COMPRESSION STRENGTH ADJUSTMENTS FOR MOISTURE CONTENT IN DOUGLAS-FIR STRUCTURAL LUMBER

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ABSTRACT

The effect of moisture content on the compression parallel to grain strength of Douglas-fir dimension lumber was evaluated using full-size on-grade members. Compression parallel to grain strength properties increased with drying throughout the entire property range.

The influence of moisture content on compression strength was observed to be strength level dependent. Linear and quadratic surface models are used to represent the relations between member moisture content and compression strength (or capacity) as a function of property level. Model parameters were derived using a Douglas-fir data set. Douglas-fir results are compared with the limited data available for the hem-fir and S-P-F commercial species groups. The comparisons suggest that the relationship between compression strength and moisture content is generally consistent for these species.

Keywords: Moisture content, compression strength, structural lumber.

INTRODUCTION

Compression strength properties for structural lumber are strongly dependent on moisture content. ASTM D 245 (ASTM 1988) recommends a 50% increase in properties when adjusting from the green condition to 15% moisture content. The historical basis for adjustments of design properties for moisture content has been reviewed in several recent papers (Green 1980; Green et al. 1988; Madsen 1982). These reviews have shown that compression parallel to grain strength is affected by moisture content to a much greater extent than either bending or tension properties. These conclusions were confirmed by rather limited compression parallel to grain studies undertaken for the hem-fir and spruce-pine-fir (S-P-F) commercial species groups (Littleford and Abbott 1978; Madsen 1982).

While the reviews show that moisture content adjustments in D 245 are based at least in part on evaluations of the behavior of full-size members, it has been

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recognized that the introduction of modern structural analysis and reliability assessment procedures will require improved moisture content adjustment models (Green 1980).

In particular, moisture adjustment procedures are required that are confirmed as being appropriate for adjusting test data through the full range of the property distribution.

The purpose of this paper is:(1) to present a brief summary of results of moisture content variation on the compression strength of 38-mm-thick Douglas-fir visually graded structural lumber (Jessome and Bellosillo (1985)); (2) to present strength property adjustment models for compression parallel to grain strength and compression capacity; (3) to evaluate the appropriateness of using the Douglas-fir models for other species groups.

The experimental project was undertaken by Forintek Canada Corp. (Jessome and Bellosillo 1985) as part of a series of parallel studies investigating Douglas-fir dimension lumber bending, tension and compression property variation with moisture content, undertaken cooperatively with the U.S. Forest Products Laboratory, Madison. These studies were designed to provide moisture adjustment models appropriate for adjustment of test data developed in the Canadian and U.S. "in-grade" lumber properties programs.

PROPERTY ADJUSTMENT MODELS

Two types of property adjustment models are considered for representing effects of moisture content on compression strength and compression capacity. The compression capacity (CA) is the product of the member ultimate stress (c) and the actual cross section area (A) at the time of test. Quadratic surface models (QSM) (Green et al. 1986, 1988) have been shown to provide a framework for a family of moisture content models including a subset identified as the linear surface models (LSM) (Barrett and Lau 1991). For bending properties, the 8 parameter QSM and 4 parameter LSM both have been found suitable for representing moisture-strength relationships.

For the linear surface models, the strength property P is assumed to be linearly related to moisture content M, below the fiber-saturation point M_p, according to:

$$P = a + bM \qquad (M < M_p) \tag{1}$$

Property values P_1 and P_2 at moisture contents M_1 and M_2 will be related by the expression

$$P_2 = P_1 + b(M_2 - M_1) \tag{2}$$

If $M_2 = 15\%$, then P_{15}, the property at 15% moisture content, is related to the property P_1 at moisture content M_1 according to

$$P_{15} = P_1 + b(15 - M_1) \tag{3}$$

The slope parameter b, derived by linear regression of property values at specified probability levels, typically will vary with property level. The variation in b can be represented as a function of P_{15}, using polynomials of the form

$$b = D_0 + D_1P_{15} + D_2P_{15}^2 + \ldots \tag{4}$$

The 4-term, 3-term, and 2-term forms of the slope parameter b (Eq. 3) to be evaluated are

$$b = D_0 + D_1P_{15} + D_2P_{15}^2 + D_3P_{15}^3 \tag{5}$$

$$b = D_1P_{15} + D_2P_{15}^2 + D_3P_{15}^3 \tag{6}$$

$$b = D_1P_{15} + D_2P_{15}^2 \tag{7}$$

The quadratic surface model form (Green et al. 1986) has an additional second-order term (cM^2) in Eq. 1 and will generally have 8 unknown coefficients developed from the complete cubic expansion of the b and c parameters.

These quadratic and linear models will be used to represent the influence of moisture content on compression parallel to grain ultimate stress and a normalized compression capacity. The normalized compression capacity C_n is obtained by dividing the test capacity by the member standard dry cross section area (A_n).

EXPERIMENTAL

Douglas-fir lumber was sampled from sawmills in British Columbia in two sizes (nominal 2 × 4 and 2 × 8) and two grades (select structural and No. 2). For each size and grade combination, 4 samples of 60 pieces were selected for evaluations of compression strength at 4 target moisture content levels (green, 10, 15, 20%). The 4 samples within a size/grade category were modulus of elasticity matched. In this regard, the experimental approach paralleled that used in earlier bending property evaluations (McLain et al. 1984; Aplin et al. 1986).

Conventional mild kiln-drying schedules, followed by a conditioning period of approximately 2 weeks, were used to achieve the target moisture contents. Each 96-inch member was tested full-length in laterally constrained compression. The cross-head displacement rate of 0.96 inches per minute was derived in accordance with ASTM D198 (ASTM 1988) requirements. Moisture content was determined at the time of test using a Delmhorst moisture meter with insulated probes at $\frac{5}{16}$ inch pin penetration (Jessome and Bellosillo 1985).

RESULTS

The effectiveness of the moisture conditioning regimes is summarized by size and grade for each moisture content target condition in Table 1. Results of the compression strength and compression capacity evaluations are summarized in Table 2 by size and grade. Trends in mean and 5th percentile compression strength are shown in Figs. 1 and 2.

Moisture intersection point

The quality of fit of a moisture content adjustment model will vary depending on the moisture intersection point chosen. The optimum moisture intersection point for quadratic and linear surface models was derived using the residual sums of squares technique (Green et al. 1986). The residual sums of squares of deviations between model predicted response and the data used to fit the model were chosen as a basis for assessing model fits. Data values for model fitting corresponded to 21 percentiles (0.02, 0.05, 0.10, . . . , 0.90, 0.95, 0.98) interpolated from each size, grade, and moisture content data set. Table 3 summarizes the optimum M_p values and the associated moisture content range over which the residual sums of squares was essentially stable. Optimum M_p values obtained using the LSM are lower than predicted using the QSM. The optimum M_p = 22% obtained in the compression study is also somewhat lower than the optimum M_p = 26% derived from bending strength studies in Douglas-fir (Barrett and Lau 1991). The stable range

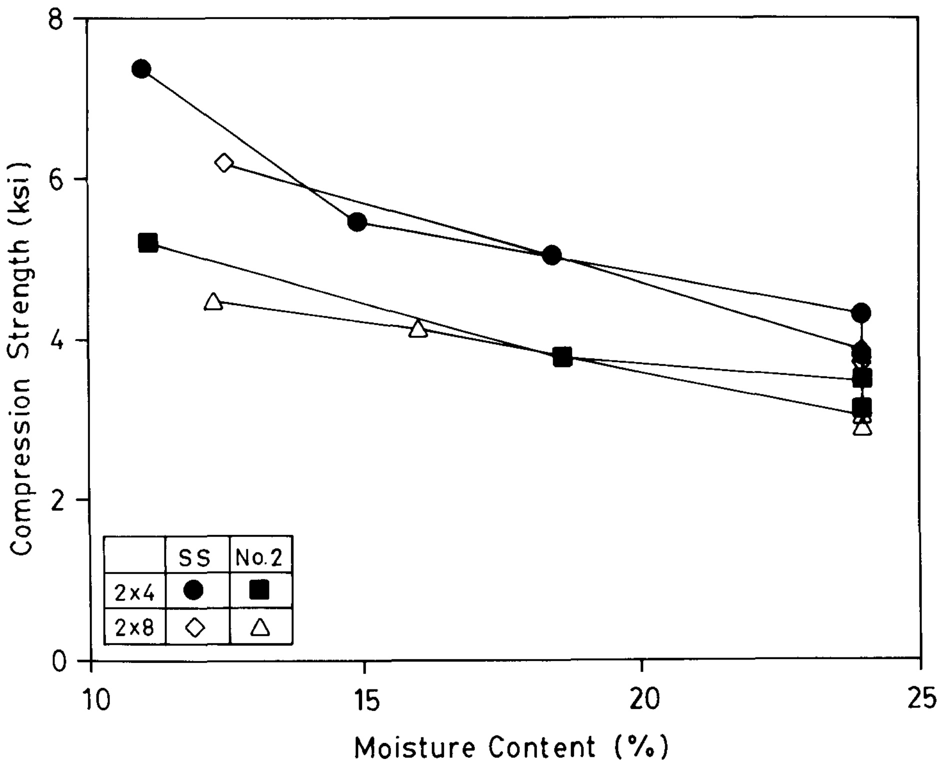

FIG. 1. Relationships between mean compression strength and moisture content for Douglas-fir dimension lumber (M_p = 24%).

for M_p values obtained in the bending and compression property studies intersect at M_p = 24%. Recognizing that smaller sample sizes were chosen for the compression study and for consistency with the lumber bending property studies, M_p = 24% was adopted.

Compression strength model

Grade and size independent quadratic and linear surface model parameters (Table 4) were derived using compression strength values interpolated at the 21 percentile levels. Goodness-of-fit was assessed using residual sums of squares (RSS) and average maximum absolute difference (MAD) criteria (Green et al. 1988). RSS results (Table 5) demonstrate that the LSM fits the data as well as the QSM. MAD results for all data adjusted to 15% moisture content (Table 6) indicate that the QSM fits the data best overall. However, differences between the 4-term LSM and QSM fits are small. Comparisons of the QSM and LSM fits for 5th percentile data adjusted to the green, 10, 15, 20% moisture content levels show that the LSM fits slightly better than the QSM (Table 7). Overall the goodness-of-fit tests indicate that the quadratic and linear models fit the compression property data nearly equally well.

The fitted 4-term representation of the slope parameter is shown with the experimental b parameters in Fig. 3. The fitted relationships for the 2-, 3- and 4-term linear models are compared in Fig. 4. Green and corresponding dry strength

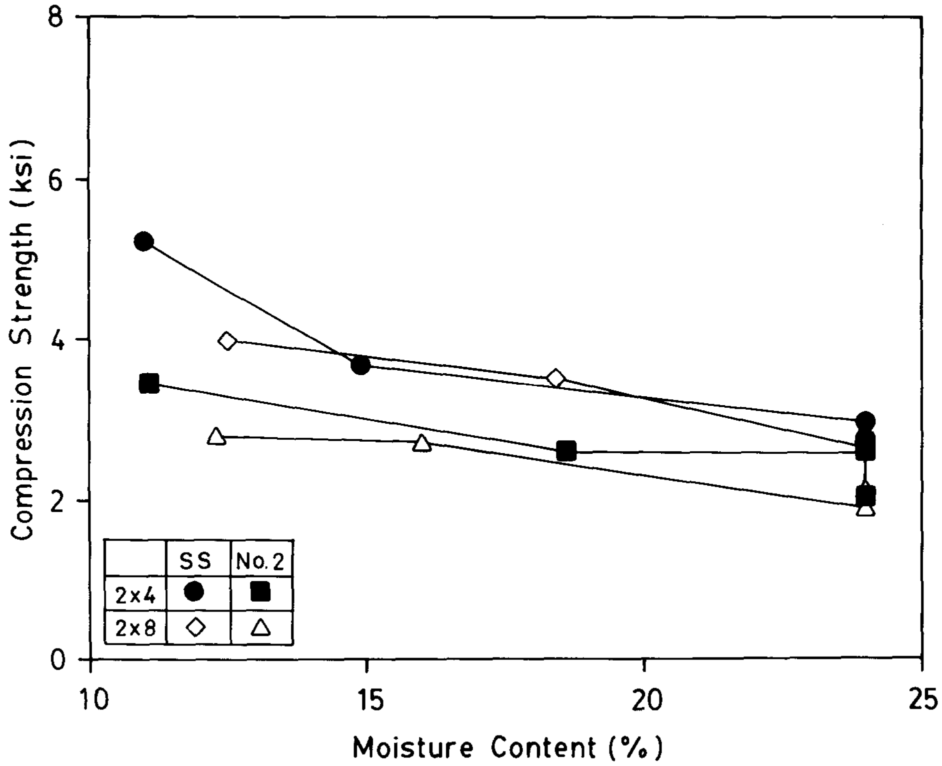

FIG. 2. Relationship between 5th percentile compression strength and moisture content for Douglas-fir dimension lumber (M_p = 24%).

values (M = 15%) derived using the 2-, 3-, and 4-term linear models are given in Table 8. Error estimates are calculated with reference to the 4-term model.

Compression capacity model

Normalized compression capacity (C_n) is obtained by dividing the actual capacity (CA) by the standard dry cross section area (A_n). Normalized compression capacity parameters were derived for the quadratic and linear surface models (Table 9). The fit of the calculated b parameters to the 4-term model is shown in Fig. 5. The 4-, 3- and 2-term model fits are compared in Fig. 6. Moisture content adjusted normalized compression capacities are converted to actual capacity values by multiplying by the corresponding standard dry section area. Goodness-of-fit results derived using the RSS and MAD criteria (Tables 10, 11, and 12) parallel those obtained in the compression strength analysis. The quality of fit of the linear and quadratic models to the normalized capacity data is very similar. Green to dry (M = 15%) property adjustments (Table 13) show the modeling errors with respect to the 4-term LSM.

Alternatively, compression capacity variation with moisture can be derived using the compression strength model and a cross section area shrinkage model. Green (1989) provides lumber shrinkage relationships for member width (S_w) and thickness (S_t). These shrinkage relationships

TABLE 1. *Effectiveness of moisture conditioning.*

Nominal size	Grade	Group	Sample size	Moisture content Mean	CV	Min.	Max.
2 × 4	SS	Green	60				
		20	60	24.9	7.2	29	29
		15	59	14.9	6.2	14	18
		10	59	11.0	8.4	9	13
	No. 2	Green	60				
		20	60	24.2	7.6	21	29
		15	60	18.6	10.9	16	24
		10	59	11.1	9.4	9	14
2 × 8	SS	Green	60				
		20	60	26.3	4.4	23	29
		15	60	18.4	11.3	14	23
		10	60	12.5	8.6	10	16
	No. 2	Green	60				
		20	60	25.9	6.9	23	29
		15	60	16.0	9.6	14	21
		10	60	12.3	4.8	12	14

CV = Coefficient of variation (percent).

$$S_w = 6.031 - 0.215M$$
$$S_t = 5.062 - 0.181M \tag{8}$$

were used to derive lumber cross section area shrinkage factors.

Calculated compression capacity CA_1^* at moisture contents M_1 will be related to the capacity CA_2^* at moisture content M_2 according to

TABLE 2. *Summary statistics for compression strength and compression capacity of Douglas-fir at 4 target moisture content levels.*

Nominal size	Grade	Group	Sample size	Compression strength Mean psi	CV	5th* psi	Compression capacity Mean psi	CV	5th* psi
2 × 4	SS	10	59	7,377	19.9	5,229	7,289	18.9	5,245
		15	59	5,457	18.0	3,664	5,562	17.8	3,797
		20	60	4,300	17.6	2,959	4,517	17.6	3,119
		Green	60	3,777	17.5	2,770	4,020	17.6	2,939
	No. 2	10	59	5,207	25.6	3,436	5,184	25.9	3,378
		15	60	3,751	20.4	2,589	3,881	20.1	2,708
		20	60	3,466	15.1	2,575	3,647	15.1	2,723
		Green	60	3,086	19.5	2,016	3,296	19.6	2,127
2 × 8	SS	10	60	6,190	21.8	3,970	6,164	21.3	4,054
		15	60	5,040	19.3	3,511	5,206	19.4	3,654
		20	60	3,851	18.8	2,635	4,145	18.7	2,872
		Green	60	3,698	20.1	2,653	3,974	20.1	2,813
	No. 2	10	60	4,484	26.2	2,781	4,536	25.7	2,860
		15	60	4,129	22.6	2,707	4,237	22.2	2,824
		20	60	3,011	22.2	1,906	3,242	22.0	2,078
		Green	60	2,867	19.1	2,128	3,096	18.9	2,312

CV = Coefficient of variation (percent).
5th = 5th percentile nonparametric estimate.

TABLE 3. *Moisture intersection (Mp) for the Douglas-fir compression strength models.*

Model	Mp	
	Stable range	Optimum
QSM	26–30+	30+
LSM		
4-term	20–24	22
3-term	20–24	22
2-term	20–24	22

TABLE 4. *Regression coefficients for Douglas-fir quadratic and linear surface models—compression strength (C).*

Coefficient	Model[1]			
	QSM	4-T LSM	3-T LSM	2-T LSM
D_0	4.87030E+01	1.24592E+01	0	0
D_1	−3.31768E+00	−7.80181E+00	−3.59447E−01	−2.36662E+00
D_2	−5.94669E+00	4.54877E−01	−9.36026E−01	−2.15548E−01
D_3	5.61805E−01	−2.10647E−02	6.09357E−02	0
E_0	−1.05634E+02	0	0	0
E_1	−5.94269E+00	0	0	0
E_2	1.59042E+01	0	0	0
E_3	−1.47869E+00	0	0	0

[1] C in ksi and MC in decimal form (e.g., 0.18).

TABLE 5. *Residual sums of squares (RSS) for Douglas-fir quadratic and linear surface models—compression strength.*

Model type	Parameters	Residual sum of squares (ksi²)
QSM	8	35.1681
LSM 4-T	4	25.2627
LSM 3-T	3	25.6023
LSM 2-T	2	26.5714

TABLE 6. *Average maximum absolute difference results for Douglas-fir moisture content adjustment models—compression strength. (All data adjusted to 15% moisture content.)*

Model type	Parameters	Average maximum absolute difference (psi)					
		Mean	percentile				
			5	25	50	75	95
QSM	8	483	661	574	475	617	1,002
LSM 4-T	4	565	650	600	558	689	1,195
LSM 3-T	3	566	530	592	582	707	1,236
LSM 2-T	2	550	516	589	531	751	1,305

$$\frac{CA_1^*}{CA_2^*} = \frac{C_1A_1}{C_2A_2} \tag{9}$$

where the compression strengths C_1 and C_2 are derived from the compression strength model and the areas are calculated using the shrinkage relationships (Eq.

TABLE 7. *Average maximum absolute difference results for Douglas-fir 5th percentile compression strength data adjusted to 10, 15, 20 and green moisture conditions.*

Model type	Parameters	Average maximum absolute difference (psi)			
		10%	15%	20%	Green
QSM	8	1,031	661	449	393
LSM 4-T	4	832	650	468	322
LSM 3-T	3	649	530	410	314
LSM 2-T	2	616	516	416	337

TABLE 8. *Comparisons of dry compression strength (C_{15}) calculated using 4-, 3- and 2-term linear surface models.*

Green strength psi	Dry compression strength				
	4-T LSM	3-T LSM		2-T LSM	
	C_{15}	C_{15}	Error[1] (%)	C_{15}	Error (%)
2,000	2,300	2,533	10.1	2,724	18.4
3,000	4,284	4,228	−1.3	4,259	−0.6
4,000	6,046	6,076	0.5	5,957	−1.5
5,000	7,739	7,761	0.3	7,886	1.9
6,000	9,464	9,147	−3.4	10,176	7.5
7,000	11,342	10,277	−9.4	13,169	16.1

[1] Error expressed with respect to 4-term LSM.

TABLE 9. *Regression coefficients for Douglas-fir quadratic and linear surface models—normalized compression capacity (C_n).*

Coefficient	Model[1]			
	QSM	4-T LSM	3-T LSM	2-T LSM
D_0	6.88387E+01	1.15085E+01	0	0
D_1	−1.40415E+01	−6.18084E+00	6.70584E+00	−2.02927E+00
D_2	−3.83586E+00	1.16957E−01	−1.16181E+00	−1.97752E−01
D_3	0.45251E+00	5.85514E−03	8.12696E−02	0
E_0	−1.58439E+02	0	0	0
E_1	2.45896E+01	0	0	0
E_2	9.85088E+00	0	0	0
E_3	−1.14266E+00	0	0	0

[1] Units: C_n in ksi and moisture content in decimal form (e.g., 0.18).

8). Ratios of dry to green member capacity derived using the 4-term and 2-term representations of C_n and CA* models are compared in Table 14.

Model application

The appropriateness of using the Douglas-fir model for other species was evaluated using S-P-F and hem-fir compression strength data derived from full-size tests of on-grade dimension lumber (Littleford and Abbott 1978; Madsen 1982). An M_p = 24% was adopted for all species. The original No. 2 and Better test data (Madsen 1982) were reanalyzed to establish the b parameters for hem-fir and S-P-F shown with the 4-term Douglas-fir model in Fig. 7. The b parameters for

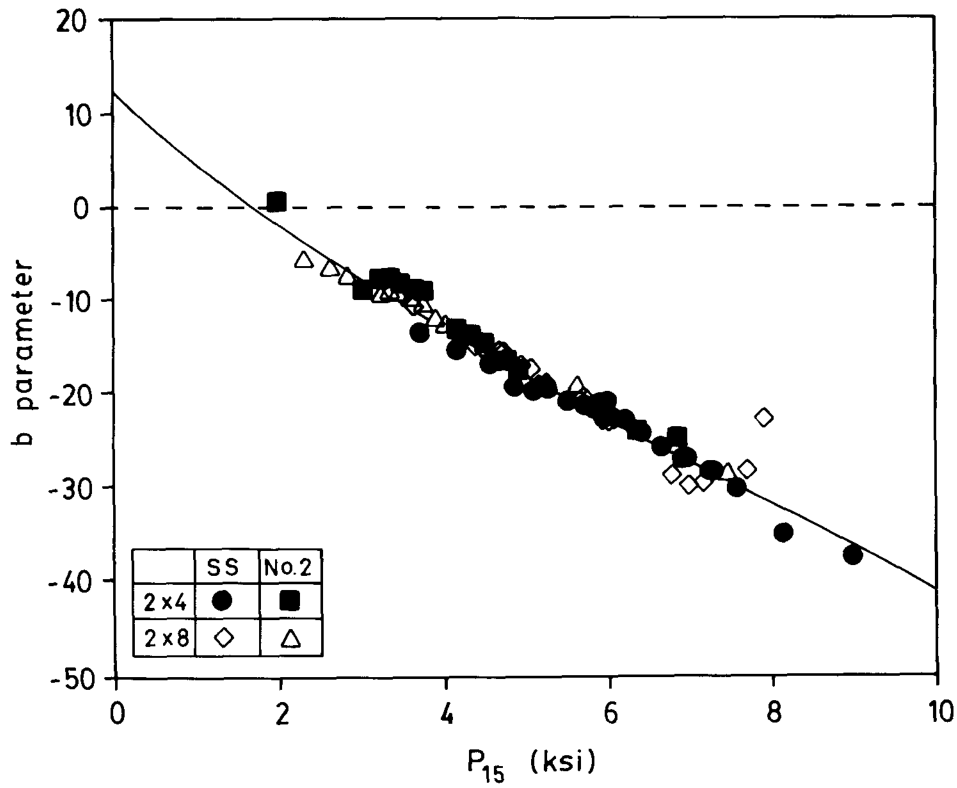

FIG. 3. Trends in b parameters as a function of dry compression strength compared with the 4-term linear surface model fitted relationship for the Douglas-fir compression strength model.

select structural and No. 2 grade hem-fir from the Littleford study were determined by scaling compression strength properties from the green, 19, and 12% cumulative distribution functions (cdf) at 6 probability levels (0.10, 0.20, 0.40, 0.60, 0.80, and 0.90). The b parameters indicated as "means" (Fig. 7), derived from the tabulated data, are presented in order to offer a confirmation of the accuracy of the scaled data. However, it should be recognized that the mean values do not necessarily correspond to the same probability level in all cdf's and therefore these results are not directly comparable to the model fitting procedures used in the study.

TABLE 10. *Residual sums of squares (RSS) for Douglas-fir quadratic and linear surface models—normalized compression capacity.*

Model	Parameters	Residual sum of squares (ksi^2)
QSM	8	31.6989
LSM 4-T	4	23.0020
LSM 3-T	3	23.2649
LSM 2-T	2	23.8953

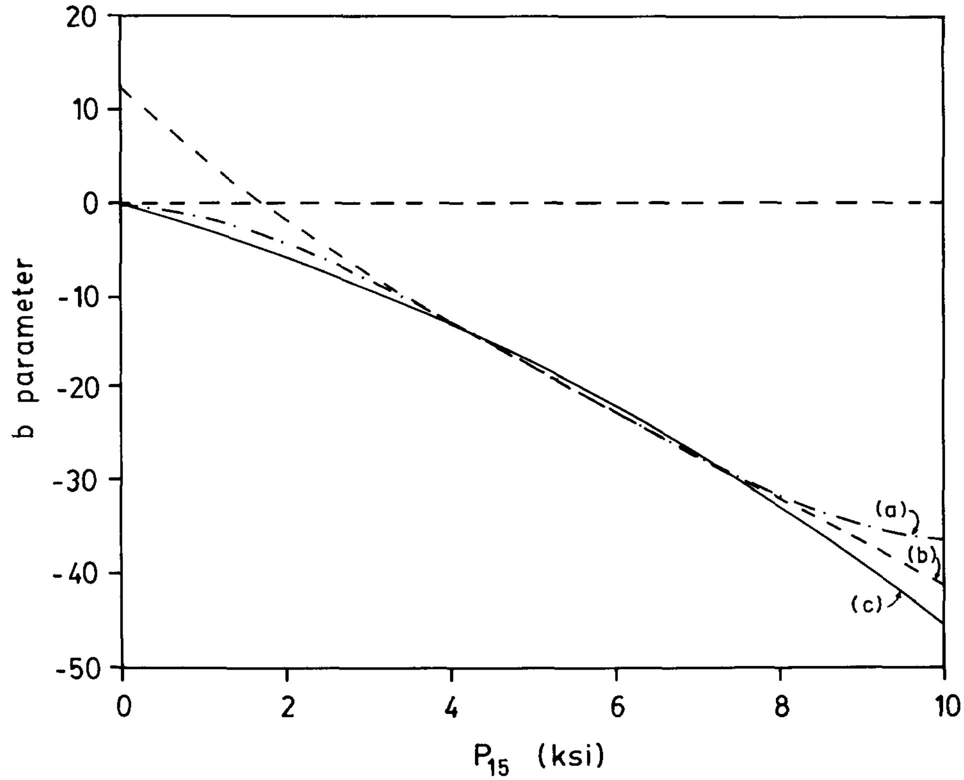

FIG. 4. Comparison of 4-term(b), 3-term(a) and 2-term(c) linear surface model fitted relationships for the Douglas-fir compression strength model.

DISCUSSION

Moisture content affects compression strength properties in a manner similar to that observed in evaluations of bending strength behavior for full size structural lumber. The magnitude of strength property changes with moisture content are significantly greater at the design property level than observed in bending properties.

Fiber saturation points M_p determined in this study agree closely with those obtained for bending. The small differences in optimum M_p values obtained for the two properties supported adopting a common $M_p = 24\%$.

TABLE 11. *Maximum absolute difference results for Douglas-fir moisture content adjustment models—compression capacity. (All data adjusted to 15% moisture content.)*

		Average maximum absolute difference (psi)					
		Mean (psi)	percentile level				
Model	Parameters		5	25	50	75	95
QSM	8	531	532	484	492	512	984
LSM 4-T	4	504	622	565	532	544	1,092
LSM 3-T	3	513	549	589	516	565	1,170
LSM 2-T	2	494	549	583	457	620	1,249

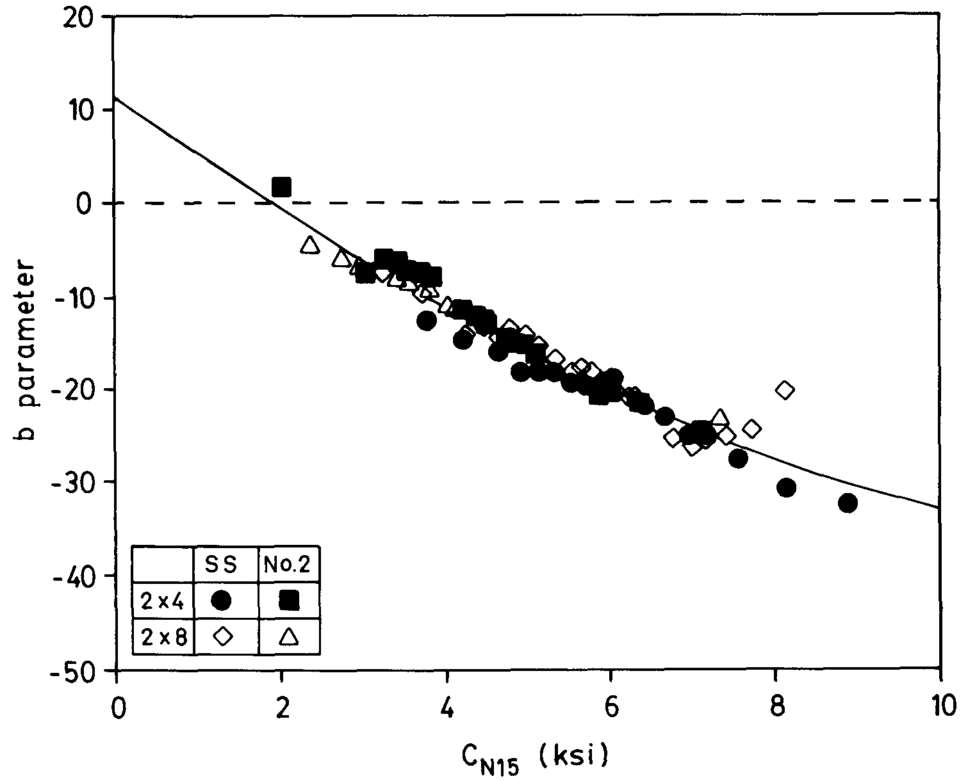

FIG. 5. Trends in b parameters as a function of normalized dry compression capacity (C_{n15}) compared with the 4-term linear surface model fitted relationship for the Douglas-fir compression capacity model.

Quadratic and linear surface models appear to fit the experimental data nearly equally well below the 25th percentile strength level as indicated by the average maximum absolute difference and the residual sums of squares criteria. At higher strength levels, the two criteria give conflicting indications of model performance. Overall the two model types appear to give very similar results within the range of test data, thereby allowing the user some choice in model selection depending on the application under consideration.

The experimental evidence shows that compression strength properties will generally increase with decreasing moisture content below the fiber saturation

TABLE 12. *Average maximum absolute differences for 5th percentile normalized capacity (C_n) adjusted to green, 10, 15, 20% moisture content.*

Model type	No. of parameters	Average maximum absolute difference (psi)			
		10%	15%	20%	Green
QSM	8	832	532	366	332
LSM 4-T	4	785	622	460	330
LSM 3-T	3	667	549	431	336
LSM 2-T	2	644	549	431	379

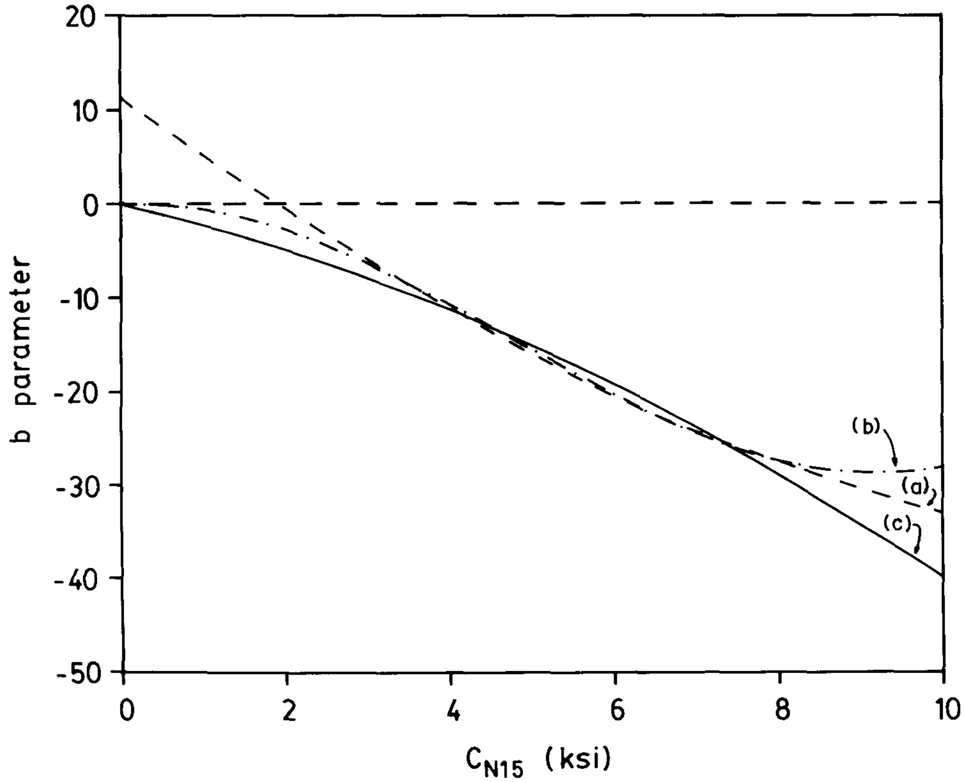

FIG. 6. Comparison of 4-term(a), 3-term(b) and 2-term(c) linear surface model fitted relationships for the Douglas-fir normalized compression capacity model.

point. This suggests that care must be taken in selecting the adjustment model to be used for data lying outside the range upon which the model is based. For instance, the 4-term LSM will predict strength decreases with drying for low strength members. Lacking experimental data to confirm this behavior, the 2-term and 3-term linear models were developed to constrain the b parameter to approach zero as compression strength approaches zero. These latter two models would provide property adjustments that we expect are more appropriate for

TABLE 13. *Comparison of dry compression capacity C_{n15} calculated using 4-, 3- and 2-term linear surface models.*

Green compression capacity	Dry compression capacity (psi) model				
	4-T LSM	3-T LSM		2-T LSM	
	C_{n15}	C_{n15}	Error	C_{n15}	Error
2000	2,061	2,336	13.33	2,593	25.78
3000	3,976	3,936	−1.01	4,022	1.15
4000	5,692	5,697	0.09	5,569	−2.16
5000	7,239	7,280	0.56	7,267	0.37
6000	8,646	8,557	−1.3	9,127	6.09
7000	9,935	9,586	−3.50	11,387	14.76

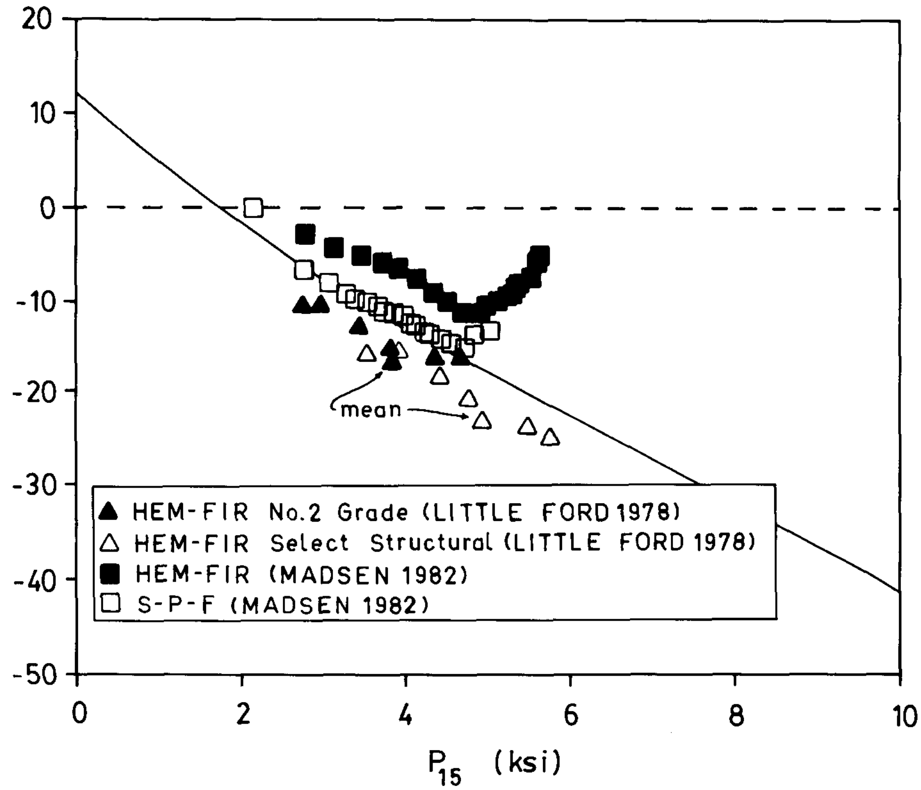

FIG. 7. Comparison of b parameter trends for hem-fir and S-P-F with the fitted Douglas-fir 4-term linear surface model relationship for compression strength (References 1: Littleford and Abbott 1978, 2: Madsen 1982).

adjustments of low compression strength members than either the quadratic or 4-term linear models.

Normalized compression capacity models provide a basis for adjustments of member capacities that directly incorporate effects of section property and member strength changes in a single-step capacity adjustment model. Comparisons of this

TABLE 14. *A comparison of capacity ratios calculated using the compression strength model (Table 4) with standardized shrinkage relationships and capacities calculated using a section capacity model (Table 9).*

Green strength psi	Dry green[1] strength ratio 4-T LSM	Compression capacity ratio			
		4-T LSM		2-T LSM	
		Strength model	Capacity model	Strength model	Capacity model
2000	1.15	1.09	1.03	1.29	1.30
3000	1.43	1.36	1.33	1.35	1.34
4000	1.51	1.43	1.42	1.41	1.39
5000	1.55	1.47	1.45	1.50	1.45
6000	1.58	1.50	1.44	1.61	1.53
7000	1.62	1.54	1.42	1.79	1.63

[1] Dry moisture content = 15%.

capacity model with capacity changes, calculated using a 2-step approach based on calculating the compression strength adjustment with the compression strength model and section property changes using the shrinkage model, showed that both the 1-step and 2-step approaches give very similar results for Douglas-fir (Table 14). The 2-term and 3-term linear models provide a general procedure for capacity adjustments which will maintain capacity increases with drying at all capacity levels. These models again appear most consistent with the experimental results.

Recognizing the limitations of the test data and the differences in sampling, conditioning, and test methods used in the various studies, the results suggest that the Douglas-fir model can be applied to other species. Figure 7 shows that the data for these species tend to be grouped about the Douglas-fir model. The b parameters for the S-P-F data follow the Douglas-fir model, exhibiting the general trend of decreasing b parameter value with increasing percentile level. The hem-fir b parameters (Littleford and Abbott 1978) are slightly smaller than predicted for Douglas-fir, but the trend parallels the Douglas-fir model through the full range of percentiles investigated. The hem-fir results (Madsen 1982) exhibit an unexpected change in trend in the b parameters for probability levels greater than 0.50. On re-examination of the Madsen data, there is also an indication of the trend reversal in the S-P-F data at approximately the same strength (P_{15}) level. The trend reversal in the hem-fir data set cannot be explained at present. Since this trend reversal at a specific strength level was not seen in the conditioned specimen tests undertaken by Littleford and Abbott (1978) or the Douglas-fir compression or bending studies, the reversal may be related to testing and conditioning procedures of the Madsen study rather than some fundamental difference in the moisture response of this species group.

CONCLUSIONS

From the analysis undertaken for this study and similar studies of moisture content strength relationships, we conclude the following:

1. The experimentally observed trends between moisture content and compression strength can be modeled using the quadratic and linear model forms previously adopted for bending property studies.
2. The moisture intersection point $M_p = 24\%$ can be adopted for Douglas-fir bending and compression properties.
3. The relationship between compression strength (or capacity) and moisture content was modeled nearly equally well using either quadratic or linear surface models within the range of the experimental data.
4. Compression capacity changes with moisture content calculated using a strength based model and traditional section shrinkage relationships, yield results in close agreement with adjustments calculated directly from the compression capacity model.
5. The linear and quadratic surface models provide a basis for modeling the differences in moisture content adjustments at different strength levels in the compression strength distribution and thereby provide a basis for property adjustments at all strength levels.
6. The limited data relating compression strength properties to moisture content for full-size dimension lumber members support the hypothesis that

the Douglas-fir models could be used for other Canadian softwood commercial species groups.

7. The trend reversals observed for the hem-fir study by Madsen (1982) suggest further research is required to examine the possible interaction of moisture conditioning regime and compression property response.

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