PREDICTING THE EFFECT OF MOISTURE CONTENT ON THE FLEXURAL PROPERTIES OF SOUTHERN PINE DIMENSION LUMBER[1]

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ABSTRACT

Current procedures for adjusting lumber properties for changes in moisture content are based on trends observed with the mean properties. This study was initiated to develop analytical procedures for adjusting the flexural properties of 2-inch-thick southern pine dimension lumber applicable to all grades and sizes as well as all levels of the cumulative frequency distribution. Equations are derived for adjusting modulus of rupture (MOR), modulus of elasticity (MOE), moment capacity (RS), and flexural stiffness (EI) for changes in moisture content. The best of these equations are significantly more accurate than current procedures for adjusting strength properties (MOR and RS). Because MOE and EI are less affected by changes in moisture content, most of the equations, including the current American Society for Testing and Materials procedure, work well for these properties.

Keywords: Analytical models, mechanical properties, bending, moisture content, dimension lumber.

NOTATIONS

M (with or without subscript)—moisture content in percent
P (with or without subscript)—property value at moisture content M
$F = P_2/P_1$—moisture content adjustment factor for adjusting property value from moisture content M_1 to moisture content M_2
Q (with or without subscript)—estimated average property value at M
M_p—the moisture content at which property changes due to drying are first observed
Subscript g—(estimated) property value at M_p
MOR—modulus of rupture
MOE—modulus of elasticity
EI—flexural stiffness
RS—moment capacity
SR—strength ratio in percent $0 \leq SR \leq 100$, the ratio of the strength of a member containing a defect to the strength of an equivalent defect-free member

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For the first time since 1912 (Cline and Heim 1912), the Forest Products Laboratory is conducting a comprehensive program to evaluate the mechanical properties of visually graded structural lumber sold in the United States. This program is called the "In-Grade" program (Galligan et al. 1980; Green 1983). Because of the magnitude of this program, the majority of the testing is being conducted in the field using portable equipment. As anticipated, the moisture content of the lumber being tested varies considerably. To correctly interpret how this lumber will perform at various end-use conditions, and to interpret causes of within- and between-mill variations in properties, it will be necessary to adjust test results for differences in moisture content. Initial investigations established that current procedures for adjusting mechanical properties for changes in moisture content were not suitable for use with in-grade data (Green 1982). Therefore, the effect of moisture content on the flexural properties of dimension lumber was evaluated and the results reported by McLain et al. (1984) for southern pine and Aplin et al. (1985) for Douglas-fir.

The objective of the present study is to evaluate analytical models that can adjust the flexural properties of southern pine dimension lumber for variations in moisture content.

BACKGROUND

Effect of moisture content on flexural properties

Wilson (1932) investigated the effect of moisture content on the mechanical properties of wood and proposed a formula that adequately described this relationship for clear wood. One form of this relationship is (U.S. Forest Products Laboratory 1974)

$$P = P_1\left(\frac{P_1}{P_g}\right)^{-\left(\frac{M-12}{M_p-12}\right)} \tag{1}$$

where subscript 1 is 12% moisture content. For longleaf pine, Eq. 1 predicts an increase in the modulus of rupture (MOR) of 70% in drying from green to an average moisture content of 12%. For over 70 years, however, it has been recognized that structural lumber is less sensitive to changes in moisture content than would be predicted from Eq. 1 (Cline and Heim 1912).

Provisions for allowing an increase in flexural properties with a decrease in moisture content were not included in initial standards of the American Society for Testing and Materials (ASTM). However, the 1930 edition (ASTM D 245-30) contained a moisture content adjustment factor for lumber 4 inches or less in thickness that has been termed the "25% rule."

$$SR_{dry} = SR_{green} + \tfrac{1}{2}(SR_{green} - 50) \tag{2}$$

The 25% rule tied the moisture content adjustment factor to lumber quality. The maximum adjustment was a 25% increase for green lumber having a strength ratio of 100% and dried to an average moisture content of 15%. The minimum (no increase) was for green lumber having a strength ratio of 50% or less. The 25% rule was carried through all revisions of ASTM D 245 up to and including the 1964 edition.

TABLE 1. *Current modification of allowable stresses for seasoning effects for lumber 4 inches and less in nominal thickness (ASTM D 245, 1984).*

Property	Percentage increase in allowable property above that of green lumber when maximum moisture content is	
	19% (15% average)	15% (12% average)
Bending (MOR)	25	35
Modulus of elasticity (MOE)	14	20
Tension parallel to grain	25	35
Compression parallel to grain	50	75
Horizontal shear	8	13
Compression perpendicular to grain	50	50

The current edition of D 245 (ASTM D 245, 1984) contains factors for increasing allowable flexural properties that are independent of lumber quality (Table 1). These factors first appeared in the 1964 edition of D 245 along with the 25% rule and were apparently an attempt to simplify the complicated set of adjustment procedures that had developed over the years since the 25% rule had first been adopted (Green 1982). ASTM standard D 2915-74 contains a formula (Eq. 3) for the moisture content adjustment factor, F. This formula is used to adjust properties based on the D 245 factors shown in Table 1.

$$F = (\alpha - \beta M_2)/(\alpha - \beta M_1) \tag{3}$$

where

α = 1.44 for MOR and 1.75 for modulus of elasticity (MOE), and
β = 0.02 for MOR and 0.0333 for MOE.

In contrast to the quality-independent adjustments given in the current ASTM standards, recent research evidence indicates that a quality-dependent adjustment factor may be justified. Gerhards (1968, 1970) investigated the effect of seasoning on MOR and MOE, using 55 matched pairs of 4 × 8 southern pine beams. One beam of each pair was tested green and the other was conditioned to 12% moisture content. Gerhards concluded that the effect of moisture content on MOE was independent of strength ratio (SR). When the lumber was dried by a mild schedule, the MOE increased about 23% in drying from green to a moisture content of 12%. In contrast, the effect of seasoning on MOR was dependent upon SR. When the lumber was dried to 12%, the increase in MOR with respect to SR varied linearly from about 50% for clear lumber to 12% for lumber with a strength ratio of about 25%. The relationship between F (called "seasoning" factor by Gerhards) and strength ratio was expressed as

$$F = 0.994 + 0.00503(SR) + 0.0104(SR_{dry} - SR_{green}) \tag{4}$$

where $(SR_{dry} - SR_{green})$ is the difference in the strength ratio of the matched specimens to be tested dry and green. By assuming that the within-pair difference is zero, we can use Eq. 4 to predict F for materials of different strength ratio when conditioned from green to a moisture content of 12% (Fig. 1).

In a series of reports, Madsen and co-workers (Madsen 1975; Madsen et al. 1980) investigated the effect of moisture content on the flexural properties of 2 ×

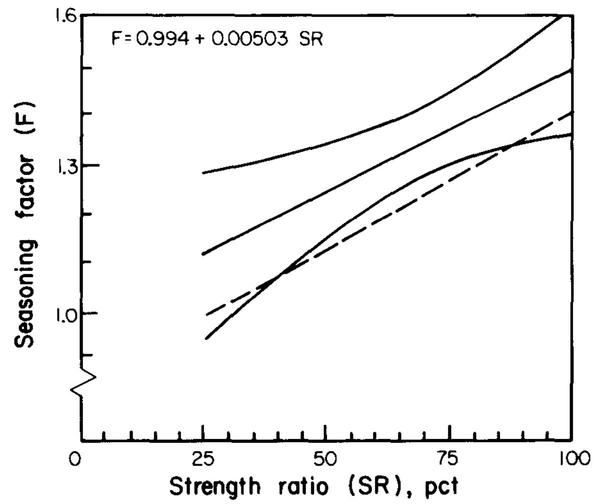

FIG. 1. Dependence of the seasoning factor for modulus of rupture on strength ratio for 4-inch-thick southern pine beams (Gerhards 1970). The solid lines are the mean trend and the 95% confidence limits for the seasoning factor obtained by Gerhards. The dashed line is the mean trend predicted by model No. 7 of this study.

6, No. 2 and Better Douglas-fir, hem-fir, and spruce-pine-fir dimension lumber. These results confirmed the trends observed by Gerhards: 1) Changes in moisture content alter MOR, dependent upon lumber quality (the stronger lumber is more affected than the weaker lumber); and 2) the effect of moisture content on MOE is not very dependent upon lumber quality. Madsen's results suggest that the 5th percentile MOR of No. 2 Douglas-fir and hem-fir only increases about 8% in drying from green to a moisture content of 15%. Fifth percentile MOR decreased

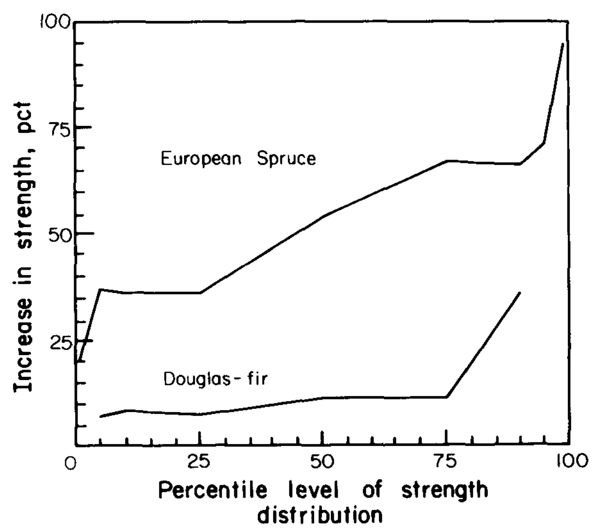

FIG. 2. Effect of strength level on the increase in bending strength due to drying (adapted from Madsen 1975; Hoffmeyer 1978).

about 2% for spruce-pine-fir. Based on these results Madsen (1982) recommends that no adjustment be taken for design purposes. The changes were large enough, however, that moisture content adjustments were recommended when analyzing Canadian In-Grade data for the purposes of establishing characteristic strength properties. Unfortunately, Madsen only sampled a No. 2 and Better grade mix, and therefore very little information could be gathered on moisture content effects for other grades.

Hoffmeyer (1978) noted a dependence between the moisture content adjustment factor and strength level for European spruce. Trends in the moisture content effect for European spruce generally parallel those found by Madsen for Douglas-fir (Fig. 2).

Selection of analytical models for adjusting lumber properties data

The data collected in the In-Grade program will be used for a variety of purposes. Some immediate applications include: 1) adjustment of properties to be used in computer programs that simulate wall and floor performance, 2) adjustment of properties to be used in engineering design codes as characteristic values (currently 5th percentile MOR and mean MOE) for visually graded dimension lumber, and 3) establishment of procedures for adjusting allowable properties for end-use moisture content that are appropriate for general design use. Many other uses could be envisioned.

For these and other applications, the user must balance the desire for accuracy against that for simplicity in selecting an appropriate model. For example, adjustments to be used in establishing characteristic values must be as accurate as possible at the critical percentiles. Since the adjustments can easily be done using a computer, simplicity is a lesser consideration. Likewise, adjustment of properties to be used in wall and floor simulations place little emphasis on simplicity but do require the procedures to be accurate at all levels of the cumulative density function for the property being studied.

For general design use, many potentially conflicting considerations should be considered:

1) How accurate must the procedure be? Should the highest accuracy be required on the adjustment of property-moisture content interactions when we may have little or no knowledge of a more critical property?
2) Must all calculations for general design use be simple enough to compute with a hand-held calculator?
3) How applicable is this adjustment to species not tested?

Such detailed discussions are clearly beyond the scope of this paper. As discussed, none of the previously published work has presented adjustment procedures suitable for all these purposes. In this paper we present a number of different types of models for adjusting flexural properties for changes in moisture content. We present enough information on the comparative effectiveness of these models so that the reader can select a model appropriate for his or her use.

PROCEDURES

In this section we will discuss the experimental and analytical procedures used in this study. First, we will briefly review the experimental procedures. This is followed by a discussion of possible analytical models. Next we will discuss the selection of the intersection moisture content, M_p. Finally we will establish our basis for comparison of individual models.

Experimental procedures

Lumber of three grades (Select Structural, No. 2, and No. 3) and three sizes (2 × 4, 2 × 6, and 2 × 8) was sampled from one mill in southeastern Virginia. The lumber of a given size and grade was divided into four equivalent populations in terms of estimated strength and stiffness in the green condition. SR based on the estimated maximum strength-reducing defect in the piece and a flatwise MOE were used as property estimators. Three of the groups were then equilibrated to moisture contents of 10, 15, and 20%. The fourth group was maintained green. All pieces were tested on edge in third-point bending using a span-to-depth ratio of 17:1. Flexural properties (MOR, MOE, EI, and RS) were calculated using the actual dimensions of the piece at time of test. Modulus of elasticity values were not corrected for deflection caused by shear stresses. Additional details concerning experimental procedures as well as an analysis of the data are given in McLain et al. (1984).

Analytical procedures

Analytical models.—In this section, five types of moisture content adjustment models are presented. For each type of model, several variations were produced by making different assumptions concerning the form of the analytical expression or by using various subsets of the data. The five model types are called: 1) the zero adjustment model (model No. 0), 2) the constant percentage model (Nos. 1–5), 3) the strength ratio model (Nos. 6–8), 4) the Weibull model (Nos. 9 and 10), and 5) the surface model (Nos. 11–14). All models contain a moisture content above which properties are assumed to be independent of changes in moisture content. The following section also discusses this value, called the intersection moisture content, M_p.

Zero adjustment model.—The simplest model is one in which properties are not adjusted to account for changes in moisture content. Thus, F is equal to one. This model is primarily useful as a baseline against which the performance of all other models can be compared.

Constant percentage adjustment models.—The second type of model adjusts a given property by a constant percentage regardless of grade or size when the moisture content changes from one level to another. All current standard adjustment procedures for dimension lumber and for clear wood are of this type.

Three variations of this model type were used in this study to model the average property value as a function of moisture content.

1) Linear ($Q = a + bM$)—this leads to an adjustment procedure similar to that given in D 2915, Eq. 3
2) Exponential ($Q = a \cdot \exp(bM)$)—this leads to an expression similar to the one used for clear wood, Eq. 1
3) Quadratic ($Q = a + bM + cM^2$)

F is then equal to Q_2/Q_1. The regression coefficients a, b, and c were estimated using all data as well as separately for each of the nine grade-size combinations.

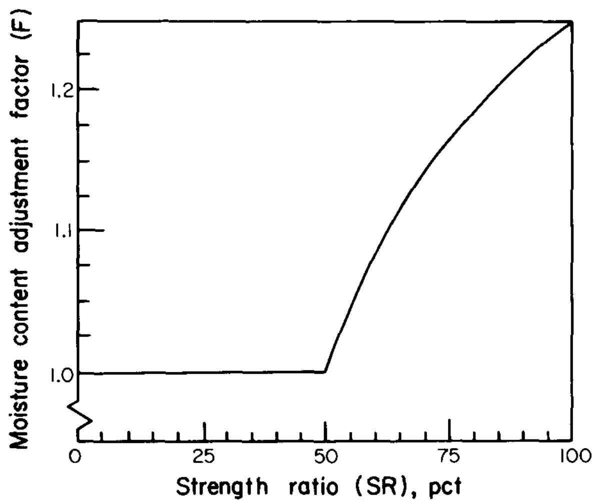

FIG. 3. Moisture content adjustment factor for 25% rule (Eq. 2).

Strength ratio models.—The third type of model assumes that F depends on the SR of the individual piece of lumber. This type is similar to the constant percentage adjustment models except that F is a function of SR. The 25% rule, Eq. 2, and Gerhards' model, Eq. 4, are models of this type. F is a linear function of strength ratio in Gerhards' model. However, with the 25% rule, it is horizontal (F = 1) for SR less than 50% and curvilinear for SR between 50 and 100% (Fig. 3).

Variations of the two historical forms of F are:

1) Linear

$$F = 1 \qquad 0 \le SR \le y_o(\text{cutoff})$$
$$F = [100 - F^*y_o + (F^* - 1)SR]/(100 - y_o) \qquad y_o \le SR \le 100 \tag{5}$$

2) Curvilinear

$$F = 1 \qquad 0 \le SR \le y_o$$
$$F = \frac{SR(100F_2^* - y_o) - y_o(100F_2^* - 100)}{SR(100F_1^* - y_o) - y_o(100F_1^* - 100)} \qquad y_o \le SR \le 100 \tag{6}$$

where F_i^* is the moisture content adjustment factor at SR = 100% when adjusting the property from green to M_i percent moisture content, i = 1, 2 ($F^* = F_2^*/F_1^*$), and where y_o is some cutoff point, below which F = 1.

To determine if additional functional forms of F should be considered, the data were stratified by SR into several subsets. Within each subset, a linear equation (Q = a + bM) was used to determine the average value for MOR and MOE as a function of moisture content. (Plots of MOR and MOE versus moisture content indicated there was no need for a more complicated model.) The resulting moisture content adjustment factors, $F = Q_2/Q_1$, for drying to four moisture content levels (M_2 = 10, 12, 15, 20% $M_1 = M_p$) were plotted against SR. These plots for MOR indicated that F varied erratically with SR. For MOE, on the other hand, F was

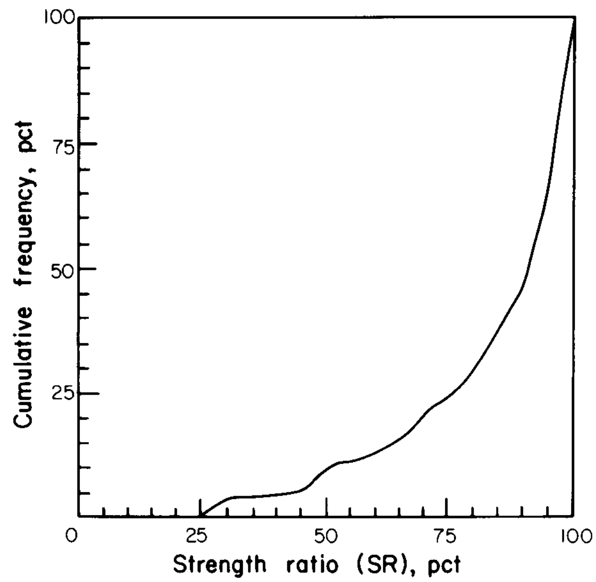

FIG. 4 Distribution of strength ratios for lumber sampled in this study.

reasonably constant. Because no clear pattern in the F-SR relationship was found for MOR, perhaps because of the limited number of pieces with SR less than 90 (Fig. 4), and although the indications for MOE were that F was constant across SR, no additional forms were thought to be necessary.

F was assumed to be equal to one for SR's between zero and some cutoff value, y_0, then linear (or curvilinear) to some value F* at SR equal to 100%. Four values of y_0 were assumed: 0, 26, 45 and 50%. The 50% cutoff value was chosen to be comparable to the 25% rule, the zero value to Gerhards' model. The values of 45 and 26% were chosen because they represent the minimum acceptable SR's for No. 2 and No. 3 grades, respectively, of Structural Light Framing.

To use the SR models, F* at a strength ratio of 100% was needed. Wilson's formula for small, clear wood, Eq. 1, could have been used. However, analysis of the data indicated that even lumber with a SR of 100% was less sensitive to changes in moisture content than indicated by Eq. 1. Therefore, the value of F* was obtained from the data for the 651 pieces which had a SR at 100% (3 to 47 pieces from each of the 36 individual grade-size moisture content combinations). As with the constant percent adjustment models, a linear function ($Q = a + bM$) or exponential function ($Q = a \cdot \exp(bM)$) was used to model the property as a function of moisture content. Coefficients to estimate $F^* = Q_2/Q_1$ were determined for all the pieces with SR of 100% and also separately by size.

The data set used for the SR models is slightly different than that used for the other models. Of the 3,787 pieces summarized in Table 7 of McLain et al. (1984), 233 could not be used for SR modeling. Of these 233 pieces, about one-third of them had incorrectly coded defect information that precluded the calculation of SR. The maximum strength-reducing defect of the remaining pieces was judged to be local grain deviation. SR formulas are available for a general slope of grain (ASTM D 245, 1984) but are not applicable to local grain deviations associated with a knot. The distribution of the actual SR's for the remaining material is shown in Fig. 4.

Weibull models.—The fourth type of model is obtained by first fitting a Weibull distribution to the data for each grade-size moisture content combination (McLain et al. 1984). The parameters of the Weibull distribution are then modeled as a function of moisture content. Given the Weibull parameters at moisture content M_1 and at moisture content M_2, it is assumed that if a property is the pth percentile in the distribution at M_1, it would also be the pth percentile in the distribution at M_2. By this assumption the property at moisture content M_2, P_2, is related to the property at moisture content M_1, P_1, by

$$P_2 = \omega_2(((P_1 - \ell_1)/\omega_1)^{m_1/m_2}) + \ell_2 \tag{7}$$

where

m_i = the Weibull shape parameter at M_i, $i = 1, 2$,
ω_i = the Weibull scale parameter at M_i, $i = 1, 2$, and
ℓ_i = the Weibull location parameter at M_i, $i = 1, 2$.

Given the appropriate Weibull parameters, Eq. 7 may be used to convert properties from one of the four tested moisture content levels to another for a given grade-size combination. To convert from any moisture content to any other moisture content, a quadratic function was used to model the Weibull parameters as a function of moisture content.

In this study a two- rather than a three-parameter Weibull distribution was used in Eq. 7. The two-parameter Weibull distribution was selected because

1) Both the two- and the three-parameter distributions fit the data reasonably well (McLain et al. 1984).
2) It is difficult to justify a nonzero location parameter for grades 2 and 3 when Select Structural often has an estimated zero location parameter (zero estimated location parameters were a result of left-skewed distributions).
3) It seems plausible that the adjustment of P_1 to P_2 should go through the origin. This will happen only if the two location parameters are equal.

The variations of the Weibull model were the result of different ways of modeling of the Weibull parameters as a function of moisture content. Originally the Weibull parameters were modeled separately for each of the nine grade-size combinations. To make it easier to extend the procedure to grades and sizes not tested, analysis of covariance was used to eliminate some of the 54 coefficients that resulted from the 9 grade-size combinations.

Surface models.—The last type of model is obtained by fitting a surface to the relationship between property and moisture content. The surface is defined by contour lines along which one moves when adjusting a property from one moisture content to another. Given a property value P_1 at moisture content M_1, a contour is found that goes through this point. The property value P_2 at moisture content M_2 is the value of this contour at M_2. Parameters for these contours are modeled as a function of moisture content and property value. The method used to define contours for the surface models was to use 21 percentiles (2nd, 5th, 10th, . . . 90th, 95th, 98th) from each grade-size-moisture content combination. Using the same underlying idea of the Weibull models (i.e., the pth percentile at one moisture

TABLE 2. *Estimated intersection moisture content M_p for southern pine dimension lumber.*

Moisture content adjustment model	Modulus of rupture (MOR)	Modulus of elasticity (MOE)	Moment capacity (RS)	Flexural stiffness (EI)
Constant percentage				
Linear (model 1)	24.5	23.8	17.9	15.7
Quadratic (model 5)	21.5	22.0	16.8	21.2
Surface				
Linear (model 11)	22.0	22.6	22.0	20.7
Quadratic (model 12)	21.3	20.5	21.0	19.8

content is converted to the pth percentile at another moisture content), contours are defined by connecting like percentiles across moisture content.[3] For any given grade-size percentile level, the four values across moisture content were used to define a contour. Two variations of the surface model are obtained by modeling the contours as either a linear or a quadratic function of moisture content. The coefficients of these contours were then modeled as a linear (linear contours) or a cubic (quadratic contours) function of the estimated property value at 15% moisture content. The choice of 15% moisture content was arbitrary, any other value could have been chosen. The surface models were fitted to each grade-size combination individually, as well as to the pooled data.

Intersection moisture content

It is generally assumed that the mechanical properties of small, clear wood specimens decrease with increasing moisture content up to some level. Past this level, properties are assumed to be independent of moisture content (USDA 1974). The moisture content above which properties are independent of moisture content is called the intersection moisture content, M_p (Wilson 1932). An M_p value is required for every model used in this study.

For clear specimens of loblolly and longleaf pine the M_p value is 21% (Wilson 1932). Traditionally, the value of M_p is chosen as the intersection of two lines on a plot of the logarithm of the property versus moisture content. The first line describes the linear relationship between log property and moisture content for dry wood, and the second is a horizontal line representing the property values for green wood (a moisture content greater than M_p). The apparent value of M_p varies with property and form of the relationship used to describe the property-moisture content relationship.

Because the apparent value of M_p is different for each moisture content adjustment model, optimum values of M_p were determined for each of the four flexural properties and for two types of the analytical models: 1) the constant percentage and 2) the quadratic surface models. For the constant percent adjustment models, the value of M_p was that which minimized the residual sum of squares when a linear, exponential, or quadratic equation was fitted to the property-moisture content data. For the surface models, the value of M_p was chosen to minimize the sum of the residual sum of squares for 189 equations (21 percentiles and 9 grade-size cells).

[3] See McLain et al. (1984) for plots of percentiles of the flexural properties versus moisture content.

TABLE 3. *Comparison of moisture content adjustment models for the modulus of rupture (MOR) and the modulus of elasticity (MOE) of southern pine adjusted to a moisture content of 15%.*

Model type	Model number	Variation	Independent of		Number of coeffi-cients	Average maximum absolute difference					
							Percentile				
			Grade	Size		Mean	5	25	50	75	95
					MOR, *psi*						
Zero adjustment	0	None	Yes	Yes	0	2,593	1,073	1,633	2,586	3,698	4,788
Constant percentage	1	Linear	Yes	Yes	2	835	1,126	1,108	1,090	1,336	1,696
	2	Quadratic	Yes	Yes	3	600	1,085	987	898	1,117	1,462
	3	Linear	No	Yes	6	741	1,091	1,076	965	1,180	1,540
	4	Linear	No	No	18	753	1,069	1,011	948	1,202	1,626
	5	Quadratic	No	No	27	494	1,031	937	721	1,015	1,465
Strength ratio linear	6	$y_o = 0$	Yes	Yes	2	798	1,101	1,030	1,039	1,241	1,081
	7	$y_o = 26$	Yes	Yes	2	829	1,062	974	1,045	1,295	1,118
	8	$y_o = 45$	Yes	Yes	2	893	1,038	978	1,074	1,352	1,179
Weibull	9	2-parameter	No	No	54	294	763	661	650	526	680
	10	2-parameter	No	No	19	531	868	900	702	725	1,095
Surface	11	Linear	Yes	Yes	2	705	1,006	1,047	1,018	821	863
	12	Quadratic	Yes	Yes	8	433	894	796	691	733	719
					MOE, 10^6 *psi*						
Zero adjustment	0	None	Yes	Yes	0	0.348	0.334	0.304	0.322	0.390	0.525
Constant percentage	1	Linear	Yes	Yes	2	0.129	0.180	0.112	0.109	0.159	0.259
	2	Quadratic	Yes	Yes	3	0.094	0.173	0.099	0.094	0.132	0.209
	3	Linear	No	Yes	6	0.116	0.169	0.101	0.109	0.158	0.243
	4	Linear	No	No	18	0.123	0.176	0.110	0.106	0.153	0.251
	5	Quadratic	No	No	27	0.080	0.166	0.089	0.084	0.111	0.174
Strength ratio linear	6	$y_o = 0$	Yes	Yes	2	0.165	0.243	0.143	0.154	0.188	0.308
	7	$y_o = 26$	Yes	Yes	2	0.175	0.255	0.154	0.165	0.198	0.311
	8	$y_o = 45$	Yes	Yes	2	0.186	0.267	0.168	0.180	0.209	0.314
Weibull	9	2-parameter	No	No	54	0.111	0.142	0.099	0.115	0.153	0.244
	10	2-parameter	No	No	19	0.080	0.135	0.089	0.105	0.133	0.175
Surface	11	Linear	Yes	Yes	2	0.111	0.142	0.099	0.115	0.153	0.244
	12	Quadratic	Yes	Yes	8	0.079	0.130	0.092	0.099	0.131	0.168

The resulting estimates of M_p vary by property, model type, and variation within model type (see Table 2). Even more variation exists if M_p is estimated by percentile level or for individual grade-size combinations. Because of this variation, there is no solid empirical evidence to reject the clear wood value of $M_p = 21$. This value was used for M_p in all subsequent modeling.

Comparison of models

For a given grade-size combination, the models were compared by adjusting the property for each of the four moisture content groups to a common moisture content. If the model adequately adjusts for the effect of moisture content, the cumulative distribution functions of the four adjusted data sets should be similar. Therefore, the performance of the models was evaluated by comparing the difference between the maximum and minimum property estimate (maximum absolute difference). This difference was calculated at the 5th, 25th, 50th, 75th, and 95th percentiles of the cumulative distribution function as well as the mean. The mean was included because it "averages" the differences over the entire distribution, while the percentiles only indicate the differences at one point in the distribution. Although the models do not fit each grade-size combination equally well, the maximum absolute differences were averaged across the nine grade-size combinations in order to more easily compare models.

The data were adjusted to four common moisture contents, 10, 15, 20% and green (M_p). The average maximum absolute difference is presented only for data corrected to a moisture content of 15% (Table 3). In general, for MOR these numbers would be about 100 psi larger if corrected to 10%, 100 psi smaller if corrected to 20%, and 120 psi smaller if corrected to M_p at the mean. For MOE, these numbers would be about 0.01×10^6 psi larger if corrected to 10%, 0.01×10^6 psi smaller if corrected to 20%, and 0.013×10^6 psi smaller if corrected to M_p at the mean. The average maximum absolute difference tends to be larger when drying to lower moisture contents as the property value tends to be larger.

EVALUATION OF MODELS

In this section we evaluate the various moisture content adjustment models. For each property, the variations within a given model type are first compared to select the most useful model of that type. Then we compare the performance of the selected models and comment on their usefulness for various applications.

Average maximum absolute differences are only given for MOR and MOE. Similar patterns were seen in RS as in MOR and EI as in MOE.

In general, models in which the coefficients are fitted to each grade-size combination separately fit the experimental data better. However, models that are independent of grade and size are preferred for two reasons. First, these models are more likely to be appropriate for grades and sizes not tested than would be grade size-dependent models which must be extrapolated to other grades and sizes. Second, because the sample size is limited for any given grade-size moisture content level combination, a model independent of grade and size is likely to be more stable and less likely to fit the peculiarities of the given data set. Coefficients for each model discussed in this section are given in the appendix.

TABLE 4. *Predicted effect of drying on flexural properties using the linear constant percent models.*

Grade	Size	Model number	Percent increase[1] in property from green[2] to			
			20	15	12	10
			Modulus of rupture (MOR)			
			pct			
All	All	1	3.4	20.1	30.2	36.9
Select Structural	2 × 4	4	4.5	27.2	40.8	49.9
	2 × 6	4	3.7	22.5	33.7	41.2
	2 × 8	4	4.1	24.8	37.2	45.5
	All	3	4.2	25.2	37.8	46.3
No. 2	2 × 4	4	3.8	22.5	33.8	41.3
	2 × 6	4	3.0	18.3	27.4	33.5
	2 × 8	4	2.6	15.3	23.0	28.1
	All	3	3.3	19.6	29.5	36.0
No. 3	2 × 4	4	2.5	14.9	22.3	27.3
	2 × 6	4	3.6	21.8	32.7	40.0
	2 × 8	4	2.9	17.3	26.0	31.8
	All	3	3.1	18.8	28.2	34.5
			Modulus of elasticity (MOE)			
All	All	1	2.0	12.3	18.5	22.6
Select Structural	2 × 4	4	2.4	14.6	21.9	26.7
	2 × 6	4	2.2	13.0	19.5	23.8
	2 × 8	4	2.1	12.8	19.2	23.4
	All	3	2.3	14.1	21.1	25.8
No. 2	2 × 4	4	2.6	15.3	23.0	28.1
	2 × 6	4	2.1	12.8	19.2	23.5
	2 × 8	4	1.9	11.6	17.4	21.2
	All	3	2.3	14.0	21.5	25.8
No. 3	2 × 4	4	1.6	9.4	14.1	17.2
	2 × 6	4	2.0	11.8	17.7	21.6
	2 × 8	4	2.1	12.7	19.0	23.2
	All	3	2.0	11.7	17.6	21.5

[1] Percent increase is $(F - 1)100 = [(a + bM_2)/(a + bM_1) - 1]100$ (see Eq. 3).
[2] Green moisture content, M_p, is assumed to be 21%.

Evaluation of individual models

Constant percentage adjustment models (Nos. 1–5).—Of the three functions used to determine a constant percentage adjustment model, the quadratic models almost always produced the smallest average maximum absolute difference (compare model 1 with model 2 and model 4 with model 5 in Table 3). In many cases the quadratic model is not a lot better than the linear model. Although the exponential model is of historical importance for clear wood, it always produced a higher average maximum absolute difference than either the quadratic or linear models, and therefore it was not included in the tables. This poor performance is due to the curvature of the MOR moisture content and MOE moisture content relationships. This curvature tends to be convex for lumber rather than concave as for clear wood.

As indicated previously, the models in which coefficients are determined for each grade-size combination should be better than the grade-size independent models. In fact, the anticipated improvement with the grade-size dependent models

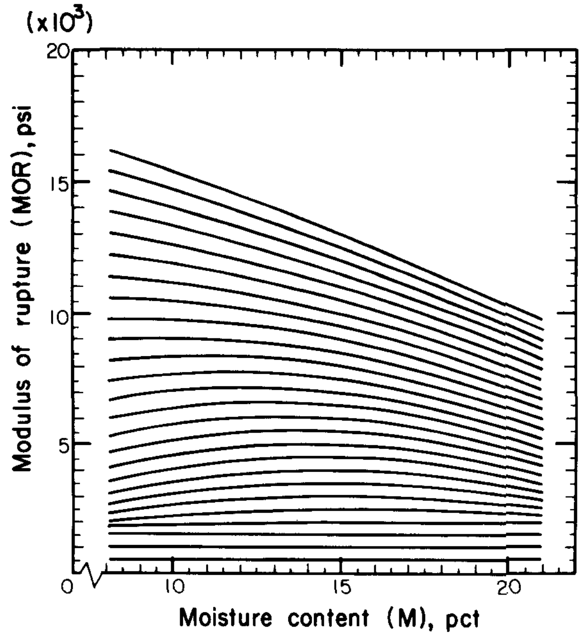

FIG. 5. Predicted modulus of rupture (MOR) using the quadratic surface model (No. 12).

(Nos. 3–5) was not always observed. Thus, for design use, the linear model which is independent of grade and size (No. 1) would appear to be the most suitable of the constant percentage models.

Because the current design procedure assumes a constant percent increase in lumber properties with drying to a specified MC level (Table 1), it is of interest to compare the current adjustments with the increases predicted by the models developed in this paper.

The percent increase in property values for drying lumber from green to 20, 15, 12, and 10% is given in Table 4 for the linear constant percent adjustment models (Nos. 1, 3, and 4). The potential instability of model 4 which is dependent upon grade and size is seen in the inconsistent pattern of property increases across grade and size. The increase predicted for MOR in the grade-size independent model (No. 1) is less than the current increase given in D 245 (Table 1). Looking at the grade (size) dependent models (models 3 and 4), although the percent increases are not overly consistent within grades or sizes, in general the increases allowed for Select Structural are near those provided in D 245, but the increases for No. 2 and No. 3 are less than those provided in the standard. For MOE, the increases for both the grade-size dependent and grade-size independent models are close to the current increase given in D 245.

Strength ratio models (Nos. 6–8).—The linear and curvilinear variations of the SR model given in Eqs. 5 and 6 resulted in very similar average maximum absolute differences. Because the average maximum absolute difference for the linear model (Eq. 5) was almost always less than that for the equivalent curvilinear model, only the results for the linear model are shown in Table 3. Both the linear and exponential equations also gave similar values of F*.

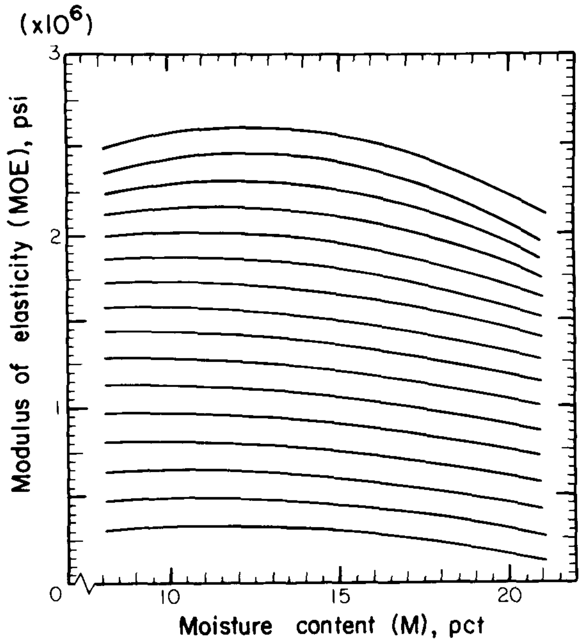

FIG. 6. Predicted modulus of elasticity (MOE) using the quadratic surface model (No. 12).

For the range of values investigated in this study, the cutoff value made little difference in the performance of the models (Table 3). The lack of sensitivity of the data to different cutoff values is due to the high proportion of data in the upper portion of the SR distribution (Fig. 4). Determination of an SR model by size did not significantly improve the fit.

McLain et al. (1984) showed that for design purposes a moisture content adjustment factor of 1.0 was reasonable for the MOR of No. 3 grade lumber. For this reason the model which uses the 26% cutoff (No. 7, Table 3) was chosen in the present study as the best SR model for all properties.

As may be seen in Fig. 1, the relationship predicted by model 7 is near the lower 95% confidence line predicted by Gerhards (1970).

Weibull models (Nos. 9 and 10).—The Weibull model with parameters determined separately for each grade-size combination (No. 9) produces smaller average maximum absolute differences than one in which an analysis of covariance is used to reduce the number of coefficients (No. 10, Table 3). However, the reduced model is preferable for adjusting the in-grade data because it can be more easily generalized for grades and sizes not tested.

Surface models (Nos. 11 and 12).—The results for the surface models shown in Table 3 include those for the linear version (No. 11) and quadratic version (No. 12). Of these two models, the quadratic model generally produced the smallest average maximum absolute difference. Although neither of the two model types is simple enough for design use, both are easily used with the help of a computer. Approximate adjustment factors may be estimated for model 12 using the contour plots shown in Figs. 5 and 6. A predicted value is obtained by determining the coordinate for a known property-moisture level and following the appropriate contour line to the moisture content level for which a predicted property value is desired. The predicted value is read on the ordinate at the intersection of the curved line and the vertical line for the desired moisture content. The contours given in Figs. 5 and 6 have been limited as shown in Table A5.

Comparison of selected models

Seven of the thirteen models discussed appear useful either for adjusting in-grade data or for use in design codes. Table 5 compares the performance of these models to that of the quadratic surface model (No. 12). The quadratic surface model (No. 12) was chosen as a basis for comparison because it is one of the more accurate models, and the results are independent of grade and size.

The Weibull models (Nos. 9 and 10) and the quadratic surface model (No. 12) predict very similar results throughout the range of properties (Table 5). The Weibull model with 54 coefficients produced the smallest average maximum absolute difference for MOR. However, this model is not recommended for general use because of the dangers of overfitting the data.

For many studies of the reliability of timber structures, the reduced Weibull model (No. 10) may be preferred because the Weibull distribution is being used extensively in reliability analysis. However, the Weibull model is not recommended for general use because of the difficulty in applying the model to adjust grades and sizes not tested in this study.

Neither the constant percentage adjustment model (Nos. 1, 3, and 4) nor the strength ratio model (No. 7) produces as small an average maximum absolute difference as the Weibull and quadratic surface models (Table 5). The fact that the SR model does not work is not surprising because the correlation between MOR and SR is poor ($R^2 = 0.283$ using all the data) and that between MOE and SR is worse ($R^2 = 0.09$). Although all three of these models offer a significant improvement in accuracy over the zero adjustment model for predicting the effect of moisture content on mean MOR, at the 5th percentile they are no better than taking no adjustment. Therefore, neither of these simpler models is recommended for adjusting MOR. Results predicted using the constant percentage adjustment models appear to work reasonably well for MOE.

The selection of a particular model can have an effect on the dry-green ratios predicted for lumber (Table 6). The dry-green ratios are simply the moisture content adjustment factors for adjusting the assumed green property to 12% moisture content. For the SR model, the minimum SR of the grade was assumed. Additional confidence in the models being recommended in this report may be gained following analysis of a similar data set for Douglas-fir dimension lumber (Aplin et al. 1985).

CONCLUSIONS

Of the analytical models evaluated in this study, we conclude that:

1) The analytical model obtained by fitting a quadratic surface to the property-moisture content relationship (No. 12) be used to adjust in-grade data to a constant moisture content level.

2) The model based on the two-parameter Weibull distribution (No. 10) is as accurate as the model 12 but is difficult to apply to grades and sizes not tested.

3) If a relatively simple model is needed as a basis for general design use, the

TABLE 5. *Performance of selected moisture content adjustment models compared to the quadratic surface model (No. 12) at a moisture content of 15%.*

Model type	Model number	Variation	Independent of		Number of coeffi-cients	Average maximum absolute difference minus average maximum absolute difference for model 12						
							Percentile					
			Grade	Size		Mean	5	25	50	75	95	Average of 5 to 95
						Modulus of rupture (MOR), *psi*						
Zero adjustment	0	None	Yes	Yes	0	2,160	179	837	1,895	2,965	4,069	1,989
Constant percentage	1	Linear	Yes	Yes	2	402	232	312	399	603	977	505
	3	Linear	No	Yes	6	308	197	280	274	447	821	404
	4	Linear	No	No	18	320	175	215	257	469	907	405
Strength ratio linear	7	$y_o = 26$	Yes	Yes	2	396	168	178	354	562	399	332
Weibull	9	2-parameter	No	No	54	−139	−131	−135	−41	−207	−39	−111
	10	2-parameter	No	No	19	98	−26	104	11	−8	376	91
Surface	11	Linear	Yes	Yes	2	272	112	251	327	88	144	184
						Modulus of elasticity (MOE), 10^6 *psi*						
Zero adjustment	0	None	Yes	Yes	0	0.269	0.204	0.212	0.223	0.259	0.357	0.251
Constant percentage	1	Linear	Yes	Yes	2	0.050	0.050	0.020	0.010	0.028	0.091	0.040
	3	Linear	No	Yes	6	0.037	0.039	0.009	0.010	0.027	0.075	0.032
	4	Linear	No	No	18	0.044	0.046	0.018	0.007	0.022	0.083	0.035
Strength ratio linear	7	$y_o = 26$	Yes	Yes	2	0.096	0.125	0.062	0.066	0.067	0.143	0.093
Weibull	9	2-parameter	No	No	54	0.032	0.012	0.007	0.016	0.022	0.076	0.027
	10	2-parameter	No	No	19	0.001	0.005	−0.003	0.006	0.002	0.007	0.003
Surface	11	Linear	Yes	Yes	2	0.032	0.012	0.007	0.016	0.022	0.076	0.027

TABLE 6. *Predicted dry-green ratios for assumed green properties of southern pine 2 × 4's when adjusted to a moisture content of 12%.*

Grade	Assumed property, green	Assumed minimum strength ratio	Dry-green ratios for model indicated				
			Constant percentage (No. 3)	Strength ratio (No. 7)	2-Parameter Weibull (No. 10)[2]	Linear surface (No. 11)	Quadratic surface (No. 12)
			Modulus of rupture (MOR)				
	psi			*psi*			
Select Structural	[1]3,360	0.67	1.379	1.209	1.186	1.128	1.249
No. 1	2,835	0.55	—	1.148	—	1.033	1.183
No. 2	2,415	0.45	1.295	1.097	1.106	1.000	1.109
No. 3	1,312	0.26	1.282	1.000	0.931	1.000	1.000
			Modulus of elasticity (MOE)				
Select Structural	1.5×10^6	0.67	1.211	1.095	1.256	1.213	1.229
No. 1	1.5×10^6	0.55	—	1.067	—	1.213	1.229
No. 2	1.4×10^6	0.45	1.211	1.044	1.261	1.216	1.230
No. 3	1.2×10^6	0.26	1.176	1.000	1.241	1.224	1.240

[1] $2.1 \times F_b$ value given in NDS for green southern pine 2 × 4's (National Forest Products Association 1982).
[2] Model 10 is unbounded.

linear constant percentage adjustment model (No. 1) is appropriate for MOE or EI. The simpler models do not appear adequate for MOR or RS.

As was stated previously, the objective of this study was to develop analytical models for predicting the effect of changes in moisture content on the strength of southern pine dimension lumber. A fundamental assumption of these models is that the change in properties with change in moisture content is relatively insensitive to the particular geographic location from which the lumber was sampled. The absolute magnitude of the properties at a given moisture content may vary from sample to sample.

Care should be exercised in using these equations with lumber mechanical properties or moisture content levels that are outside of the range of data used to establish the coefficients. It is our experience that failure to place limits on the use of these equations may sometimes yield unrealistic or even illogical results. We do not recommend that these equations be used for moisture contents less than 8%.

For MOR and MOE, property limits were established by comparing trends predicted using the models with actual trends observed near the extremes of the data. These limits are given in Appendix Table A5. Applicable limits for EI and RS may be determined by appropriate scaling of the MOR and MOE limits.

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APPENDIX

Tables A1–A4 give the coefficients for most of the models presented in this paper. It is always risky to use analytical models to predict properties that fall outside the range of the experimental data on which the models are based. Property limits for the data obtained in this study are given in Table A5.

TABLE A1. *Coefficients of linear constant percentage adjustment models.*[1]

				Coefficients for indicated property			
Size	Grade	Model number	Coefficient symbol	Modulus of rupture (MOR)	Modulus of elasticity (MOE)	Moment capacity (RS)	Flexural stiffness (EI)
All	Select Structural	3	a	14,044	2.34304	3,238.8	0.25509
			b	−314	−0.03684	−58.1	−0.00181
All	No. 2	3	a	9,566	1.97745	2,212.6	0.21863
			b	−186	−0.03104	−32.5	−0.00170
All	No. 3	3	a	9,115	1.83678	2,107.4	0.20251
			b	−172	−0.02547	−29.5	−0.00106
All	All	1	a	10,888	2.03829	2,520.4	0.22482
			b	−214	−0.02923	−37.9	−0.00135

[1] $F = P_2/P_1 = (a + bM_2)/(a + bM_1)$.

TABLE A2. *Coefficients of linear strength ratio model with 26% cutoff, model 7.*[1,2]

Size	Grade	Coefficient symbol	Coefficients for indicated property: Modulus of rupture (MOR)	Modulus of elasticity (MOE)	Moment capacity (RS)	Flexural stiffness (EI)
All	All	a	16,196	2.32770	3,702.0	0.24684
		b	−316	−0.03174	−66.0	−0.00092

[1] If SR > 26, F = [100 − F*y_o + (F* − 1)SR]/(100 − y_o); F* = (a + bM_2)/(a + bM_1) for lumber with SR = 100; y_o = 26.
[2] If SR ≤ 26, F = 1.

TABLE A3. *Coefficients to be used in calculating Weibull parameters, model 10.*[1,2]

Size	Grade	Coefficients[3,4]: A_0	A_1	B_0	B_1	B_2
		Modulus of rupture (MOR)[5]				
2 × 4	Select Structural	3.67188	0.09598	12.57049	0.19055	−0.01773
	No. 2	2.05910	0.05891	5.99041	0.58290	−0.02577
	No. 3	1.82650	0.06114	9.48142	0.06586	−0.00934
2 × 6	Select Structural	3.48644	0.09598	11.82050	0.19055	−0.01773
	No. 2	1.87367	0.05891	5.24041	0.58290	−0.02577
	No. 3	1.64105	0.06114	8.73143	0.06576	−0.00934
2 × 8	Select Structural	3.14681	0.09598	10.91933	0.19055	−0.01773
	No. 2	1.53404	0.05891	4.33924	0.58290	−0.02577
	No. 3	1.30143	0.06114	7.80258	0.06576	−0.00934
		Modulus of elasticity (MOE)[6]				
2 × 4	Select Structural	5.65920	−0.03345	1.68130	0.07685	−0.00372
	No. 2	4.56337	−0.03186	1.35760	0.07702	−0.00357
	No. 3	3.68080	−0.00216	1.54337	0.04309	−0.00242
2 × 6	Select Structural	6.05965	−0.03345	1.73859	0.07685	−0.00372
	No. 2	4.96382	−0.03188	1.41489	0.07702	−0.00357
	No. 3	4.08125	−0.00216	1.60066	0.04309	−0.00242
2 × 8	Select Structural	6.05653	−0.03345	1.67163	0.07685	−0.00372
	No. 2	4.95482	−0.03186	1.34793	0.07702	−0.00357
	No. 3	4.07226	−0.00216	1.53370	0.04309	−0.00242
		Moment capacity (RS)[5]				
2 × 4	Select Structural	3.89354	0.08741	35.48912	0.67420	−0.04821
	No. 2	2.13363	0.05667	16.57581	1.80910	−0.11905
	No. 3	1.91467	0.05815	26.89652	0.28151	−0.20686
2 × 6	Select Structural	3.69254	0.08741	83.09581	1.66486	−0.07353
	No. 2	1.93264	0.05667	36.39153	4.46737	−0.18158
	No. 3	1.71368	0.05815	61.87738	0.69517	−0.31552

TABLE A3. *Continued.*

Size	Grade	Coefficients[3,4] A_0	A_1	B_0	B_1	B_2
2 × 8	Select Structural	3.34835	0.08741	134.93881	2.89286	−0.02490
	No. 2	1.58844	0.05667	53.78530	7.76252	−0.06150
	No. 3	1.36948	0.05815	98.06960	1.20792	−0.10686
			Flexural stiffness (EI)[6]			
2 × 4	Select Structural	6.29639	−0.05804	8.27747	0.34976	−0.01363
	No. 2	5.10069	−0.05567	6.77529	0.35402	−0.01383
	No. 3	4.22623	−0.02719	7.57582	0.20305	−0.00864
2 × 6	Select Structural	6.70363	−0.05804	34.14009	1.35722	−0.05289
	No. 2	5.50793	−0.05567	28.31010	1.37376	−0.05367
	No. 3	4.63347	−0.02719	31.41737	0.78794	−0.03352
2 × 8	Select Structural	6.68964	−0.05804	78.49211	3.10869	−0.12114
	No. 2	5.49394	−0.05567	65.14061	3.14658	−0.12293
	No. 3	4.61948	−0.02719	72.25580	1.80476	−0.07677

[1] $P_2 = \omega_2[(P_1/\omega_1)^{m_1/m_2}]$; $m_i = A_0 + A_1M_i$, $i = 1, 2$; $\omega_i = B_0 + B_1M_i + B_2M_i^2$, $i = 1, 2$.

[2] This model is unbounded. If bounds are desired: if $P_2 > P_1$ and $M_2 < M_1$ then $P_2 = P_1$, if $P_2 < P_1$ and $M_2 > M_1$ then $P_2 = P_1$.

[3] For sizes not tested, the coefficients A_0, B_0 can be estimated from plots of A_0 and B_0 versus standard dry dimensions (3½, 5½, 7¼). The coefficients A_1, B_1 and B_2 are independent of size.

[4] Coefficients for No. 1 grade should be somewhere between those for No. 2 and those for Select Structural. The exact position must be determined by the user.

[5] Property modeled as $P = P/10^3$.

[6] Property modeled as $P = P/10^6$.

TABLE A4. *Coefficients of surface models.*

Model number	Model type	Coefficient symbol	Coefficients for indicated property: Modulus of rupture (MOR)[1]	Modulus of elasticity[2] (MOE)	Moment capacity[1,3] (RS)	Flexural stiffness[2,4] (EI)
11	Linear[5]	a	133.859	−0.006277	31.430	−0.001666
		b	−0.049787	−0.017072	−0.039368	−0.000376
12	Quadratic[6]	a	−1,045.0	6.53×10^{-2}	−309.22	0.00526
		b	7.368×10^{-1}	-4.52×10^{-2}	0.8251	−0.0045
		c	-9.210×10^{-5}	-6.2×10^{-3}	-4.176×10^{-4}	−0.2230
		d	3.063907×10^{-9}	1.740×10^{-2}	5.814617×10^{-8}	1.170
		e	33.75	-2.655×10^{-3}	9.978	-2.118×10^{-4}
		f	-2.3230×10^{-6}	1.419×10^{-3}	-2.5778×10^{-2}	-3.0×10^{-4}
		g	2.7301×10^{-6}	1.77×10^{-4}	1.2445×10^{-5}	1.047×10^{-2}
		h	-9.10214×10^{-11}	-5.81×10^{-4}	-1.72787×10^{-9}	-4.402×10^{-2}

[1] P is in psi.
[2] P is in 10^6 psi.
[3] Property modeled as $P = P/d^2$ where d = 3.5, 2 × 4; 5.5, 2 × 6; 7.25, 2 × 8.
[4] Property modeled as $P = P/d^3$ (d as in footnote 3).
[5] Let $T = [P_1 + a(15 - M_1)]/[1 + b(M_1 - 15)]$, $S = a + bT$, $P_2 = S(M_2 - M_1) + P_1$ if $S > 0$ then $P_2 = P_1$; if MOR and $S < -500$ then $S = -500$; if MOE and $S < -0.05$ then $S = -0.05$; RS and $S < -0.001785$ then $S = -0.001785$; EI and $S < -95$ then $S = -95$.
[6] Find T such that if $A = a + bT + cT^2 + dT^3$; $B = e + fT + gT^2 + hT^3$; $P_1 - T = A(M_1 - 15) + B(M_1^2 - 225)$; and if $B > 0$ then $P_2 = P_1$. If MOR and $T > 14{,}000$ then $A = -374.0392$, $B = -6.13312$; MOE and $T > 2.4$ then $A = 0.1913256$, $B = -0.006172624$; RS and $T > 3{,}400$ then $A = 45.958934$, $B = -1.7152025$; EI and $T > 0.33$ then $A = 0.02153659$, $B = -0.0016435637$; and $P_2 = P_1 + A(M_2 - M_1) + B(M_2^2 - M_1^2)$.

TABLE A5. *Recommended property limits at a moisture content of 15% for the models presented in this report.*[1]

Property	Size	Grade	Applicable range: Minimum	Applicable range: Maximum
			psi	
Modulus of rupture (MOR)	All	Select Structural	2,000	14,000
		No. 2	2,000	11,500
		No. 3	2,000	11,500
Modulus of elasticity (MOE)	All	Select Structural	200,000	2,500,000
		No. 2	200,000	2,300,000
		No. 3	200,000	2,300,000

[1] Models should not be used to adjust data to moisture contents below 8%.