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Temperature adjustments for the North American in-grade testing program

by J. David Barrett, David W. Green, and James W. Evans

Abstract

This report summarizes the available research information evaluated by the North American In-Grade Technical Committee and the resulting temperature adjustment relationships used by the Committee to adjust bending strength, modulus of elasticity (MOE), and tension strength to a common reference temperature of 73°F. Since compression property data collected in the United States and Canada was collected in a laboratory environment, no compression strength adjustments were required.

Introduction

In-grade testing of structural wood products is a testing procedure typically involving full-size tests of structural products representative of products as manufactured. This terminology has been employed in testing plywood properties.[1] The concept has also been widely used in the development of dimension lumber strength properties.

Madsen[2] envisioned in-grade testing as a field testing technique, permitting evaluations of large numbers of specimens of products as sampled and tested in the mill environment. Consequently, in-grade testing programs have typically used faster loading rates than laboratory testing standards such as ASTM D 198, Standard Methods of Static Test of Timbers in Structural Sizes. The field testing equipment may have different deflection measuring procedures and somewhat different performance capabilities than test equipment required for testing in accordance with ASTM D 198 procedures.

ASTM D 4761-88, Standard Test Methods for Mechanical Properties of Lumber and Wood-Based Structural Material, was developed specifically to standardize in-grade testing procedures for structural lumber. The standard permits testing in non-laboratory environments. The test methods provide procedures that are applicable under true field conditions, such as in a plant using specimens which are not equilibrated to standard climate conditions.

U.S. In-Grade Testing Programs

The U.S. Forest Products Laboratory (FPL) and the U.S. Grading Agencies have completed full-size lumber in-grade testing programs to evaluate the mechanical properties of visually graded dimension lumber. The mechanical property evaluations were conducted in accordance with the methods described in ASTM D 4761-88. Bending and tension mechanical properties were evaluated in the field environment. Actual conditions encountered at the testing sites varied depending on local environment conditions. The U.S. grading agencies took air and/or wood temperature measurements at intervals during the testing programs to provide a basis for any subsequent adjustment of mechanical property data deemed necessary during data analysis. The specific climate measurement techniques, measurement equipment, and data recording procedures employed by the individual agencies are described in Appendix A.

All compression mechanical property evaluations for the U.S. program were conducted at the FPL using standard laboratory climate conditions and equilibrated test specimens. Compression property data was not adjusted for temperature effects.

Canadian In-Grade Testing Program

The Canadian In-Grade Testing Program was designed to provide comparable data to that derived in the U.S. In-Grade Testing Program. The Canadian program was conducted in a laboratory environment using laboratory-type testing equipment. With the exception of loading rates and deflection measuring equipment, the Canadian program was conducted in accordance with ASTM D 198 requirements. Since the ASTM D 198 requirements are stricter than those of D 4761, the Canadian program also meets the requirements of the latter standard.

Since all mechanical property evaluations undertaken in the Canadian Lumber Properties Program were conducted in the lab-

[1] Smith, G.R. 1974. The derivation of dowable unit stresses for unsanded grades of Douglas-fir plywood from in-grade strength test data. Rept. 105. council of Forest Industries of British Columbia, North Vancouver, B.C., Canada.

[2] Madsen, Borg. 1977. In-Grade Testing - Problem Analysis Structural. Res. Series Rept. No. 18. Dept. of Civil Engineering, Univ. of British Columbia, B.C., Canada.

oratory environment, no data adjustment for temperature effects was required.

Temperature adjustment factors for strength properties

Clear wood properties

The mechanical properties of wood are known to be affected by temperature. In general, wood mechanical properties decrease as wood is heated. The specific effects of temperature on properties are strongly affected by the heating period and wood moisture content (MC).

The Wood Handbook[3] shows general trends indicating that strength properties for dry wood (MC = 12%) will increase by approximately 20 percent for a temperature change from 68°F to 0°F. The temperature effect is larger for a higher MC level and smaller as wood MC approaches the oven-dry state. Trends for the immediate effects of temperature on clear wood mechanical properties at various moisture conditions are summarized in Appendix A.

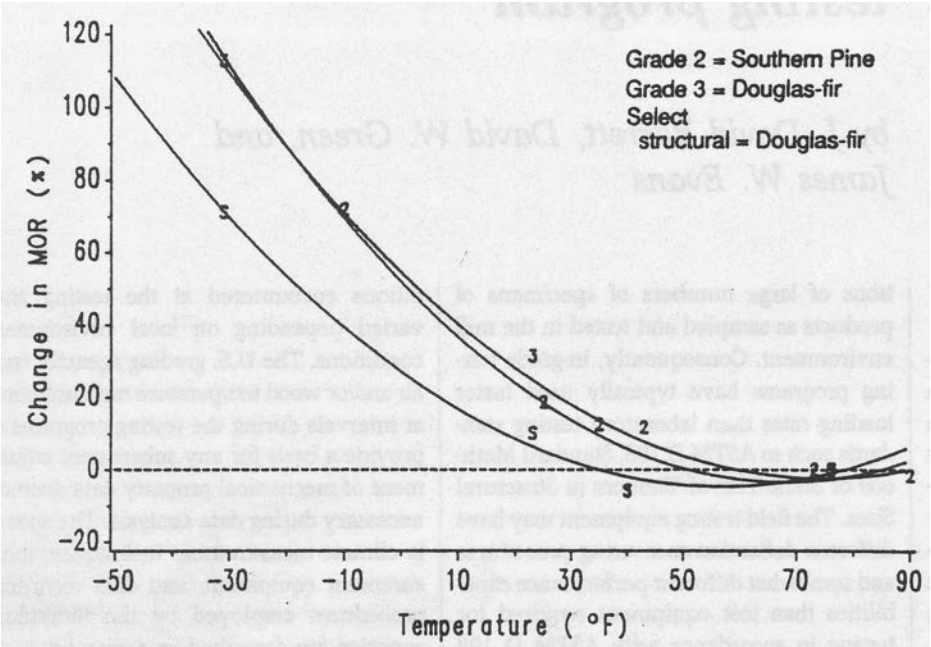

Figure 1. - Percentage change in green MOR versus temperature.

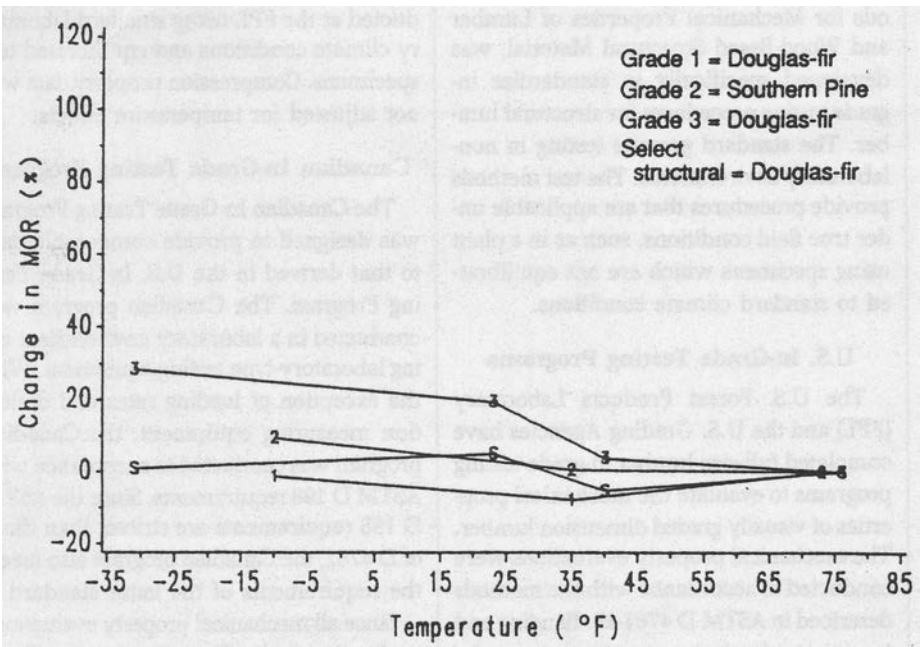

Figure 2. - Percentage change in dry MOR versus temperature.

Structural size dimension lumber

Studies conducted at the FPL and Forintek Canada Corporation demonstrated that temperature also has a significant influence on strength properties of dimension lumber. An interaction of temperature effects with MC also exists for visually graded dimension lumber.

Results of the FPL and Forintek studies were analyzed by Green and Evans (Appendix A) to provide a basis for developing temperature adjustments for bending and tension property data for nominal 2-inch dimension lumber.

The percentage change in green modulus of rupture (MOR) (Fig. 1), was found to be grade dependent. Select structural material exhibited substantially smaller increases in strength as temperature decreased than either No. 2 or No. 3 grade material.

The percentage change in dry MOR of dimension lumber (Fig. 2) is smaller than observed for green material. The results suggest a grade dependence. The increase in strength with decreasing temperature is greater for lower quality material. It was concluded that MOR was independent of temperature at an MC of 12 percent.

Results for bending MOE (Figs. 3 and 4), follow the same general pattern observed for the MOR behavior. Grade does not appear to significantly affect temperature adjustment for MOE. Increases in MOE with lower temperatures are still significantly greater for green material.

The effects of temperature on tension strength have been studied to a very limited extent. Results given by Green and Evans (Appendix A) show temperature has a substantial influence on tension strength of green lumber. There is no information

[3] U.S. Department of Agriculture. 1974. Wood Handbook: Wood as an engineering material. USDA Forest Serv., Madison, Wis.

available on influence of temperature on dry tension strength of lumber.

Temperature adjustments procedure for in-grade data

In the joint U.S.-Canadian In-Grade Program, mechanical property data is adjusted to a reference temperature of 73°F. The general form of the adjustment model is shown in Figure 5. Adjustments are provided for the percent property change for green (PCG) and dry (PCD) material. Where these adjustment models intersect the zero adjustment line, upper temperature limits for the green (TG) and dry (TD) curves are specified. For temperatures *T*, greater than the specified limits, the corresponding percent property changes are zero.

For temperature adjustment purposes, dry lumber is assumed to have an MC of 12 percent and green material is assigned an MC of 23 percent. The maximum and minimum temperatures encountered in the property adjustments of the U.S. in-grade data base are shown in Table 1.

Given a property value *P*, determined at an MC *M*, and temperature T, the adjustment procedure for MOR, MOE, and tension strength proceeds as follows:

1. Calculate *PCG* for the temperature *T*. If the temperature *T* is greater than the limiting temperature *TG*, then *PCG* = 0.0.
2. Calculate *PCD* for temperature *T*. If the temperature *T* is greater than the limiting temperature *TD*, then *PCD* = 0.0.
3. Determine *PCM*, the percent change in property at MC *M*, according to:
   a. For $M < 12$ percent then PCM = PCD
   b. For $M > 23$ percent then PCM = PCG
   c. For $12 < M < 23$ then

$$PCM = PCD + \frac{(M-12)}{11}(PCG - PCD)$$

Adjustment equations relating PCG and PCD to test temperature *T* for MOR, MOE, and tension strength are summarized in Table 2 with the corresponding upper temperature limits applicable to each model.

Application

To illustrate, assume a bending strength (MOR = 6,000 psi) has been determined at a temperature of 30°F and the member MC is 18 percent.

Applying the adjustment procedure and using the parameters of Table 1, the following results are obtained:

Given: P = 6,000 psi; T = 30°F M = 18

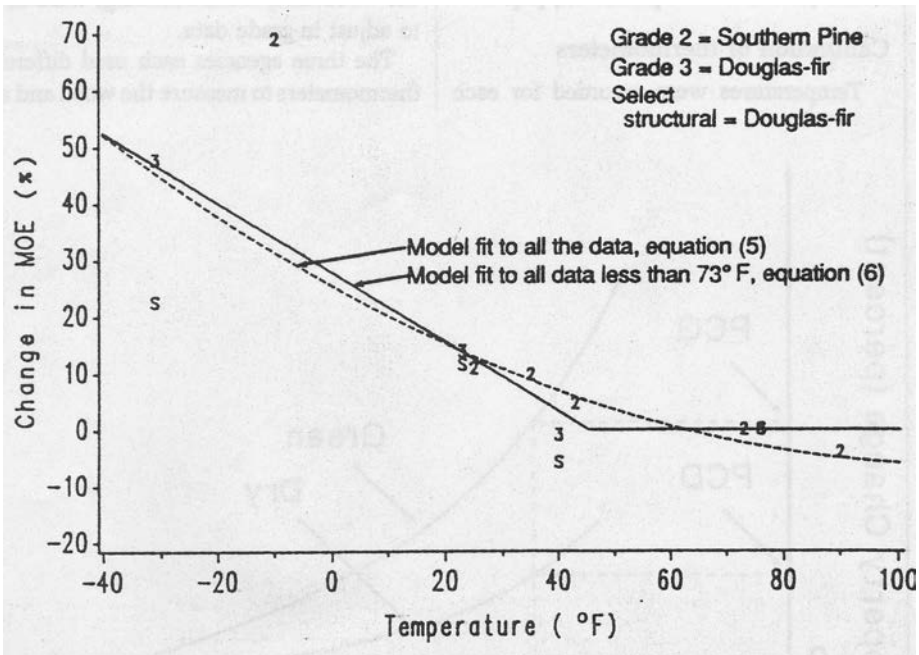

Figure 3. - Green MOE versus temperature.

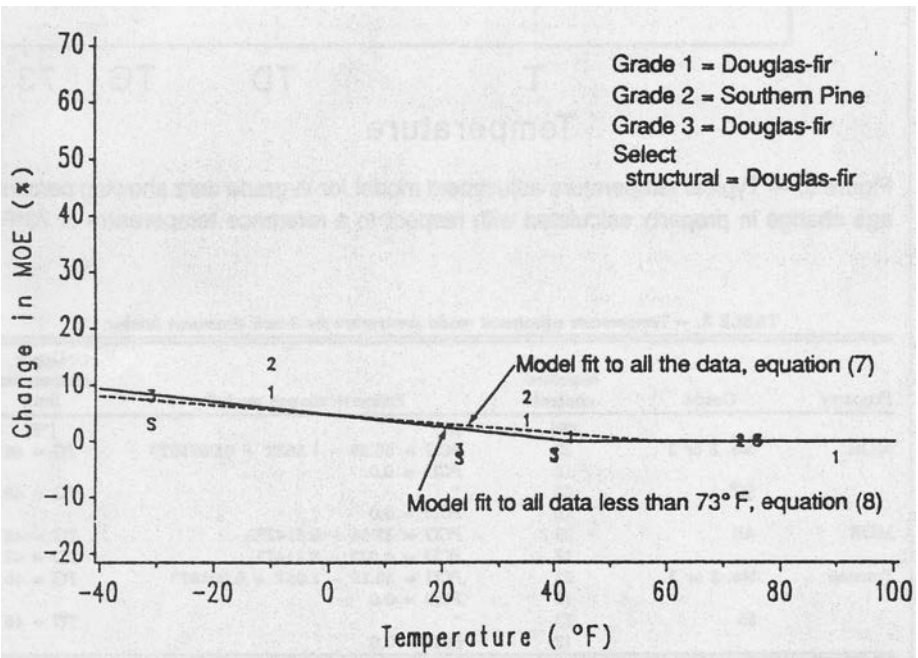

Figure 4. - Dry MOE versus temperature.

TABLE 1. - *Maximum and minimum temperatures for U.S. species groups.*

Species	Minimum	Maximum
	(°F)	
Douglas-fir-Larch	24	104
Southern Pine	47	101
Hem-Fir	27	85
US SPF	33	77
Mixed Species	15	85
Douglas-fir (South)	64	91
(Minor) Southern Pine	52	96
Yellow-Poplar	54	84
Aspen-Cottonwood	46	79

percent,

then: PCG = 16.47 percent: PCD = 0 and PCM = 8.98 percent

The calculated property at the reference temperature P_{ref} is given by:

$$P_{ref} = P/(1+PCM/100) = 5{,}505 \text{ psi}$$

Summary

In-grade testing in accordance with ASTM Standard D 4761-88, Standard Test Methods for Mechanical Properties of Lumber and Wood-Based Structural Material, permits evaluation of wood properties in the field using unequilibrated specimens. Evaluation of technical properties of dimension lumber established using this test standard requires methods for adjusting mechanical properties temperature and moisture conditions.

This report summarizes the available research information evaluated by the North American In-Grade Technical Committee and the resulting temperature adjustments relationships used by the Committee to adjust bending strength, MOE, and tension strength to a common reference temperature of 73°F. Since compression property data collected in the United States and Canada was collected in a laboratory environment, no compression strength adjustments were required.

Appendix A temperature adjustment procedures[4]

All flexural and tensile testing in the U.S. In-Grade Testing Program was conducted in the field using portable testing equipment (7). Because it was not possible to condition the lumber to one standard temperature prior to test, the temperature of the wood at time of test was recorded. This appendix documents procedures used to adjust in-grade data for changes in temperature.

In the discussion to follow we concentrate on four topics: 1) calibration of the thermometers: 2) adjustment of moisture meter readings for temperature; 3) adjustment of flexural properties for temperature and 4) adjustment of tensile properties parallel to grain for temperature. Where possible, reference will be made to published (or soon to be published) papers.

Calibration of thermometers

Temperatures were recorded for each "lot"of in-grade data.[5] A lot sometimes consisted of 10 pieces and sometimes consisted of 20 pieces. This temperature was assumed to apply to all pieces in the lot. Readings were recorded for both the wood temperature and the air temperature, usually using separate thermometers. Although both thermometers were calibrated, only the wood temperature readings were used to adjust in-grade data.

The three agencies each used different thermometers to measure the wood and air

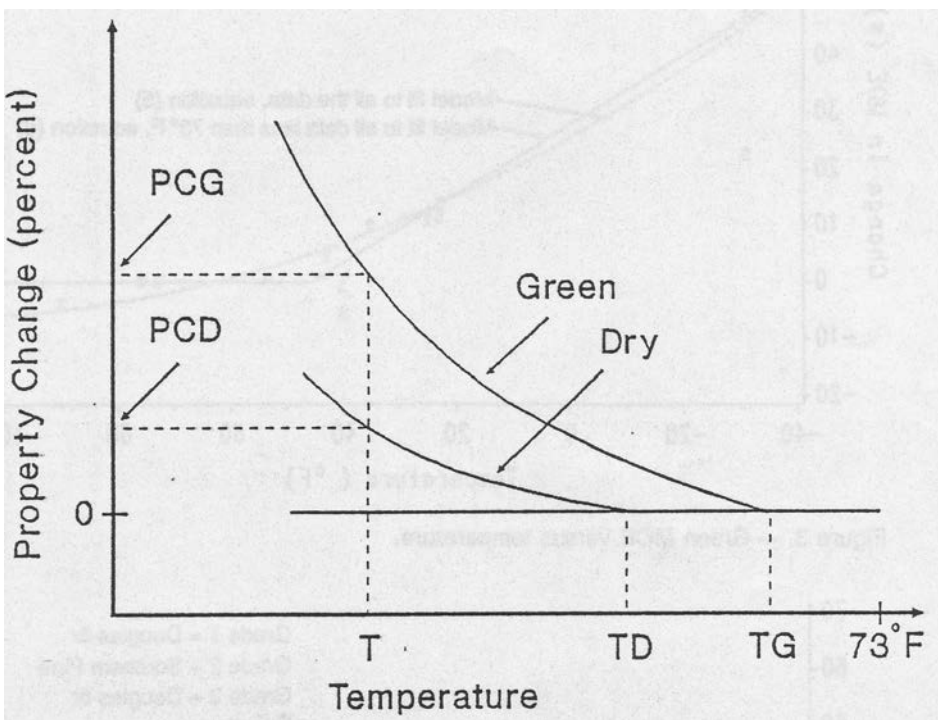

Figure 5. - Typical temperature adjustment model for in-grade data showing percentage change in property calculated with respect to a reference temperature of 73°F.

TABLE 2. - *Temperature adjustment model parameters for 2-inch dimension lumber.*

Property	Grade	Moisture content	Property change model[a]	Upper temperature limit
		(%)	(%)	(°F)
MOR	No. 2 or 3	23	$PCG = 56.89 - 1.563T + 0.00715T^2$	$TG = 46$
		12	$PCD = 0.0$	
	SS[b]	23	*	$TG = 46$
		12	$PCD = 0.0$	
MOE	All	23	$PCG = 27.91 - 0.614T$	$TG = 45$
		12	$PCD = 4.823 - 0.114T$	$TD = 42$
Tension	No. 2 or 3	23	$PCG = 38.29 - 1.05T + 0.0048T^2$	$TG = 46$
		12	$PCD = 0.0$	
	SS	23	*	$TG = 46$
		12	$PCD = 0.0$	

[a] Percentage property changes calculated with respect to a reference temperature of 73°F.
[b] SS = Select Structural.
* Use 60 percent of adjustment of No. 2 grade of corresponding property and MC.

[4] This appendix was prepared by David W. Green and James W. Evans, USDA Forest Serv., Forest Prod. Lab., Madison, Wis.

[5] Temperatures were not recorded in Part I, phase A, of the program. For these specimens the lowest daily temperature recorded by the nearest U.S. Weather Bureau recording station was used for all temperature adjustments.

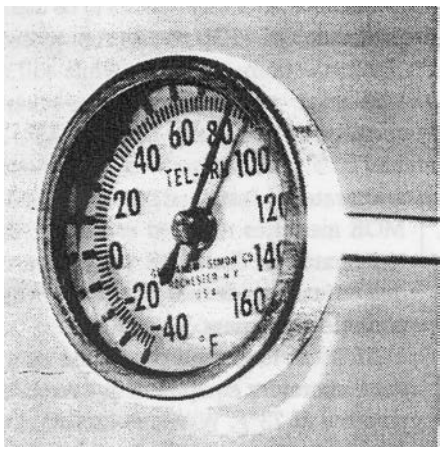

Figure 6. - Pocket thermometer used by West Coast Lumber Inspection Bureau to measure wood and air temperatures.

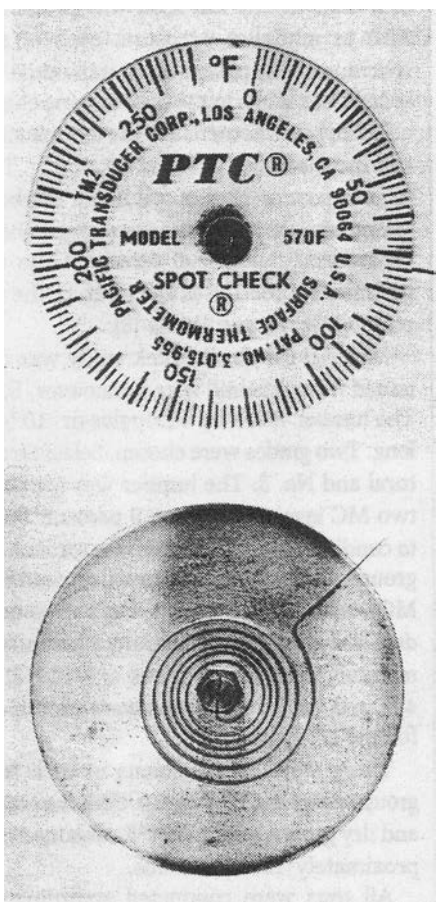

Figure 7. - Surface thermometer used by Western Wood Products Association to measure wood temperature (similar type of thermometer used by Southern Pine Inspection Bureau); front view (top); back view (bottom).

temperatures. Both the Southern Pine Inspection Bureau (SPIB) and the Western Wood Products Association (WWPA) used a standard red liquid thermometer to record air temperture. West Coast Lumber Inspection Bureau (WCLIB) used a pocket thermometer to record air temperature and to record wood temperature (Fig. 6). To record wood temperature, the WCLIB thermometer was wedged between the boards and left for a period of time. Both WWPA and SPIB used surface thermometers to messure wood temperature. Figure 7 shows the surface thermometer used by WWPA. The SPIB surface thermometer was similar.

The thermometers were calibrated at the FPL. The thermometers were placed in various conditioning chambers along with two precision laboratory thermometers. The laboratory thermometers were accurate to the nearest 0.5 degree and had been recently checked against a reference thermometer. The surface thermometers were calibrated both in the air, on a smooth wood surface, and on a rough wood surface. There was no difference in the calibration readings for the three situations.

Table 3 lists the sdjustment factors used for all thermometers. To adjust in-grade dats, all the wood temperatures recorded for the WCLIB tests were increased by 2°F. The readings for the WWPA thermometer were increased by 7°F. The error for the SPIB thermometer readings was not constant but instead decreased as the actual temperature increased (Fig. 8). A linear equation was fit to the data, and the wood temperatures were adjusted using this equation:

$$\text{Actual temperature} = 15.75016 + 0.8588482\ (\text{recorded temperature}) \quad [1]$$

where temperature is in degrees Farenheit.

TABLE 3. — *Calibration factors added to in-grade temperature readings used to correct agency thermometers.*

Agency	Wood temperature	Air temperature
	(°F)	
West Coast Lumber Inspection Bureau	+2	+2
Western Wood Products Association	+7	+2
Southern Pine Inspection Bureau	variable[a]	+2[b]

[a] Actual temperature = 15.75016 + (0.8588482) temperature recorded, r^2 = 0.997.
[b] Any data collected after January 1, 1985, used a replacement thermometer, correction = +1°F.

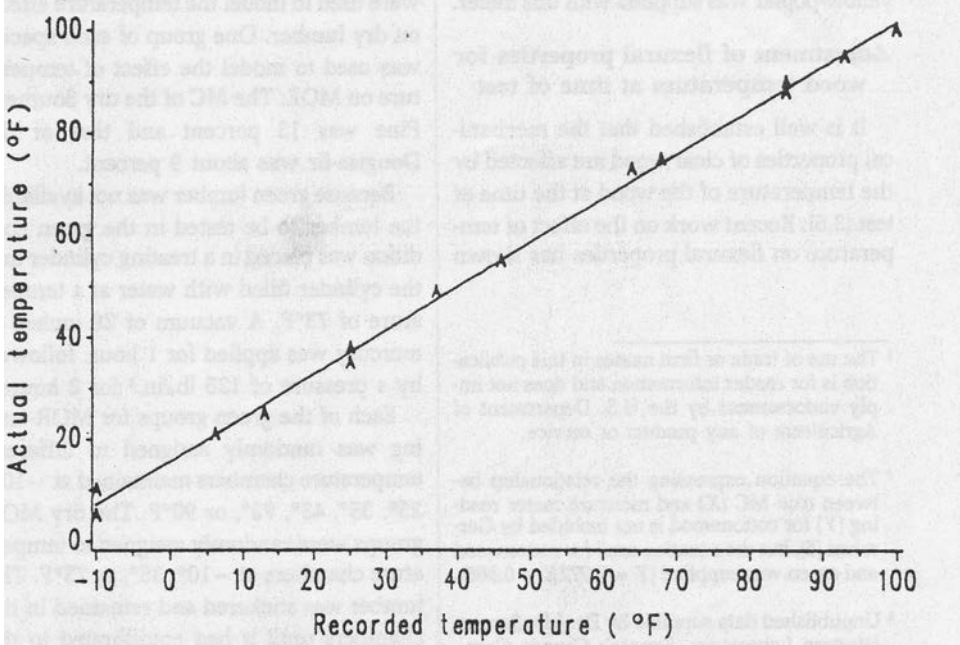

Figure 8. - Southern Pine surface thermometer calibration.

Adjustment of moisture meter readings

The MC of all flexural specimens was determined using a Delmorst[6] electrical resistance moisture meter. Because the readings were taken at the test temperatures, the meter readings were corrected to the MC at 73° F. Although published adjustment procedures are available for adjusting meter reading for change in MC (11), adjustments for all species except Southern Pine and Yellow-Poplar were made using the result of a more extensive study recently completed by Forintek Canada Corp (5). The analytical model recommended by Forintek is[7]:

$$MC_{73} = \frac{MC_T - B}{A} \qquad [2]$$

where:

$$A = 0.881\,(1.0056)^T$$
$$B = -0.567 + 0.026T - 0.000051T^2$$
$$T = °C$$

MC_{73} = moisture meter reading adjusted to 73°F

MC_T = moisture meter reading at wood temperature, T

MC readings for Southern Pine and Yellow-Poplar were measured by the SPIB. These Delmorst meters were supplied with a dial face already corrected for Southern Pine. The species adjustment factor for yellow-poplar was supplied with this meter.

Adjustment of flexural properties for wood temperature at time of test

It is well established that the mechanical properties of clear wood are affected by the temperature of the wood at the time of test (3,6). Recent work on the effect of temperature on flexural properties has shown that the properties of dimension lumber are also sensitive to wood temperature at time of test (8). Thus, it was necessary to adjust in-grade data for the effect of temperature on flexural properties. In addition to the data from the study by Green and Evans (8), unpublished data were also available from a study conducted by Forintek Canada Corp.[8] The In-Grade Technical Committee decided that the data from both studies would be used to derive an adjustment model.

Summary of experimental procedures

The Forest Products Laboratory study utilized both Douglas-fir and Southern Pine dimension lumber. The Southem Pine lumber was 2 by 4 inches, commercially graded as No. 2 Dense. The Douglas-fir was graded as No. 1 for strength-reducing reasons in the middle 24 inches of the span. Because this is not typical No. 1 grade lumber, this lumber will be called "special" in this appendix. Prior to testing, the lumber for each species was separated into groups of equal size based on ranked MOE values. There were 50 specimens in each group (except the Douglas-fir MOE that had 75 specimens).

Six groups for each species were used to model the effect of temperature on the MOR of green lumber and three groups were used to model the temperature effects on dry lumber. One group of each species was used to model the effect of temperature on MOE. The MC of the dry Southern Pine was 13 percent and that of the Douglas-fir was about 9 percent.

Because green lumber was not available, the lumber to be tested in the green condition was placed in a treating cylinder and the cylinder filled with water at a temperature of 73°F. A vacuum of 28 inches of mercury was applied for 1 hour, followed by a pressure of 125 lb./in.^{2} for 2 hours.

Each of the green groups for MOR testing was randomly assigned to different temperature chambers maintained at - 10°, 25°, 35°, 43°, 73°, or 90°F. The dry MOR groups were randomly assigned to temperature chambers at - 10°, 35°, or 73°F. The lumber was stickered and remained in the chambers until it had equilibrated to the chamber temperature.

The lumber of each species to be used for determination of MOE was first placed in the temperature chambers while still dry. The MOE measurements were taken at temperatures of - 10°. 25°. 35°. 43°. 73°, and 90°F. The lumber was then saturated with water as described previously and the MOE measures repeated at each of these temperatures. The MOE tests were conducted just outside the test chambers using portable equipment.

All MOR tests were conducted on standard laboratory equipment at a room temperature of 73°F. With one exception, the specimens were tested on edge in third-point bending according to procedures given in ASTM D 198 (1). To minimize exposure to the laboratory temperatures, testing was done at a rate of crosshead motion of 2 in./min. The test span was 60 inches. Also to minimize exposure, each of the specimens was placed in an individual insulated box while in the conditioning chamber. The box was carried to the test machine and the specimen removed for testing. The total exposure of the specimen to room temperature prior to failure averaged about 45 seconds. Additional details of the experimental procedures are given in the report by Green and Evans (8).

Material for the Forintek study was obtained from one mill near Vancouver, B.C. The lumber was 2 by 6 Douglas-fir, 10 feet long. Two grades were chosen, Select Structural and No. 3. The lumber was tested at two MC levels, green and 9 percent. Prior to conditioning, the lumber was sorted into groups of 50 specimens each using ranked MOE values. The groups were then randomly assigned to temperature chambers maintained at temperatures of –31°, 23°, 40°, and 76°F (two groups were combined for the 76°F group).

There were 50 specimens in each test group except the 73°F group. Both the green and dry groups tested at 73°F contained approximately 100 specimens.

All tests were conducted according to procedures of ASTM D 198 (1), except that the rate of crosshead motion was 0.6 in./min. To minimize exposure to room temperature, the test machine was positioned outside the condition chamber and the specimens removed one at a time.

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[6] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

[7] The equation expressing the relationship between true MC (X) and moisture meter reading (Y) for cottonwood is not included by Garrahan (5), but the equation used for cottonwood and aspen was supplied ($Y = 0.772X + 0.866$).

[8] Unpublished data supplied by Dr. J.D. Barrett, Western Laboratory, Forintek Canada Corp., Vancouver, B.C., Canada.

TABLE 4. - *Effect of temperature on the flexural properties of 2- by 4-inch dimension lumber (8).*

Species and grade	Approximate[a] average moisture content	Temperature at test	MOR Mean	MOR SD[d]	MOE[b] Mean	MOE[b] SD	MOE[c] from MOR samples Mean	MOE[c] from MOR samples SD
	(%)	(°F)	----- (lb./in.²) -----		--- (10⁶ lb./in.²) ---		--- (10⁶ lb./in.²) ---	
Southern Pine No. 2 dense	145	-10	8,880	2,749	2.030	0.338	1.857	0.393
		25	6,066	1,898	1.331	0.290	1.399	0.317
		35	5,753	1,875	1.318	0.311	1.320	0.277
		43	5,713	1,734	1.257	0.284	1.283	0.264
		73	5,117	1,178	1.201	0.265	1.227	0.270
		90	5,027	1,383	1.152	0.271	1.190	0.263
	13	-10	8,162	4,131	-	0.252	1.686	0.335
		25	-	-	1.613	0.352	-	-
		35	7,501	2,720	1.600	0.357	1.597	0.342
		43	-	-	1.541	0.240	-	-
		73	7,460	2,491	1.505	0.337	1.482	0.339
		90	-	-	1.504	0.346	-	-
Douglas-fir Special	10	-10	4,721	2,755	1.606	0.290	1.622	0.266
		35	4,407	1,990	1.531	0.297	1.562	0.280
		43	-	-	1.487	0.292	-	-
		50	-	-	1.487	0.292	-	-
		73	4,785	2,054	1.478	0.297	1.563	0.286
		90	-	-	1.434	0.270	-	-

[a] Actual moisture content varies slightly with property and temperature group. Exact value given in (8).
[b] Same pieces tested at all temperatures.
[c] Samples for each temperature "matched" by MOE prior to testing.
[d] SD = standard deviation.

TABLE 5. - *Effect of temperature on the flexural properties of 2- by 6-in. Douglas-fir dimension lumber.*

Grade	Average MC	Temperature at test	MOR Mean	MOR SD	MOE Mean	MOE SD
	(%)	(°F)	-- (10³ lb./in.²) --		-- (10⁶ lb./in.²) --	
Select Structural	72	-31	12.104	2.882	2.055	0.423
		23	7.790	1.924	1.871	0.364
		40	6.660	1.691	1.580	0.282
		76	7.078	1.590	1.678	0.331
	11.2	-31	10.440	3.914	2.026	0.360
		23	10.875	3.278	1.907	0.384
		40	9.798	2.815	1.920	0.374
		76	10.352	2.547	1.968	0.399
No. 3	80	-31	7.633	3.021	1.513	0.335
		23	4.713	1.647	1.166	0.279
		40	3.371	1.582	1.015	0.248
		76	3.590	1.345	1.025	0.237
	11.8	-31	6.009	2.965	1.326	0.349
		23	5.593	2.665	1.208	0.301
		40	4.859	2.381	1.194	0.308
		76	4.679	2.251	1.228	0.315

Prior to publication of the Forintek study, additional details of the experimental procedures may be found in Aplin and others (2).

Experimental results

Tables 4 and 5 present a summary of the experimental results of the Forintek and FPL studies. Results are not presented in Table 4 for the resaturated Douglas-fir, because it was not possible to bring the MC at the center of the boards above the fiber saturation point (8).

Modulus of rupture. - Temperature can have a significant effect on the MOR of dimension lumber (Tables 4 and 5). The temperature effect is especially noticeable with green lumber. For green Southern Pine lumber, the MOR value at - 10°F is 72 percent higher than at 73°F (Table 2). This is almost identical to the increase anticipated for green clear wood (Table 6). For green Select Structural Douglas-fir, the mean increase in MOR to - 31°F is 71 percent compared to the value at 76°F. For green No. 3 Douglas-fir it is 113 percent (Table 5). On the basis of clear wood tests we would have expected an increase in MOR to - 31°F (Table 4) of about 93 percent.

The MOR of dry lumber is not very sensitive to changes in temperature. The mean value for Southem Pine only increased about 9.5 percent when tested at –10°F (Table 4) as compared to an expected increase of about 23 percent for clear wood (Table 6). The MOR of "special" Douglas-fir decreased about 1 percent (Table 4). For dry Select Structural Douglas-fir, the MOR at –31°F is only about 1 percent higher than that at 76°F, but the MOR of No. 3 Douglas-fir is 28 percent higher (Table 5). The anticipated clear wood increases to -31°F should be about 30 percent.

With only 50 specimens per temperature group, it is not possible to draw definitive conclusions about the effect of temperature on MOR at various levels of the cumulative frequency distribution. Based on the percent change in MOR relative to the properties at the base temperature, the green Southern Pine data suggests that the effect is less at the lower percentile levels. However, the results for Douglas-fir are not consistent.

In general, the Douglas-fir MOR values from the Forintek study decrease from 76 to 40°F and then increase to –31°F(Tables 5 and 7). Whether this is a real trend or an

anomaly of this data set is not known. This trend is generally not seen with the Southern Pine data or with clear wood data.

Modulus of elasticity. - As with MOR, MOE increases with decreasing temperature. For green Southern Pine, the mean MOE at -10°F is 69 percent higher than that at 73°F (Table 4). For green Douglas-fir, the MOE of Select Structural lumber at −31°F is 22 percent higher than that at 76°F. For green No. 3 lumber, the increase to −31°F is 48 percent (Table 5). For clear wood, the expected increase in green MOE is about 33 percent to -10°F and 43 percent to -31°F (Table 6).

The MOE of dry lumber is much less sensitive to change in temperature than is that of green lumber. In the FPL study (Table 4), the MOE at -10°F is 11 percent higher than that at 73°F for dry Southern Pine and 9 percent higher for Douglas-fir. In the Forintek study (Table 5), the mean MOE of Select Structural lumber is 3 percent higher at −31°F than at 76°F. For No. 3, the increase in MOE is 8 percent to −31°F. The anticipated increase in clear wood MOE is 11 percent to −10°F and 14 percent to −31°F (Table 6).

TABLE 6. - *Approximate middle trend effects of temperature on mechanical properties of clear wood at various moisture conditions (6).*

Property	Moisture condition	Relative change in mechanical property from 20°C (68°F) (%) At −50°C (−58°F)	At +50°C (122°F)
Modulus of elasticity parallel to grain	0	+11	−6
	12	+17	−6
	Green	+50	–
Modulus of elasticity perpendicular to grain	6	–	−20
	12	–	−35
	≥20	–	−38
Shear modulus	Green	–	−25
Bending strength	≤4	+18	−10
	11 to 15	+35	−20
	18 to 20	+60	−25
	Green	+110	−25
Tensile strength parallel to grain	0 to 12	–	−4
Compressive strength parallel to grain	0	+20	−10
	12 to 45	+50	−25
Shear strength parallel to grain	Green	–	−25
Tensile strength perpendicular to grain	4 to 6	–	−10
	11 to 16	–	−20
	≥18	–	−30
Compressive strength perpendicular to grain at the proportional limit	0 to 6	–	−20
	≤10	–	−35

Analytical models

Previous work on developing analytical models to describe the effect of temperature on flexural properties (8) suggests two approaches: 1) analytical models based on the absolute property at the test temperature, and 2) analytical models based on the change in property at the test temperature relative to the property at a base temperature. Review of the previous work, as well as review of the new data supplied by Forintek, indicated that a model based on the percentage change in property relative to the property at 73°F would tend to minimize differences across percentile lev-

TABLE 7. - *MOR of green lumber at various temperatures relative to the MOR at the base temperature.*[a]

Species	Grade	Temperature (°F)	Basis for comparison	Comparison of values at various percentile levels $\bar{X}$	5	10	25	50	75	90	95
Southern Pine	No. 2D	−10	Difference[b]	3,682	1,481	1,438	2,374	2,950	4,787	6,149	6,589
			Percent change[c]	71.9	42.9	38.9	56.4	57.1	79.0	91.0	92.8
		25	Difference	948	−438	51	538	1,083	986	2,116	2,160
			Percent change	18.5	−12.7	1.4	12.8	21.0	16.3	31.3	30.4
		35	Difference	634	−1,226	−752	590	590	985	1,557	1,860
			Percent change	12.4	−35.5	−20.3	14.0	11.4	16.2	23.0	26.2
		43	Difference	595	−1,015	−592	243	953	883	1,214	1,419
			Percent change	11.6	−29.4	−16.0	5.8	18.5	14.6	18.0	20.0
		90	Difference	−91	−962	−388	54	−183	−423	438	617
			Percent change	−1.8	−27.9	−10.5	1.3	−3.5	−7.0	6.5	8.7
Douglas-fir	Select Structural	−31	Difference	5,025	3,216	3,638	4,077	5,377	6,421	6,502	6,908
			Percent change	71.0	80.8	93.0	70.5	75.3	80.0	71.3	70.6
		23	Difference	711	104	963	1,011	771	1,101	979	1,585
			Percent change	10.0	2.6	24.6	17.5	10.8	13.7	10.7	16.2
		40	Difference	−419	−213	397	−97	563	−648	−444	378
			Percent change	−5.9	−5.4	10.1	−1.7	7.9	−8.1	−4.9	3.9
	No. 3	−31	Difference	4,043	863	1,127	3,396	4,186	5,120	5,804	6,413
			Percent change	112.6	55.9	62.2	142	114.4	113.2	105.8	107.9
		23	Difference	1,123	491	633	908	1,099	1,488	1,474	1.548
			Percent change	31.3	31.8	34.9	41.0	30.0	32.9	26.9	26.1
		40	Difference	−219	−228	−312	−202	−491	−403	125	757
			Percent change	−6.1	−14.8	−17.2	−8.4	−13.4	−8.9	2.3	12.7

[a] 73°F for Southern Pine and 76°F for Douglas-fir.
[b] Differences are expressed in terms of 10^6 lb./in.^{2} (MOR at indicated temperature − MOR at base temperature.)
[c] (Difference − value at base temperature) × 100.

TABLE 8. - *MOE of green lumber at various temperatures relative to the MOE at the base temperature.*[a]

Species	Grade	Temperature (°F)	Basis for comparison	Comparison of values at various percentile levels $\bar{X}$	5	10	25	50	75	90	95
Southern Pine	No. 2D	−10	Difference[b]	0.829	0.586	0.702	0.793	0.865	0.898	0.903	0.788
			Percent change[c]	69.0	73.9	79.1	76.8	72.8	66.3	58.6	45.9
		25	Difference	.130	.101	.105	.107	.140	.128	.140	.085
			Percent change	10.8	12.7	11.8	10.4	11.8	9.5	9.1	4.9
		35	Difference	.117	.085	.078	.104	.096	.102	.145	.032
			Percent change	9.7	10.7	8.8	10.1	8.1	7.5	9.4	1.9
		43	Difference	.056	.044	.007	.054	.072	.048	.039	−.063
			Percent change	4.7	5.5	0.8	5.2	6.1	3.5	2.5	−3.7
		90	Difference	−.049	−.061	−.041	−.060	−.061	−.062	−.027	−.132
			Percent change	−4.1	−7.7	−4.6	−5.8	−5.1	−4.6	−1.8	−7.7
Douglas-fir	Select Structural	−31	Difference	.377	.237	.229	.375	.362	.405	.512	.623
			Percent change	22.5	21.7	19.1	25.6	21.3	20.9	24.4	28.7
		23	Difference	.193	.081	.117	.172	.206	.185	.227	.314
			Percent change	11.5	7.4	9.8	11.7	12.1	9.5	10.8	14.5
		40	Difference	−.098	−.022	.005	−.091	−.137	−.147	−.129	−.960
			Percent change	−5.8	−2.0	0.4	−6.2	−8.1	−7.6	−6.1	−4.4
	No. 3	−31	Difference	.488	.299	.283	.490	.453	.556	.592	.690
			Percent change	47.6	46.7	40.4	57.6	44.6	45.6	44.3	46.3
		23	Difference	.141	.093	.063	.124	.142	.160	.253	.198
			Percent change	13.8	14.5	9.0	14.6	14.0	13.4	19.0	13.1
		40	Difference	−.010	−.042	−.008	0.00	−.006	−.022	−.008	0.00
			Percent change	−1.0	−6.6	−1.1	0.00	−0.6	−0.2	−0.6	0.00

[a] 73°F for Southern Pine and 76°F for Douglas-fir.
[b] Differences are expressed in terms of 10^6 lb./in.^{2} (MOR at indicated temperature − MOR at base temperature.)
[c] (Difference − value at base temperature) × 100.

els (Tables 7 and 8). This is the approach taken in this appendix.

Because the properties of lumber are a function of both MC and temperature, there is an obvious need to predict properties at MCs other than those used in this study. To adjust in-grade data, a linear interpolation was made between the properties reported for green lumber and those for dry lumber. As in the study by Green and Evans (8), the average MC for dry lumber is assumed to be 12 percent. For MOR, we thus interpolate between the property green and no change at 12 percent. The same is done for MOE except that the MOE temperature curve at 12 percent is not flat.

Modulus of rupture. - Quadratic equations were fit to the MOR data for individual grades expressed as a percentage of the properties at the base temperature (Fig. 4). Based on these results, it was decided to combine the results for No. 2 and No. 3 grade material. The quadratic equation for the green MOR of the combined No. 2 and No. 3 data is:

$$\% \text{ change in MOR} = 53.8944 - 1.58316T + 0.011030T^2 \quad [3]$$

where Tis expressed in °F. After investigating several options, Select Structural lumber was modeled as 60 percent of the value given by Equation [3].

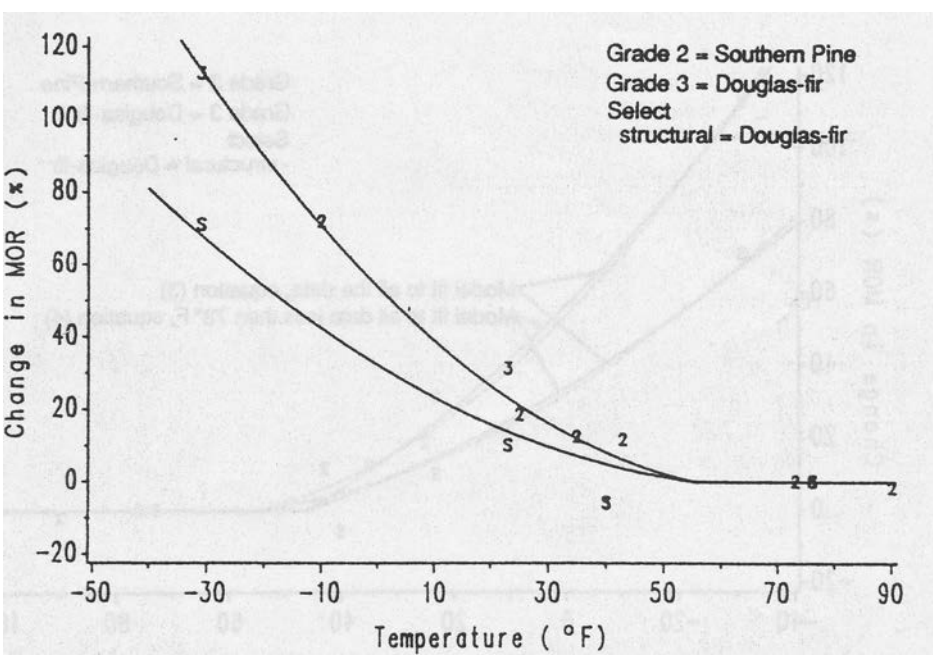

Figure 9. - Fitted MOR versus temperature percentage model - green data.

Quadratic models fit to the green MOR data fall below the zero percent change line over some portion of the temperature range (Fig. 1). The modulus reaches a minimum from 50° to 75°F (depending upon grade). Past this point the lines increase and eventually are above the zero line. It does not seem logical that green properties should increase with increasing temperature. Gerhards' (6) results for clear wood suggest that at best the curve may tend to flatten out over some midrange of temperature before

continuing its downward trend. Therefore, we decided to assume that MOR is independent or temperature above 56°F [Fig. 9).

In deriving the curves shown in Figure 9 all of the data were used to establish the quadratic portion of the curve [Equation [3]). An alternative procedure would be to use only the data below the reference temperature to establish the quadratic equation and to use the reference data only to establish the cutoff temperature. This procedure in effect "weights" the curves toward the Douglas-fir results. Using only the data below 73°F, the quadratic portion of the curve becomes:

$$\% \text{ change in MOR} = 56.8904 - 1.56207T + 0.0071543T^2 \quad [4]$$

The cutoff point for Equation [4] is 46°F.

There is little difference between the results predicted by Equations [3] and [4] over much of the temperature range (Fig. 10). Within the range of the data, the maximum difference is about 4.5 percent at 46°F. Selection of a particular equation should be governed by concerns for the intended application. Because most of the green lumber that was tested at lower temperatures was Douglas-fir, it was the consensus of the In-Grade Technical Committee that the curve fit to the data below 73°F, Equation [4], would be used in adjusting in–grade data.

In the previous study by Green and Evans (8), it was concluded that MOR was independent of temperature at an MC of about 12 percent. Inspection of Figure 2 indicates that, although some curves have a slightly positive slope and some a slightly negative dope, it is still reasonable to assume a zero slope for lumber at an MC of 12 percent.

Modulus of elasticity. - Equations were fit to the MOE data using the same approaches as for MOR. For green MOE, a quadratic equation provided the best fit to all the data:

$$\% \text{ change in MOE} = 25.54972 - 0.564765T + 0.00250466T^2 \quad [5]$$

The cutoff point is 63°F. A straight line provided the best fit to the green MOE data below 73°F:

$$\% \text{ change in MOE} = 27.91398 - 0.613821T \quad [6]$$

with a cutoff point of 45°F. Within the range

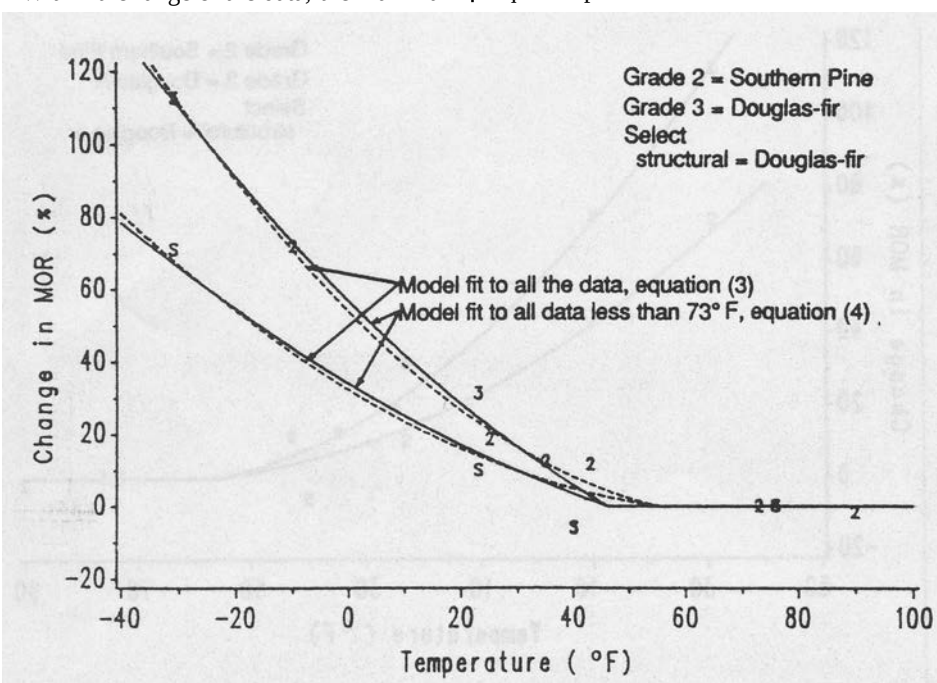

Figure 10. - Fitted MOR versus temperature percentage model - green data.

TABLE 9. - *Effect of temperature on the tensile strength parallel to the grain of Southern Pine 2 by 4s.*

Temperature at test	Moisture content: Average	Moisture content: Minimum core	Maximum tensile stress: Mean	SD	Minimum	Maximum
(°F)	(%)		(lb./in.²)			
73	117	52	4,544	1,594	1,379	9,059
−10	121	48	6,784	2,797	2,990	14,348

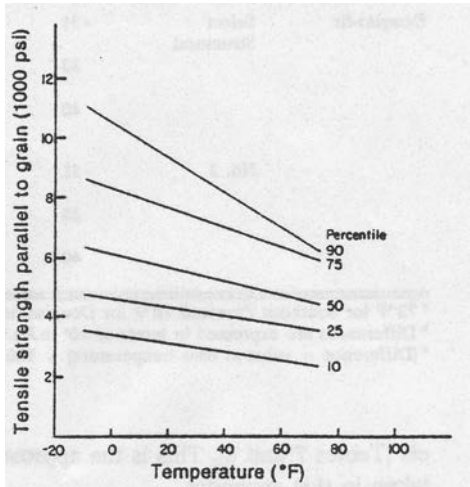

Figure 11. - Effect of temperature on the tensile strength parallel to grain of green Southern Pine 2 by 4s at various percentiles of the cumulative frequency distribution.

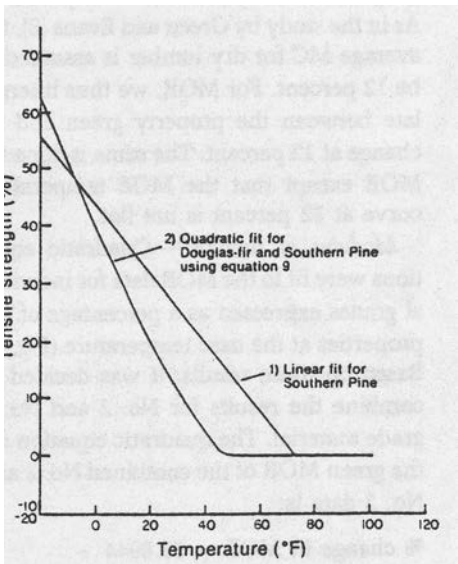

Figure 12. - Effect of temperature on tensile strength parallel to grain of green lumber.

of the test data, the maximum difference between Equations [5] and [6], considering the equations to be cut off at 0 percent change in MOR, is about 5 percent (Fig. 3).

A straight line provided the best fit to the dry MOE data. Using all the data, the linear equation is:

$$\% \text{ change in MOE} = 4.802662 - 0.081546T \quad [7]$$

with a cutoff temperature of 59°F. Using only the data below 73°F, the equation for dry MOE is:

$$\% \text{ change in MOE} = 4.843212 - 0.113983T \quad [8]$$

with a cutoff temperature of 42°F (Fig. 4).

As with MOR, it was decided to use Equations [6] and [8] to adjust in-grade data.

Adjustment of tensile strength parallel to grain for wood temperature at time of test

Unlike flexural properties, the effect of colder temperatures on the tensile strength of clear wood parallel to the grain is not well established (6,9). Recently, however, a study was completed on the effect of temperature on the tensile strength of lumber parallel to the grain (9). This study forms the basis for adjustment procedures used with the in-grade data.

Summary of experimental procedures

This study utilized the 50 MOE specimens that were available after the completion of the FPL flexural study described in the previous section. At the conclusion of the flexural study, the green specimens were stored for 30 days at 35°F. The specimens were next allowed to come to room temperature and then resaturated with water as described previously. Using the ranked MOE procedure, the specimens were separated into two groups. One group was tested at room temperature; the other group was equilibrated to - 10°F prior to testing at 73°F.

The specimens were tested at a rate of loading of 400 lb./in^2/sec. The average time to failure was 45 seconds. No frozen specimen was exposed to room temperature for more than 90 seconds prior to failure.

Experimental results

As was observed with MOR, tensile strength of green lumber is sensitive to changes in temperature. At - 10°F, the tensile strength of green Southern Pine is 49.3 percent higher than that at 73°F (Table 9). Also, as with MOR (8), the stronger lumber is more sensitive to changes in temperature than is weaker lumber. Comparing extreme order statistics, the minimum value at - 10°F is 46.1 percent higher than that at 73°F. The maximum MOR value at - 10°F is 63.1 percent higher than at 73°F. This fanning of percentile levels is shown graphically in Figure 11.

Freezing also changed the nature of the tensile fracture. At room temperature, the stronger pieces of lumber usually exhibited splinter fractures. At - 10°F, the stronger pieces usually broke in a brash manner with little indication of splinter fracture surfaces. Of course, the lower strength pieces that contained large knots usually failed in a brash manner whether at - 10°F or at 73°F.

Analytical models

To adjust in-grade data to a common temperature, it was necessary to develop a model that was applicable at all levels of the strength distribution and applicable at all MC levels. Since only a very limited amount of material was available for testing, some judgment was required in formulating the model.

The fanning effect of the strength-temperature relationship has already been noted. If the sample size had been larger, it would be possible to model strength changes at various levels of the cumulative frequency distribution. With only 25 specimens per temperature, such models would not be very reliable. Maximum reliability is achieved by modeling mean trends. The fanning of the tensile strength-temperature relationship with increasing percentile levels can be minimized by expressing the strength at –10°F as a percentage of the strength at 73°F.

Figure 12 presents several alternatives for adjusting tensile strength for changes in wood temperature at time of test. The most conservative estimate would be to connect a straight line between the percent change in tensile strength at - 10°F and that at 73°F (curve 1). However, professional judgment indicates that such a relationship would be overly severe. In our previous study on flexural properties, a nonlinear relationship was found between bending strength and temperature. Historically, tensile strength has been assumed to vary proportional to flexural strength (4). Studies on the effect of MC on the flexural (10) and tensile (12) strength of lumber also indicate a correspondence between the forms of the tensile and flexural property-MC relationship. Therefore, it seems reasonable to assume [illegible] strength-temperature relationship. The [illegible] higher than that at 73°F. For tensile strength, the increase was 49.3 percent. Thus, the increase in tensile strength was 46 percent of the change in MOR. Estimating the tensile strength as a percentage of the previously developed relationship for MOR allows us to calculate the tensile strength of lumber at any combination of temperature and MC.

Curve 4 (Fig. 12) is the tensile strength-temperature relationship estimated as a function of the model used to adjust in-grade flexural data (Equation [4]). For No. 2 grade lumber, this equation is 67.3 percent of Equation [4], or:

$$\% \text{ change in tensile strength} = 38.2872 - 1.05127T + 0.0048148T^2 \quad [9]$$

The corresponding equation for the tensile strength of Select Structural lumber as a function of temperature was assumed to be 60 percent of Equation [9].

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Errata

Barrett, J. David; Green, David W.; Evans, James W. 1989. Temperature adjustments for the North American in-grade testing program. In: In-grade testing of structural lumber; Proceedings 47363. Madison, WI: Forest Products Research Society: 27–38.

Property change model equations for MOE are represented incorrectly in Table 2 (p. 30). That portion of the table should read as follows:

TABLE 2 .– *Temperature adjustment model parameters for 2-inch dimension lumber.*

Property	Grade	Moisture content (%)	Property change model	Upper temperature limit (°F)
MOE	All	23	$PCG = 27.91 - 0.614T$	$TG = 45$
		12	$PCD = 4.823 - 0.114T$	$TD = 42$