Mechanical Grading of Timbers for Transportation Industry

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Abstract
The grading of structural timbers is currently based on visual assessment of growth characteristics and defects, with properties derived from tests of small clear specimens. More efficient design of timber structures and more efficient use of the nation’s forest resource demand more precise assignment of allowable properties than is possible with the visual grading system. In this paper, we summarize available data on the mechanical properties of structural timbers and evaluate an approach for mechanical grading based on nondestructive testing. Potential mechanical grades for timbers are discussed, and preliminary yield data are presented for oak timbers.

Keywords: Grading, mechanical, timber, transportation

Introduction
Timbers are lumber $\geq$ 127 mm ($\geq$ 5 in.) in the least dimension. Structural timbers are used in a variety applications—from transportation structures such as railroad bridges to timber-frame buildings for farm, residential, and commercial use. At present, the grading of structural timbers is based on visual assessment of growth characteristics and defects, with allowable properties derived from tests of small clear specimens. For those not intimately familiar with the grading process, timber grading is very confusing. Unlike the descriptions for standard 38-mm- (nominal 2-in.-) thick visually-graded dimension lumber, grade descriptions for timbers are not standardized across all species. Descriptions are not even identical for the same species—grade name combinations if graded by different agencies. For most species, the grade descriptions for timbers to be used in bending (beams and stringers) are different from those to be used to support axial loads (posts and timbers). The classifications of “beams and stringers” and “posts and timbers” are based on cross-sectional dimensions. A comparison of design stresses between these classifications reveals that it is possible to increase certain allowable properties simply by changing the cross-section. This is an anomaly created by having a definition based on size.

Property assignment procedures for visually graded timbers may be very inefficient for some species. For example, the commercial grouping Red Oak is composed of nine species (Table 1), each with a different 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 lower than those of the other species. Thus, ASTM D245 (ASTM 1995) procedures limit some properties of the Red Oak grouping to those of southern red oak. Mounting a large-scale testing program on full-sized timbers would

Table 1—Mean clear wood properties of species in the Red Oak group.

Species	Modulus of rupture (MPa)	Modulus of rupture ($\times 10^3$ lb/in^2)	Modulus of elasticity (GPa)	Modulus of elasticity ($\times 10^6$ lb/in^2)
Black oak	95.8	13.9	11.3	1.64
Cherrybark oak	124.8	18.1	15.7	2.28
Laurel oak	86.9	12.6	11.6	1.69
Northern red oak	98.6	14.3	12.5	1.82
Pin oak	96.5	14.0	11.9	1.73
Scarlet oak	120.0	17.4	13.2	1.91
Water oak	106.2	15.4	13.9	2.02
Willow oak	100.0	14.5	13.1	1.90
Southern red oak	75.2	10.9	10.3	1.49

not remove this barrier because the weakest species would still control the properties of the commercial grouping. Furthermore, the general adjustment factor applied to all strength properties is 10 percent greater for hardwoods than it is for softwoods. Thus, everything else being equal, hardwoods will have allowable properties 10 percent lower than those of softwood species. This situation encourages overly conservative structural designs and may prevent producers from receiving full value for their local resource.

Mechanical grading was developed in the early 1960s for standard 38-mm- (nominal 2-in.-) thick lumber of softwood species to address limitations of the visual grading system when applied to engineered structures. Research has shown that mechanical grading can provide more precise property assignments for this size of lumber from hardwood species (Green and others 1993). However, mechanical grading procedures have not been developed for timbers produced from either softwood or hardwood species. The objectives of this paper are to summarize an ongoing program at the Forest Products Laboratory (FPL) to develop technical justification and procedures for the mechanical grading of structural timbers and to discuss potential advantages and limitations of these procedures.

Background

Mechanical Grading of Standard 38-mm (Nominal 2-in.) Lumber

Mechanical grading has been used commercially for standard 38-mm- (nominal 2-in.-) thick lumber since the early 1960s (Galligan and others 1978). Several procedures are available for machine grading of lumber. 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 controlled by visual restrictions on allowable edge-knot sizes (Galligan and others 1978). Qualitying 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. For each MSR grade, six allowable properties must be assigned: bending strength (F_b), modulus of elasticity (E), ultimate tensile stress (UTS) parallel to grain (F_t), ultimate compressive stress (UCS) parallel to grain (F_c), shear strength parallel to grain (F_v), and compression strength perpendicular to grain (F_{cp}). A specific gravity (SG) value is also associated with each grade (AFPA 1991). Traditionally, modulus of elasticity (MOE) and modulus of rupture (MOR) values are used to establish the grade cut-off settings on an MSR machine. These settings and the visual quality criteria are used to obtain the F_b and E values. Other property values are determined either as a function of MOR (UTS and UCS) or by the clear-wood procedure of ASTM D245 and D2395 (F_v, F_{cp}, SG) (ASTM 1995). The UCS value is obtained using the following relationship (Green and others 1993):

$$UCS/MOR = 2.061(1/MOR) + 0.338$$
$$\text{if } MOR \geq 2.835 \times 10^3 \text{ in}^2 \ (\geq 19.55 \text{ MPa})$$

or

$$UCS/MOR = 1.06$$
$$\text{if } MOR < 2.835 \times 10^3 \text{ in}^2 \ (< 19.55 \text{ MPa})$$

The F_c values are obtained by dividing UCS by a factor of 1.9 (ASTM D2915, ASTM 1995). The 1.9 factor accounts for long-term in-service loading plus a factor of safety. The traditional relationship between UTS and MOR for MSR lumber is a discontinuous function (Green and Kretschmann 1991). The allowable F_t value is calculated by dividing the UTS value by 2.1 (ASTM D2915).

All of these relationships were developed using test results for softwood species (Green and Kretschmann 1991). The MSR procedure was recently extended to standard 38-mm- (nominal 2-in.-) thick lumber of hardwood species (Green and others 1993). Accomplishing this extension required research to show that the property relationships assumed to apply to softwood dimension were also applicable to hardwood species. First, we needed to demonstrate a significant relationship between MOR and MOE—of which there was no real doubt. Then, we had to establish relationships between other properties. For example, tests established that the relationship assumed between UCS and MOR of softwood species was also applicable to oak and maple. Finally, we needed to grade lumber by the MSR process at a mill and to verify through testing that the assumed

Table 2—Properties of lowest mechanical grade for standard 38-mm- (nominal 2-in.-) thick lumber compared to visual equivalents.[a]

Grade	Red Oak		Mixed Maple	
	F_b	E	F_b	E
MSR	1,650	1.4	2,100	1.8
Select Structural	1,380	1.4	1,300	1.3
No. 1	990	1.3	942	1.3
No. 2	960	1.2	910	1.1
No. 3	570	1.1	500	1.0

[a]Grade names represent allowable bending stress F_b expressed in pounds per square inch and allowable MOE in million pounds per square inch. 1 lb/in^2 = 6.894 kPa. Green and others 1993.

properties were actually being obtained. With Red Oak standard 38-mm by 210-mm (nominal 2- by 9-in.) lumber, the mechanical grading procedure was able to demonstrate that most of the lumber graded as No. 3 or better by visual grading procedures actually had properties equal to or better than those assigned to Select Structural (Table 2) (Green and others 1993). Even better results were demonstrated for Mixed Maple standard 38-mm (nominal 2-in.) lumber.

Historical Data on Property Relationships for Timbers

The most extensive data on the mechanical properties of timbers was obtained early in the 20th century. A bulletin by Cline and Heim (1912) contains the results of 2,760 tests of softwood species ranging from standard 89- by 89-mm (nominal 4- by 4-in.) to standard 286- by 286-mm (nominal 12- by 12-in.). Tests were conducted in both bending and compression parallel to grain and for both green and airdried material. Although it is not possible to use these data to assess the properties of lumber graded by today's standards, the data illustrate that there is a significant relationship between MOR and MOE for timbers. Some pieces called "green" in Cline and Heim's bulletin were actually quite dry, and some of the "airdried" pieces had moisture content over 19 percent. By first discarding all airdried members with moisture content over 19 percent and all green members with moisture content less than 28 percent, statistically significant MOE–MOR relationships are obtained for a wide range of species and sizes (Table 3). Some historical data from other sources are also included in Table 3, as well as results from two recent studies on Southern Pine and Mixed Oak. Although the coefficient of determination (r^2) values are often less than the value of 0.5 anticipated for standard 38-mm- (nominal 2-in.-) thick dimension lumber, they would not be unusual given the small sample sizes used with a number of the species and the lack of lower quality material tested in many historical studies.

Current Research on Mechanical Grading of Timbers

Establishment of Property Relationships

Research at FPL and West Virginia University (WVU) has focused on the properties of structural timbers. Work at FPL has focused on Southern Pine and Mixed Oak, and that at WVU on Eastern Hemlock and Mixed Maple. The FPL research will be discussed here. Just as was done with standard 38-mm- (nominal 2-in.-) thick hardwood lumber (Green and others 1993), it was necessary to establish relationships between properties that could be used to assign allowable design values to structural timbers. Bending and compression parallel-to-grain tests were conducted on 200 dry Southern Pine 6 by 6 timbers (Green and Kretschmann, submitted for publication) and 150 Mixed Oak 7 by 9 timbers (Kretschmann and Green, submitted for publication).[1] These data yielded relationships between MOR and MOE that could be used for initial proposals of grade boundaries (Table 3).

In producing MSR timbers, it is necessary to have a method for measuring MOE on every piece. Pulse-echo, longitudinal stress wave techniques provide an alternative that could be applied in a mill (Schad and others 1995; Kretschmann and Green, submitted for publication). In our research, we obtained the stress wave measurement of MOE (PE MOE) by placing a double-threaded screw in the end of the timber and attaching an accelerometer. Pulse energy was introduced to the specimens 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 timber using the following equation:

$$\text{PE MOE} = K\, c^2 \rho \qquad (1)$$

where K is a conversion constant.

The MOR–MOE relationships for our Mixed Oak and Southern Pine timbers are given in Table 3. The r^2 value for the oak is about the value expected for standard 38-mm- (nominal 2-in.-) thick dimension

[1]Note: 6 by 6 timber refers to nominal 6- by 6-in. (standard 140- by 140-mm) timber; 7 by 9 timber refers to nominal 7- by 9-in. (standard 165- by 210-mm) timber.

Table 3—MOE-MOR relationships for timbers.[a]

Species	Size	Moisture content (percent)	N	MOR = A + B(MOE)[b] A	B	r^2	Ref[c]
Red Oak	7 by 9	Green	220	14.3	2.553	0.51	1
Eastern Hemlock	6 by 8	Green	80	4.6	3.009	0.47	2
Sitka Spruce	8 by 16	Green	20	10.5	2.259	0.28	2
Western Hemlock	8 by 16	Green	28	7.6	2.783	0.37	4
	8 by 16	Green	35	-7.5	4.394	0.46	3
Douglas Fir	6 by 12	Green	26	13.1	2.601	0.24	4
	5 by 8	Green	62	-2.6	3.657	0.69	4
	8 by 16	Green	166	5.0	3.487	0.44	4
Red pine	6 by 12	Green	15	4.3	2.990	0.71	4
Redwood	6 by 12	Green	14	14.1	2.255	0.32	4
	7 by 9	Green	14	-3.3	4.580	0.76	4
	8 by 16	Green	14	12.0	2.709	0.44	4
Southern Pine	5 by 8	Green	24	4.6	3.405	0.71	4
	5 by 12	Green	92	5.4	3.054	0.53	4
	8 by 12	Green	23	6.1	3.113	0.66	4
	8 by 16	Green	29	11.6	2.577	0.34	4
Eastern larch	6 by 12	Green	15	3.1	3.371	0.34	4
Western larch	5 by 8	Green	14	-0.2	3.741	0.70	4
	8 by 12	Green	30	6.5	3.268	0.58	4
	8 by 16	Green	32	7.9	2.743	0.33	4
Southern Pine	6 by 6	14	99	11.2	2.105	0.34	5
Sitka Spruce	8 by 16	17	20	-1.2	3.911	0.56	2
Western Hemlock	8 by 16	17	29	2.8	3.506	0.36	2
	8 by 16	18	42	1.7	3.603	0.42	4
Douglas Fir	6 by 12	17	28	-1.8	4.417	0.53	3
	5 by 8	15	30	-4.0	3.966	0.36	4
	8 by 16	17	37	-9.2	4.954	0.59	4
Western larch	8 by 12	18	26	-8.2	4.862	0.50	4
	8 by 16	18	18	-13.4	5.390	0.43	4

[a]For the Cline and Heim (1912) data, we dropped all "dry" pieces with moisture content > 20 percent and all "green" pieces with moisture content < 28 percent.
[b]Unit of measurement is giga Pascals for MOE and mega Pascals for MOR.
[c]Reference 1, Kretschmann and Green (submitted); 2, Markwardt (1931); 3, Littleford (1967); 4, Cline and Heim (1912); and 5, Green and Kretschmann (submitted).

lumber. This study was more comprehensive than the study on Southern Pine. The oak timbers came from West Virginia and Pennsylvania and were harvested in two installments 1.5 years apart. The r^2 of our Southern Pine data was slightly lower than expected, but nevertheless significant and useful. The study on Southern Pine had a more limited scope compared to the study on Mixed Oak, and the lower r^2 value is probably a result of the limited sample size.

Figure 1 shows the relationship between compression strength and bending strength. The relationship for timbers appears to follow the general trend found for standard 38-mm (nominal 2-in.) dimension lumber (Green and Kretschmann 1991). The UCS/MOR ratio for green timber was a little lower than that for dry timbers or dry dimension lumber. This decrease in the ratio with increasing moisture content was also found for standard 38-mm- (nominal 2-in.-) thick softwood lumber (Green and Kretschmann 1991). We conclude that the general UCS–MOR relationship used to assign properties to mechanically graded lumber could be applied to dry mechanically graded Southern Pine timbers and a slightly more conservative relationship could be used for Mixed Oak.

We did not conduct tensile tests on timbers. However, property relationships between MOR and MOE, and between UCS and MOR, seem to follow the trends expected for dimension lumber. Thus, we see no reason to doubt the ratio between tension and bending strength of 0.55 given in ASTM D245.

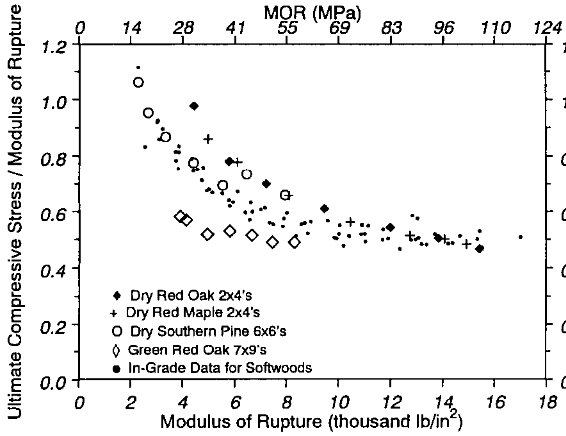

Figure I—Relationship of compression strength to bending strength for lumber.

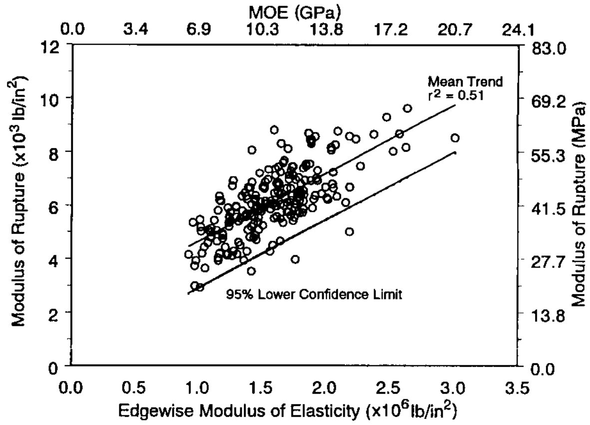

Figure 2—Relationship of strength to stiffness for oak 7 by 9 lumber.

Potential for Mechanical Grading of Oak Timbers

Having established the technical foundation for mechanical grading, next we wanted to verify that the procedure would work in the field. This involved establishing some target grade boundaries, sorting timbers according to these boundaries, and testing a sample of the graded pieces to verify that they had the intended properties. We chose Mixed Oak timbers for this evaluation.

The first step was to establish a 95-percent lower confidence limit on the MOE–MOR regression. This could be used to set MOE and MOR grade boundaries for proposed mechanical grades. Non-strength-reducing characteristics, such as wane or decay, were set equivalent to those of No. 2 timbers. Which grades to sort was somewhat an arbitrary decision. To obtain additional information on potential grades to evaluate, we obtained stress wave values on an additional 168 green 7 by 9 oak timbers. Using these data, we chose a target grade with properties equivalent to those of Select Structural Southern Pine timbers (AFPA 1991). Thus, one of our target grades was 1500f-1.5E, or an allowable F_b value of 10.3 MPa (l.5 × 10^3 lb/in^2) and an E of 10.3 GPa (1.5 × 10^6 lb/in). For a higher grade, we chose properties equal to those of Dense Select Structural Douglas Fir–Larch beams and stringers (AFPA 1991). Our second target grade was thus 1900f-1.7E. Of the 168 mill-run pieces in this preliminary data set, 93 percent fit the 1.5E criterion and 70 percent fit the 1.7E criteria.

The next step was to grade 400 timbers that met the MOE and visual requirements. Of the timbers that met our proposed grade, 60 pieces for each of the two grades were randomly selected to be shipped to FPL for testing. Combining the data from the first 100 bending tests with the 120 pieces from the second sample yielded an MOE–MOR regression with an r^2 value of 0.51. This value is about what would be expected for standard 38-mm (nominal 2-in.) dimension lumber. Revised grade boundaries can be set by fitting a 95-percent confidence bound to the data (Fig. 2). The final step will be to obtain some yield information on other sizes of Mixed Oak timbers using the proposed grading criteria.

Conclusions

From the results of our research to date, no technical barriers have been identified that would hinder the implementation of a mechanical grading system for solid sawn timbers. Many practical concerns would still need to be addressed. Practical details relating to use of the system at specific sites would need to be considered, as well as details of a quality assurance system. Producers and users would have to agree on grades of mutual interest. Ideally, the system might become accepted by the American Lumber Standards Committee with monitoring by existing grading agencies. Without such acceptance, individual companies would have to proceed on a proprietary basis. Future research will address the application of this concept to other species and its use in grading recycled timbers or timbers “in-place” in structures.

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