.23 (1,048)	2.887	0.32	7.21 (1,046)
STATMOE	PE MOE	100	0.25 (0.0359)	0.844	0.55	1.31 (0.19)
UCS	STATMOE	50	10.28 (1,491)	1.008	0.35	3.06 (444)
UCS	PE MOE	50	3.63 (526)	1.515	0.48	2.73 (396)
STATMOE	PE MOE	50	−0.34 (−0.0492)	0.958	0.56	1.45 (0.21)
(b) All data combined						
MOR	STATMOE	220	14.27 (2,070)	2.552	0.51	6.03 (874)
95% MOR	STATMOE	220	2.43 (352)	2.545	—	—
MOR	PE MOE	220	1.44 (209.3)	3.418	0.44	6.48 (940)
STATMOE	PE MOE	220	−2.74 (−0.398)	0.844	0.63	1.48 (0.21)
MOR	SWperFT	220	106.56 (15,455)	−0.226	0.34	6.99 (1,014)
STATMOE	SWperFT	220	34.42 (4.99)	−0.082	0.58	1.56 (0.23)
UCS	STATMOE	75	6.94 (1,006)	1.315	0.68	2.85 (414)
UCS	PE MOE	75	0.24 (34.37)	1.824	0.74	2.56 (372)
STATMOE	PE MOE	75	−2.79 (−0.405)	0.958	0.81	1.38 (0.2)
UCS	SWperFT	75	64.91 (9,415)	−0.151	0.69	2.81 (408)
STATMOE	SWperFT	75	39.85 (5.78)	−0.100	0.77	1.52 (0.22)
SPGRodod	SWperFT	295	1.09 (1.09)	−0.0013	0.24	0.06 (0.056)

Note: PE MOE = pulse echo modulus of elasticity in GPa ($\times 10^6$ lb/in.^{2}); STATMOE = static edgewise modulus of elasticity in GPa ($\times 10^6$ lb/in.^{2}); MOR = modulus of rupture in MPa (lb/in.^{2}); 95% MOR = predicted 95% lower confidence limit modulus of rupture in MPa (lb/in.^{2}); SWperFT = stresswave time in μs/m (μs/ft); UCS = ultimate compressive stress in MPa (lb/in.^{2}); SPGRodod = specific gravity of specimen ovendry weight and ovendry volume.

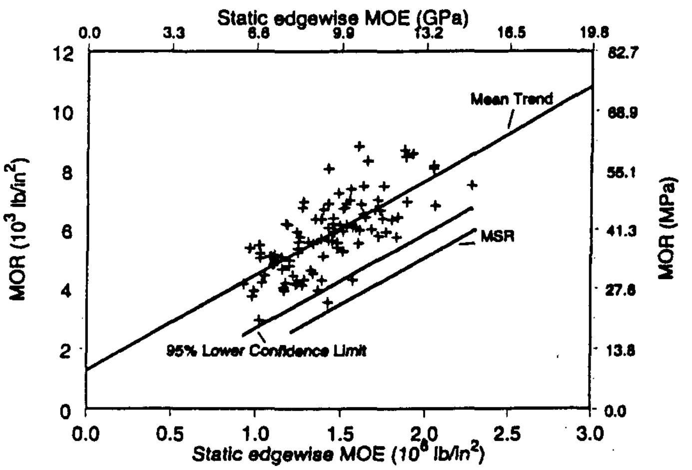

FIG. 1. Relationship of Static MOE to MOR for Initial Sample of 7 by 9 Green Mixed Oak Timbers

Determination of Potential Mechanical Grades

Using only the minimum MOE (0.82 times mean MOE) grade criteria, we sorted the initial 168-piece PE MOE sample from West Virginia into several potential grades to get an estimate of grade yield (Table 7). These sorts suggested that virtually all of the lumber would make the 8.48 GPa (1.23 X 10^6 lb/in.^{2}) boundary for an average 10.3 GPa (1.5 X 10^6 lb/in.^{2}) MOE, and a significant yield could be obtained at higher grades. Therefore, we were encouraged that the results with timbers might be just as favorable as those we obtained with 38- by 210-mm (2- by 9-in. nominal) dimension lumber (Green et al. 1993).

TABLE 7. Initial Timber Yield Estimates

Allowable MOE [MPa ($\times 10^6$ lb/in.^{2})] (1)	Yield (%) (2)
10,300 (1.5)	93
11,000 (1.6)	86
11,700 (1.7)	70
12,400 (1.8)	54

Grade Qualification Sample

The results of the bending tests for the qualification sample are represented in Figs. 2 and 3. The boundaries for the minimum acceptable MOR values 21.7 and 28.3 MPa (2.1 X 1,500 = 3,150 and 2.1 X 1,950 = 4,100 lb/in.^{2}) and minimum MOE values 8.48 and 9.58 GPa (1.23 and 1.39 X 10^6 lb/in.^{2}) are also shown. The results show that only one point fell below the strength boundary. For both the lower and higher grade pieces, six points were below the minimum MOE boundary. This reinforces the visual results, which suggested that there is no problem making the strength boundaries. However, it does appear that a slight adjustment to the stress wave PE MOE selection boundary is needed.

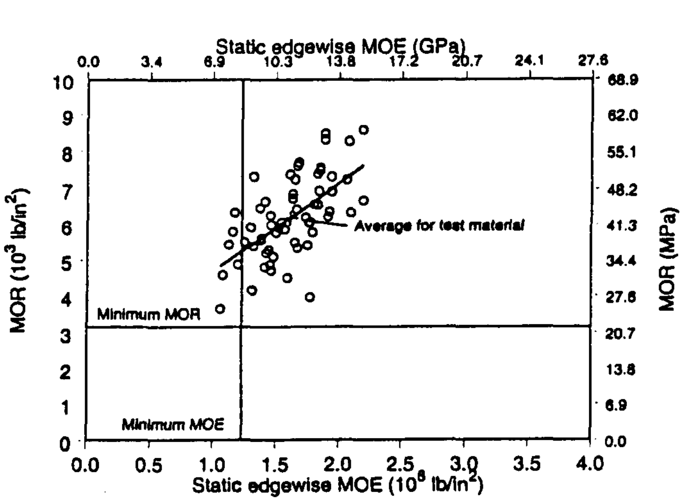

FIG. 2. *Test Results from Qualification Sample for Proposed* 1500f-1.5E Grade

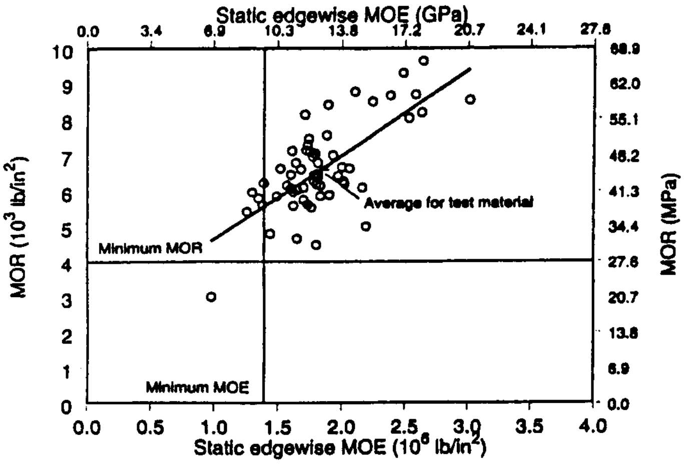

FIG. 3. Test Results from Qualification Sample for Proposed 1950f-1.7E Grade

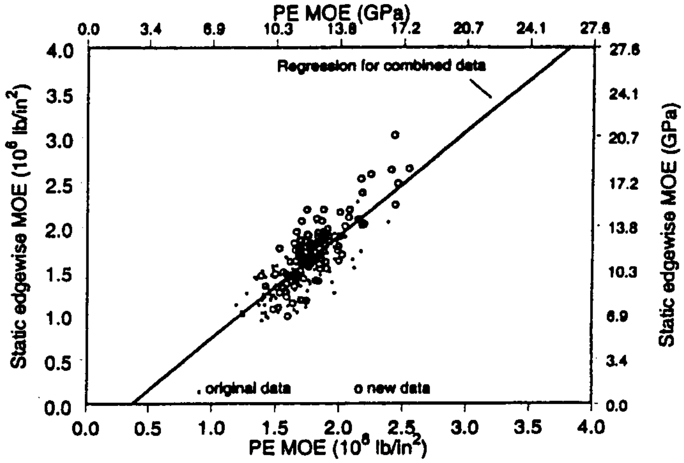

FIG. 5. Relationship of PE MOE to Static Edgewise MOE for Original and Combined Data

Property Relationship for Combined Data

Test results from the grade qualification phase of our study demonstrate the technical feasibility of developing a mechanical grading system for timbers. For future use, we combined the first and second sample data sets so that all data on property relationships were used (Table 6).

Static MOE and MOR

The combined relationship of static MOE to MOR given in Table 6 is shown in Fig. 4. The r^2 value remained the same as in the initial data set. The relationship for the 95% lower tolerance limit is also shown. The more extensive sample provided an improved estimate of the 95% lower tolerance limit (Table 6). This new 95% lower tolerance limit equation is recommended for determining future MOE cutoff boundaries.

PE MOE and Static MOE

The combined relationship of PE MOE to static MOE given in Table 6 is shown in Fig. 5. Although slightly lower than expected, the coefficient of determination is still significant and useful. The lower values may be a result of limited data and the nonuniformity of properties in the large cross sections. The new relationship for the more complete data set has considerably different slope than the one used for selecting the initial qualification sample. Use of this relationship would have brought static MOE values for the second sample into compliance with the requirements for the two grades.

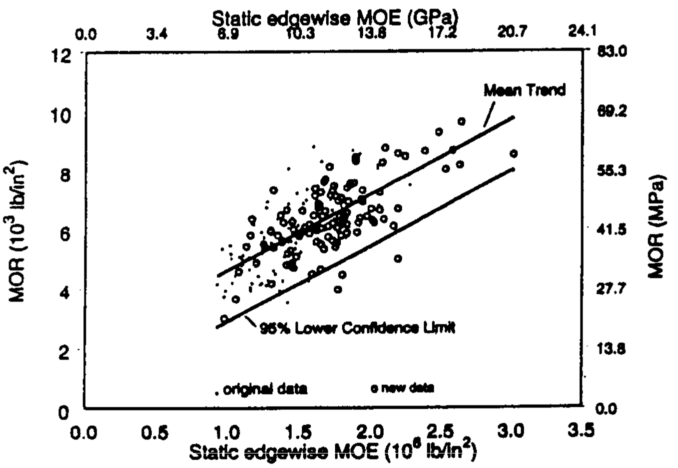

FIG. 4. Relationship of Static Edgewise MOE to MOR and 95% Lower Confidence Interval for Combined Sample of 7 by 9 Green Mixed Oak Timbers

UCS/MOR and MOR

Fig. 6 shows the relationship between compression strength and bending strength. The relationship for timbers appears to follow the general trend found for softwood 38-mm (2-in. nominal thickness) dimension lumber (Green and Kretschmann 1991). The UCS/MOR compared with MOR for green oak timbers is less than that for dry data. We believe that this is because the oak was tested green, not because it is oak. A reduction in the UCS/MOR ratio with increasing moisture content has been shown for softwood dimension lumber (Green and Kretschmann 1991). Data on dry oak 32-mm (2-in. nominal) dimension lumber shown in Fig. 6 (Green et al. 1993) are at least as high as those of dry softwood species, and the UCS/MOR ratio found in a companion study on dry Southern pine timbers parallel the expected results from dry 38-mm (2-in. nominal) dimension lumber (Fig. 6; Green and Kretschmann 1997). The slight degree of instability is probably a result of our limited number of specimens.

Inverse Wave Speed and Static MOE

The correlation between static MOE and inverse stress wave speed is only slightly less than that between static and PE MOE. The relationship between inverse of the wave speed and static MOE is given in Table 6. The r^2 value of 0.58 suggests the possibility of using stress wave speed to estimate static MOE and thus avoid having to measure or estimate density in calculating PE MOE [(l)]. This could be a decided advantage

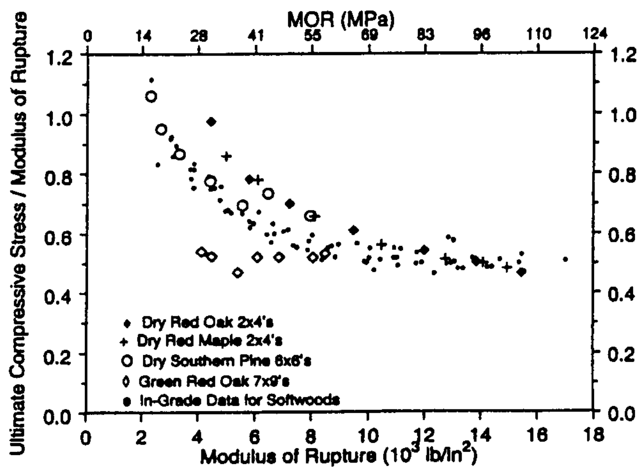

FIG. 6. Relationship between UCS/MOR to MOR for Combined Sample of 7 by 9 Green Mixed Oak Timbers

in an industrial application of this procedure. However, it is cautioned that significant variation in stress wave speed could result if there were large differences in moisture content between specimens. It is recommended that considerable additional data be obtained before a manufacturer rely solely on stress wave speed, plus visual characteristics, to sort timbers into grades.

CONCLUSIONS

We conclude the following from our study:

- Significant correlation exists between PE MOE, static MOE, MOR, and UCS for oak timbers.
- The relationship between UCS parallel to the grain and MOR follows the observed trend for 38-mm (2-in.) dimension lumber of hardwood or softwood species. As expected for green specimens, the absolute values are somewhat lower.
- There appears to be no technical barrier to the development of a mechanical grading system for oak timbers.
- Inverse wave speed shows promise as a means of sorting oak timbers for mechanical stress grades.
- The qualification sample for the two grades demonstrated that a revised PE MOE-edgewise MOE relationship must be used to ensure that an acceptable number of timbers are greater than the required edgewise MOE boundary. With this adjustment, mechanical grades of 1500f-1.5E and 1950f-1.7E could be produced. We estimate good yields of each grade.

Our initial results are favorable, but a certification process must be conducted by an independent grading agency to certify the proposed timber grades for production. The paper work for quality control also needs to be developed.

ACKNOWLEDGMENTS

The writers acknowledge Use interest and assistance of the Burke-Parsons-Bowlby Corp., Reedy, W.Va., and the Southern Pine Inspection Bureau, Pensacola Fla., in the completion of this research.

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